HYDROLOGICAL STUDIES OF LAKE NAINITAL, KUMAUN HIMALAYAS, UTTAR PRADESH

FINAL REPORT OF THE PROJECT

SPONSORED BY
DEPARTMENT OF ENVIRONMENT, GOVERNMENT OF UTTAR PRADESH
THROUGH
NAINITAL LAKES REGION SPECIAL AREA DEVELOPMENT AUTHORITY



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NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247667
1998 - 99

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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 sediment in significant amounts. In addition, various anthropogenic activities viz. deforestation, construction activities and improper management of wastes have aggravated the rate of sediment delivery, endangering the useful life span of the lake.

The Hydrological Studies of Lake Nainital was aimed to understand the complexities of different processes taking place in Lake Nainital. The important aspects which need to be well understood for the better planning and management of a surface water body are: the water sources and availability of water at different times (water balance), sedimentation pattern and water pollution aspects. It has been stated by various investigators that Nainital lake is getting filled- up at a high rate and the availability of lake water is being reduced. It has also been predicted that if the present rate continues, the lake will be almost completely filled- up in around 380 years. The present report contains the details of various investigations carried out related to water balance, sedimentation rates and estimation of lake life, water quality aspects, hydrodynamics and long term meteorological variations by the National Institute of Hydrology, Roorkee (NIH). Besides conventional techniques, isotopic and remote sensing techniques have also been employed to obtain the precise and correct information about various processes.

Efforts have been made to bring out the maximum possible relevant information about Lake Nainital which is required to manage the lake in an efficient manner. Presently, it has been observed that the most of the sediment reaches the lake deposits at the entry points and comparatively less sediment reaches the deeper portions of the lake. Therefore, if the deposited sediment in the deltas are removed every year, the lake may survive for longer period (around 2200 years as reflected by dating studies). Similarly, the water input to the lake remains sufficient even after the decrease of about 20 - 25% of rainfall in the past 40 years in lake catchment. Phosphorous has

been found as the limiting pollutant in case of Lake Nainital and its internal recycling during winter season is one of the important phenomenon. Some useful suggestions have been made to restrict the external loading and internal recycling of the phosphorous. Lake Nainital has been found most eutrophied lake among the five lakes of Kumaun region. Therefore, in order to reduce the eutrophication level of Lake Nainital, the drainage of lake water from the hypolimnion instead of epilimnion has been suggested by employing suitable siphoning device.

This report has been prepared by Dr. Bhishm Kumar, Sc. E and Sri Rm. P. Nachiappan, PRA at National Institute of Hydrology with the assistance of Dr. S. P. Rai, Sri Vinod Kumar and Sri B. C. Dongarakoti, Sri. Anurag Pattnaik and Sri. Y.S. Rawat who have worked under the Nainital lake Project in various capacities. The contribution of Sri U. Saravana Kumar, Dr. S.V. Navada and other scientists from BARC, Mumbai in the analysis the sediment samples for Cs-137 and Pb-210 composition and in the interpretation of the results is highly appreciated. Assistance was also rendered by the staff of water quality laboratory of NIH in the collection and analysis of samples and Soil water laboratory in conducting certain soil / sediment related experiments. The meteorological data was provided by the UP State Observatory.

It is hoped that this report will provide useful information on the status of sedimentation and other processes going on in the lake and suggestions for possible remedial measures to the interested investigators, as well as the authorities associated with general and water supply management of Nainital lake.

(S. M. SETH)
DIRECTOR

ACKNOWLEDGMENTS

I am grateful to the Department of Environment, Govt. of U.P., which funded the project titled "Hydrological Studies of Lake Nainital" to the National Institute of Hydrology, Roorkee. Specially, my thanks are due to Dr. I.P. Singh, Director and Sri H. S. Yaduvansi, Joint Director - cum - Chief Appraisal for providing some valuable suggestions to improve the quality of this report. I am also thankful to Sri O P Verma, Deputy Director and Sri Umesh Chandra Srivastava, Asst. Director, Department of Environment, Govt. of U.P. who always encouraged and provided necessary information to complete this project.

I express my sincere thanks to the Chairman and Secretary of Nainital Lakes Region Special Area Development Authority (NLRSADA), Nainital who always showed their interest and provided necessary support without which it was not possible to complete the field work carried out at Nainital. Specially, I am thankful to Sri U D Choube, the then Secretary, NLRSADA, and Sri Lokesh Kumar, Secretary NLRSADA who were very cordial and provided official and moral support that made this project successful. The project grant which in turn was routed through NLRSADA, was also released timely, for which I express my sincere thanks to Secretary as well Accounts Officer of NLRSADA, Nainital. I also express my thanks to the staff of NLRSADA who directly and indirectly helped during the fieldwork carried out for this project at Nainital.

I feel deeply obliged by the Jal Sansthan Division, Nainital for providing a room at Mallital bank of Lake Nainital where the datalogger and other sensors were installed for the continuous recording of the hydrometeorological data. I express my sincere thanks to the Executive Engineer, Assistant Engineer and the concerned Junior Engineer of Jal Sansthan Division, Nainital for this great help. I am also thankful to the Executive Engineer and other staff of U.P. P.W.D., Nainital Division, who provided the required 100 years hydrological data, related to Lake Nainital and springs including other valuable records of British period. The Jal Nigam Division, Nainital also provided the necessary

information about the construction of deep tube-wells at the Mallital Bank of Lake Nainital. I express my thanks to the Executive Engineer, Assistant Engineer and other staff of U.P. Jal Nigam Division, Nainital for their help extended during the project period.

It will be a great fault on my part, if I do not pay my gratitude to Prof. K. S. Valdiya, the then Professor of Geology at the Department of Geology, Kumaun University, Nainital, who provided necessary information and guidance at the initial stage of this project. My thanks are also due to Prof. Goel (Head), Dr. Sharma, Dr. Pant and Dr. Kotlia of Geology Department, Kumaun University, who held very fruitful discussions at various occasions and were always ready to help our project team. Director, U.P. State Observatory at Manora Hills, Nainital was kind enough to provide the required meteorological data and to allow our project team to stay in his guesthouse. I express my thanks to the Director, U.P. Observatory at Manora Hills, Nainital, his colleagues Dr. Wahabuddin and other scientists and staff for timely help. I am also thankful to the management and staff of Nainital Club who extended their courtesy and allowed us to stay most of the time at Nainital Club during the field trips made to Nainital.

Prof. Satish Chandra, the then Director, NIH was instrumental in getting this project sanctioned by the Govt. of U.P. I am very much thankful to Prof. Satish Chandra for his valuable official support, encouragement and guidance at the initial stage of this project.

Dr. S M Seth, Director, NIH always encouraged to complete this project successfully. He was always ready to provide necessary official support and guidance without which it was not possible for me to complete this project. I express my sincere thanks to Dr. S M Seth, Director, NIH for his great support and guidance.

I am thankful to Sh. Rm.P. Nachiappan, PRA for his commendable contribution in the fieldwork as well as in the analyses of data and in the preparation of this report. My thanks are also due to Dr. S P Rai, Project Officer, Sri Vinod Kumar, T.A., Sri Bhuwan

Chandra Dongarakoti, JTA, Sri Sanjay Bharti, Sri Suresh Chand Joshi, JTA, all project staff, who contributed a lot in the field work and data preparation/analyses including other laboratory works. I also express my thanks to Sri Jagmohan, JRA, Sri Rajeev Gupta, S.R.A. and, Sri Rakesh Kumar Goel, Tech. Gr. II who also helped in the field work and laboratory analyses of the water samples. My thanks are due to Sri Yogendra Kumar, Technician Gr. II and Shyam Kumar, Technician Gr. III who helped in the installation of various instruments in Nainital lake catchment. Thanks are also due to Sri Kameshwar Tiwari, Driver for safe driving in the ghat roads during many of the field trips in difficult conditions and also for lending a helping hand to the project staff in transporting the instruments to the field.

I am also thankful to Dr. Rajiv sinha and Dr. C. K. Jain for being associated with project in the initial stages as Team Members. I am thankful to Dr. S. Balakrishnan, the then Assistant Professor and Dr. Rm. Manickavasagam, Associate Professor, Department of Earth Sciences, Univ. of Roorkee for providing laboratory facilities to analyse lake water samples for water quality parameters. Thanks are also due to Dr. Pradeep Kumar, Associate Professor and Sri Wudneh Ayele, Trainee Officer, Civil Engineering Department, Univ. of Roorkee for the valuable study of eutrophication level in Kumaun lakes, carried out by them, the results of which have been incorporated in this report.

At last but not the least, I express my thanks to the Scientists and staff of Nuclear Hydrology Division, Water Quality Laboratory and Soil - Water Laboratory at the National Institute of Hydrology who helped in various ways in the completion of this project.

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Sc. E & Project Co-ordinator

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Appendix A: Geohydrological characteristics of the Nainital lake catchment

Appendix B: Water balance of Lake Nainital

Appendix C: Rates and pattern of sedimentation in Lake Nainital

Appendix D: Water quality of Lake Nainital and surrounding springs

Appendix E: Hydrodynamics of Lake Nainital

Appendix F: Recharge sources, discharge points and interconnection of springs with Lake Nainital

1.0 INTRODUCTION

Nestling snugly at an altitude of 1938 metres on the southern extremity of the lesser Himalayan zone in Kumaun is Nainital - a veritable heaven on earth. It's named after the famous Naina Devi, whose temple stands on the north-western corner of the lake. The reporting of its existence in 1841 by P. Baron, a Britisher, opened the floodgate of influx of Britishers to the resort and thus started widespread colonisation.

Nainital lake is the heart of Nainital town. It will be more appropriate to say that the town came into existence only because of Lake Nainital. In past few decades, more and more construction activities have been initiated in order to cope-up with the continuously increasing load of tourists. These have not only increased the possibility of landslides / 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 Nainital is now threatened with environmental degradation as a consequence of hillside instability and silting of the lake basin. The major landslides of 1867, 1880, 1890, 1924, 1982, and 1987 bear evidence of the instability of the hillsides.

The water quality of the lake has also been considerably changed with time. When the degradation of water quality was realised by the concerned residents of Nainital town, they increased their voice. As a consequence, the Nainital lake Development Authority came into existence in the year 1989 which later on was renamed as Nainital Lakes Region Special Area Development Authority (NLRSADA) in the year 1992.

Keeping in view the alarming situation of Lake Nainital, as predicted on the basis of investigations carried out in past by the other investigators, a project entitled 'Hydrological Studies of Lake Nainital' was sponsored by the Department of Environment, Lucknow, Govt. of Uttar Pradesh (U.P.) through NLRSADA to the National Institute of Hydrology in the year 1993. During the course of studies, the Interim

Report-I & II were submitted. The present report provides the details of the project objectives and studies carried out with the findings and suggestions. The main aspects of studies, i. e., water balance, sedimentation, water quality, hydrodynamics and long term hydrometeorogical variations along with recharge sources and discharge points, have been included in the present report.

2.0 OBJECTIVES

The project entitled `Hydrological Studies of Lake Nainital' was sponsored by the Department of Environment, Government of U.P., Lucknow through, Nainital Lakes Special Area Development Authority, to the National Institute of Hydrology, Roorkee in the year 1993, with the following objectives.

i. To study the water balance,
ii. To study the sedimentation rate/pattern-causes and to suggest remedial measures,
iii. To study the lake water quality/pollution and to suggest remedial measures,
iv. To study the Hydrodynamics and
v. To study the recharge sources of lake.

The project was initially sanctioned with the project grant of- Rs. 8.43 lakhs and later on the revised grant of Rs. 7.682 lakhs was released in five instalments by the Directorate of Environment, Government of U. P. through Nainital Lakes Region Special Area Development Authority. The last instalment was released in the month of December 1997.

3.0 FINDINGS OF THE PROJECT

The neotectonic Lake Nainital is the main source of drinking water supply to Nainital town. Publications in the recent past inferred accelerated sedimentation

threatening the existence of Lake Nainital. Therefore, in order to understand the various hydrological processes going on with the lake and the current status of Lake Nainital, water balance including the sub-surface inflow and outflow components and sedimentation rates/pattern have been studied using conventional as well as isotopic methods. The water quality of the lake and its horizontal as well as vertical variations with time has also been studied. Efforts have been made to identify the main pollutants in Lake Nainital with the eutrophication level in comparison to other lakes of Kumaun region. The hydrodynamics and meteorological variations that affect the lake water quality and water availability have also been studied.

A sophisticated data logger consisting of 13 sensors was installed at the Mallital bank of the lake, in the Jal Sansthan Pump House, for recording hydrometeorological and hydrological data. Three water level recorders and four raingauges were also installed at the selected locations in the Nainital lake catchment. Indigenously designed sediment traps were installed at 12 points (at different depths) in the lake, but unfortunately damaged by inane tourists.

Field trips were undertaken regularly (monthly/bimonthly) to survey different water parameters in situ, i. e., dissolved oxygen, temperature, electrical conductivity, and pH in the lake at different points with respect to depth. Water samples were collected from different locations for the various analyses in the laboratory, such as, suspended sediment concentration, TDS, major and minor ions and trace elements including pollution determinants like nitrogen and phosphorous etc. A total of 5200 analyses have been carried out on 400 samples collected over a period of 21 months. Sediment cores were also collected from different locations to estimate the rates and pattern of sedimentation in the lake over a period of past 150 years. The sediment chemistry has also been studied using core samples. Various advanced techniques and methodologies like isotopic, remote sensing, geochemical etc. including conventional methods have been used to study the various processes in the lake. The past 100 years' literature obtained from the UPPWD, Nainital Division located at Nainital and the studies carried out by the various investigators in the past few decades were thoroughly surveyed to get some useful information about

the lake. The important findings and recommendations are given in this section while the details of the each study are given separately in the appendices for the convenience of the readers.

3.1 Water Balance

Water balance studies carried out using conventional and isotopic methods indicate that 35 to 45% of the total volume of water generated due to rainfall in the lake catchment contributes to lake quickly in the form of direct precipitation fall on the lake surface area and surface runoff. Specifically, the lake receives 30% of its total inflow as surface runoff from the catchment and 16% as input from the direct precipitation falling on the lake surface. Total inflow from perennial drains such as Naina Devi drain comes out approximately 1.67 m (15 % of the total input) in terms of depth with respect to lake surface area. The total losses of water from the lake due to pumping, evaporation and discharge through sluices are about 3.18m, 1.22m and 3.39m during 1994, respectively and 3.46m, 1.24m and 4.37m during 1995, respectively. In other words, the pumping from the lake through infiltration well and deep tube-wells installed at the Mallital bank of the lake accounts 32% of the total outflow from the lake, evaporation accounts only 12% while the water drained out from the lake through the sluices gates to control the water level in the lake during the rainy season accounts 41%. The subsurface outflow through springs discharging downstream of the lake catchment is estimated as 1.69m (15% of the total outflow). The net subsurface inflow has been determined as the residual of the water balance equation and is equal to 4.33m and 4.27m during 1994 and 1995, respectively (39% of the total input). This variation in subsurface inflow is due to variation in amount and intensity of rainfall. These values strongly indicate that the ground water contribution to the lake is a major component.

The details of water balance computations are given in Appendix - B.

3.2 Sedimentation

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

The details of the estimation of sedimentation rates and pattern using conventional as well as radiometric techniques are given in Appendix - C.

3.3 Effect of Sedimentation on Water Balance

The total sedimentation in Lake Nainital, taking into account the mean accumulation rates, 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 the normal environmental conditions. Considering the error limits in the estimated time periods by both the methods, the lake will completely be filled up in 2200 years.

As complete long term information on different water balance components is not available in case of Lake Nainital, the relation of surface outflow from the lake with respect to the rainfall in the lake catchment in the past 100 years has been used to assess the effect of sedimentation on water balance of the lake. To assess the effect of

development of the town since early 1970s, the period 1901 - 1970 has been considered as one group and 1971 - 95 as the second group. There is a noticeable decrease in the surface outflow for the given rainfall in the latter period. This decrease is due mainly to the increase in pumping from lake. Based on the estimated rate of sedimentation, there must have been an increase of 3,20,000 m^3 in the overall annual outflow from the lake. If all other outflow components of the lake water balance equation such as evaporation, abstraction etc., remained within reasonable limits, the increase would then be noticeable in the surface outflow of the lake. But, since the abstraction from the lake through pumping has increased manifold (as a consequence of increase in demand) such increase in surface outflow is not noticed. On the contrary, there is significant decrease in the surface outflow from the lake. More details are given on this topic in Appendix - B.

3.4 Useful Life of Lake Nainital

The useful life of the lake is between 82 years to 380 years as predicted by the earlier investigators using the bathymetric sounding data, collected manually. The useful life estimated by sediment balance 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.

In the present study, ^{210}Pb and ^{137}Cs dating techniques have been used to estimate the useful life of Lake Nainital. The estimated useful life comes to be 2163 $\pm$ 77 years (^{137}Cs) and 2479 $\pm$ 312 years (^{210}Pb). If we take the Average of the useful life estimated by radiometric dating techniques, it comes around 2200 yr. This age of Lake Nainital has been determined ignoring the deposition of sediments the entry points of drains into the lake (can be removed every year) and the landslides that may occur in the future in Nainital lake catchment. More details about the estimation of lake life are given in Appendix - C.

3.5 Water Quality and Level of Eutrophication

The following table summarises the water types of different sources of water in and around Lake Nainital:

Source	Location	Water type
Lakes	Nainital, Khurpatal	Magnesium Bicarbonate
U/s Spring	Parda Dhara, Alma Cottage, Lake View & Chuna Dhara	Magnesium Bicarbonate
Drain	Naina Devi	Magnesium Bicarbonate
D/s Spring	Sipahi Dhara, Gupha Mahadev, Rais Hotel, S5 Takula village & Sariyatal	Magnesium Bicarbonate
D/s Spring	S2, S3, S4 & Durgapur	Magnesium Sulphate
D/s Spring	Ratighat	Calcium Bicarbonate
Wells	Sukhatal, Mallital	Magnesium Bicarbonate

It is interesting to note that the hardness of the lake water has not changed significantly, at least for the past 45 years. The data on lake water hardness is given below.

Year	No. of Samples	Hardness (mg/L)	Year	No. Of Samples	Hardness (mg/L)
1954	12	300	1967	11	343
1955	9	300	1968	10	349
1956	16	320	1969	13	347
1957	14	312	1970	15	345
1958	14	300	1971	17	337
1959	12	320	1972	17	348
1960	10	305	1973	24	368
1961	13	302	1974	23	380
1962	12	300	1975	24	400
1963	14	340	1994_	11	326
1964	13	336	1995_	40	306
1965	9	344	1996_	14	330
1966	14	340			

Data collected under the present study that pertains only to surface waters

To denote the nutrient status or else to describe the effects of the nutrients on the general water quality of the lakes, three descriptive terms that are broadly classified as oligotrophic, mesotrophic and eutrophic were used.

Oligotrophic (Greek for "little food") lakes are usually characterised by low nutrient concentrations in the water, a diverse plant and animal community, a low level of primary productivity and biomass, and good over all water quality for most uses. By contrast, eutrophic (Greek for "well fed") lakes have a high level of productivity and biomass, frequent occurrence of algal blooms, anoxic bottom water, enhanced growth of littoral zone aquatic plants, and poor water quality for many uses. Mesotrophic is the transition state between oligotrophic and eutrophic.

Various authors have provided specific boundary values of total phosphorus, chlorophyll-a, and Secchi depth for these trophic conditions. There are however, limitations to fix the values to delineate lake trophic conditions; some overlap is inevitable i.e., some waters are classified in one trophic condition based on one parameter and in other trophic condition based on a second parameter.

In the present study, the trophic status of five Kumaun lakes have been determined based on the boundary values of total phosphorus given by Wetzel (1975). The criteria are shown in the table given below.

General relationships of lake productivity to average concentrations of epilimnetic total phosphorus (after Wetzel 1975)

General level of productivity	Total phosphorus (µg/l)
Ultra - oligotrophic	< 5
Oligo - mesotrophic	5 - 10
Meso - eutrophic	10 - 30
Eutrophic	30 - 100
Hypereutrophic	> 100

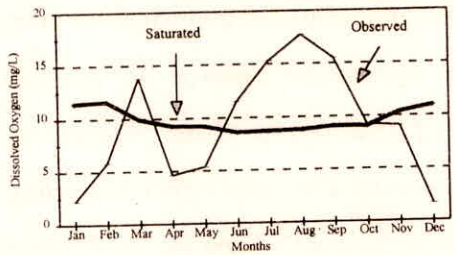
The Kumaun lakes can, therefore, be classified in the trophic states on the basis of the data given in the above table. Several investigators have also developed a numerical trophic state index in an attempt to remove the subjectivity inherent in the terms oligotrophic, mesotrophic and eutrophic. Total phosphorus, chlorophyll - a and Secchi depth relationships were used by Carlson (1977) to develop a numerical Trophic State Index (TSI) which is probably the most commonly used. The Carlson TPTSI has been used for determining trophic state index of the Kumaun lakes including the trophic states are shown in the table given below:

Trophic states and Trophic state index of Kumaun lakes

Lake	Average total phosphorus (µg/l)	Trophic state	Trophic state Index (TSI)
Nainital	127.25	Hypereutrophic	74
Bhimtal	26.43	Meso-eutrophic	51
Khurpatal	16.17	Meso-eutrophic	44
Sattal	6.67	Oligo-mesotrophic	32
Naukuchiatal	3.00	Ultra-oligotrophic	20

The other observations with regard to the water quality aspects of Lake Nainital are given below:

1. The dissolved oxygen in the epilimnetic zone varies from 18.4 mg/1 (maximum) in rainy season, (observed in the month of August 1995) to 1.3 mg/1 (minimum) in winter (observed in the month of Dec.1994). The D.O. value below 9 m is negligible. Anoxic condition exists in the hypolimnion region for most part of the year. During annual turnover, the D.O. is around 2-3 mg/l in the hypolimnion region. Epilimnion however is sufficiently rich in D.O. except during winter. The epilimnetic zone is supersaturated in D.O. during March, and between June and



October. During summer the lake epilimnion is undersaturated probably due to intake by micro-organisms. However, during winter the epilimnetic zone is highly undersaturated due to the lake - turnover and mixing process.

2. During monsoon season, the total dissolved solids (TDS) calculated from the electrical conductivity, is comparatively lower in the epilimnetic zone than the hypolimnetic zone. The TDS values (in mg/L) for epilimnion & hypolimnion are 370 & 580 during July, 270 & 370 during August, 300 & 350 during September and 360 & 470 during October, respectively. Therefore, it is contemplated that the bottom water is more mineralised (and hardened) and chemically polluted than the water in the top zone.

3. Only Nitrate nitrogen and orthophosphate have been found as the major pollutants for Lake Nainital. Phosphate concentration increases during water turnover. This is probably released from the sediments. NO_3-N is observed in higher concentration in winter. From the available data, it appears that PO_4-P is the limiting factor. If the phosphate content of the inflow could be controlled by suitable measures, the trophic state of the lake could be ameliorated.

4. The major inorganic ion, i.e., calcium seems to be brought into the lake in dissolved form. This is possible, as the ground water component is significant in the lake water balance. The Ca is brought in by the over saturated (with respect to Ca) groundwater tends to precipitate as Calcite between May and August or co-precipitate with Mg to form dolomite. But this has to be further investigated.

5. Sulphate is also present in significant concentration in the lake. The quality of springs indicates that the source for sulphate could be dissolution of pyritiferous shales. Various geologists have also reported the presence of gypsum in the rock formations. Sodium and potassium vary within very narrow range. Chloride is not significant. Maximum concentration of Cl observed in the lake is of the order of 40 mg/l, that too only once in the entire study period.

6. Poisonous elements like Pb (Lead) have been detected in the sediments in considerable amounts as laboratory chemicals. These elements may mix with the water and reach the upper layer when the hypolimnetic water mix with the epilimnetic water during mixing period (November to February). The over all dissolved oxygen level also reduces tremendously during this period in the lake water. The mixing of bottom and top layers water is more dominant during the period from mid-December to mid-January. Therefore, due to reduced D. O. level and mixing of poisonous elements in the water, the fish mortality is observed in Nainital lake almost every year but, more in colder years.

More details related to the water quality and pollution aspects of Lake Nainital are given in Appendix - D.

3.6 Geomorphology and Hydrometeorology

1. Nainital lake is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalaya at 1937 m above sea level.

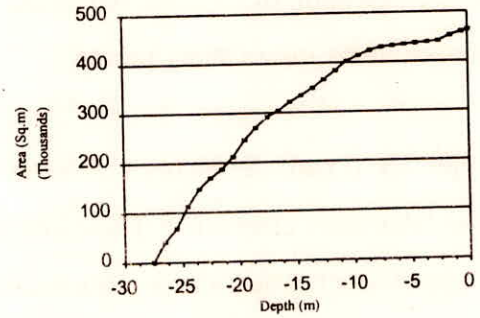
2. It is located between $29^0 24'$ N latitude and $79^0 28'$ E longitude.

3. The lake is 1423 m long and 250 to 423 m wide.

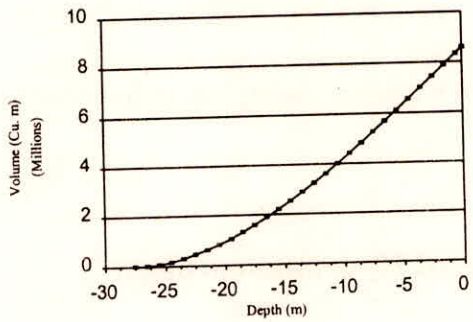
4. It is physically divided in two parts by a 100-m wide Ridge, located near the

library in north and near the Pashan Devi Temple in south.

5. The max. depth of lake has been observed 27.3 m in north part and 25.5 m in south part.



6. The relation between area Vs depth and volume Vs depth were not available for Lake Nainital for the complete depth. These relations have been established first time.



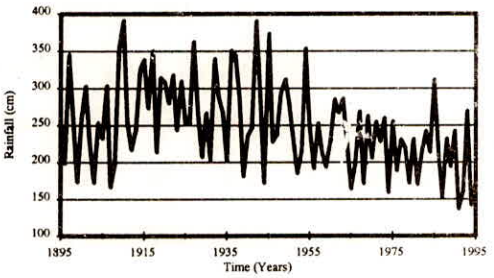
7. The volume of the lake at its max. level is 8.58 Mm^3 while surface area is 0.465 km^2. The lake shore line is 3458 m.

8. The total catchment area of the lake is 4.7 km^2 occurring between 1937 m to 2600 m altitude above sea level.

9. The lake catchment comprise of 48% forest, 19.3% built-up, 18.3% barren and 10.4% water bodies.

10. The average rainfall in the lake catchment is 248.8 cm with occasional snowfall amounting to 200 to 600 mm in a year.

11. An interpretation of 100 years data of rainfall (PWD data), indicate a general decline trend (25-30% decrease in the past 40 years). However, this declining trend does not cause any alarm as the water balance computations for the year 1994 and 1995 indicate enough inflow, for the sustainability of the Lake. Moreover,



there the time series analyses reveals that there is no systematic trend in the Nainital rainfall.

More details on geomorphology and geohyrological characteristics of Nainital lake catchment are given in Appendix - A.

3.7 Interconnection of lake with springs

The Lake Nainital and several upstream and downstream springs in the surrounding area were investigated for their hydrogeochemical characteristics. The study reveals that the upstream springs reflect the basin geology. The subsurface contribution to the lake by limestone and dolomite aquifers could be substantial as the lake shows lower sulphate concentrations than the surface run-off through the drains (including rainy season) as well as the groundwater from the calcareous shales.

The interconnection between the Lake Nainital and downstream springs Sipahi Dhara, Gupha Mahadev and Rais Hotel spring are established through the similarity in the

dissolved ion concentrations and stable isotopic composition. Further, through the water quality data on the stratified lake and that of these downstream springs, it has been shown that the leakage from the lake take place in the epilimnion zone, i.e. between 0 to 6 m from the maximum lake level. The water pumped from the open well located in the northern bank of the lake is found to be as seepage from the lake. The tubewells TW1, TW2 and TW3 show a mixture of lake water and the groundwater. The springs S1, S6, S7, S9, S10, S11 and S12 do not have connections with the Lake as they show a more depleted $\delta^{18}O$ value during non-rainy season.

The temporal variations in the calcium, magnesium and bicarbonate ions within the Lake Nainital are probably brought about by precipitation during summer season and dissolution during winter season. The saturation indices calculated for calcite and dolomite indicate that while the lake water is super saturated with respect to calcite and dolomite during winter, is under saturated during summer. Therefore these ions are unsuitable for chemical mass balance estimates. On the other hand Cl^- may be conservative, but the difference between the end members i.e., the groundwater and the lake is not significant to be used as a tracer. Sulphate may be used as a tracer in the case of Lake Nainital in addition to stable isotopes.

The details of the interconnections of springs with the lake including the recharge sources and discharge points are given in appendix - F.

3.8 Hydrodynamics

The surface water temperatures ranges from 9.2°c to 22.4°c to in the South basin, while in the North basin, it ranges from 8.4°C to 23.6°c. The temperature in the bottom waters of South basin ranges from 8°c to 9.4°c, and in North basin from 8°c to 9.2°c. The lake is thermally well mixed during the period December to February. However the minor difference between the top and bottom waters are observed in December. During January the difference between epilimnion and hypolimnion water is just 0.4 °C. The lake continues to loose energy and in February the minimum temperature condition is observed

in the entire column of lake waters. The thermocline develops during March and the onset of stratification is seen to develop in the month of April. The stratification intensifies during May. The vertical temperature difference was higher during June when the thermocline was at 7.5 m below surface. The stratification continues up to November, when, the thermocline sinks to the bottom. And the thermocline disappears totally during the third week of December and the winter turn over takes place. It has been reported that algal blooms are associated with this process, as the nutrients from hypolimnion, hitherto unavailable to the biota in the surface waters, is released as a consequence of turnover. It can be seen from Figures 1a and 1b, that the development of thermocline is first observed in March at 3m depth and later, it starts to sink and is observed at a depth of 13.5 m in November, before completely disappearing by the end of November.

The knowledge of vertical exchange coefficients is useful for gaining information on influence of groundwater on the hydrology of a lake by adopting stable isotope mass balance technique. The estimated vertical exchange coefficients have been using this techniques are presented below.

Vertical exchange coefficients estimated from lake temperature data

Month	Vertical exchange Coefficient (m/d)	Remarks	Month	Vertical exchange Coefficient (m/d)	Remarks
January	0	Well mixed	July	0.003	stratified
February	0	Well mixed	August	0.007	stratified
March	0.017	Stratified	September	0.008	stratified
April	0.007	Stratified	October	0.005	stratified
May	0.005	Stratified	November	0.031	stratified
June	0.004	Stratified	December	0	well mixed

Apart from the above vertical exchange coefficients derived from the temperature data, the following important parameters have been studied to understand the hydrodynamic characteristics of Nainital lake.

i) Electrical Conductivity

ii) Stable isotopes

iii) Environmental tritium

In addition, the lake water retention period estimated assuming the lake as a well-mixed water body is 2.1 years while the groundwater retention period is 3 years. The more accurate retention periods may be estimated assuming lake as two box model in which the mixing of surface runoff from the top and groundwater from the bottom sides may be considered when the lake is stratified.

The details of the variation of above parameters and the estimation of water retention periods are described in Appendix - E.

4.0 RECOMMENDATIONS

1. The public awareness programme for the population of Nainital town including the tourists should be organised at different levels in order to avoid the pollution problem and each tourist or a group of tourists should be provided an instruction booklet regarding **what you can do and what you can not do - to conserve the lake'** in order to avoid unwanted pollutants and waste materials reaching the lake. It should clearly be mentioned that a penalty of Rs. 100 to 1000 would be imposed, if the instructions were not followed strictly. The nominal charges of the instruction booklet etc. can be charged from the tourists while delivering it to them at the time of entry into the town. The same instructions should be applicable strictly to the residents of Nainital town.

2. Lot of unauthorised residences has come up all along Naina Devi Drain/ Pardha Dhara spring including Bhutiya Market whose sewerage is not connected with the main sewerage system of the town. The pollutants are also reaching the lake through Rickshaw Stand drain. Therefore, house/kitchen wastes are going into the lake continuously through Naina Devi and Rickshaw Stand drains, causing a major

pollution threat to the lake. As an immediate measure, the flow from these drains should be diverted during non-monsoon seasons when the discharge is comparatively less but highly polluted. However, it will be better for the good health of Lake Nainital that the sewerage and kitchen wastes disposal from the unauthorised constructions and leakage from the sewerage pipe lines should be tackled on the top priority.

3. The poisonous elements such as arsenic, mercury, chromium and lead are reaching the lake only due to the anthropological activities. The possible sources may be the laboratories where such chemicals are being used for some testing/educational purposes and later on these are being disposed off into the drains that are joining the lake or at places from where these elements reach the lake during the rainy season. One of the main sources of lead may be the paint, which are used in large scale for the painting of boats and other items/buildings. The other sources of lead are exhaust from the vehicles and geological formation. Therefore, efforts are required to spread the message to take care in this respect by the people concerned for disposing such chemicals carefully at the places/drains that do not have direct and indirect access to the lake.

4. As already stated that phosphorous is a limiting factor in case of Lake Nainital, it is essential to control the external as well as internal recycling of phosphorous to control the increasing eutrophication level in the lake. In addition, the sediment entry reduces the lake capacity along with the increase of different types of pollutants therefore, some of the methods that may be used to control the phosphorous entry, its internal release (recycling), the algal growth and reduction/removal of sediments in case of Lake Nainital are suggested below.

Phosphorous inactivation

Internal release of phosphorous (P) may be a significant source that could delay recovery of Lake Quality. Sediment P release can be controlled by adding aluminium salts

to the water having problem, resulting in an aluminium hydroxide floc that settles to the sediment surface forming a barrier to further release, even if anoxia persists. This is a powerful, effective and popular technique. Sediment oxidation through enhanced denitrification and resulting improved complexation with iron is included with P inactivation.

Dilution and Hypolimnetic Withdrawal (siphoning)

Dilution involves the addition of low nutrient water to reduce lake nutrient concentrations and can be effective where external or internal sources are not controlled. Simple flushing removes algal biomass and may be accomplished with large volume of water even if nutrient concentration is high. Nutrient enriched hypolimnetic waters may be preferentially removed through siphoning, pumping or selective discharge through sluice gates instead of low nutrient surface water. This has been shown to be effective at accelerating P exports, reducing surface P concentrations and improving hypolimnetic oxygen content in many cases.

Presently, the lake water is being drained out from the upper portion of the lake by opening the sluice gates. It is done to control only the water level in the lake during the rainy season, but not to control the eutrophication level. The lake water in the upper portion is comparatively less polluted during the rainy season and unknowingly we are draining the less polluted water from the lake. This is a great loss to the natural purification capability of the lake. Therefore, the water from the lake bottom should be drained in rainy season by constructing a siphon system at Tallital Dat region replacing the present practice. The details of this system can be discussed if Authorities are interested.

Artificial Circulation / Hypolimnetic Aeration

Although a potential exists for control of internal loading from anoxic hypolimnion (especially with iron addition), that potential has not been adequately demonstrated as yet

to place this technique under algae control. This technique is used to prevent or eliminate thermal stratification through the mixing action of the rising column of air bubbles. However, it is highly effective at increasing dissolved oxygen in the hypolimnion without destratifying the lake. But most importantly it can cause light to limit algal growth in situations where nutrients are uncontrollable and can neutralise the factors favouring dominance while blue-green algae. This is usually accomplished with an air lift device, which brings cold hypolimnetic water to the surface, where gases are exchanged, followed by its return to deep water. This procedure can improve lake or reservoir discharge quality, allow a cold water fishery to reestablish, provide a daytime refuge for zooplankton (from a warm water fishery), and eliminate problems with iron and manganese in potable water supplies. This technique can be applied in case of Lake Nainital. In fact NIH, Roorkee, has already received one proposal from the University of Lund, Sweden to apply this technique on Lake Nainital. But, presently it is only in the initial stage.

Adding Copper Sulphate

This has been a commonly used treatment for lakes and water supply reservoirs suffering from algal biomass and taste and odour problems, for at least a century. It is included because it is commonly practised, rather than because it is advocated. This method can be used to control algal biomass in case of Lake Nainital.

Trapping and Retention of Sediment at the entry points

In order to restrict the entry of sediments into the lake in future, a wall of atleast 1.5 ft. height should be constructed at the entry point into the lake of such drains through which maximum sedimentation occurs or a sediment trap structure should be set-up in the drains along the side of Mall road including Naina Devi Drain. These structures should be cleaned periodically without fail, otherwise the situation as prevails with Naina Devi drain and Rickshaw Stand drain will occur where the similar exercise has been tried but due to non-cleaning of sediments retained due to obstruction of wall, the levels of drains have been up lifted and there is no benefit of construction of such walls. However, the

perennial drains with little discharge can have the provision of small size net (strong enough) at the lower side of the wall to allow water to enter into the lake during non-monsoon periods.

Sediment Removal

This technique can be multipurpose, resulting in control of both algae and macrophytes. It is an effective procedure and is frequently recommended for deepening shallow lakes for macrophytes control, curtailing internal nutrient loading by eliminating the enriched sediment layer or eliminating sediments contaminated with toxic substances. The significant advantage of this technique over nutrient inactivation is that the source is removed rather than simply covered over.

It has been observed that most of the sediment deposition takes place near the debauching points of drains which later on slide to the deeper section. Although, the slide rate of the sediment is very less, the sediments will be deposited at faster rates at the shallower parts of the lake, as being taking place in the present, the capacity of surface area and ultimately the lake will reduce tremendously. Therefore, the deposited sediments should be removed from these areas every year during the period of summer when the lake level reduced and these areas become dry. This can bring the lake area to its original with in few years, if the removal of sediments is continued at least for a period of 10 years. Therefore, there is a need to evolve a programme to remove the sediments deposited at the banks and nearby areas in the past few decades.

Protection from Landslides

Landslides occur frequently in the Himalayas. Therefore, mountainous lakes receive large amount of debris and other types of material / sediment due to landslides which either reduce the overall size of the lake. The landslide prone area can be monitored continuously for the precipitation - runoff relationship in the lake catchment. The infiltration of precipitation water at higher rates weakens the landslide prone area.

Therefore, if the surface runoff seems comparatively less than it should be as per the characteristics of the area (it can be calculated using empirical formulae), the area should be treated for reducing the infiltration of precipitation water. The surface channel network can also be developed in the area to allow the rapid draining of precipitation water. The surface run-off may be diverted from the weathered and fractured zones by taking suitable measures. However, it requires a separate study in case of Lake Nainital.

5.0 FOLLOW-UP ACTION

Basically two aspects of the lake, i.e., the increasing sedimentation and deterioration of Lake water quality are to be taken care in case of Lake Nainital. These require the following actions.

1. Instruction booklet for the tourists and residents of Nainital town for "What to do and what should not do" with the provision of suitable fine/punishment, if instructions are not followed strictly, and organisation of public awareness programmes at all levels.

2. Regular cleaning of the dustbins and waste material collection sites including their proper maintenance with time.

3. Suitable instructions to the each boatman for keeping the dustbin in his boat and to take care that the tourists should throw no remains of the eatable items into the lake during the boating.

4. Construction of the 0.5 m wall at the entry points of the drains to restrict the entry of the sediments and remains of the eatables into the lake and regular cleaning of the material deposits along the wall side.

5. Draining out polluted water from the deeper portions of the lake by installing suitable siphoning device at the Tallital Dat to control the water level in the lake during

the rainy season as well as to reduce the pollution level instead of draining out fresh water as per the present practises.

6. Removal of deltas, if any, every year from the areas near to the entry points of the drains and removal of the sediments from the shallow portions of the lake.

7. Cutting the tree branches which touch the lake water and removal of the falling trees from the lake sides.

8. Installation of suitable water circulation devices to increase the D. O. level at the deeper depths in Tallital and Mallital lake sections separately at 4-5 sections.

9. Removal of leakage in the sewerage line, if any, and to restrict the entry of sewerage and kitchen waste from the unauthorised constructions in the town including Bhutiya market.

10. Treatment of the lake water and top surface of the lake sediments by adding suitable chemicals as suggested above.

11. The Nainital lake catchment is a landslide prone area as a number of major landslides have occurred in the pasts (the recent one occurred on 25th July 1998) which have reduced the lake capacity considerably. Therefore, there is an urgent need to study the weak zones prone to landslides. This can be achieved by studying the surface run-off and infiltration characteristics in different parts of the lake catchment. Britishers originally initiated these types of hydrological observations in Nainital lake catchment in late nineteenth century to understand and avoid the landslides.

Besides this, the forest plantation should be increased instead of cutting the trees in the Nainital lake catchment. The building construction activities should also be reduced to the minimum keeping aside the vested interests that is to be looked into by the local administration.

The actions listed at SL. No. 1 to 3 are to be taken care by Nainital Local administration or NLRSADA. The actions listed at SL. No. 4 to 7 are to be taken care by the UPPWD Division Nainital while the actions listed at SL. No. 8 to 10 are to be taken care by Nainital Jal Sansthan and Jal Nigam Divisions as per their distribution of work. However, the UP Forest Division, Nainital, should look into the increasing afforestation in the lake catchment. The action listed at SL. No. 11 may be taken care by any expert agency in the field of Hydrology and Water Resources. This agency should have high level experts in case of NGO and/or experts from the national and state level government / semi-government organisations who are involved in the R & D work on Hydrology and Water Resources.

In order to implement and monitor the actions to be taken for the revival of Lake Nainital, a Steering Committee should be constituted under the chairmanship of Commissioner Kumaun Mandal with members from the district administration (District Magistrate), Superintending Engineers concerned from the UP PWD, UP Jal Sansthan and UP Jal Nigam, Secretary NLRSADA, Chief Town Planner, Geologist Concerned from the GSI, DFO, Nainital, a Water Resources expert from state or national level organisation and Engineering Geology / Civil Engineering expert from academic institutions. In order to maintain the interest of public, 1 or 2 vigilant representative of the public (resident of Nainital town) should also be included in this committee. The above committee may also consider development of a buffer zone around the lake. A buffer zone - to be maintained by the local authorities - has to be developed, in which there will be no construction or other sort of anthropogenic activities. This concept of buffer zone is being rapidly adopted by Lake Managers in developed countries. Such an action in the urbanised Nainital lake catchment will certainly help in improving the lake quality.

APPENDIX - A

GEOLOGIC AND HYDROLOGIC CHARACTERISTICS OF NAINITAL LAKE CATCHMENT

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1.0 INTRODUCTION

Over a century ago, the renowned geologist Reverend C.S. Middlemiss (1890) remarked that "The Geology of Nainital, in its purer scientific aspects, is neither very attractive nor very instructive". Very many workers and scientists have since been attached to the mystic hills. Many a geologist has been propelled to know what has been concealed beneath the verdure of green mountain grass, dotted with the sombre oak, rhododendron and cypress. Notable among them being Auden (1934), Heim and Gansser (1939), Thomas (1952), Sarkar et al.(1967), Pal and Merh (1974) and in recent times Valdiya (1988).

The geological settings of an area play an important role in framing its hydrological features. In this section, the geological and hydrological outlines of Nainital Lake Catchment have been discussed along with other related features like geomorphological characteristics and relation of spring discharge with rainfall and structures.

2.0 GEOLOGICAL SETTING

The Nainital hills encompass a rock succession that includes 1800-2000 Ma granites and the sediments ranging in age from 1600 to 500-600 Ma. The pre-Cambrian granite complex, designated as the Amritpur granite in the south and Debguru Porphyroid in the north-forms the foundation on which rests, of course botanically, more than 6000m thick succession of sedimentary rocks. The sediments are divisible into two groups - the lower Jaunsar group comprising of sheds, quartzites and subordinate conglomerates. The upper Mussoori group consisting of the Blini, Krol and Tal formations. It is made up of conglomerates, shales, limestones and dolomites.

The lake watershed includes three Lithostratigraphic units of the Krol Nappe. These are the Lower, Middle and Upper Krol, presumed to be of the upper Palaeozoic age. The Naina-Deopatta, Sher-ka-Danda and Snow view ridges which border the lake

catchment on the north and west are composed of the shales and marks of the lower Krol. A major fault line-the Nainital fault separates the catchment from the Ayarpatta ridge on the southwest. This third unit is composed chiefly of limestones, dolomites, subordinate black shades and sandstones of upper Krol. A small part of the Ayarpatta ridge area is composed of red shales and marks of the middle Krol.

The Nainital fault as suggested by Pal and Merh (1974) is normal in nature and is the most conspicuous and striking structural features of the area. It cuts the Nainital lake watershed into two halves and bisects the Nainital syncline along its hinge. The height of the scarps, as described by them indicates that the amount of throw of this fault is not less than 100 metres. The Lithostratigraphic succession of the Nainital hills of the Krol Belt, as given by Valdiya (1988) is as follows:

	Jal Fm	Narain Nagar Member Giwali Khet Member Sherwood Member Bist college Member
Mussoorie Gr.	Krol Fm	Pashandevi Member Barapatthar Member Hanumangarhi Member Manora Member
	Blini Fm	Kailakhan State Pangot Member
	Jaunsar Upper	Laria Kantha Quartzite Bhumiadhar Fm
Jaunsar Gr.		Batalghat Fm.
	Jaunsar Lower	Jantwalgaon Limestone Bhawali Quartzite Bhimtal volcanies
		.....Salari Thrust..... Amritpur Granite .....M.B.T..... Lower Siwalik

As evident from the succession given by Valdiya the great succession of sedimentaries of the Nainital massif is divisible into lower argillo-arenaceous Jaunsar Group and the upper Argillo Calcareous Mussoorie Groups (Valdiya 1980). Representing the southeastern end of the Krol catchment that extends southeast from Solan in Himachal Pradesh, the sedimentary pile succeeds a highly tectonised foundation of Amritpur Granite discernible only in the narrow southeastern extremity. It is thrust southwards over the Siwalik province as an allocthonous sheet-the Krol Nappe. While the narrow southern part of the Nainital massif is made up of predominantly argillo-calcareous sedimentaries of the younger Mussoorie gr., the larger northern part is constituted exclusively of rocks of the older Jaunsar group.

In spite of a good deal of work carried out in different parts of the Krol Belt, its stratigraphy remains entangled in confusion. Fresh fossil discoveries from certain horizons of the hitherto unfossiliferous formations have not helped solve the tangle, and the differences in the interpretation of stratigraphic order and age still persist. Valdiya (1988) has suggested considerable modifications in the stratigraphic model earlier proposed by himself, based primarily on Auden's (1934,1937) model of the Krol belt in Himachal and Garhwal.

Thus, in view of the difficulty in regional correlation and difference in the views on age, the geology of the Nainital Hills was taken up in isolation by Valdiya (1988). He made no attempt to tie it up with the stratigraphy of either the inner belt of Kumaun lesser Himalayas or the top locality in Himachal Pradesh.

3.0 NAINITAL LAKE CATCHMENT

District Nainital of Kumaun region is well known for its picturesque lakes. It is felt that due to unscientific use of lake water and improper management, the water availability in Nainital lake is reducing continuously. The higher sedimentation rates and reduction in discharge of the recharge sources to the lake have adversely affected the

storage capacity and water availability in the lake. The frequent change of land use pattern and deforestation in the area have affected the zones of recharge to the lake and ultimately the input to the lake has been reduced accordingly. Due to typical geologic nature, presence of faults and instability of hill slopes lead to frequent land slides and mass movements which ultimately affects the hydrology of the lake catchment.

The deposition of sediment at the entry points of the Nalas (drains) in Nainital lake has reached to an alarming state, the main sources of sediments are the debris from the surrounding hills and house-building material including the debris due to frequent small and big landslides in the lake catchment.

Further, the Naini lake has been showing signs of accelerated eutrophication due to human interference in the catchment area. Eutrophication is carried when the water of a lake is not able to purify itself because its dissolved oxygen is consumed in oxygen-demanding biochemical processes, thereby, developing an aerobic condition. The prolific growth due to the presence of phosphate and nitrate nutrients and overcrowding of algae and weeds and their eventual death and decay creates the same situation. One of the major causes of eutrophication of lake is the indiscriminate discharge of untreated domestic waste along with refuse and solid waste through 26 major drainage channels resulting in severe impairment of physical, chemical and biological quality of lake water.

The causes of deterioration of the Naini lake are manifold. The infrastructural facilities such as water supply, sewerage, solid waste disposal, traffic and transportation and tourists facilities have fallen short of requirement. Due to this, the rain water fed channels serve as conduit to carry sewage overflow and also the solid waste, which are dumped into the channels which finally reach the lakes. Some of the springs contributing water to the lakes have dried up, and some are in the process of drying. On the other hand, the need of water is increasing day by day.

3.1 Geomorphology

Lake Nainital is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalayas (Fig. 1). It is located 29^0 24' N (latitude) and 79^0 28' E (longitude) at an altitude of 1937 meters above sea level. The maximum length of the lake is 1423 m and the width vary from 423 m to 250 m. The maximum depth of the lake 27.3 m and mean depth 18.52 m (not 16.3 m as estimated earlier). The surface area of lake is 0.463 Km^2 while the volume is 8.58 Mm^3 and the shore line is 3458 m. The shoreline is steep, except at a few places where the drains have deposited silt and debris. The lake is divided into two sub-basins by 100 m wide transverse underwater ridge, 7 m to 20 m below the lake surface. The bathymetric study (Rawat, 1987 and Hashimi et al., 1993) reveals that the lake consists of two V-shaped basins, one in the north and the other in the south with maximum depths of 27.3 m and 25.5 m respectively. The catchment area of the lake is 4.7 km^2 (estimated using GIS package and also from UPPWD records), ranging in height from 1937m to 2600m, out of which 48.4% is forest, 18.3% is barren, 19.3% is built-up area and 10.4% is water body. However different figures have been reported by different investigators, e.g., NEERI, Nagpur (1989)- 11.8 km^2 and Khanka (1991)- 5.85 km^2, 3.6 km^2 (from the map presented by Valdiya, 1988) .

The mean hill slope of the area is 19° where large part being confined to the slope group of 20° to 25° and the maximum slope reaching 47° to 49° (Rawat, 1987). The average slope of the snow view - Sher-ka-Danda ridge is 18°, varying between 5° to 35°. At many places the slopes exhibit convex bulges resulting from continuing creep movement. The slopes are locally broken by scarps and fringed at the base by a succession of debris cones and fans. The depth of lake where the dividing ridge has been observed is 8.6 m. An outlet for draining out excess water is situated at the north-eastern end. The fluvial morphometry such as drainage density, stream frequency, bifurcation ratio and drainage tenure of the Naini Lake Watershed is a function of variation in rock type (Table 1).

Table -1: Details of fluvial morphometry of Nainital Lake Watershed.

Stratigraphic Fm	Rock type	Parameters DaD m/km	S.F.	B.R.	D.Tenure Ch /km
Lower Krol	Shales & Marks	6.05	8.15	4.5	9.50
Middle Krol	Red Shales & Marks	4.15	5.30	3.2	6.25
Upper Krol	Dolomites & Limestone	0.30	1.25	2.0	1.30

after Rawat, J.S. (1988)

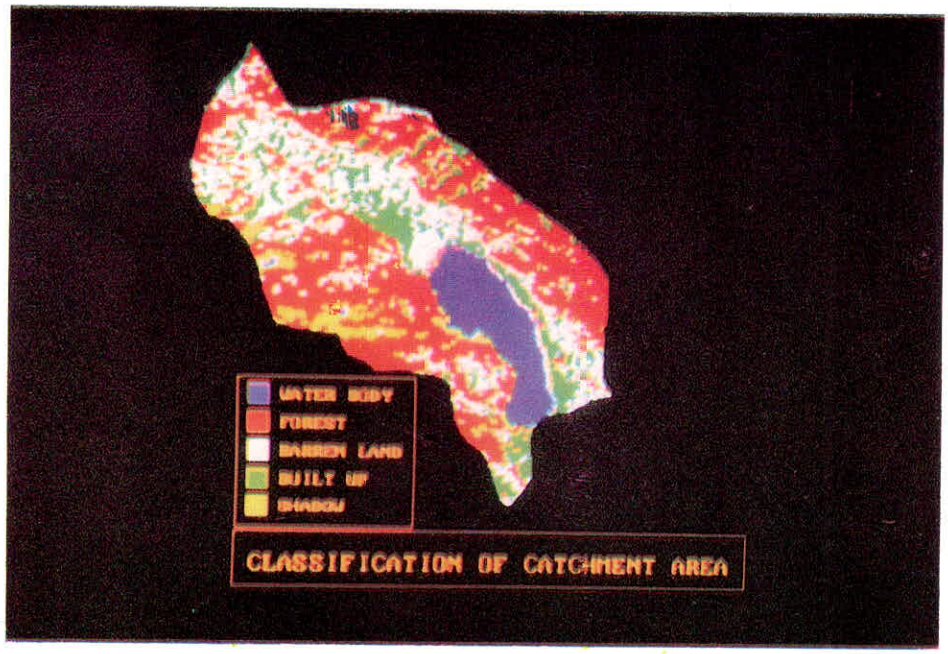
3.2 Hydrogeology

The structure of Naini lake catchment is characterized by complex tectonic movement related to recurrent movements on the active main boundary thrust and related tear faults (Valdiya, 1981, 1988). The rotational movement along Nainital fault, passing through the catchment has been the causative factor for the origin of Lake Nainital (Valdiya, 1988). The NW-SE trending Nainital fault passing from lake catchment and follows Balia Nala in down side. The Nainital fault and these associated fracture have caused shearing and shattering of the rocks responsible for hillslope instability and attendant erosion. Quite after the establishment of natural drainage like the Balia Nala, subrecent movements of order of 20m to 80m within the lake catchment caused uplift of northeastern Sher-ka-Danda range relative to Ayarpatta ridge. This is evident from the contrasting portrayal by the various workers (Hukku et.al. 1974; Pal and Merh, 1974; Pande 1974; Fuchs and Sinha, 1974; Sharma, 1981; Valdiya, 1988).

The crescent-shaped water body of the Naini lake is surrounded by steep mountain slopes of Nainital hills. The contributions from precipitation, springs, and streamlets from the surrounding watersheds helped in further evolution of the lake. The previous flow of the lake was towards NW through Sariatal region before land slips sealed this



Photograph showing Lake Nainital and Surroundings



Photograph Indicating Different Land Uses in Nainital Lake Catchment

channel, shifting the flow to the south through Tallital region. Geological and geomorphological evidences favour the idea of a slide in the southern Sariatal/Khurpatal region.

Lake catchment 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. 1). The lake catchment receives about 248.8 cm of average annual rainfall as computed over a period of one hundred one years (1895-1995). The extremes being 390.98 cm in 1910 and 136.7 cm in 1991. Thus the catchment collects abundant rainwater. About 80% of the total rainfall occurs during monsoon season (between middle of June to the middle of September). Besides rainfall, there are occasional snowfalls in and around the lake catchment during the winter, varying between 200 mm to 600 mm in recent years (Khanka, 1991).

3.2.1 Drainage Network

The geology of the area has a marked influence on the initial drainage network. The main stream - Bara nala follows the toe of the Nainital fault, and to most significant feature is the development of subsequent streams that tend to follow features, faults and joints, thus giving rise to the parallel pattern of streams as on the Sher-ka-Danda ridge. The convene show view is characterized by subparallel streams. The major stream during the Naini-Deopatta ridge closely follows the Nainital fault. Streams are much less common on the Ayarpatta ridge, which is composed of massive dolomites and limestones. As is clear the highly permeable rocks, i.e. limestone and dolomite of the upper Krol are characterized by very low water of morphometry parameters. Dramatic changes are seen in the fluvial morphometry in the M.Krol and L.Krol (Rawat, 1988).

The relationships between slope, lithology, slope form and drainage in the Naini lake Catchment (Rawat, 1988).

Area	Lithology	Slope form	Drainage Pattern	Mean Slope	S.D.
Naini Dolomite Deopatta Limestone Ridge	Straight Planar	-	Mostly devoid of drainage	32°	4.40
Snow view Ridge	Shales & Merh	Convene to parallel straight	S - parallel	21°	4.27
Ayarpatta Ridge	Mostly dolomite, limestone	Modulating	Coarse drainage lines	18°	5.48
Landslide deposits	Recent deposits	Concave	B	7°	4.19

3.2.2 Springs

The springs are active on the Sher-ka-Danda slope below Tallital and also outside the lake catchment. The major ones on the Sher-ka-Danda slope being near Glenmore, Oak Lodge, Primrose Cottage, Drain No.6, Kumaun Lodge, Lake House and The Poplars. These springs are located in the gullies formed in the calc-argillaceous grey slates of the Manora Member and are structurally controlled. The Rajpur spring located east of Kumaun Lodge in the purple slates lies in the vicinity of the transverse faults. These springs discharge minimal quantities of water. In contrast, the spring located near the Mallital water works discharges a considerable amount of water.

The main feeder stream Bara Nala emanating from the debris fans at the foot of the Naina peak, derives a larger part of its discharge from the "Parda" spring at the water-works, pouring out water at varying rates from 574 gallons per minute to 141 gallons per minute (Sharma, 1981). The Old Reserve Police Line Spring, located in a

gully north of Gangipur discharged to be extent of 15.51 and 18.91 cubic metres per minute in 1975 and 1977 respectively (Sharma, 1981). The spring is controlled by the E-W trending fractures. The Sipahi Dhara spring, the Ketalpani Spring and the Krishnapur Spring are the other important ones which are fracture controlled.

3.2.3 Relation of Spring Discharge with Rainfall and Structure

It has been observed that all the afore-mentioned springs snow maximum discharge between July and October, when the area receives maximum rainfall, (Sharma, 1981). Hence, the spring discharge is directly related to the rainfall. The location of springs as mentioned earlier is structurally controlled, most of them occurring along faults, fractures and thrusts. Five springs are located in the narrow belt delineated by the Manora Thrust entering from Hanumangarhi to Bhumiadhar. Likewise four of them are along the MBT from Baldiakhan to Jeolikote. Apart from these the Lariakantha fault also features a couple of springs in the northwester part of the area. The Parada Dhara spring is located near the NW-SE running Nainital Fault. In the lake catchment all the springs feature in the fault-dissected, crushed and sheared terrain of the Sher-ka-Danda and hence bear a significant relation with these faults.

More details about springs and their interconnections with Lake Nainital are given in other sections namely, Lake Water Quality Aspects and Recharge Sources and Discharge Points.

3.2.4 Infiltration characteristics

The infiltration may be defined as the downward movement of water through soil surface due to combined forces of the capillarity and gravity contributing to replenishment of soil moisture, recharge to groundwater and ultimately augmenting streamflows during lean seasons. Infiltration rate is the volume of water entering the soil profile per unit surface area and time. Although several factors such as intensity of rainfall, soil characteristics, soil moisture content, vegetal cover, land use, entrapped air

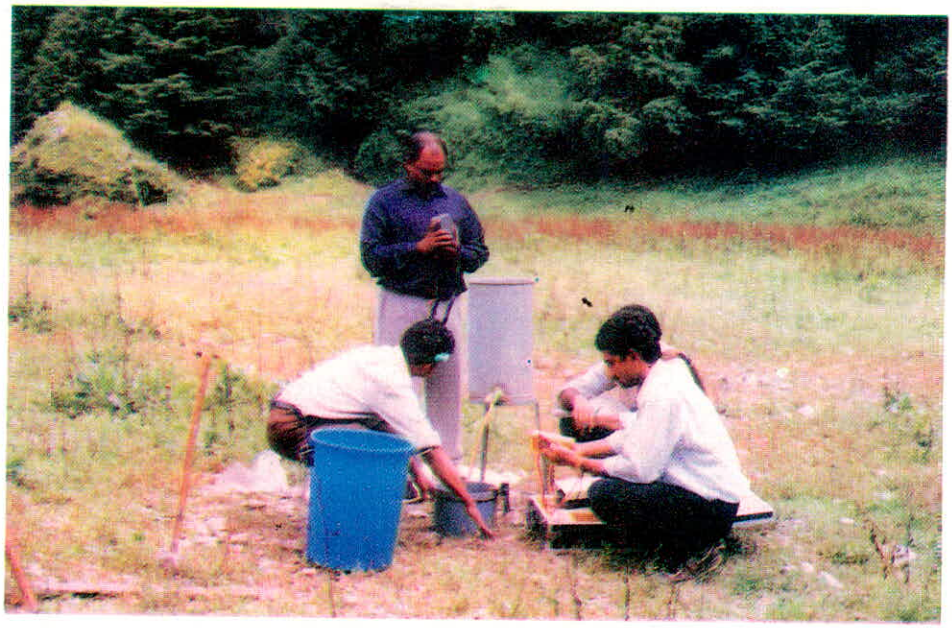
and weather etc. influence the infiltration characteristics of a catchment or basin, one of the chief factors is the pore size distribution in the soil column (V. P. Singh, personal communication). In the mountainous terrain as the flow gets concentrated along the valley bottoms, knowledge of infiltration characteristics along the natural surface drainage channels are vital for hydrological studies of mountainous catchments. Keeping the above facts in view, few infiltration tests were conducted in the Lake Nainital catchment.

Infiltration tests were conducted during the month of August, 1998, i.e. during the mid-monsoon season, so that the soil cover will be near saturation. The tests were conducted using single ring infiltrometer of 30 cm inner diameter and 45 cm height. the bottom rim of the ring was bevelled to facilitate easy-drive into the soil with less disturbance. The infiltrometers were installed such that 30 cm of the ring was inside the soil column and 15 remained exposed. Polythene sheets were spread inside the infiltrometer prior to the actual start of the test. The sheets were removed instantly so that the initial infiltration rate could be obtained. However, as the soil was fully saturated no decreasing trend was seen in the infiltration rate in all the three test sites. A constant head of 5 cm was maintained during the tests with the help of a storage tank, water level controller and solenoid valve set-up developed at the National Institute of Hydrology. The tests were conducted at three different sites in the Lake Nainital catchment, they are:

i) Assembly Cottage campus near the Lake View Cottage along the Birla Vidyamandir Road. The site was characterised by grassy land, slopy & macropore dominated shale with little soil cover. The final infiltration rate was 50 cm/hr.

ii) Forest Chauki along the Birla Vidyamandir Road. The site was characterised by thick clayey soil. The final infiltration rate was 1.1 cm/hr.

iii) Sukhatal lake bed. The site was characterised by flat land, macropore dominated shale with little soil cover. The final infiltration rate was 78 cm/hr.



Infiltration Test is being Conducted in Sukhatal Catchment Which is Understood to be a Major Source of Subsurface Inflow to Lake Nainital



Infiltration Test Conducted in other Parts of Nainital Lake Catchment to Understand the Subsurface Inflow to Lake Nainital

From the above results it is seen that the infiltration rate varies greatly. The higher infiltration rates along the valley bottoms could be a reason for the low rainfall - runoff relationship (25-30%) in the Lake Nainital catchment (refer water balance report). Further, the higher infiltration rate in the Sukhatal lake bed could be the reason for the drying-up of the Lake Sukhatal at the end of monsoon season.

REFERENCES

Auden, J. B. (1934) Geology of the Krol belt, Rec. Geol. Surv. Ind., 67: 357-454

Auden, J. B. (1937) Structure of the Himalaya in Garhwal. Rec. Geol. Surv. Ind., 71: 407-435

Heim, A. and Gansser, A. (1939) Central Himalaya. Mem. soc. Helv. Sci. Nat., 73:1-245

Hashimi, N.H., Pathak, M.C., Jauhari, P., Nair, R.P., Sharma, A.K., Bhakuni, S.S., Bisht, M.K.S. and Valdiya, K.S. (1993) Bathymetric Study of the Neotectonic Nainital lake in Outer Kumaun Himalaya. Geol. Soc. Ind., 41: 91-104.

Hukku, B. M., Srivastava, A. K. and Jaitle, G. N. (1974) Evolution of lakes around Nainital and the problem of hillsie instability. Him Geol. 4: 516-531

Middlemiss C. S. (1890) Geological sketch of Nainital; with some reference on the natural conditions governing mountain slopes. Records of GSI, 21(4): 213-234

Pal, D. and Merh, S. S. (1974) Stratigraphy and structure of the Nainital area in Kumaun Himalaya. Him Geol. 4: 547-562

Pande, I.C. (1974) Tectonic interpretation of the geology of the Nainital area. Him Geol. 4: 532-546

Rawat, J. S. (1987) Morphology and morphometry of the Nainital lake, Kumaun, Lesser Himalaya. Geol. Soc. India, 30: 493-498.

Sarkar, S. n., Kehair, M. M. and Sood, S. J. (1967) Tectonic patterns of a part of Krol -Natghat belt around Nainital. Pun. Centr. Adv. Studies Geol. Punjab Univ., Volume 4, Punjab University, Chandigarh.

Sharma, A. K. (1981) Structural Study of Area East of Nainital with Special Reference to the Hillslide Instability. Ph.D Thesis, Kumaun University, Nainital.

Thomas, A. N. (1952) The origin of Kumaun lakes in the Himalayas, U.P. Current Sci. 55:394-398

Valdiya, K. S. (1980) Geology of Kumaun Lesser Himalaya, wadia Instt. of Him. Geol., Dehradun.

Valdiya, K. S. (1981) Tectonics of the central sector of the Himalaya. In: F.M. Delany and H. K. Gupta (Eds.) Zagros-Hindukush-Himalaya: Geodynamic evolution. Amer. Geophy. Union, Washington, 87-110

Valdiya, K. S. (1988) Geology and Natural Environment of Nainital Hills. Kumaun Himalaya. Gyanodaya Prakashan, Nainital, India.

APPENDIX - B

WATER BALANCE OF LAKE NAINITAL

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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 with the continuously increasing load of tourists. These have not only increased the possibility of land slides / instability in the area but, the forest cover has also come down considerably. All the anthropological activities have degraded the ecological environment that may lead to hydrological imbalance in case of Lake Nainital. The water quality of lake has also been considerably affected. To address the related prblems the Nainital lake Development Authority came into existence in the year 1989 which later on was renamed as Nainital Lakes Region Special Area Development Authority (NLRSADA) in the year 1992. Keeping in view the alarming situation of Lake Nainital as predicted on the basis of investigations carried out by earlier investigators, a project entitled 'Hydrological studies of Lake Nainital, District Nainital, UttarPradesh' was sponsored by the Department of Environment, Lucknow, Government of UttarPradesh through NLRSADA in the year 1993. This report on the study of Water balance of Lake Nainital 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 Himalayas (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 18.52 m. The lake is subdivided into two sub-basins by 100 m wide transverse underwater ridge, 7 to 20 m below the lake surface. The volume of the lake is 8.58 Mm^3. The average annual rainfall in the basin is 248.8 cm. The area of the lake basin is 4.7 km^2 out of which the surface area of lake is 0.46 Km^2 and that of Sukhatal sub-basin is 0.75 km^2. Therefore, the exclusive catchment area of Lake Nainital is 3.49 km^2. The landuse pattern of the entire lake basin is 48.4% forest, 18.3% barren, 19.3% built land and 10.4% water bodies.

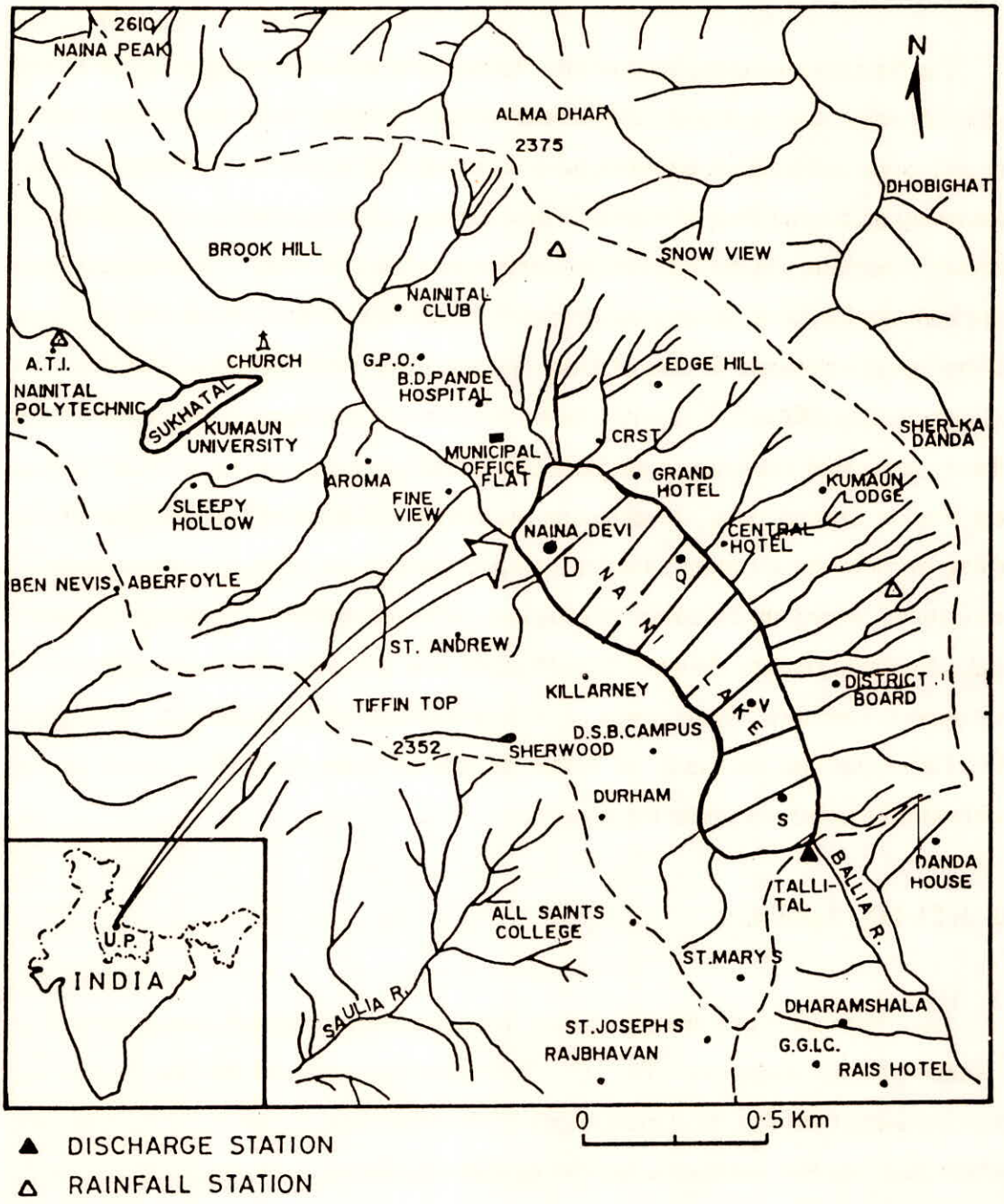


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

2.1 Geology and Geomorphology

The geology of the area has been well studied by many investigators. The notable works are of Middlemiss(1890), Auden(1942) and Valdiya(1988). Valdiya(1988) has given a detailed geological map of Nainital and its environs (Figure 2). The lake basin is made completely of folded and faulted rocks of Krol and Tal formations which are ascribed to Cambrian age. The lake catchment is diagonally cut by the Naini fault or the Lake Fault, as called by some geologists. The chief rock types are calcareous slates, ferruginous shales, argillaceous limestone, dolomite and dolomitic sandstones. The rotational movement along Naini fault 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 fractures have caused shearing and shattering of the rocks responsible for hillslope instability. Almost half the areal extent of the lake basin is covered with debris generated by mass-movements in past.

3.0 WATER BALANCE

The water balance of lakes provide very useful information about the availability of water in lakes at any time. In order to utilize the lake water in a planned and systematic manner and to manage the required availability of water in the lake, the knowledge of different components of water balance of lake is essential. Nainital lake is the major water source, except for the water that is directly tapped from the springs, for drinking and domestic purposes to the people living in and around the lake basin. The lake is mainly fed by precipitation water during the rainy season and inflow from the number of perrennial springs such as Pardha Dhara and subsurface inflow. Unfortunately, the study of various parameters of water balance has not been carried out in detail in the past. The lack of knowledge on few input and output parameters such as subsurface inflow, use of lake water for domestic and industrial purposes, evaporation loss and leakage from lake including the outflow through sluices gates has created uncertainty in determining the availability of water in lake. Therefore, to understand the

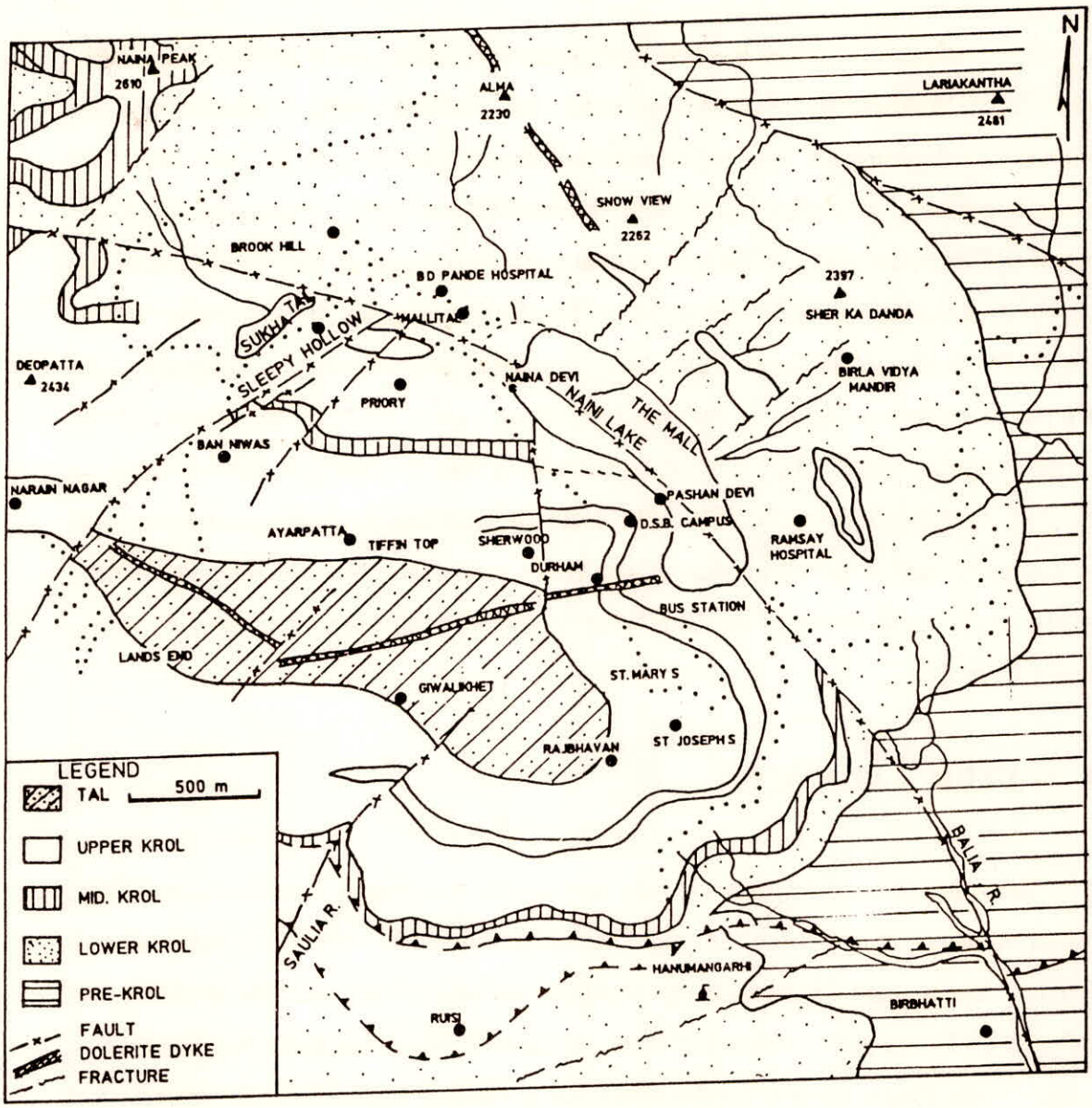


Fig. 2. Geological map of the Nainital Lake Basin showing its much faulted nature (After Valdiya, 1988).

behaviour of different inputs and outputs, the water balance study of Lake Nainital has been carried out in detail by using both conventional and isotopic techniques. The methodology followed and results obtained are summarised in the following sections.

3.1 Previous Work

No serious attempts have been made earlier to compute the water balance of Nainital lake. During the British period, more emphasis was given to hillslope instability and accordingly a hillslide committee, was constituted which met from time to time to analyse the hill slope stability and to recommend safety measures. The sluices at the Tallital end of the lake were originally installed upon the recommendations of one such committee of in 1888, and at the same time raingauges were also installed. The hillslide committee of 1907 gave instructions regarding regulation of the draining of water from the lake. The hillslide committee 1927 made recommendations to measure various hydrological parameters for computation of percentage of runoff. The committee suggested a procedure to be followed to maintain the hydrological record on daily basis.

Very few studies have been carried out in the lake catchment, that focus on some aspects of the hydrology (Sharma, 1981; Bartarya, 1988; Valdiya & Bartarya, 1989). Valdiya & Bartarya (1989) pointed out 25 to 75% decrease in spring discharge in the past 5 to 50 years in the Gaula catchment of which the Lake Nainital basin is a tiny part located in the north-western side.

3.2 Methodology

The conventional methodologies used for computing input and output components of the water balance equation are described below. The general water balance equation may be written as

$$\Delta S = \text{Inflow} - \text{Outflow} \qquad (1)$$

In case of Lake Nainital, the inflow term includes surface inflow (S_i), subsurface inflow

inflow (SS_i), inflow through drains (D_i), and direct precipitation (P_i). The outflow term includes controlled surface outflow through sluices and surface leakage through sluice gates (S_o), free water evaporation (E_o), subsurface outflow (SS_o) and pumping by government agencies (W_o). Incorporating the above, the Eqn. 1. could be written as

$$\Delta S = S_i + SS_i + D_i + P_i - S_o - SS_o - E_o - W_o \qquad (2)$$

The estimation of each of the above parameters is presented below.

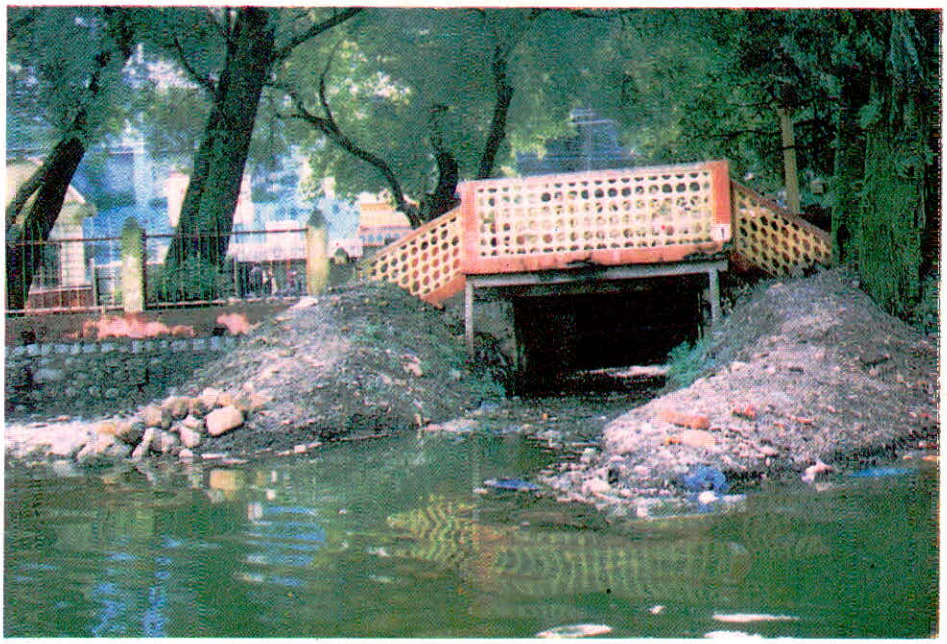
3.2.1 Precipitation

Perceptible variation of rainfall in mountainous area is a common phenomenon. Therefore to avoid the errors in measuring the precipitation in the study area, three raingauges (automatic self recording type) were installed at different locations, i. e., at the ATI campus, Alma cottage and at Rattan cottage. Besides these raingauges, the data of PWD raingauge have also been used for the present study.

By using Thiessen polygon method, the weighted factor for each raingauge has been determined (refer table). The mean daily rainfall in the basin has been computed using the rainfall data collected from the above raingauges and the respective weighting factors. The average daily rainfall data collected during the study period have been plotted (cumulative) and shown in Fig.- 3. Major part of rainfall occurs during the rainy season as non-monsoon rain is much less in comparison to the monsoon rains.

Weighting factors of different raingauge stations established in Lake Nainital Basin.

Sl. No.	Rain Gauge station	Weighting factor
1.	Alma Cottage	0.16
2.	ATI Campus	0.45
3.	PWD Site	0.14
4.	Rattan Cottage	0.25



Sediment Deposits at the Meeting Point of Drain Number 1 (Rickshaw Stand Drain) and the Lake



Sediment Deposits at the Meeting Point of Drain Number 2 and the Lake



Delta Formation in the Lake Near the Nala Mouths



Delta Formation and the Garbage Dumps

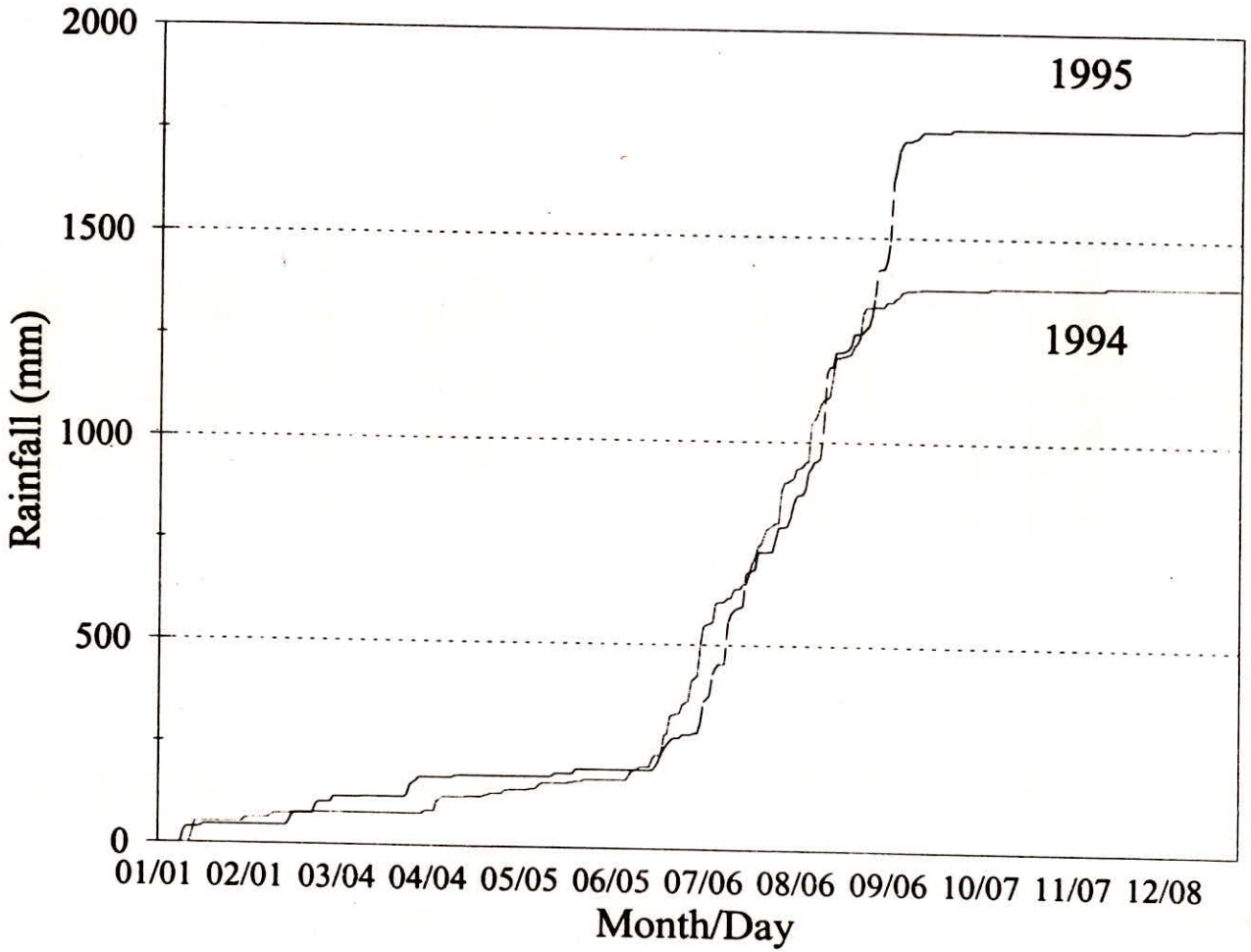


A View of Land Slide that Occurred in July 1998 at the Shore of Lake Nainital



A Bird's Eye View of Lake Nainital Before the Landslide Occurred

Fig. 3 Cumulative rainfall during 1994 and 1995



3.2.2 Lake volume

Information on the lake volume is a basic requirement for any study pertaining to a lake. Computation of the lake volume using depth contours can be made by several methods (Chow, 1964).

i) Volume of lake may be determined by measuring the area enclosed by the depth contours (the location coordinates plotted against depth) and the area under the curve so obtained may be planimetered or otherwise measured.

ii) In another method, the area enclosed by successive pairs of depth contours is averaged out and multiplied by the contour interval to yield a series of volume elements which are then summed using the following relation;

$$V_{A_1A_2} = \frac{h}{3} * (A_1 + A_2 + \sqrt{A_1A_2}) \qquad (1)$$

where, h is the contour interval, A_1 is the area enclosed by the upper contour and A_2 is that enclosed by the lower contour. Summation of the results of repeated successive applications of above equation will yield the lake volume.

3.2.2.1 Calculation of volume of Nainital lake

Bathymetric survey of Nainital lake has been carried out by several investigators using conventional (manual) sounding methods (Holland, 1895; Purohit, 1981; Rawat, 1987). Bathymetric survey carried out by Hashimi et al. (1993) using sophisticated state-of-the-art equipment has resulted in gaining bathymetric data-base of crucial import, both for tectonic interpretation and future comparison & studies. The survey was carried out in November, 1989 by using a highly sensitive echo-sounder, sub-bottom profiler and side-scan sonar and Motorala Miniranger III. Hashimi et al.(1993) presented detailed bathymetric contour (1 meter interval) of Nainital lake floor which has been used in the present study to calculate the volume of Lake Nainital. The measurement of area of each



Self Recording Raingauge Installed in ATI Campus at Nainital



Self Recording Raingauge Installed near Ratan Cottage at Nainital

contour was carried out by using a digital planimeter. The contours for the shallower depth zone (upto 4 m) were not readable from the map of Hashimi et al. (1993). Therefore, the calculation of area was worked out with the help of map preesented by Hashimi and others, from 4 m to 27 m depth only. For the calculation of area from surface to 4 m depth, the data reported by United Province PWD (Byrnes, 1929) has been used. Byrnes (1929) has reported the contouring of lake at the interval of 1 foot, from maximum lake level (surface) upto the depth of 12 ft. This data was further interpolated to determine the depth contours in the shallow zone. Thus, the complete area and then the volume of lake, have been computed and are presented in Table- 1 and 2. The variation of lake area and volume with respect to depth have been shown in Figures-4 & 5.

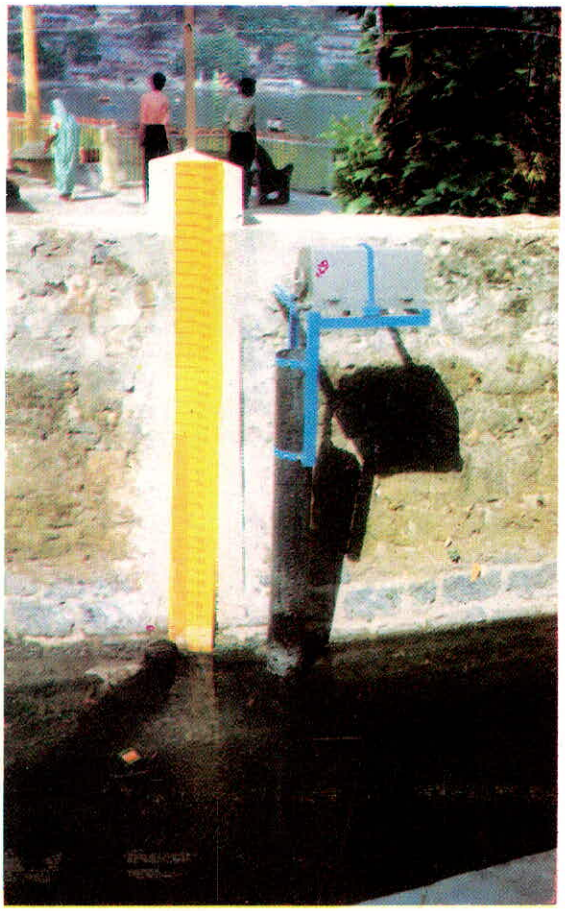
3.2.2.2 Change in storage

As a natural process, the lake level changes with respect to time. However, the change in the water level in 24 hours (a day) or in a month or in a year indicates the change in storage of the lake. With the daily observations of lake gauge, the increasing or decreasing trend of the lake storage can be studied with time which can be used to understand the various processes going on with the lake and the availability of lake water at different times quantitatively. Since the installation of sluices in 1888, the lake level is being monitored by UP PWD which is used to regulate the sluice openings.

In 1994, two water level recorders were installed under the present study at north and south sides of the lake including a staff gauge (installed in 1995) for manual monitoring of the daily lake levels. For computation of change in storage, these lake levels were analysed to determine the trend of water level, i. e., increasing or decreasing with time. The variation of daily water level for each month during the year 1994 have been plotted and shown in Fig.-6(a) and 6(b) while the variation of lake stage with rainfall have been shown in Fig.-7(a) and 7(b) for the years 1994 and 1995 respectively. The abrupt decrease in water level indicates the draining of water through sluice gates to regulate the water level in lake.

Table- 1: Lake area at different depth intervals and layer-wise volume for the whole lake

Depth (m)		Area (m^2)	Volume (m^3)
From	To	Upper Layer	
+0.53	0	463365	244852
0	1	459730	456442
1	2	451721	445786
2	3	441625	440263
3	4	439340	438196
4	5	437052	435908
5	6	434765	433621
6	7	432478	431335
7	8	430192	427015
8	9	423846	418739
9	10	413653	407967
10	11	402307	393040
11	12	383846	374868
12	13	365961	357466
13	14	349038	341704
14	15	334423	327959
15	16	321538	312650
16	17	303846	297541
17	18	291280	280378
18	19	269615	257771
19	20	245000	228752
20	21	211346	200165
21	22	186376	180226
22	23	169230	161404
23	24	147115	130994
24	25	112307	87332
25	26	67307	53487
26	27	40769	15713
Greater than 27		769	133
Total Volume (0 = 3.28 m in PWD Gauge i.e. DAT level on 22.11.1989)			8,581,714



Water Level Recorder Installed at Naina Devi Drain at Nainital



Staff Gauge Installed at Mallital Bank of Lake Nainital



Water Level Recorder Installed at Mallital Bank of Lake Nainital



Water Level Recorder Installed at Tallital Bank of Lake Nainital

Table- 2: Layer wise volume and cumulative volume of Lake Nainital, considering the North (Mallital) and South (Tallital) sub-basins separately.

Depth (m)	Tallital sub-basin	Cumulative Volume (m^3)	Mallital sub-basin	Cumulative Volume (m^3)	Total lake Cum. Volume (m^3)
+0.53	-	-	-	-	8,581,714
0	_	_	_	_	8,336,862
1	_	_	_	_	7,880,420
2	_	_	_	_	7,434,634
3	_	_	_	_	6,994,371
4	_	_	_	_	6,556,175
5	_	_	_	_	6,120,267
6	_	_	_	_	5,686,646
7	_	_	_	_	5,255,311
8	_	_	_	_	4,828,296
9	_	_	_	_	4,409,556
10	_	_	_	_	4,001,588
11	_	_	_	_	3,608,547
12	_	_	_	_	3,233,679
13	_	_	_	_	2,876,212
14	_	_	_	_	2,534,507
15	_	_	_	_	2,206,547
16	_	_	_	_	1,893,896
17	_	_	_	_	1,596,355
18	106,831	418,484	150,940	897,493	1,315,977
19	87,438	311,653	141,314	746,553	1,058,206
20	69,578	224,215	130,586	605,239	829,454
21	58,463	154,637	121,764	474,653	629,289
22	48,761	96,174	112,643	352,889	449,063
23	35,042	47,413	95,952	240,246	287,659
24	12,371	12,371	74,961	144,294	156,665
25	-	-	53,487	69,333	69,333
26	Nil	-	15,713	846	15,846
27	Nil	-	133	133	133

Fig. 4 Variation of surface area of lake nainital with depth

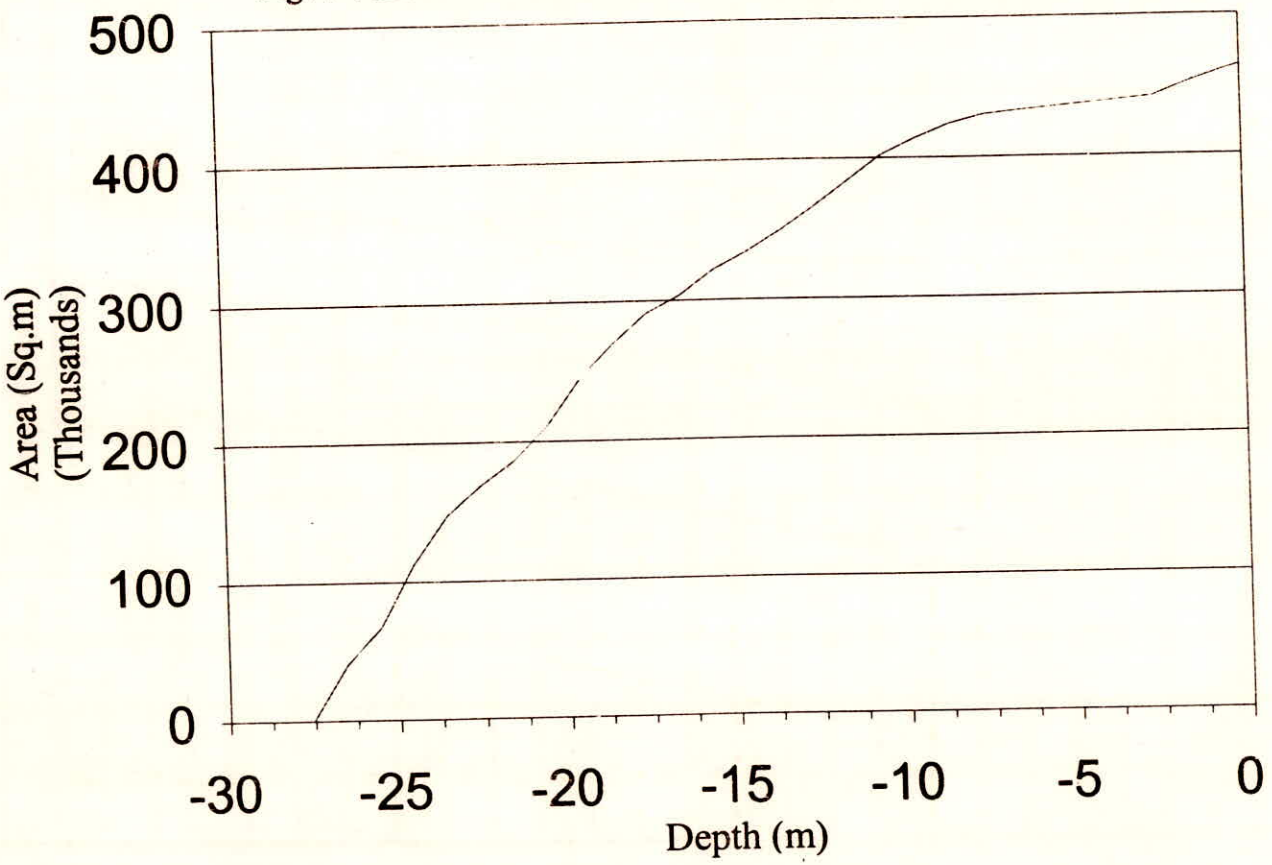
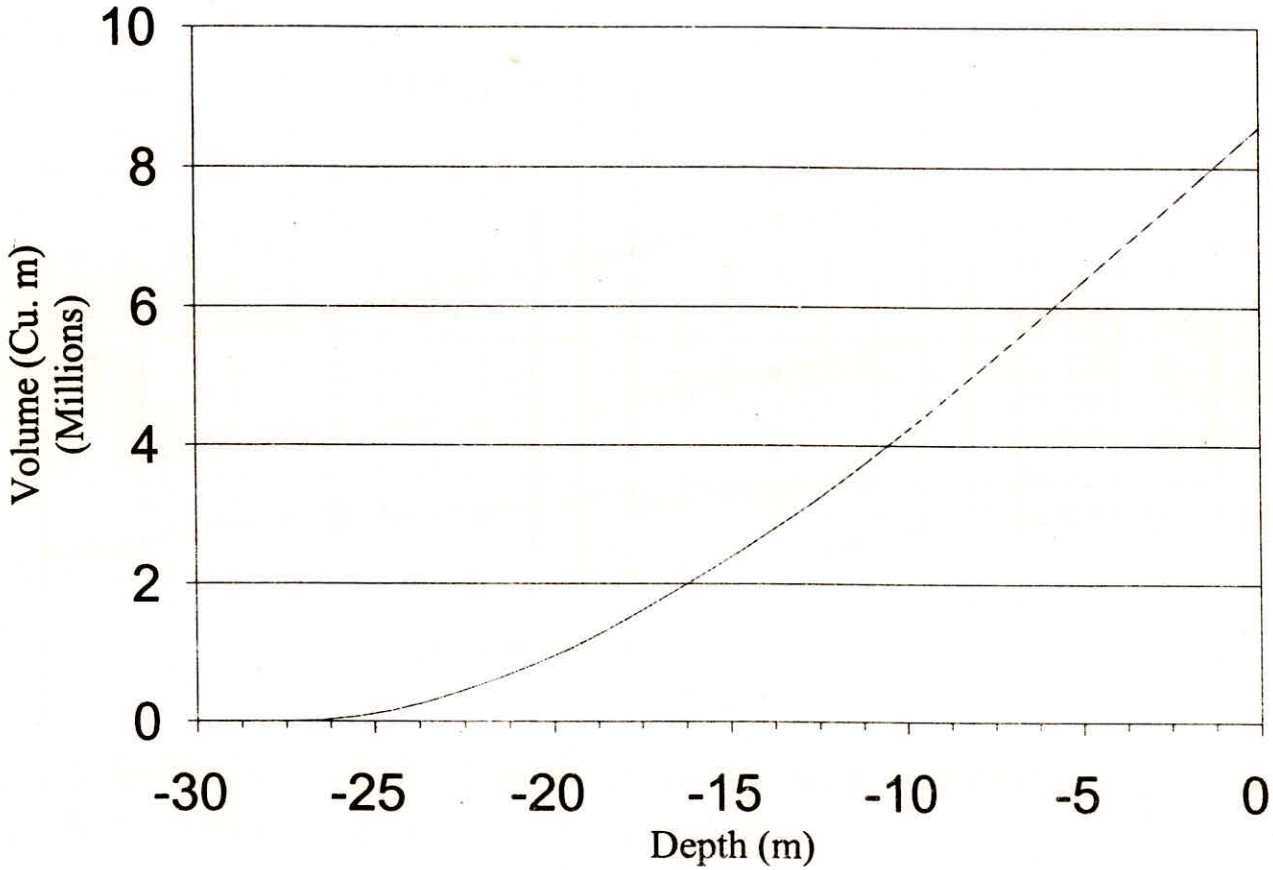


Fig. 5 Variation of volume of lake nainital with depth



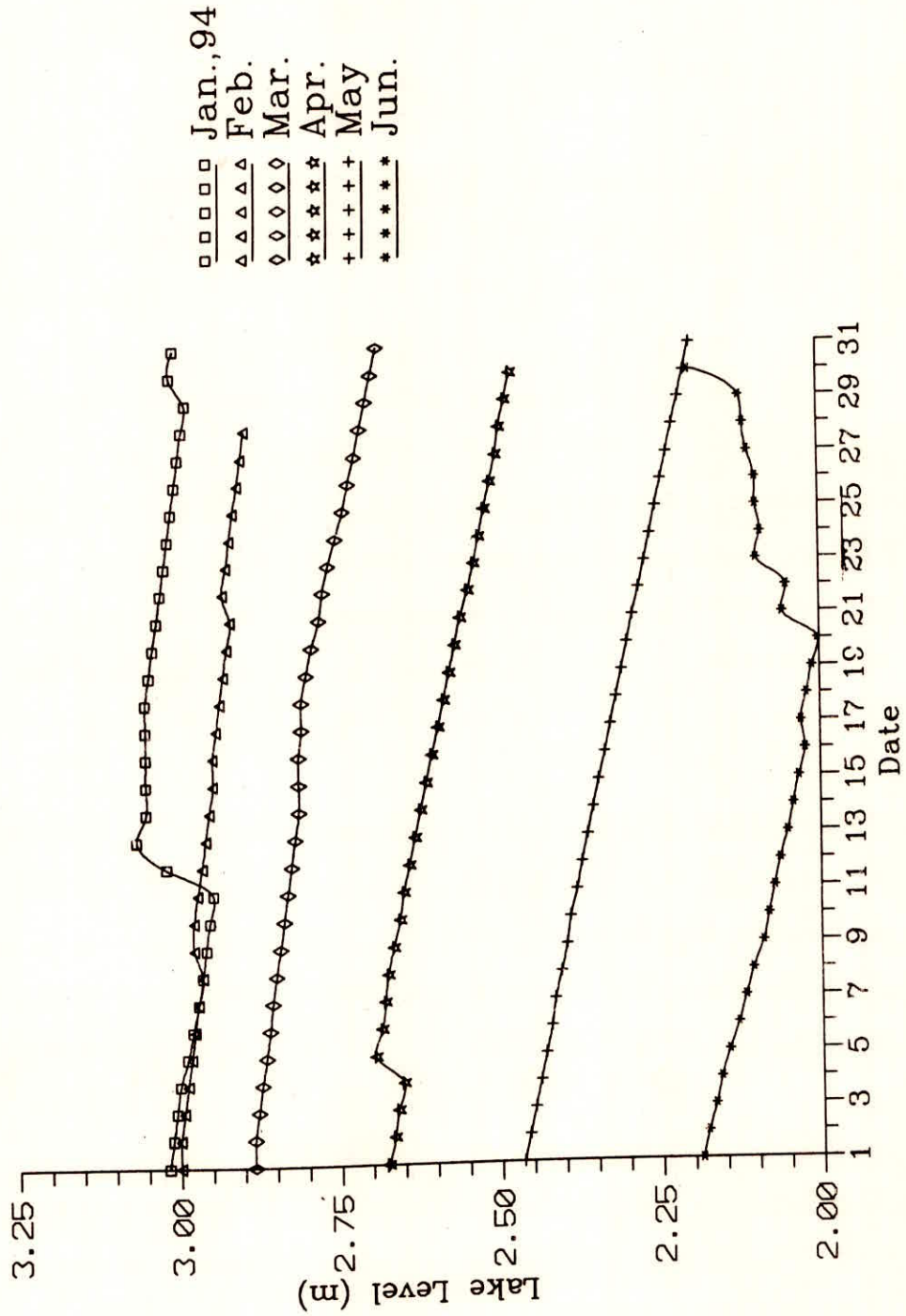
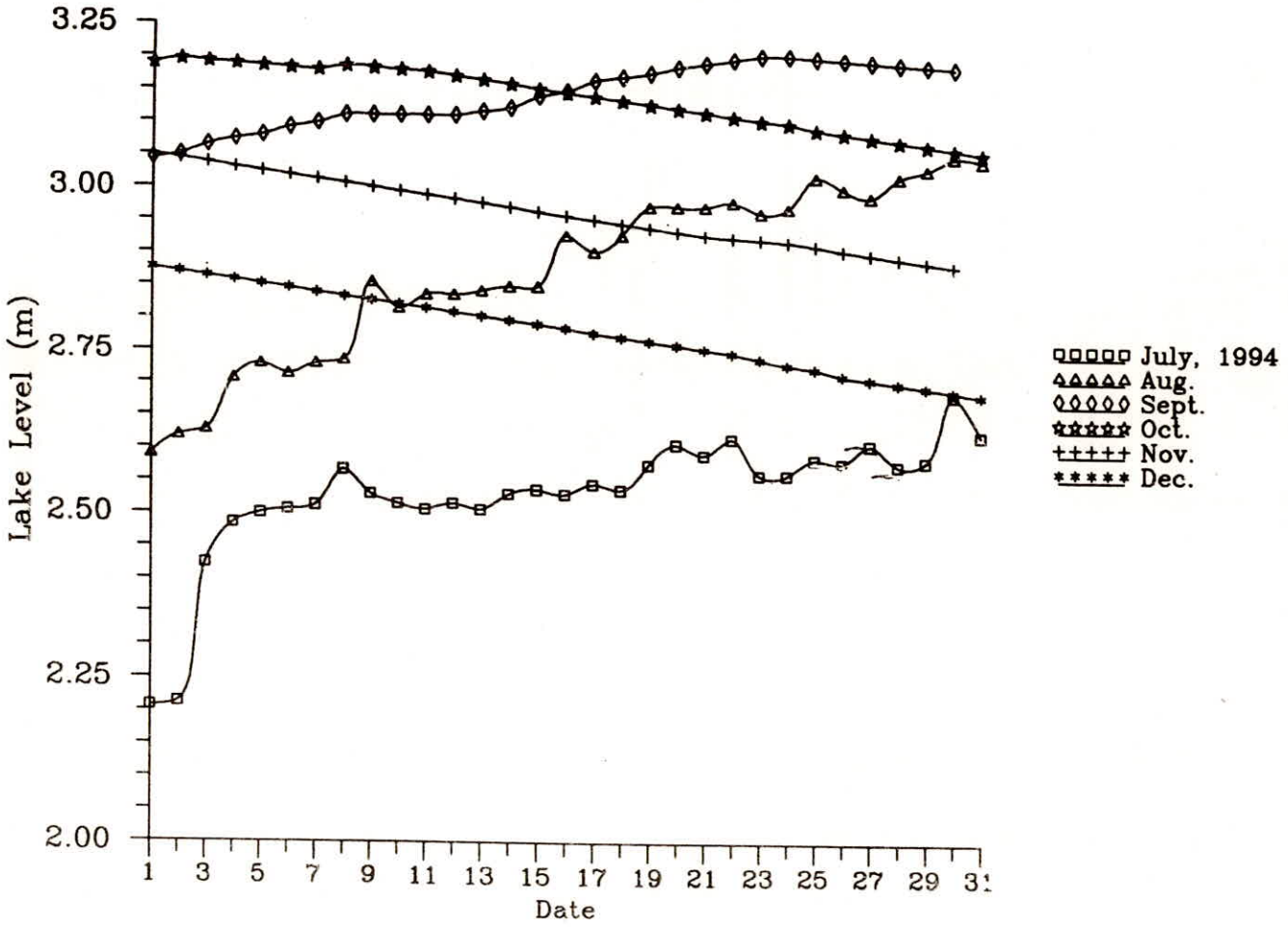


Fig. 6a: Variation of lake level with time during the year 1994.

Fig. 6b: Variation of lake level with time during the year 1994.



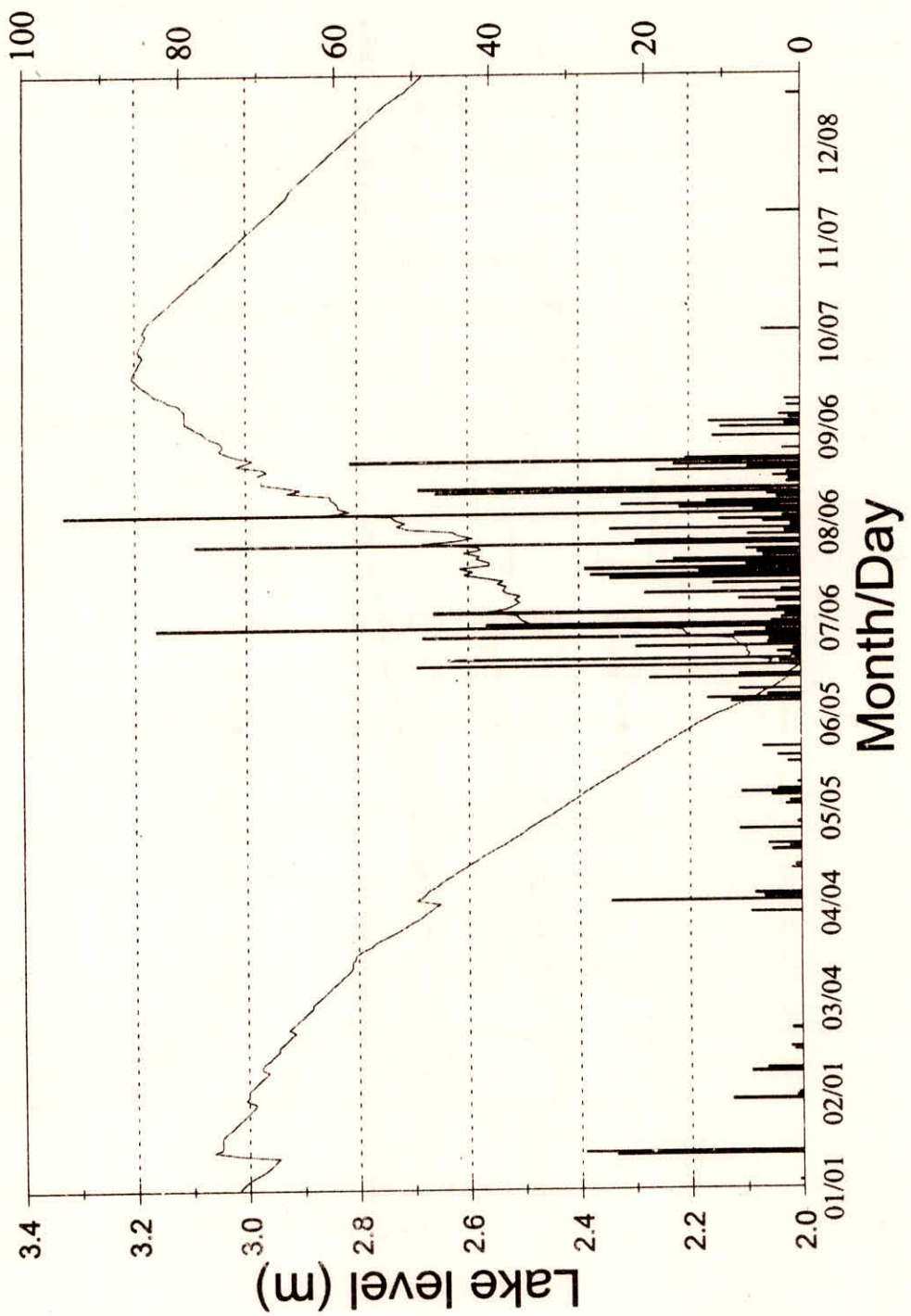
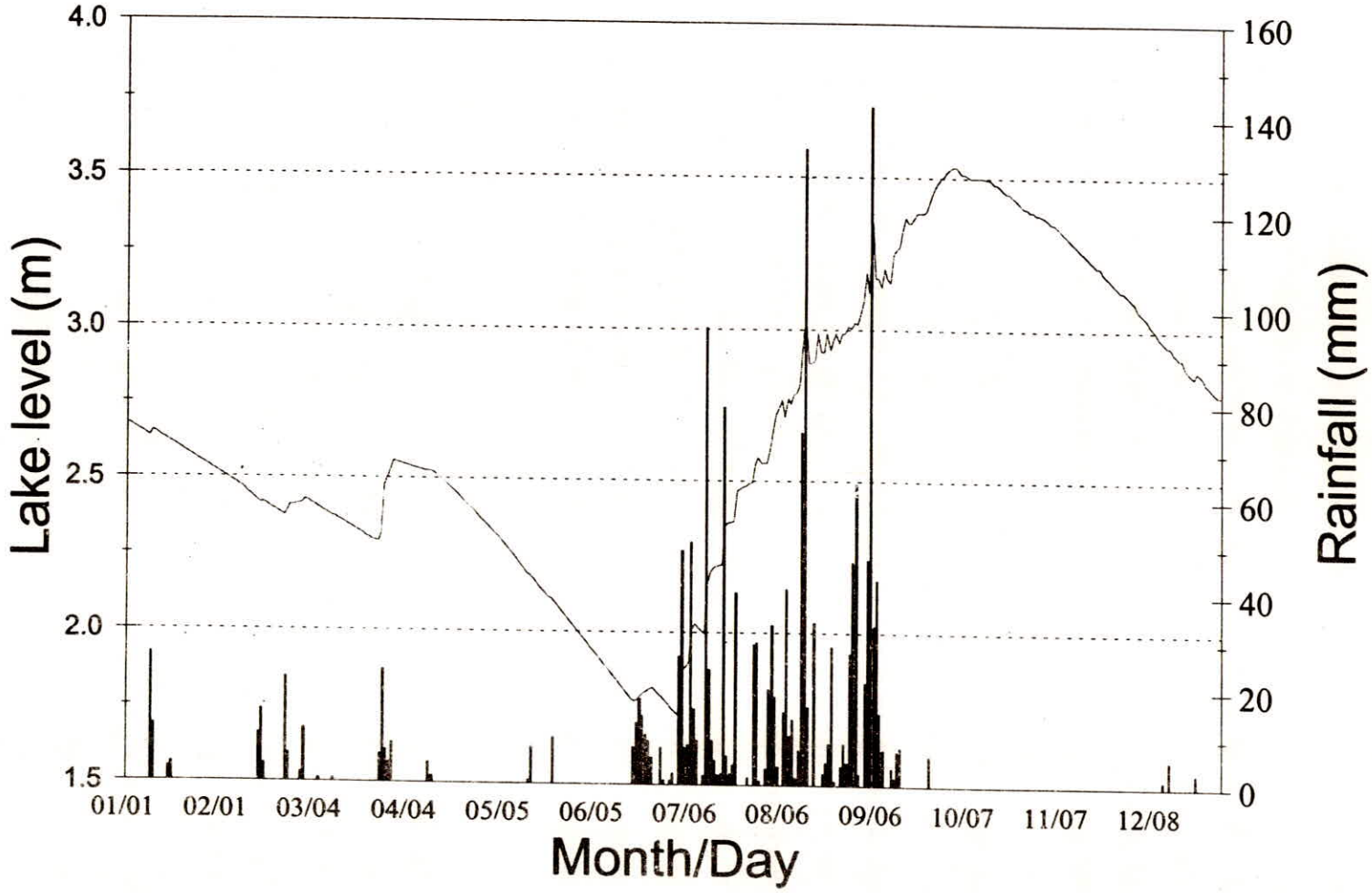


Fig. 7a Variation of lake stage of Lake Nainital along with daily rainfall during 1994

Fig. 7b Variation of lake stage of Lake Nainital along with daily rainfall during 1995



In general, the lake level follow the decreasing trend upto 2nd or 3rd week of June, depending upon the onset of monsoon. After which, the level starts increasing upto mid September. However, the fluctuations can also be easily seen in the water levels during rising trend also due to opening of the sluices to drain out the excess amount of water i. e., to regulate the lake level (the maximum lake level is 12.5 feet in the PWD gauge installed at Tallital bank). The trend of change in the lake level can be defined as the rate of change of water level with respect to input to and output from the lake at any time or time period. The drop and rise in water level indicates only less input and more output or more input and less output from a water body respectively but, in addition to this, water level trend (real time data of change in water level) can distinguish the role of any unknown process taking place. For example, surface runoff can be determined corresponding to a rainfall event if we have the information of trend of change in water level prior to the related inflow. Similarly, if surface runoff is known, the subsurface inflow or subsurface outflow can also determined with the information of trend of change in water level . The trends of change in the water level in lake have been determined at different times from the plots of water level with time and the variation of trend with rainfall are shown in figures 8(a) and 8(b) for the years 1994 and 1995 respectively.

The maximum and minimum variation of lake levels since 1900 to 1994 are shown in Table 3. The maximum change of 8.05 feet has been recorded in 1935 followed by 7.7 feet in 1955 while the minimum change of 4.3 feet in lake level was observed in 1935 & 4.5 feet in 1939 since its recording from 1931. Maximum and minimum fluctuations in the lake level mainly depend upon the annual rainfall (surface runoff) and withdrawal from the lake.

The following equations have been used to calculate the lake surface area (in m^2) from the lake level (LL) data.

For LL between 3.81 and 2.44 m AREA = 6.86 * LL + 437232
For LL between 2.44 and 1.80 m AREA = 14.35 * LL + 418999
For LL between 1.80 and 1.49 m AREA = 6.12 * LL + 433787
For LL less than 1.49 m upto 0 m AREA = 2.29 * LL + 438698

Fig. 8a Variation of weekly water level trend for 1994 and 5-year avg for the period 1991-95, along with weekly rainfall in 1994

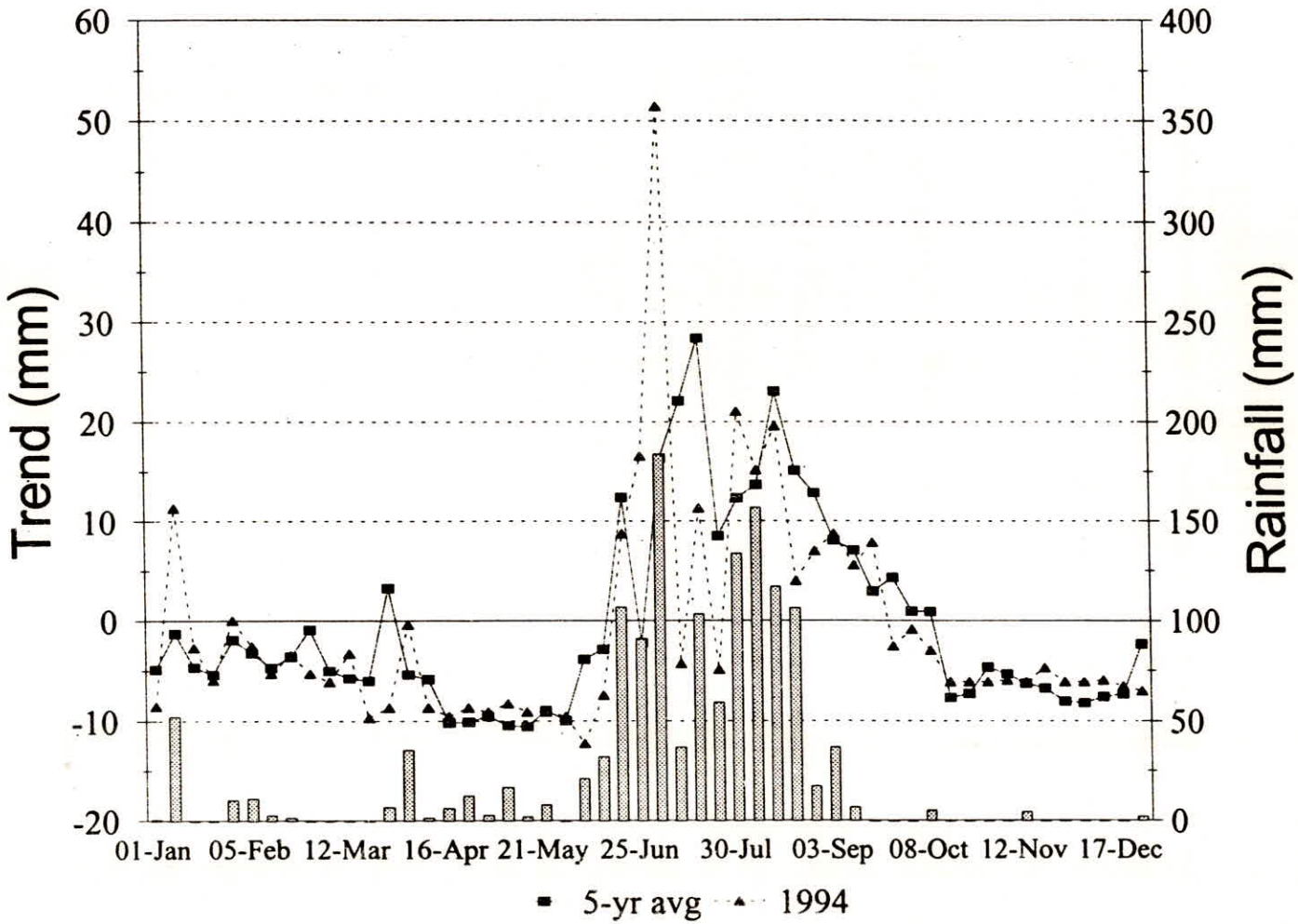


Fig. 8b Variation of weekly water level trend for 1995 and 5-year avg for the period 1991-95, along with weekly rainfall in 1995

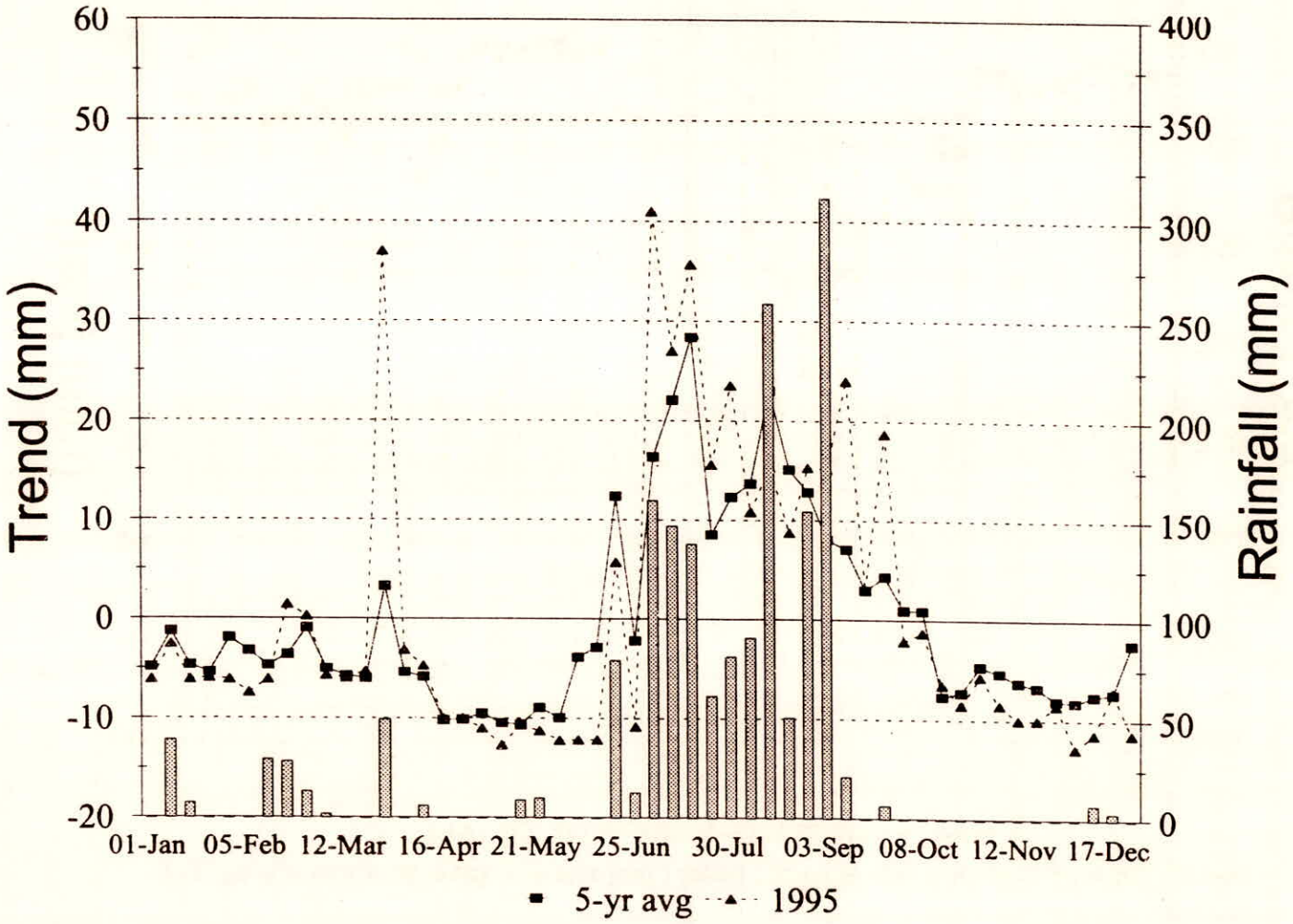


Table- 3: Minimum and maximum lake levels and fluctuations recorded from 1900 onwards

Date	Minimum Lake Level(ft)	Date	Maximum Lake Level(ft)	Fluctuation (ft)
June,1900	0.80	Sep.,1900	2.60	1.8
June,1901	1.08	Sep.,1901	3.18	2.10
June,1902	0.60	Aug.,1902	2.40	1.80
June,1903	0.65	Oct.,1903	3.15	2.50
June.1904	0.70	Oct.,1904	6.20	3.5
June,1905	0.20	Oct.,1905	3.75	3.55
June,1906	1.00	Oct.,1906	3.90	2.90
June,1908	0.10	Oct.,1908	3.60	3.50
June,1909	0.80	Oct.,1908	3.95	3.15
June,1910	1.00	Jul., 1910	5.08	4.08
June,1911	1.50	Oct.,1911	4.30	2.8
June,1912	1.25	Oct.,1912	4.35	3.1
May,1913	1.50	Oct.,1913	4.25	2.75
June,1914	1.50	Sep.,1914	4.60	3.1
June,1915	1.60	Oct.,1915	4.30	2.7
May,1916	0.90	Oct.,1916	3.20	2.30
June,1923	0.00	Oct.,1923	4.30	4.30
May,1924	1.20	Nov.,1924	4.85	6.05
.....	....	.....	.....	.....
July, 1931	4.70	Oct.,1931	12.00	7.3
June,1932	5.00	Oct.,1932	12.20	7.2
June,1933	7.40	Oct.,1933	12.20	4.8
June,1934	5.72	Oct.,1934	11.93	6.21
June,1935	4.30	Sep.,1935	12.35	8.05
June,1936	6.40	Oct.,1936	12.40	6.00
June,1937	6.65	Oct.,1937	12.47	5.82
June,1938	7.06	Oct.,1938	12.36	5.3
June,1939	4.50	Sep.,1939	11.50	7.0
June,1940	6.10	Sep.,1940	12.50	6.4
May,1941	6.70	Sep.,1941	11.80	5.1
June,1942	6.50	Oct.,1942	12.46	5.96
June,1943	6.30	Oct.,1942	12.50	6.2
June,1944	6.78	N.A.	N.A.	N.A.
June,1946	7.60	Sep.,1946	12.45	4.85
June,1947	5.90	Oct.,1947	12.50	6.6
July,1948	5.90	Oct.,1948	12.50	6.6
June,1949	7.07	Sep.,1950	06.45	N.A.
.....	....	.....	.....	.....
June,1955	4.73	Sep.,1955	12.43	7.7
June,1956	9.40	N.A.	N.A.	N.A.
.....	....	.....	.....	.....
June,1975	7.00	Oct.,1975	12.00	5.0
.....	....	.....	.....	.....
N.A.	N.A.	Sep.,1989	11.35	N.A.
June,1990	8.80	Oct.,1990	11.55	2.75
June,1991	7.70	Sep.,1991	10.92	3.22
June,1992	6.40	Sep.,1992	11.61	5.21
June,1993	7.05	Sep.,1993	12.60	5.55
June,1994	6.60	Sep.,1994	10.51	3.91

where LL is the lake level in mm. The LL corresponds to the readings taken at the PWD staff gauge. 3.81 m corresponds to 12.5 ft in the gauge and 0 m corresponds to 0 ft. of the gauge, which is 1933.19 m above mean sea level. The results are then used to compute the volume between two lake levels by following the method given by Zumberge and Ayers (1964) described under section 3.2.2. The change in total storage with respect to rainfall for the years 1994 and 1995 are given in table-4.

Table 4: Change in storage (m^3) of Lake Nainital during 1994 and 1995.

Months	1994	1995
Jan.	-8,010	-72,580
Feb.	-53,290	-45,640
March	-91,950	+62,010
April	-94,400	-94,640
May	-1,26,480	-1,55,550
June	+1,577	-1,10,380
July	+1,91,070	+3,62,850
Aug.	+1,92,490	+2,08,790
Sept.	+66,270	+2,31,440
Oct.	-60,310	-64,300
Nov.	-79,850	-1,29,340
Dec.	-90,580	-1,42,040
Total	-1,53,490	+50,210

3.2.3 Surface inflow

The actual surface inflow to the lake has been treated in two parts, the first being the unmonitored inflow and 24-hour response of the lake to daily rainfall and the second being the continuous inflow through the drains / channels. The latter has been separately dealt as channel inflow (D_i) which has been computed using observed values.

3.2.3.1 Lake Level Trend Analysis Method

The surface inflow to the lake can be computed from the change in storage taking into account the lake level trend (as outlined in section 3.2.2.2). This Lake Level Trend Analysis (LLTA) method is not very different from the hydrograph analyses method used in the estimation of groundwater recharge. The trend represents and accounts for different losses from the lake and also accounts for any subsurface inflow as well as subsurface outflow - as it does not vary drastically over the time interval (24-hours) that is being considered for the estimation of surface inflow. The change in water level in mm over a week's period is averaged and considered as constant for that particular week. Figures 8a and 8b show the trend during the years 1994 and 1995, respectively. Further, the five year (1991-1995) average trend has also been shown in the figures. The daily surface inflow estimated by LLTA method has been shown in Figure 9a along with that estimated by SCS-CN method (described in the following section) for the year 1995. The monthly estimates of surface inflow to the lake by both the methods for the year 1995 are shown in figure 9b. The rainfall - runoff relationship computed using the surface inflow data estimated using LLTA method for the monsoon and nonmonsoon seasons of 1995 are shown in Figures 10a and 10b.

3.2.3.2 Soil Conservation Service - Curve Number (SCS-CN) Method

The S_i has also been estimated by Soil Conservation Services - Curve Number (SCS-CN) method. The runoff curve number method has been developed by Soil Conservation Service of US Department of Agriculture. SCS-CN method is more useful for estimation of 24 hour run-off from small catchments, as it is based on 24-hr rainfall-runoff data. In this method, runoff depth is a function of total rainfall depth and an abstraction parameter called curve number (CN). The CN varies from 1 to 100 and it is a function of the following catchment characteristics:

1. Hydrologic soil type
2. Land use and treatment
3. Ground surface conditions and
4. Antecedent moisture condition (AMC).

Fig. 9a. Daily surface inflow to Lake Nainital during the year 1995, estimated by SCS-CN and LLTA methods

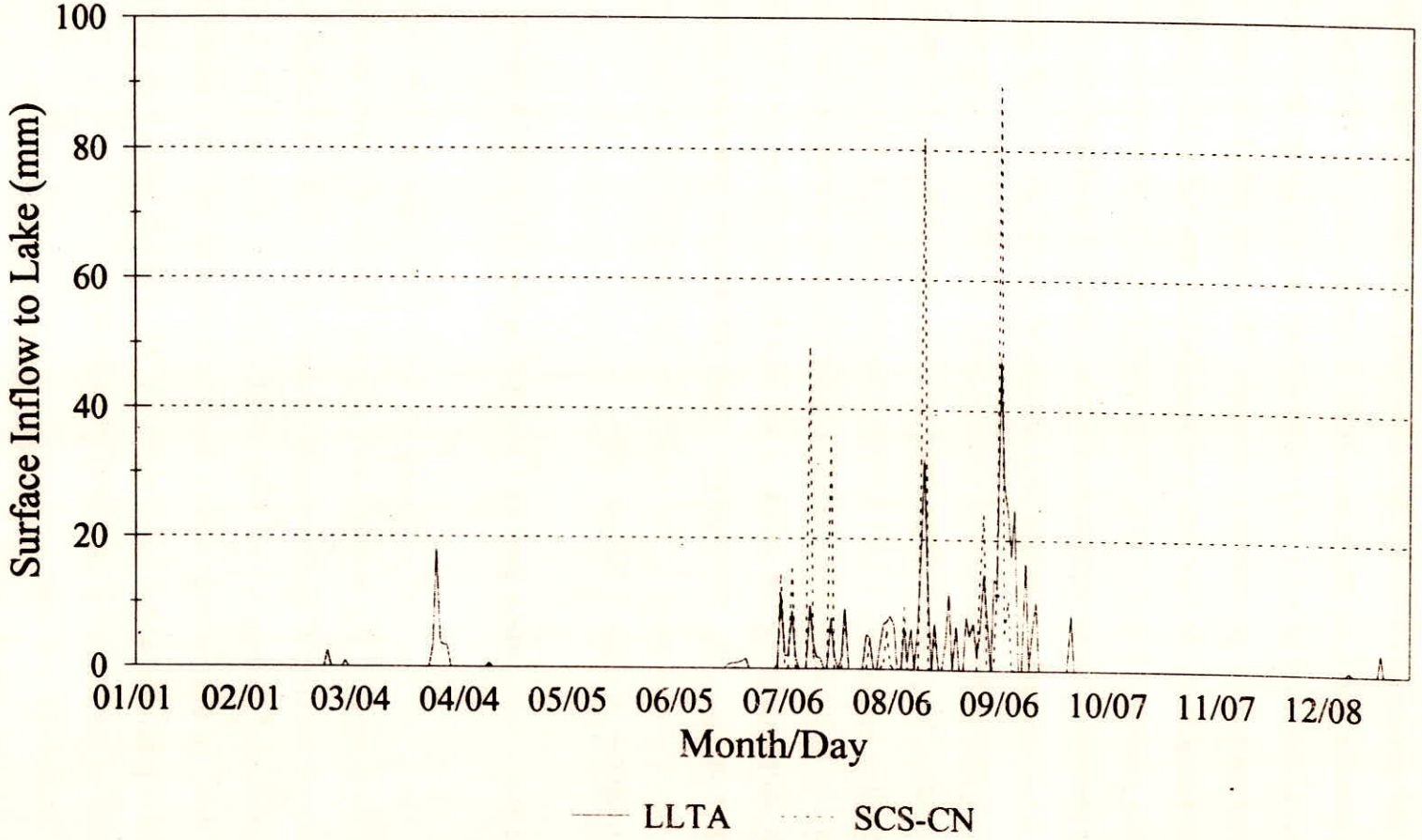


Fig. 9b. Monthly surface inflow to Lake Nainital during the year 1995, estimated by SCS-CN and LLTA methods

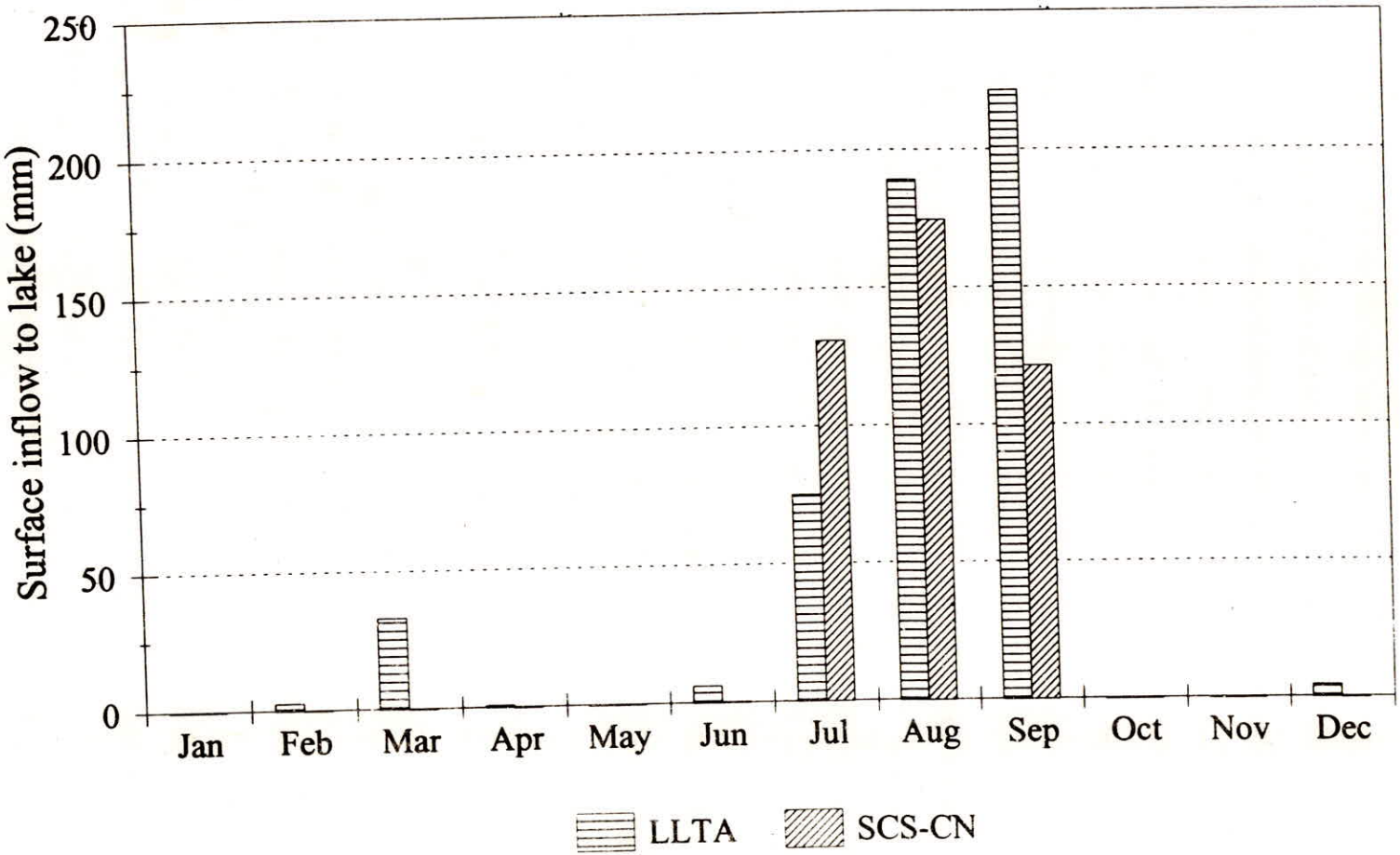


Fig. 10a Rainfall - runoff relation in Lake Nainital basin for 1995 monsoon by LLTA method

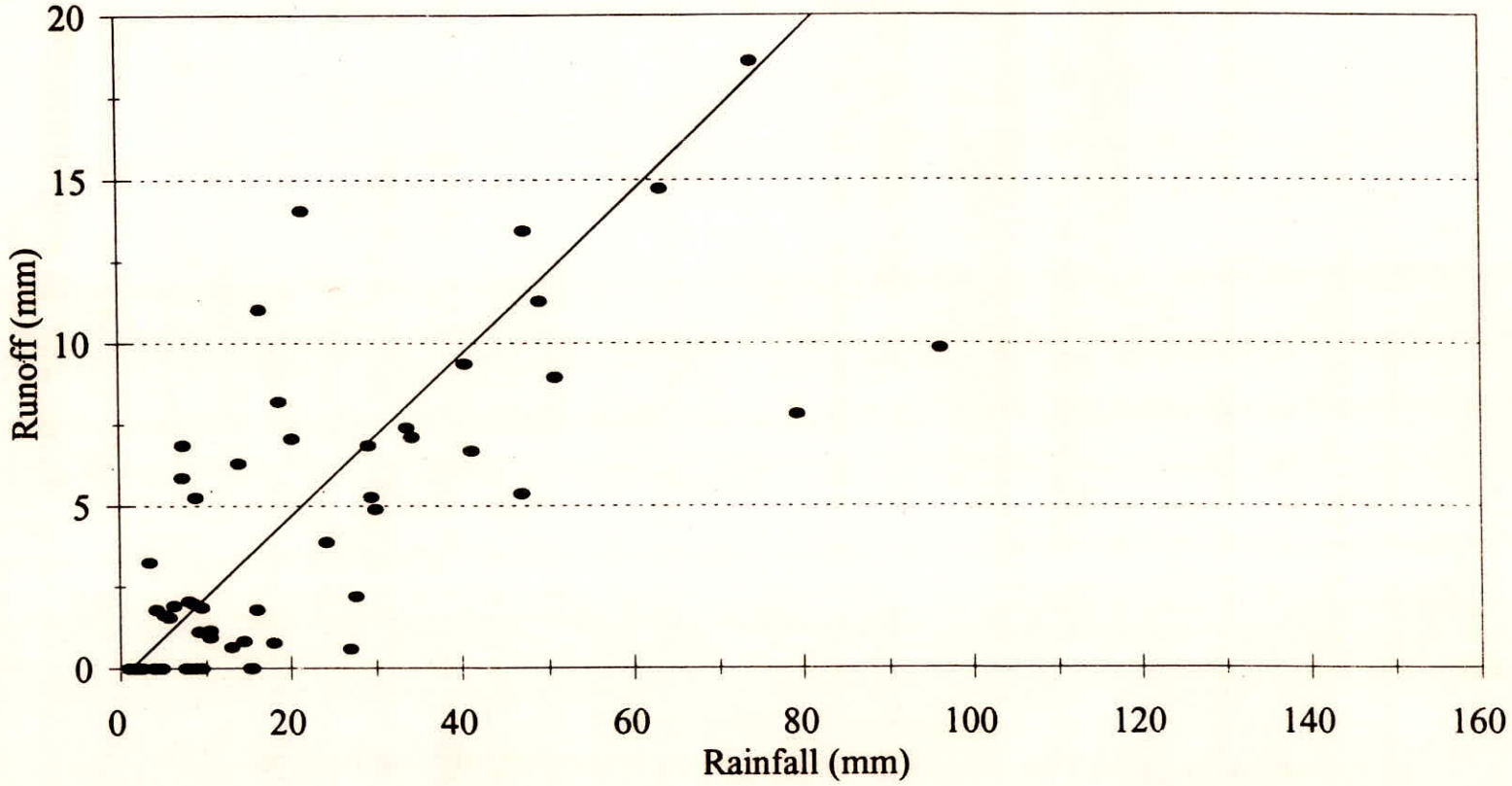
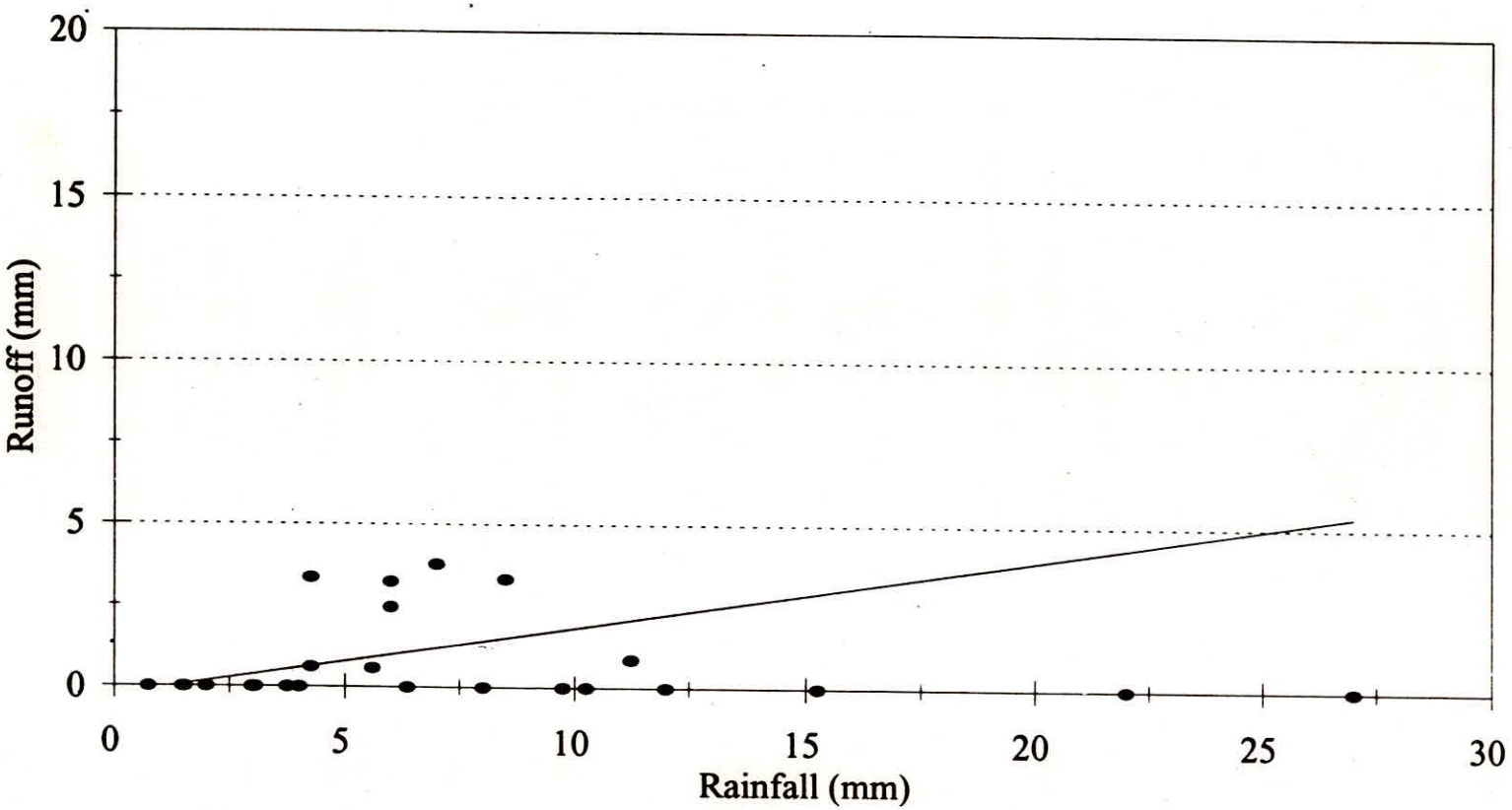


Fig. 10b Rainfall - runoff relation in Lake Nainital basin for 1995 non-monsoon by LLTA method



The basic theory of this well established and widely used method is that the runoff starts after an initial abstraction (mainly interception, infiltration and surface detention) of I_a and that the ratio between actual retention to the potential retention (S) is equal to the ratio of direct runoff (Q) to rainfall (P) minus initial abstraction. i.e.

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \qquad (2)$$

rewriting the above equation we get:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (3)$$

The quantity I_a is related to S so that, $I_a = 0.2$ S. This relation was expressed by Soil Conservation Service based on rainfall-runoff data from small experimental watersheds. Using this relationship, between initial and potential abstractions, equation (3) could be rewritten as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (4)$$

The parameter S depends upon catchment characteristics as outlined above. The Soil Conservation Service expressed S as a function of Curve Number (CN):

$$S = \frac{1000}{CN} - 10 \qquad (5)$$

CN is determined from the hydrologic soil type and antecedent moisture conditions. The hydrologic soil group are labelled as A, B, C or D. A short description of these soil groups are given in the following table:

Soil group	Soil characteristics	Minimum Infiltration rate (in./h)
A	Deep sand, deep loess and aggregated silts; High infiltration rates when wetted thoroughly.	0.30 - 0.45
B	Shallow loess and sandy loam; moderate rate of water transmission.	0.15 - 0.30
C	Clay loams, shallow sandy loam, clayey soil; Slow rate of water transmission.	0.05 - 0.15
D	Plastic clays, and soils that swell on wetting; High runoff potential and slow infiltration rates when wetted thoroughly.	<0.05

The antecedent moisture condition (AMC) refers to the soil water content at a given time. The SCS-CN method has three levels of AMC, depending on the total rainfall in the 5-day period preceding the storm, viz. AMC I, AMC II and AMC III. In AMC I, the soils are dry but not to the wilting point. AMC II reflects average conditions and AMC III has highest run-off potential with the catchment practically saturated from antecedent rainfalls. The values that are generally adopted as a measure to determine the AMC level is given in the following table:

Antecedent Moisture Condition (AMC)	Total 5-day antecedent rainfall (cm)	
	Dormant season	Growing season
I	Less than 1.3 cm	Less than 3.6 cm
II	1.3 to 2.8 cm	3.6 to 5.3 cm
III	More than 2.8 cm	More than 5.3 cm

The appropriate CN for a variety of landuses, soil treatment or farming practices along with hydrological conditions (state of vegetation growth) has been presented by SCS (1969) for AMC II. Using the land use information obtained from forest map and SPOT imagery data of 1989 and soil characteristics of the Nainital catchment, the CN has been taken from the table of curve numbers for urban areas and agricultural lands presented by SCS and as given in Ponce (1989). The following table presents the type and percent area under different Landuse, the appropriate CN and the weighted CN for AMC II for the Nainital lake catchment. The CN thus determined for AMC II has been converted to AMC I and AMC III using the relations expressed by Hawkins et al. (1985).

Land use	Ratio of area under the given Landuse to total catchment area	Hydrologic soil group	CN for AMC II
Reserved Forest	0.2352	A	30
Other Forest	0.2294	B	36
Built-up	0.4545	C	92
Barren	0.0448	C	86
Flats near lake	0.0125	A	76
Roads	0.0237	-	98
Composite Curve Number for AMC II			64

The surface inflow to the lake has been thus computed with the curve numbers determined on the basis of AMCs and daily rainfall data using the equations (4) and (5), with a spreadsheet software (QProWin). The estimated runoff in units of depth has been converted to units of volume using the exclusive catchment area of the Lake. Since the Sukhatal sub-catchment do not contribute to the surface inflow to the lake (there is no surface outlet from the Sukhatal catchment) it has been excluded in the estimations. The variation of different inflow components (including surface inflow using SCS-CN method) have been shown in Fig.-11 for the year 1995.

Inflow through drains [D_i]:

The Nainital catchment has a very good drainage network. There are a total of 49 public drains which after a series of interconnections join the lake through 21 outlets. Out of these 21 outlets, 14 are from the Sher-ka-danda side and 6 are from Ayarpatta side of the catchment. The remaining one, Naina Devi drain, which is the largest of all drains joins the lake from the Northeastern part. Since Naina Devi drain and Rickshaw stand drain are the perennial ones, the discharge of these drains have been monitored under the present study. The measurement was made adopting the velocity-area method. The measurements of water currents at different points in the three major drains were made using a pygmy-current meter.

3.2.4 Surface outflow

a) Discharge Through Sluices

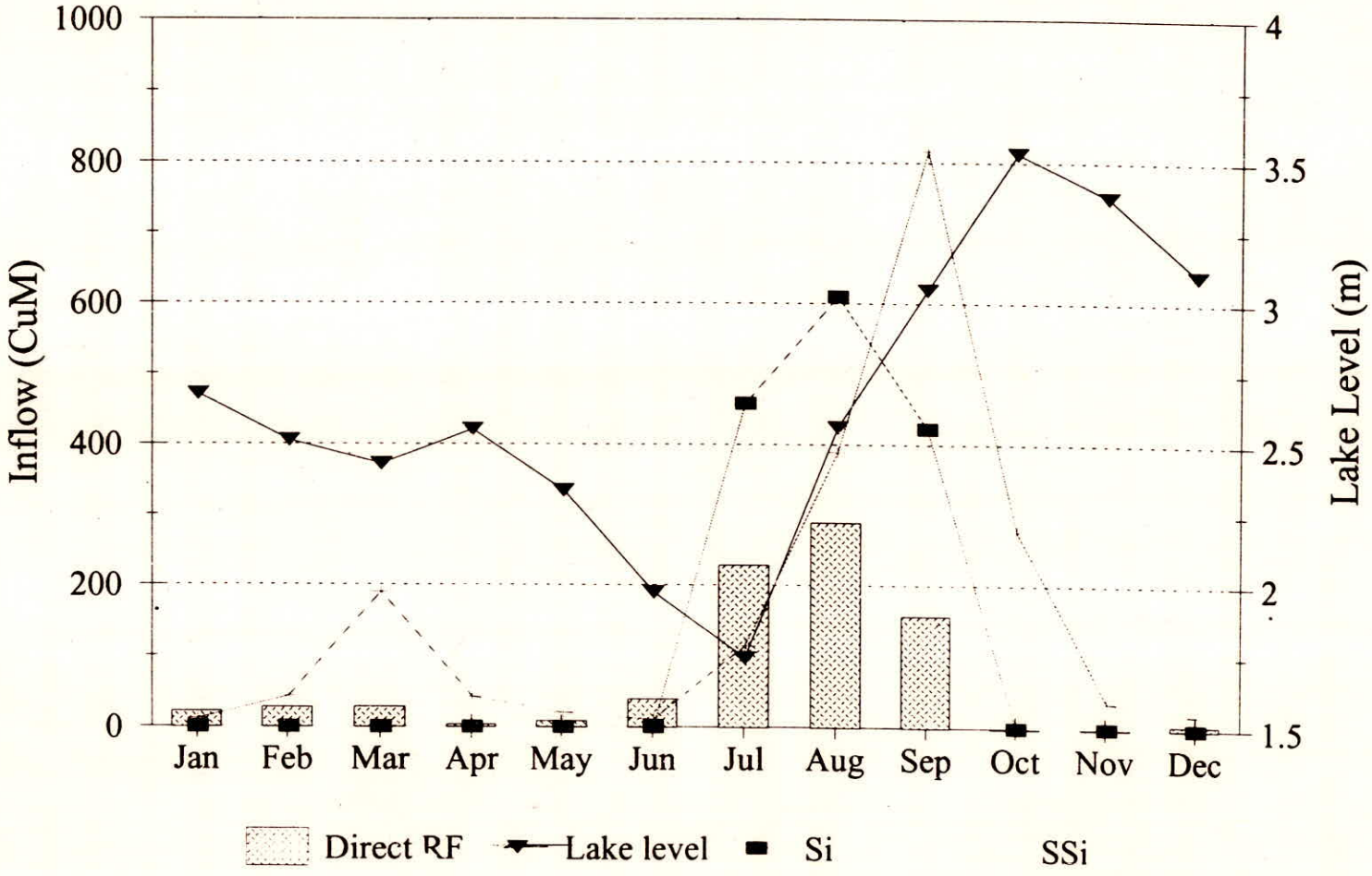
Surface outflow from the Nainital lake occurs only in the months of rainy season because, the water level in lake is maintained at Tallital bank by the PWD, Nainital with the help of sluice gates. The lake outlet contains 5 gates, each 2.5 ft. wide and 1.25 ft. high, worked by screw type regulatory system. Each opening will have an area of 3.75 square feet. All the sluices are opened simultaneously and to the same extent. The Hill Slide Committee of 1927 formulated some regulations regarding the opening of sluices and the same are still followed, the important features of which are listed below.

If the gauge is below 9 ft., the sluices are not to be opened more than 6", and so long as the gauge is below 9.5 ft., the sluices as a rule are not to be opened more than 12", but in the event of abnormally heavy or continuous rainfall, the District Engineer/Surveyor must use his discretion in this matter. These regulations are mainly to avoid any damage to the geotechnically sensitive Balia ravine. The discharge through the lake outlet has been calculated by using the hydraulic equation for submerged rectangular openings. The equation for the gates installed in Lake Nainital has been given by Byrnes (1930) and the same has been adopted in the present study.

$$Q = 252780 * (h_1 - h_2) * \frac{\sqrt{h_1 + h_2}}{2} \qquad (7)$$

Where Q is the discharge in cubic feet per hour, h_1 and h_2 are the head to the bottom and top of the rectangular sluice opening in feet. The information on h_1 and h_2 have been obtained from the sluice gate operation records i.e., the time & extent of gate opening and the lake level at the time of sluice opening and closing. The records are well maintained by the UPPWD, Nainital. Further, under the present sluice operational procedures of the PWD, the sluices are never completely closed since the first day of its opening in any hydrological year until the 15th of October in that year, when the sluices are finally sealed. Leakage of lake is allowed during this period through a sluice opening of about half an inch. Therefore in the computation of the sluice discharges, the leakage has also been taken into consideration.

Fig. 11. Variation of different inflow components of Lake Nainital during 1995

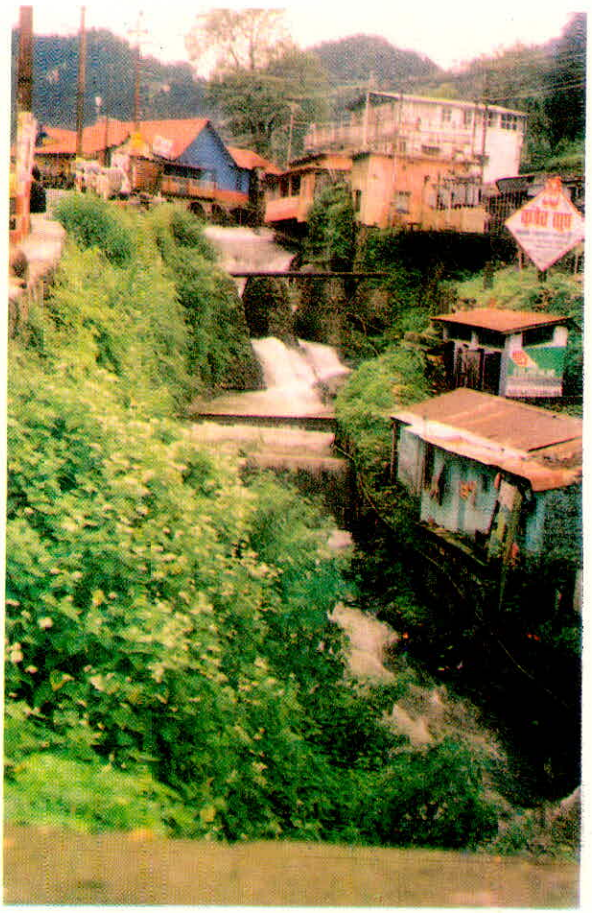




Boat Club Drain Discharging Water into Lake During Monsoon Season



Naina Devi Drain (near Water Works) Discharging Water into Lake During Monsoon Season



Discharge of Water from Nainital Lake Through Sluices Gates Located at Tallital Bank of Lake Nainital, During Monsoon Season.



Leakage of Lake Water through Sluices Gates Located at Tallital Bank of Lake Nainital, During Monsoon Season

b) Pumping from Nainital Lake:

The water supply from springs and lake through pipe lines was first introduced in the year 1898 in Nainital town. In those days, springs were tapped directly for domestic use by the general public, which is still continued in some places, while the steam engine plant was used to pump the water to high zones. In 1923, electric pumping stations were installed to supply water from lake to Nainital town. Presently, some deep tubewells as well as an open well, located at the banks of the lake, are being used to pump the lake water including groundwater. There are three tubewells in addtion to the eight pumping sets installed in the open well located near in the Mallital bank of the lake Out of the tubewells, one deep tubewell, constructed recently is operated by UP Jal Nigam and the rest are operated by Jal Sansthan, Nainital. The Jal Sansthan and Jal Nigam authorities maintain the records of total pumping hours of tubewells. Therefore, the data of total pumping hours and discharge capacity of pumps & tubewells have been collected from the Jal Sansthan and Jal Nigam offices located at Nainital. One more well is operated by Army authorirties at the Mall road side bank of the lake near the Library, to meet the water requirement of military establishment at Lariakanta. The details of the of the discharge capacities of the pumps installed at lake banks are given below.

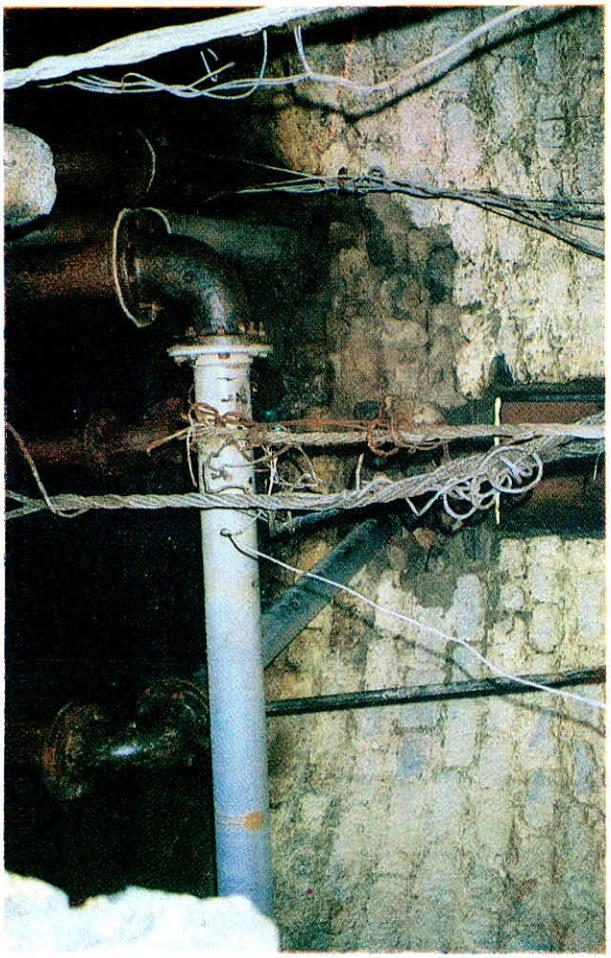
Pump No.	Location	Year of installation	Pump Capacity m^3 / hour
1	Open well	1923	69.00
2	Open well	1989	120.00
3	Open well	1985	142.20
4	Open well	1958	95.40
5	Open well	1958	72.00
6	Open well	1958	72.00
7	Open well	1958	95.40
8	Open well	1983	244.80
TW1	Tube well 1 Jal Sansthan	1991	90.00
TW2	Tube well 2 Jal Sansthan	1991	132.00
TW3	Tube well 3 Jal Nigam	1994	204.00
MW1	Military Pump House	1980	360.00

The total discharge of lake water through pumping has been calculated for the period from Jan. 1994 to Dec. 1995, on monthly basis. The withdrawal of lake water for meeting the water supply demand of city Nainital has been determined by taking 80% efficiency of the electric pumping sets as per the discussion held with the engineers concerned of Jal Sansthan. The monthly data on water pumped from the lake area during the years 94 and 95 is shown in Table- 5. The monthly discharge of these pumps and tubewells varied between 2,23,580 m^3/month to 4,99,100 m^3/month during 1994-95. The quantum of water pumped varies significantly in different months depending upon the demand. During April to June, pumping is higher and during September to November it is lower (Table- 5).

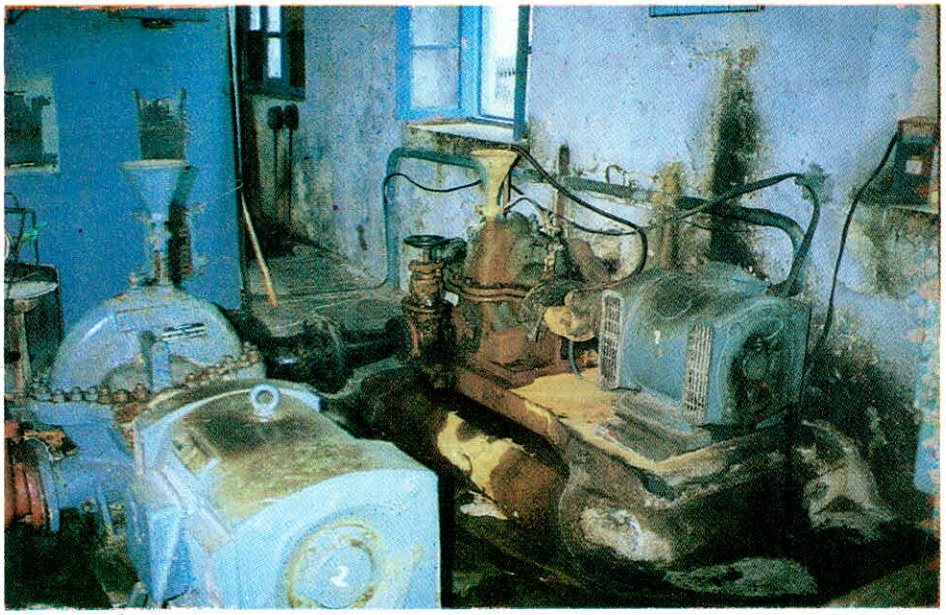
Table- 5: Total discharge of water pumped (m^3) out from Lake Nainital in different months and years during the study period.

Months	1994	1995
January	2,44,470	3,72,970
February	2,43,550	3,56,250
March	2,95,500	4,09,180
April	3,34,900	4,79,270
May	4,59,290	4,99,100
June	4,69,130	4,68,240
July	4,02,760	4,40,690
August	2,68,120	3,21,450
September	2,23,580	2,42,750
October	3,18,820	2,34,330
November	3,34,170	2,95,700
December	3,40,930	3,31,990
Total	39,35,220	44,51,920

The values presented in Table - 5, are total water pumped through the wells located in the banks of the Lake Nainital. However, from the stable isotope data it has been found that not all the water that is being pumped is lake water. The water drawn



Open Well (Filtration Well) Constructed During British Period near Mallital Bank, Being Used to Draw Water by Eight Electric Pumps to Meet Out City Water Supply



Electric Pumping Sets Being Used to Draw Water from the Open Well for City Water Supply

from the wells is a mixture of both lake water and groundwater. Based on the stable isotopic signatures of lake water and groundwater, it has been estimated that the proportion of lake water in the water that is being pumped varies from 25% during winter season (January - March), 20% during summer season (April - June), 80% during Monsoon season (July - August), and 40% during post-monsoon season (September - December). Based on these information the values of Wo have been corrected accordingly and included in water balance calculations.

3.2.5 Evaporation

The estimation of evaporation is rather complicated. Several equations for estimating evaporation from free water surfaces exist in literature. In a recent and most comprehensive article, Winter *et al* (1995) have evaluated 11 equations for the estimation of lake evaporation. Of the three types of approaches to the estimation of evaporation, viz. energy balance, mass transfer and combination (Penman type), the first one yields more reliable results, if data on all associated energy terms are available. Alternatively, if sufficient data are available, the combination methods yield better results. Based on the relative merits outlined in the literature, the Penman method (Jensen, 1974) was chosen. The equation for the estimation of evaporation is:

$$\frac{\Delta}{\gamma + \Delta} * (Q_N + G) + \frac{\gamma}{\gamma + \Delta} * 15.36 * (0.5 + 0.01 * U_2) * (e_0 + e_a) \quad (8)$$

Where, γ and Δ are the weighting factors. Q_N is the net solar radiation. G is the advected energy which is negligible. U_2 is the wind velocity in m/s at 2m above lake surface. e_0 and e_a are the saturated vapour pressure (mb) at the water surface temperature and actual vapour pressure (mb) at air temperature, respectively. Δ is the slope of the vapour pressure versus temperature curve and is expressed in mb/°C. The following equation can be used for the computation of Δ, which is the slope of the vapour pressure vs. temperature curve.

$$\Delta = \frac{25083}{(T + 237.3)^2} \exp\left(\frac{17.3 * T}{T + 237.3}\right) \quad (9)$$

where T is the mean air temperature in °C.

γ, the psychrometric constant is computed using the following equation:

$$\gamma = \frac{0.61 * P}{1000} \qquad (10)$$

where P is the mean atmospheric pressure in mb. The atmospheric pressure data have been collected from UP State Observatory at Manora that is located 2 km south of the lake site, at almost a similar altitude. Since the solar radiation data for the site was not available, the net radiation (Q_N) was computed using the following relationship:

$$Q_N = Q_S * (1-\alpha) - Q_{LN} \qquad (11)$$

where, α is the albedo (reflection coefficient), Q_S is the global solar radiation and Q_{LN} is the net long wave radiation. The α for the present study was computed by using the values presented for different amount of cloud cover (Ter-Makaryantz, 1960). The sunshine hours data collected by Uttar Pradesh State Observatory (UPSO) located about 2 km south of the lake was used to generate the cloud cover data. Rao *et al* (1971), after analysing meterological data collected from IMD Stations from all over India, proposed the following equation for the computation of Q_S.

$$Q_S = Q_A * [0.325 * COS\Phi + 0.385 * (\frac{n}{N})] \qquad (12)$$

where Φ is the latitude and n and N are actual and maximum possible sunshine hours, respectively. Q_A, the extraterrestrial radiation and N for the site were computed using the Duffie-Beckman equations (Allen, 1996). Q_{LN} was computed by the following equation (Shuttleworth, 1992):

$$Q_{LN} = -f\epsilon\sigma T^4 \qquad (13)$$

where, σ is the stefan boltzmann constant, T is the absolute temperature in Kelvin, f is

the adjustment factor for cloud cover, which is roughly equal to (0.1+0.9*n/N) (Singh, 1992) and ϵ' is the emissivity factor, which was computed using the Idso-Jackson equation. e_0 can be calculated using the following equation (Linsely et al., 1975):

$$e_0 = 33.8639 * [(0.00738\ T_0 + 0.8072) - 0.000019 * |1.8\ T_0 + 48| + 0.001316] \quad (14)$$

The actual vapour pressure e_a can be computed by multiplying the relative humidity with the saturated vapour pressure at a given air temperature. The parameters, required for the Penman equation, viz., air & water temperatures and relative humidity were measured at the lake site. Evaporation data was also collected directly from a USWB Class-A Pan installed at the lake site. The values of estimated evaporation from Lake Nainital and estimated & measured parameters used for the computation of evaporation are presented in Table- 6(a) and 6(b) respectively.

Table 6(a): Monthly variations of evaporation (m^3) from Nainital lake during different years.

Months	1994	1995
Jan.	30,380	31,740
Feb.	27,680	36,850
March	50,350	55,660
April	63,830	62,310
May	72,580	72,070
June	62,370	56,860
July	54,410	55,430
Aug.	47,030	51,090
Sept.	50,780	46,930
Oct.	47,050	45,100
Nov.	28,500	35,180
Dec.	28,980	26,020
Total	5,63,930	5,75,240

Table- 6(b): Values of measured and estimated parameters used in the estimation of evaporation from Lake Nainital by Penman Method for the year 1995.

1995	Atm. Press.	Sun Shine	Air Temp.	Lake Temp.	Wind Velo.	Rel. Humi.	Alpha Coeff.	Net Radn.	Lake Evap.
Units	mb	Hrs.	°C	°C	m/s	%	-	ly/day	mm
Jan	812.78	6.76	4.43	8.82	3.19	58.42	0.087	145.19	2.14
Feb	812.37	6.22	6.41	8.78	3.23	53.42	0.074	191.07	2.68
Mar	813.48	8.61	10.05	12.08	4.89	47.96	0.068	278.47	3.80
Apr	812.82	6.47	15.31	15.96	4.15	47.30	0.058	310.60	4.38
May	812.26	8.25	20.22	19.90	4.73	61.95	0.061	368.75	5.15
Jun	809.57	2.41	21.78	22.47	3.60	68.88	0.056	288.31	4.12
Jul	809.27	3.10	18.77	21.51	2.75	85.74	0.057	295.06	3.90
Aug	810.02	2.91	18.41	20.93	2.72	87.43	0.056	272.73	3.58
Sep	811.97	4.53	17.18	20.13	2.25	81.10	0.064	256.56	3.40
Oct	814.50	8.28	15.32	18.42	2.12	72.64	0.062	239.31	3.22
Nov	813.86	8.94	12.22	14.64	1.75	51.17	0.076	169.25	2.60
Dec	814.15	7.76	8.67	11.17	1.82	53.81	0.087	129.19	2.08

3.2.6 Subsurface inflow and subsurface outflow

These are most difficult parameters to be estimated or arrived at by any means, among all the components of the water balance equation as given in equation (2). Attempts have been made by researchers world-over to find a suitable method to estimate the subsurface inflow to a lake. Use of seepage meters have been reported, but with limited success. The reason for its limited application is due to logistic problems of installation of the meters and periodic retreival and replacement of the collectors. The most widely adopted method is to assign the residual values of equation (2) to the sub-surface components. Winter (1980) cautioned that this pratice will lead to adding up of the accumulated errors in other components of the water balance equation to the sub-surface terms. Another option to estimate the sub-surface inflow may be the estimation of sub-surface outflow and then deducting it from the residuals. Conventionally this may be done by identifying all possible sub-surface outflows (springs) and to measure their discharge. Alternatively, stable isotope mass balance method could be adopted.

Under the aegis of the then UPPWD, the average monthly discharge of the downstream springs were monitored and were included in the water account statement prepared by the PWD. The main objective of the water accounting exercise was to judge the efficency of the surface drainage systems to avoid land-slides. Although there were certain flaws in the accounting system leading to under or over estimation surface run-off (during certain years the accounted water far exceeded the total annual rainfall in the basin) the spring discharge data are very useful in arriving at an approximate estimate of sub-surface outflow. The monthly discharge data of different springs located downstream of the lake are available with the UPPWD for selected period and the same have been collected. The period for which the discharge data are available (1931, 1947-52, 1966-79) is small. However, the data are very useful. Out of the nine springs such as, Tallital spring, Fairy Hall Spring, Old Reserve Police Lines (Rais Hotel), Mota Pani (Siahidhara), Katarpani, Cantonement drain etc., Rais Hotel and Sipahidhara alone account for 90 - 94% of the total annual spring discharge. Some of the springs for which discharge were measured have since gone dry, and the discharge of major springs such as sipahidhara has decreased considerably. The aggregate monthly discharge of all springs and also that of sipahidhara have been presented in Table 7. The discharge of sipahidhara spring only was monitored during 1995. Based on the ratio of discharge of sipahidhara spring to the total discharge of all springs using the available historic data, the total discharge of all the springs for the year 1995 has been computed and has been presented in Table 7. Considering the computed spring discharge as well as the pumping through the wells as sub-surface outflow (SS_o) the SS_i has been estimated by solving equation 2 and the results are presented in Table 10a and 10b.

One of the major sub-surface inflow source to the Lake Nainital is the contribution from the Sukhatal sub-catchment (0.75 km^2) through the Naini fault (also called as Lake fault). Since this fault extends beyond the lake basin (upstream direction), it is possible that more water that percolates into the ground outside the catchment area in the vicinity of the fault zone finds its way to the Lake Nainital through the sub-terranean pathway. However this theory has to be verified with further studies using tracer techniques.

Table 7. Comparison of the discharge of Sipahidhara spring (SD) and that of all springs that were measured during the period 1947 to 1952 and 1995. (The discharge of Sariyatal spring is not included in the total discharge. Values given are in thousands of cubic meters.)

Year	1947		1948		1949		1950		1951		1952		1995	
Month	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total
Jan	94	169	88	165	135	260	88	171	87	178	87	178	14	
Feb.	79	143	79	148	109	199	80	156	79	156	79	156	11	
Mar.	91	163	89	169	108	195	90	171	89	172	89	172	1	
Apr.	87	156	84	159	83	160	80	157	81	152	81	152	0.60	
May.	91	163	75	150	75	138	75	146	33	89	33	87	-	
Jun.	95	169	63	125	73	142	71	140	31	82	30	82	-	
Jul.	98	181	70	154	300	539	-	36	302	424	109	223	-	
Aug.	94	178	301	554	301	549	401	709	401	583	201	361	40	
Sep.	94	171	315	588	389	671	291	535	290	530	146	316	50	
Oct.	95	172	302	570	241	446	235	443	235	461	139	293	28	
Nov.	88	162	246	425	166	327	164	328	164	324	124	253	19	
Dec.	91	166	172	309	152	256	156	263	155	260	116	233	18	

4.0 ESTIMATION OF SEDIMENTATION RATE

The evaluation of sediment accumulation rate has been attempted by both modern radiometric dating techniques of sediments and also by conventional sediment balance method.

4.1 Radiometric Methods

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

In order to estimate the sedimentation rate in Lake Nainital using radiometric sediment dating techniques, sediment cores were collected from different parts of the lake with a gravity corer. The length of collected cores ranged from 42 to 57 cm. Of these cores, three cores (Fig. 1) viz. Q, S & V which were considered to be representative of lake's sedimentary environment were subjected to radiometric dating. The cores were sliced into 2 cm sections and analysed at Bhabha Atomic Research Centre, Mumbai, India, for ^{210}Pb and ^{137}Cs activities. The profiles of ^{210}Pb and ^{137}Cs activities in different sediment cores with respect to depth are shown in Figure 12. The standard counting error in case of ^{210}Pb method was generally less than 10% in the upper sections of the cores and slightly higher at the deeper sections. In case of ^{137}Cs, the standard counting error was less than 10% in the core sections.

At the sampling location 'Q', the ^{137}Cs profile closely paralleled its weapon fall-out record pattern reported by earlier investigators (McHenry et al., 1973; Livingston and Cambray, 1978) i.e., an initial appearance in 1952-53; a subsidiary peak in 1957-58; and a major peak in 1963-64. With the depth corresponding to 1963-64 as time marker, the average sedimentation rate of Lake Nainital was computed and is listed in Table- 8.

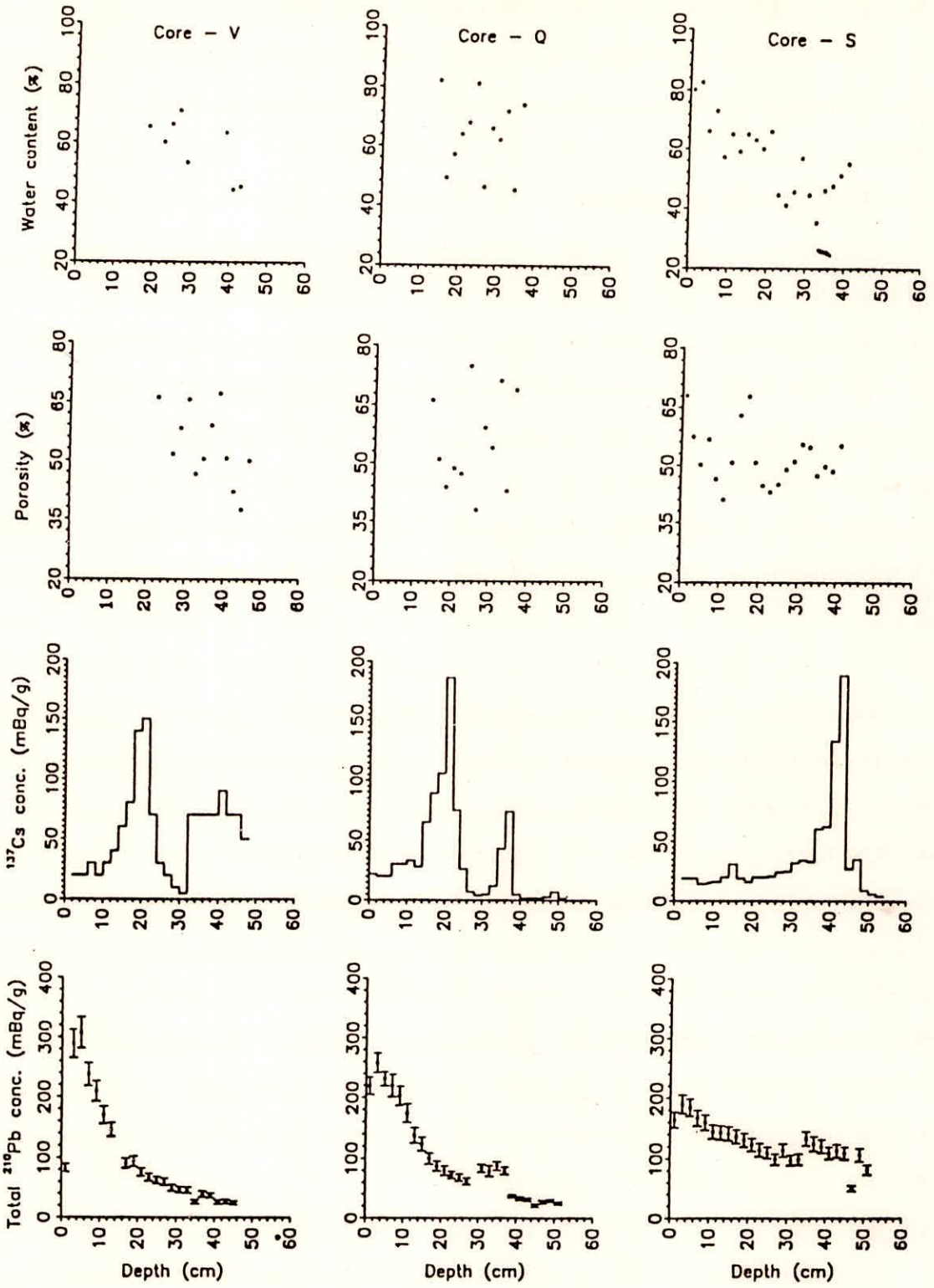


Fig. 12. ^{210}Pb and ^{137}Cs activity profiles in three core samples along with moisture content and density.

Table- 8: Sedimentation rates estimated by ^{210}Pb and ^{137}Cs in Lake Nainital.

Sample Code	^{210}Pb Method (cm/yr)	^{137}Cs Method (cm/yr)
V	0.48 ± 0.04	0.60 ± 0.07
Q	0.64 ± 0.18	0.70 ± 0.03
S	1.24 ± 0.44	1.35 ± 0.05
D [Das et al. (1994)]	1.15 ± 0.09	-
Average	0.75	0.86

The close similarity in the deposition and fall-out pattern of ^{137}Cs probably indicates that the residence time of ^{137}Cs in the lake water is small and post-depositional mobility of the radionuclide in the sediment core, if any, is insignificant. However, the ^{137}Cs profile of Lake Nainital may be viewed as an ideal case. Due to short length of the core obtained, the initiation and subsidiary peaks of 1952-53 and 1957-58 are not clearly seen in core samples 'V' and 'S' respectively (Fig.- 12). As the atmospheric deposition flux of ^{210}Pb at the lake site is unknown, the available mean atmospheric flux of ^{210}Pb at Mumbai station, India, (0.025 Bq/cm^2/yr; Joshi et al., 1969) and the inventory supported by this flux, was assumed to be similar to the Nainital area (the annual rainfall at Nainital and Mumbai are comparable). As seen in Fig.- 12, at location 'V', the (total) ^{210}Pb profile shows a more or less an exponential decrease in concentration with depth to a constant value maintained by in-situ decay of ^{226}Ra. At other locations, the (total) ^{210}Pb concentration profile is not an exponential type (i.e., non-monotonic). Companion measurements of ^{137}Cs indicated that the top portions of the sediment deposit were not lost during coring.

4.2 Sediment Balance Method

Sediment inflow to the lake has been monitored at the two major inflow points to the lake. The variation of Suspended Sediment (SS) concentration in the inflow with time is shown in Fig.-13. 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 surface inflow gives the total suspended sediment input to the lake.

The sediment outflow from the lake has been computed using the discharge from the lake through the sluices and the average SS concentration in the epilimnion (0.55 g/L). The rate of sediment accumulation in the lake, thus calculated is 0.69 cm/yr. The detailed sediment balance has been presented in Table- 9.

Table- 9: Rate of sediment accumulation estimated by Sediment Balance Method

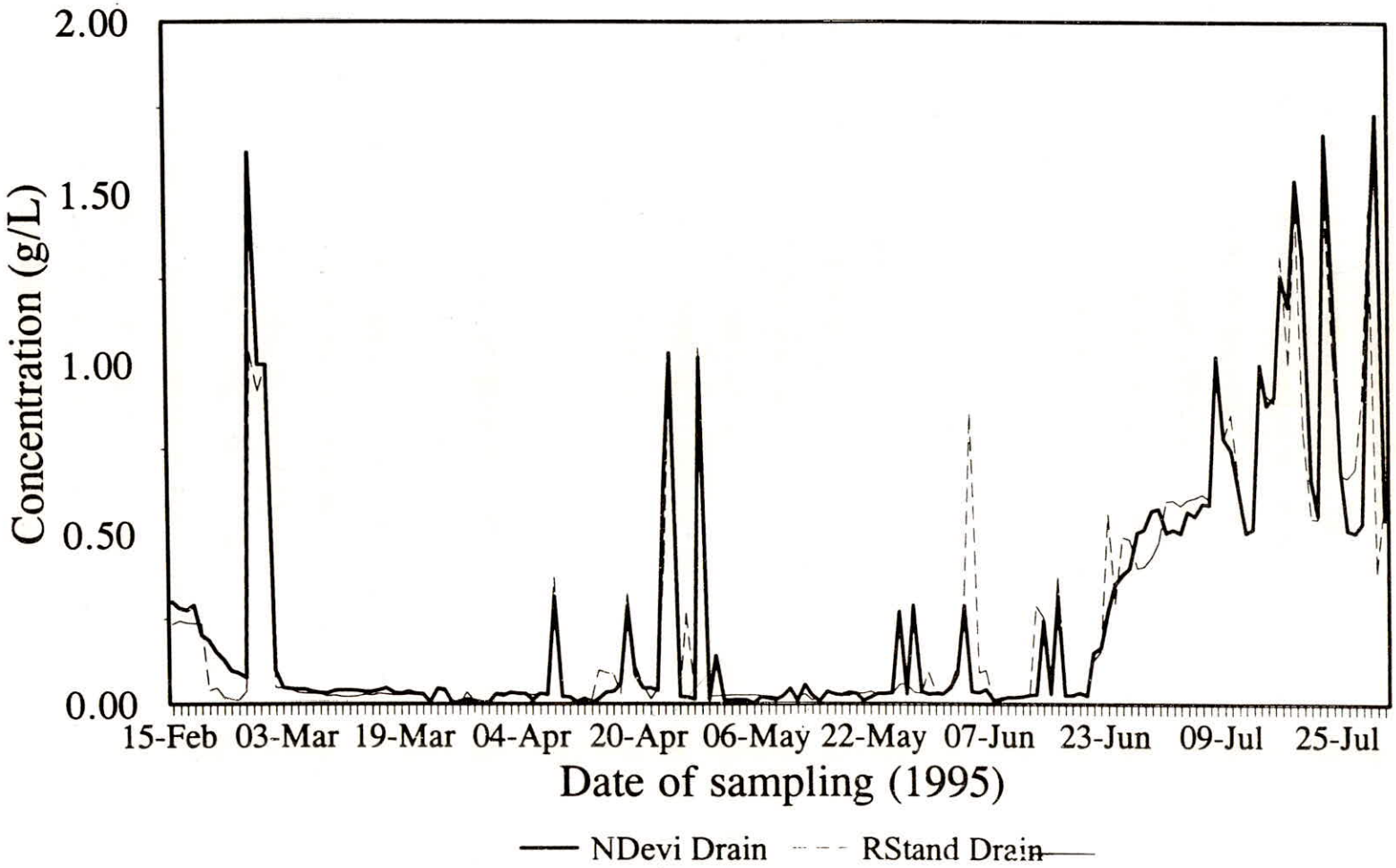
	Suspended Sediment Concentration	Total Susp. Sediment load (M^3)
Inflow through drains and during light rains	0.41 g/L	1500
Inflow during heavy rains	1.25 g/L	5097
Outflow through sluices	0.55 g/L	3422
Inflow - Outflow (sediment accumulation rate)	-	3175 (0.69 cm/yr)

5.0 EFFECT OF SEDIMENTATION ON WATER BALANCE

The sedimentation rates in different parts of the Lake Nainital have been estimated using Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) dating of sediment cores (Saravanakumar *et al.*, 1997). The sedimentation rate obtained by ^{210}Pb varies from 0.48 cm/yr to 1.24 cm/yr while in case of ^{137}Cs, it varies between 0.60 cm/yr and 1.35 cm/yr in different parts of the lake. 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 receive sediment at lower rate (0.48 cm/yr).

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

Fig. 13. Variation of suspended sediment inflow to Lake Nainital



As complete long term information on different water balance components is not available in case of Lake Nainital, the relation of surface outflow from the lake with respect to the rainfall in the lake catchment in the past 100 years has been used to assess the effect of sedimentation on water balance of the lake. The plot of surface outflow versus rainfall is shown in Fig.- 14. To assess the effect of development of the town since early 1970s, the period 1901 - 1970 has been considered as one group and 1971 - 95 as the second group. There is a noticeable decrease in the surface outflow for the given rainfall in the latter period. This decrease is due mainly to the increase in pumping from lake.

Based on the estimated rate of sedimentation, there must have been an increase of 320000 m^3 in the overall annual outflow from the lake. If all other outflow components of the lake water balance equation such as evaporation, abstraction etc., remained within reasonable limits, the increase would then be noticeable in the surface outflow of the lake. But since the abstraction from the lake through pumping has increased manifold (as a consequence of increase in demand) such increase in S_o is not noticed. On the contrary there is significant decrease in the surface outflow from the lake as seen from figure 14.

6.0 RESULTS AND DISCUSSION

A cursory glance of the Tables- 10a and 10b giving the values of the monthly water balance component of the lake indicates that the subsurface inflow is the major component. The net gain to the lake due to subsurface inflow accounts for nearly 39% of the annual inflow to the lake and the surface inflow accounts only for about 30%. The remaining is accounted by direct precipitation over lake surface (16%) and by inflow through the perennial drains(15%). Since the catchment rock formation is highly fractured with presence of several structural faults, one may expect significant groundwater inflow to the lake. The hydrologic residence time of the lake is about 1.72 years, considering in terms of depth the volume of lake (18.52 m) and outflow from the lake (10.76 m).

Fig.14. 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)

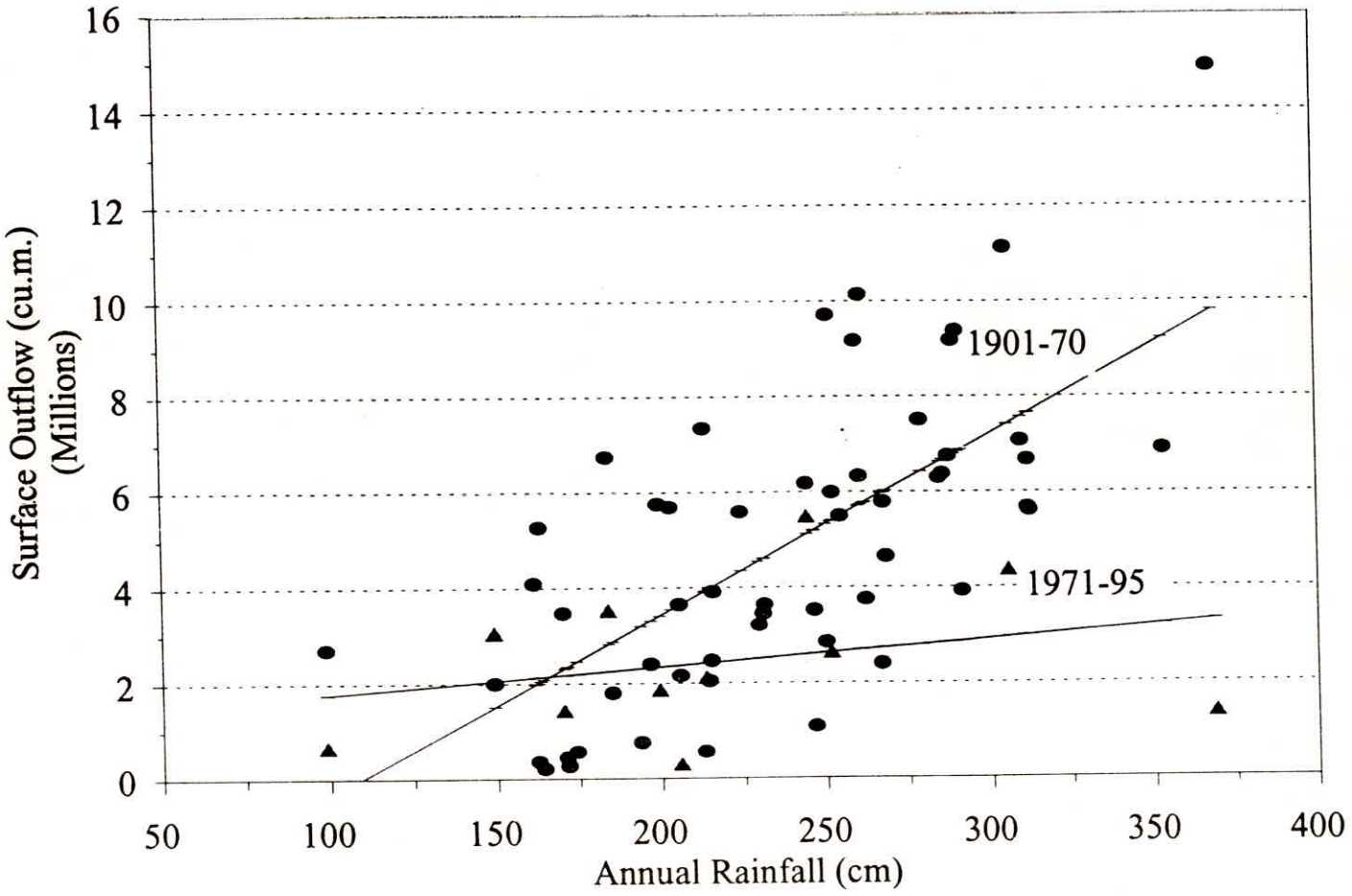


Table- 10a: Values of the water balance components of Lake Nainital for the year 1994.

1994	L-Level	Pptn	ΔV	P_i	D_i	S_i	SS_i	S_o	E_o	Wo	SS_o
	M*	mm	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3
Jan	3.008	62	-8	29	54	0	34	0	30	61	34
Feb	2.948	15	-53	7	53	0	19	0	28	61	43
Mar	2.798	0	-92	0	48	0	30	0	50	74	46
Apr	2.598	62	-94	28	41	0	15	0	64	67	47
May	2.334	28	-126	13	40	0	38	0	73	92	52
Jun	2.092	242	2	109	40	56	1	0	62	94	48
Jul	2.529	491	191	223	75	417	343	427	54	322	64
Aug	2.873	432	192	197	121	354	467	569	47	214	117
Sep	3.141	43	66	20	104	0	598	389	51	89	127
Oct	3.139	5	-60	2	75	0	288	185	47	128	65
Nov	2.963	4	-80	2	62	0	93	0	29	134	74
Dec	2.781	2	-91	1	59	0	80	0	29	136	66
Net(M^3)		1386	-153	631	772	827	2006	1570	564	1472	783
Net(M)			-0.33	1.36	1.67	1.78	4.33	3.39	1.22	3.18	1.69
% to total Inflow / Outflow				14.88	18.27	19.47	47.37	35.76	12.87	33.54	17.83

* Lake level in UPPWD Gauge, Zero of the gauge is 1933.81 M above msl

Table- 10b: Values of the water balance components of Lake Nainital for the year 1995.

1995	L-Level	Pptn	ΔV	P_i	D_i	S_i	SS_i	S_o	E_o	Wo	SS_o
	M*	mm	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3	10^3 M^3
Jan	2.677	46	-73	21	54	0	11	0	32	93	34
Feb	2.512	59	-46	27	53	0	43	0	37	89	43
Mar	2.430	62	62	28	48	0	190	0	56	102	46
Apr	2.552	6	-95	3	41	0	42	0	62	72	47
May	2.335	19	-156	8	40	0	20	0	72	100	52
Jun	1.975	89	-110	40	40	0	10	0	57	94	48
Jul	1.743	509	363	228	75	458	114	40	55	353	64
Aug	2.561	632	209	289	121	610	389	775	51	257	117
Sep	3.049	341	231	157	104	423	816	998	47	97	127
Oct	3.530	0	-64	0	75	0	277	212	45	94	65
Nov	3.375	0	-129	0	62	0	36	0	35	118	74
Dec	3.100	10	-142	5	59	0	19	0	26	133	66
Net(M^3)		1773	50	805	772	1491	1967	2025	575	1602	783
Net(M)			0.11	1.74	1.67	3.22	4.27	4.37	1.24	3.46	1.69
% to total Inflow / Outflow				15.99	15.35	29.60	39.06	40.61	11.52	32.16	15.71

* Lake level in UPPWD Gauge, Zero of the gauge is 1933.81 M above msl

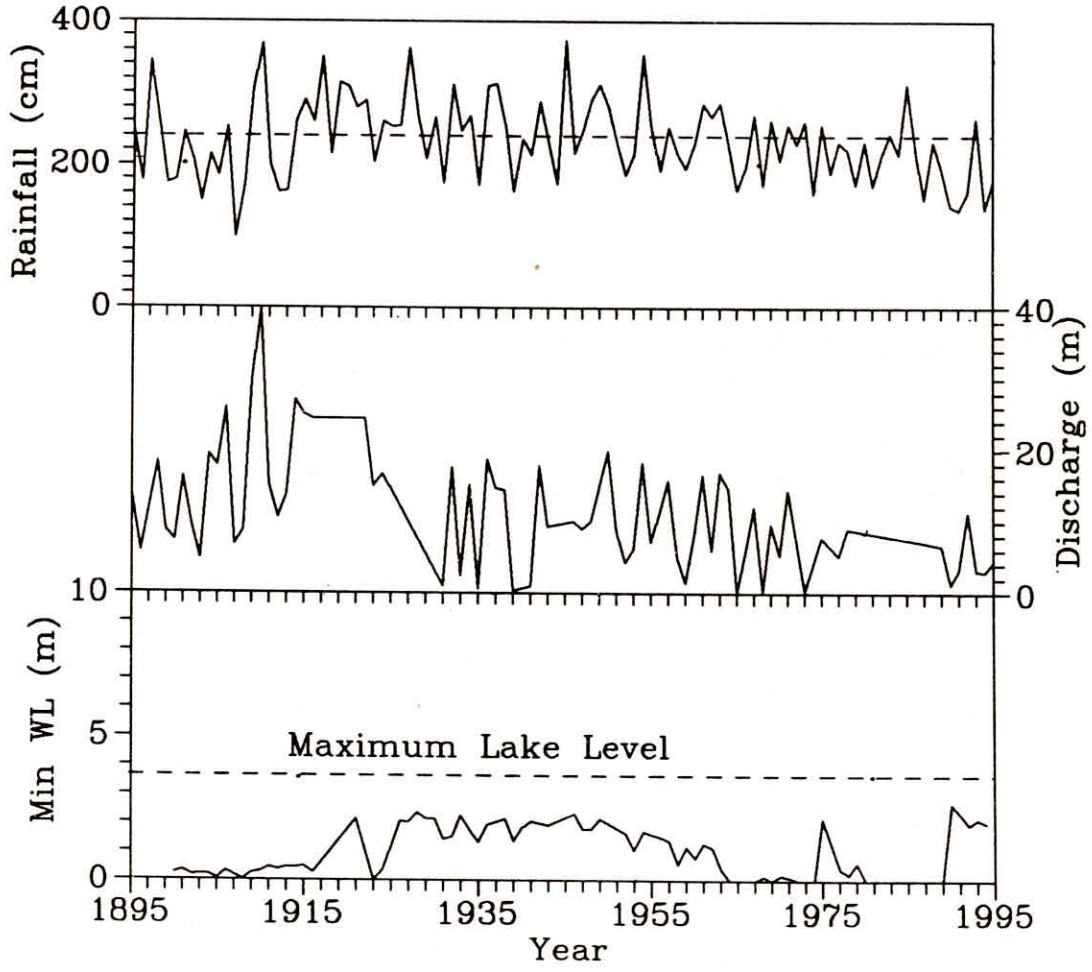
The variation in the subsurface inflow (Fig.- 11) to the lake is also corresponding to the nature of precipitation. The significant inflows during the months of February, March & April is influenced by the heavy snowfall and rainfall during late winter. The subsurface inflow declines during May and June and again shows an increasing trend upto September and then declines, also probably in line with the precipitation with a lag period of approximately one month. It is also notable that in spite of zero rainfall in the month of October the lake level continues to rise, which is mainly due to the subsurface inflow. This phenomenon has been observed for the period (from 1895 to 1995) for which lake level and rainfall records are available. The annual rainfall in the catchment, the minimum water level recorded in the lake and the quantity of water drained through the sluice gates for the past 100 years are shown in Figure 15. It is observed that even during the years of below normal rainfall, there is no water shortage, and that a substantiative quantity of water had to be drained through the sluice gates.

Tables- 10a and 10b also reveals that one of the major outflow from the lake is pumping (32%), while 41% of annual outflow is accounted by discharge through the sluices, which are operated only during rainy season. Free water eveporation accounts for about 12%. Remaining 15% water is attributed to the subsurface outflow as springs.

7.0 CONCLUSIONS

Water balance of Lake Nainital has been computed for the first time. The values of different components have been calculated adopting either direct field observations or established estimation methods. The study reveals that there is significant subsurface inflow to the lake. Since the lake is bifurcated by a fault zone (Naini Fault or Lake Fault), the inflow could be through this and other associated faults and fractures. Further, the dolerite dyke present at the SW side of the lake catchment probably acts as a barrier of southward groundwater flow and diverts the flow towards the lake. Pumping of lake water for the city water supply accounts for the maximum withdrawal. Therefore the pumping strategy adopted will have a direct bearing on the water availability during different seasons. The discharge through the sluices during the rainy season accounts for

Fig. 15. Annual rainfall, Surface outflow and Minimum lake level of Lake Nainital from historic data



nearly one third of the current outflow. This implies that even for a hydrological year of below normal rainfall, there would not be any scarcity of water, provided the present withdrawal trend is not disturbed.

The sedimentation rate, estimated by both radiometric dating techniques of the lake sediment cores and by sediment balance method compare well with each other. The average sedimentation rate in the lake is around 0.69 cm/yr. This rate is not too high to threaten the lake's existence as the useful life of the lake, computed using the average rate of sedimentation is around 2200 years. However, the sedimentation plays a major role in the hydrological characteristics of the lake. The negative effects which have resulted due to sediment accumulation are a) reduction in the capacity of the lake which is, however, not significant and b) reduction in the discharges of the downstream springs, around which certain communities or dwellings have developed over the years.

REFERENCES

Allen R. G., 1996. Assessing integrity of weather data for reference evapotranspiration estimation. J Irrig. and Drain. Engrg. Div., ASCE., 122(2): 97-106

Auden J. B., 1942. Geological report on the hillside of Nainital. Unpublished report of GSI., Calcutta, India

Bartarya, S.K., 1988. Geohydrological and Geomorphological Studies of Gaula River Basin, District Nainital with special reference to the problem of erosion. Unpublished Ph.D. Thesis, Kumaun University, Nainital, 266pp.

Byrnes, W.F., 1930. Technical Report on Hillside Safety, PWD Report, Kumaun Provincial Div., Nainital, pp. 80.

Das, B.K., Singh, M., and Borkar, M.D., 1994. Sediment accumulation rate in the lakes of Kumaun Himalaya, India using ^{210}Pb and ^{226}Ra. Environ. Geol., 23: 114-118.

Goldberg, E. D., 1963. Geochronology with ^{210}Pb In: Radioactive dating. Intl. Atomic Energy Agency, Vienna, Austria.

Hashimi, N.H., Pathak, M.C., Jauhari, P., Nair, R.P. Sharma, A.K. Bhakuni, S.S., Bisht, M.K.S. and Valdiya, K.S., 1993. Bathymetric Study of the Neotectonic Naini Lake in Outer Kumaun Himalaya, G.S.I., Vol.41, No.2, pp. 91-104.

Hawkins, R. H., Hjelmfelt, A. T. and Zevenbergen, A. W., 1985. Runoff probability, storm depth and curve numbers, J. Irrig. and Drain. Engrg. Div., ASCE, 111(4):330-340

Holland, T.H., 1896. Report on the Geological Structure and Stability of the Hill Slopes Around Nainital, Geol. Surv. India, 132pp.

Jensen M. E., 1974. Consumptive use of water and irrigation water requirements, Rep. of the Tech. Committee on Irrig. Water Requirements, Irrig. and Drain. Engrg. Div., ASCE, New York, NY, USA.

Krishnaswamy, S. and Lal, D., 1978. Radionuclide limnochronology. In: A. Lerman (Editor) Lakes: Chemistry, Geology, Physics, Springer-verlag.

Krishnaswamy, S., Lal, D., Martin, J. M., and Meybeck, M., 1971. Geochronology of lake sediments, Earth Planet. Sci. Lett., 11:407-414

Linsely, R. K., Kohler, M. A. and Paulhus, J. L. H., 1975. Hydrology for Engineers, McGraw-Hill Intl. Book Co., New Delhi.

Livingston, D. and Cambray, R. S., 1978. Confirmation of Cs-137 dating by algal stratigraphy in Rosthene Mere. Nature, 276: 259-261.

Middlemiss C. S., 1890. Geological sketch of Nainital; with some reference on the natural conditions governing mountain slopes. Records of GSI, 21(4): 213-234

Ponce, V. M., 1989. Engineering Hydrology : Principles and Practices, Prentice-Hall Inc., NJ, USA

Purohit, R. and Singh S.P., 1981. Seasonal variation in physio-chemical Limnology of shallow zones of Nainital lake, Western Himalaya (India), Proc. Indian Natn. Sci. Acad., B. 47, No.2, pp. 194-203.

Rawat J.S.,1987. Morphology and morphometry of Naini Lake, Kumaun Lesser Himalaya, G.S.I., Vol. 30, No.6, pp. 493-498.

Rao K. N., George C. J. and Ramashastri, K. S., 1971. Potential Evapotranspiration over India, Scientific Report No. 136, India Meteor. Dept., New Delhi, India.

Ritchie, J. C. and McHenry, J. R., 1985. A comparison of three methods for measuring recent rates of sediment accumulation. Water Resour. Bull., 21: 99-103

Robbins, J. A. and Edgington, D. N., 1975. Determination of recent sedimentation rates in Lake Michigan using ^{210}Pb and ^{137}Cs. Geochim. Cosmochim. Acta, 39: 285-304

Saravanakumar U., Navada S. V., Rao S. M., Nachiappan Rm. P., Bhishm Kumar, Krishnamoorthy T.M., Jha S. K. and Shukla V. K., 1999. Determination of recent sedimentation rates and pattern in Lake Nainital, India by ^{210}Pb and ^{137}Cs dating techniques. Applied Radiation and Isotopes 51(1):97-105.

Sharma, A.K., 1981 Structural Study of Area East of Nainital with Special reference to the Hillslide Instability, Unpublished Ph.D. Thesis, Kumaun University, Nainital, pp.126.

Shuttleworth W. J., 1992. Evaporation In: D. R. Maidment (Editor-in-Chief) Handbook of Hydrology, McGraw-Hill Inc., New York, NY, USA

Singh V. P., 1992. Elementary Hydrology, Prentice-Hall Inc., NJ, USA

Ter-Makaryantz N. Ye, 1960. On the daily mean albedo of sea, Trans. Main Geophy. Obs. Issue 100, Leningrad, USSR

Valdiya, K.S., 1988. Geology and Natural Environment of Nainital Hills, Kumaun Himalaya, Gyanodaya, Prakashan, Nainital, pp. 155.

Valdiya, K.S. and Bartarya, S.K. 1989. Diminishing Discharges of Mountain Springs in a part of Kumaun Himalaya, Current Science, Vol. 58, No. 8, pp. 417-426.

Walling, D. E. and He, Q., 1993. Towards improved interpretation of ^{137}Cs profiles in lake sediments. In: J. Mamanus and R.W. Duck (Editors) Geomorphology and Sedimentology, Wiley.

Winter T. C., Rosenberry D. O. and Sturrock A. M., 1995. Evaluation of 11 equations for determining evaporation for a small lake in the north central United States, Water Resources Res. 31(4): 983-993

APPENDIX - C

RATES AND PATTERN OF SEDIMENTATION IN LAKE NAINITAL

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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 Lakes Region Special Area Development Authority (NLRSADA) 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 NLRSADA 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 to 20 m below the lake surface. The volume of the lake is 8.3 Mm^3. The Average annual rainfall in the basin is 248.8 cm. The catchment area of the lake is 4.7 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.

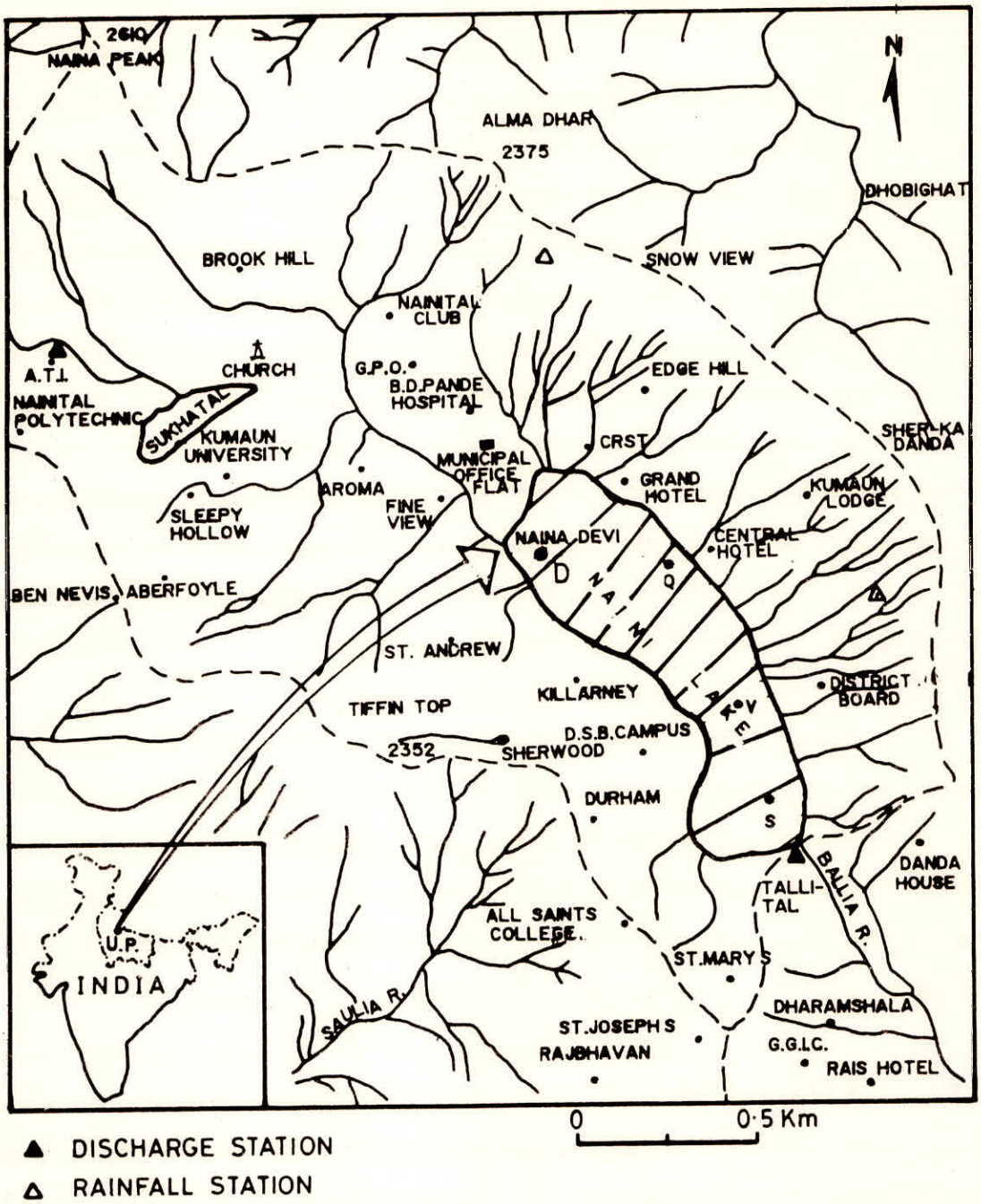


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

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.

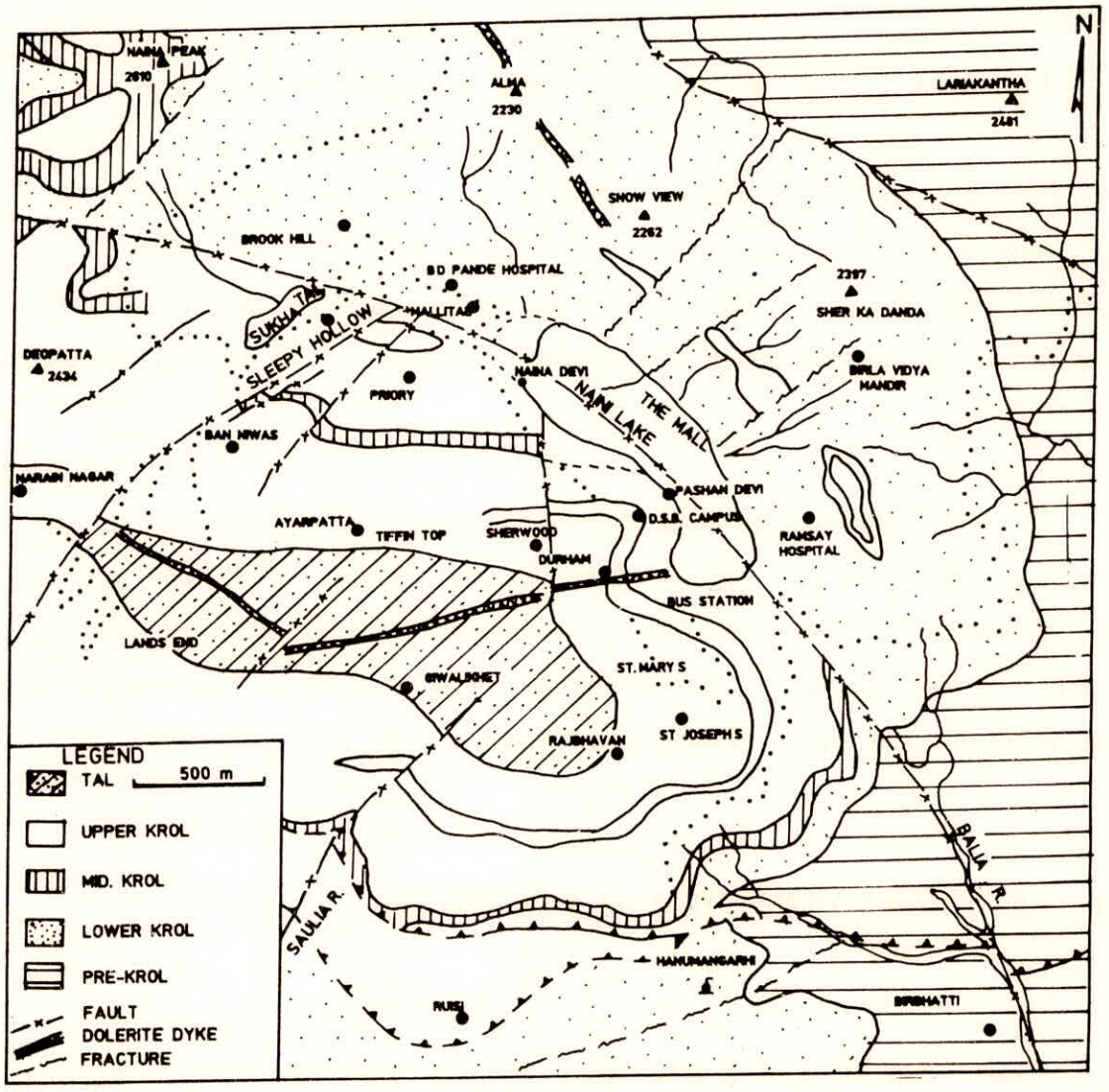


Fig. 2. Geological map of the Nainital Lake Basin showing its much faulted nature (After Valdiya, 1988).

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. The latest one occurred on 25th July, 1998.

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 NLRSADA.

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 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)		
	1970	1975	Diff.	1970	1975	Diff.	1970	1975	Diff.	1970	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	9.63	-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	19.68	+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		
	1-4	+0.22	121208.29	25453.74		
	4-6	+0.21	64622.29	13570.68	192193.41	38438.68
	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		
	1-4	+0.83	121208.29	100602.88		
	4-6	+1.07	64622.29	69145.85	565866.46	113173.29
	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		Results indicating
	1-4	-0.88	121208.29	-106663.29		
	4-6	-1.12	64622.29	-72376.96	-591228.16	only scouring during this
	6-7	-1.77	35649.51	-63099.63		
	7-10	-1.84	154653.97	-284563.30		selected period.
	10-0	-1.05	27093.60	-28448.28		
1972-1975	0-1	+0.48	50103.75	24049.80		
	1-4	+0.58	121208.29	70300.80		
	4-6	+0.79	64622.29	51051.61	251423.81	83807.94
	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		
	1-4	+0.34	121208.29	41210.80		
	4-7	+0.84	64622.29	53636.50	216283.03	14418.87
	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		
	1-4	+0.23	121208.29	27877.91		
	4-7	+0.25	64622.29	16155.57	236858.34	21532.57
	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		
	1-4	+1.10	121208.29	133329.12		
	4-7	+1.59	64622.29	102749.44	655159.73	218386.58
	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		
	1-4	+0.75	121208.29	90906.22		
	4-7	+0.99	64622.29	63976.07	341631.18	56938.53
	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

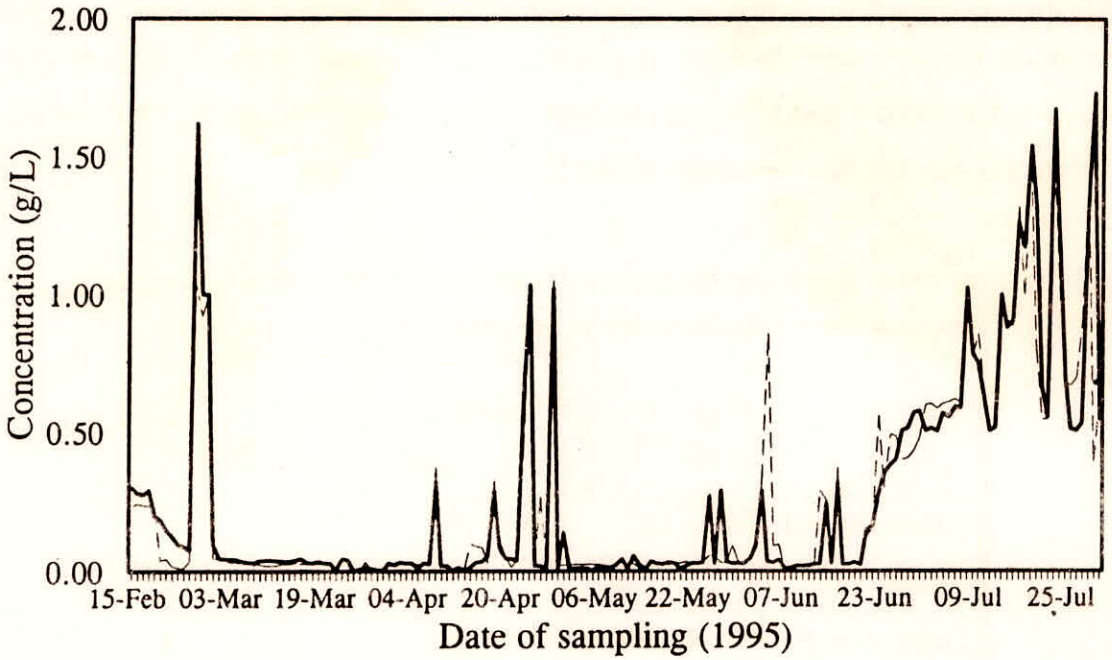
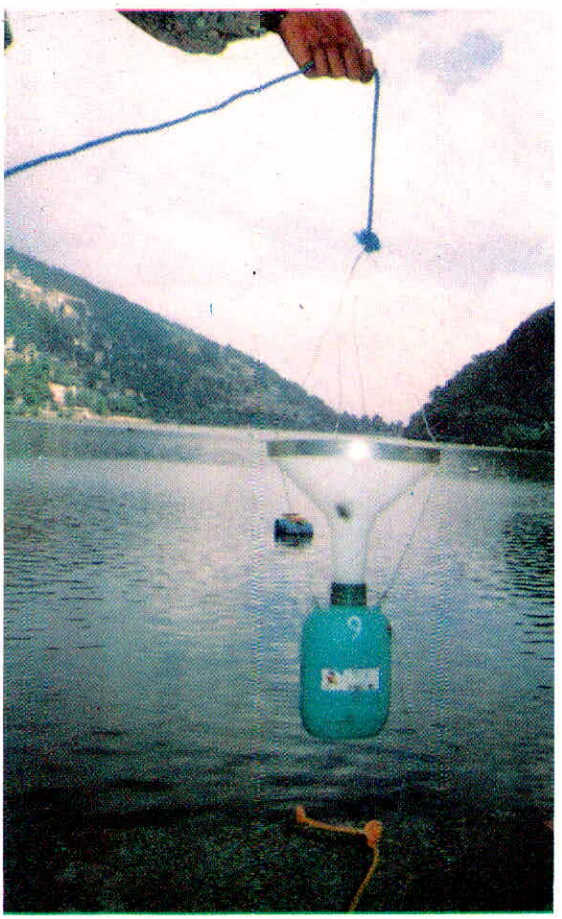


Fig. 3. Variation of suspended sediment concentration with time in nalahs draining into the lake Nainital.



Sediment Traps Installed at Different Depths and at Different Locations in Lake Nainital



A View of Buoy (blue colour) Installed in Lake Nainital with Weighing Type Suspended Sediment Sensor and other Sensors

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 normally 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:-

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

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

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

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

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

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) = reservoir capacity (C) / 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).

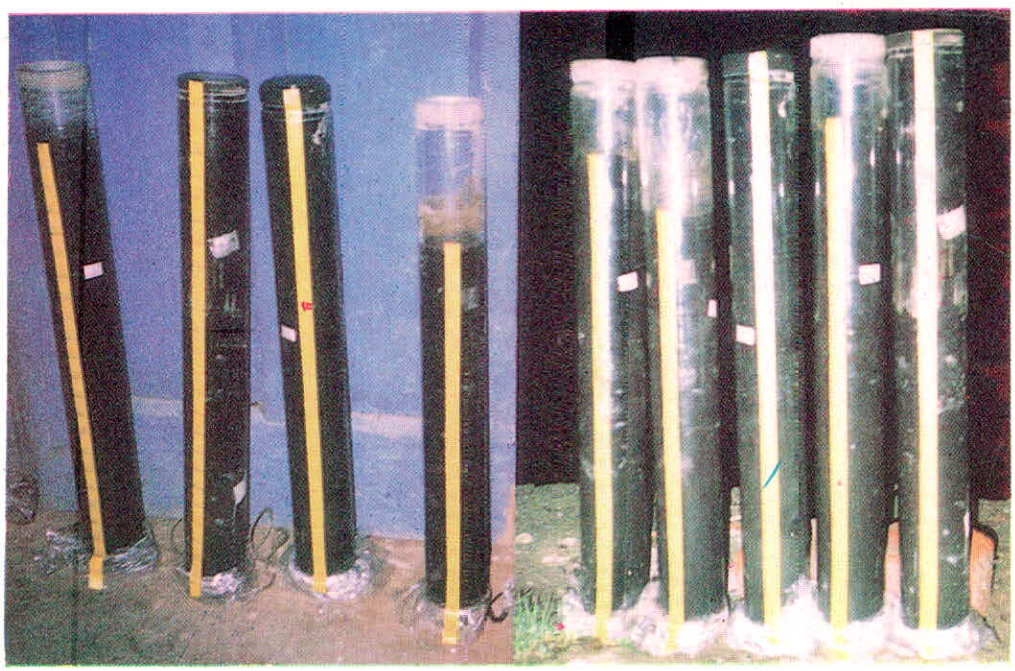
Out of the collected core samples, three cores (Q, S & V) which were considered to be representative and cover the maximum sedimentary environment of the lake (Fig. 1) were subjected to radiometric dating. The cores were sliced into 2 cm pieces and analysed at Bhabha Atomic Research Centre, Mumbai for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



Sediment Core is being collected from Nainital Lake Using a Gravity Corer



Sediment Cores Collected from Different Parts of Lake Nainital using a Gravity Corer

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 applicable (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

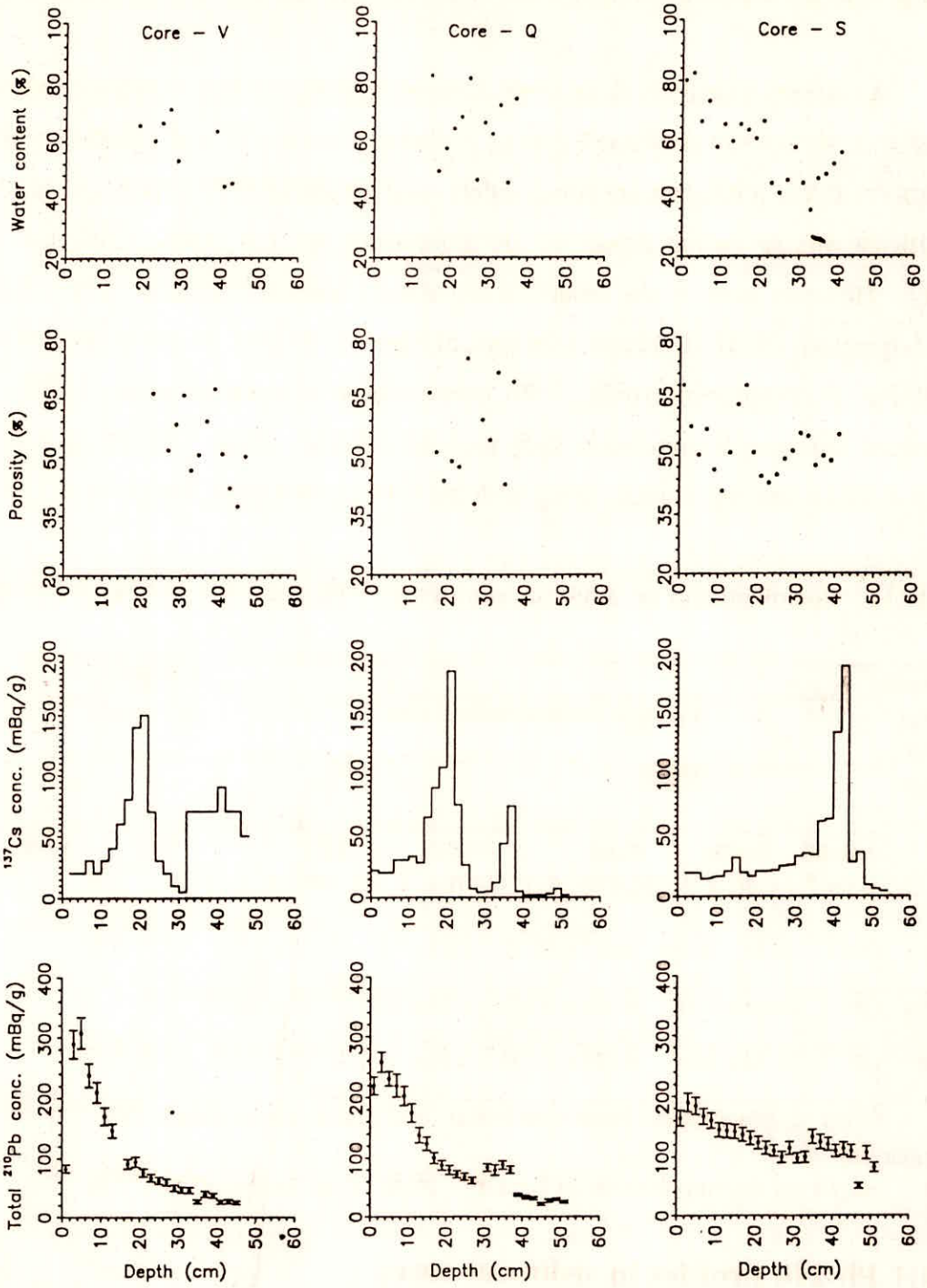


Fig. 4. ^{210}Pb and ^{137}Cs activity profiles in three core samples along with moisture content and density.

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:

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

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

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:

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

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

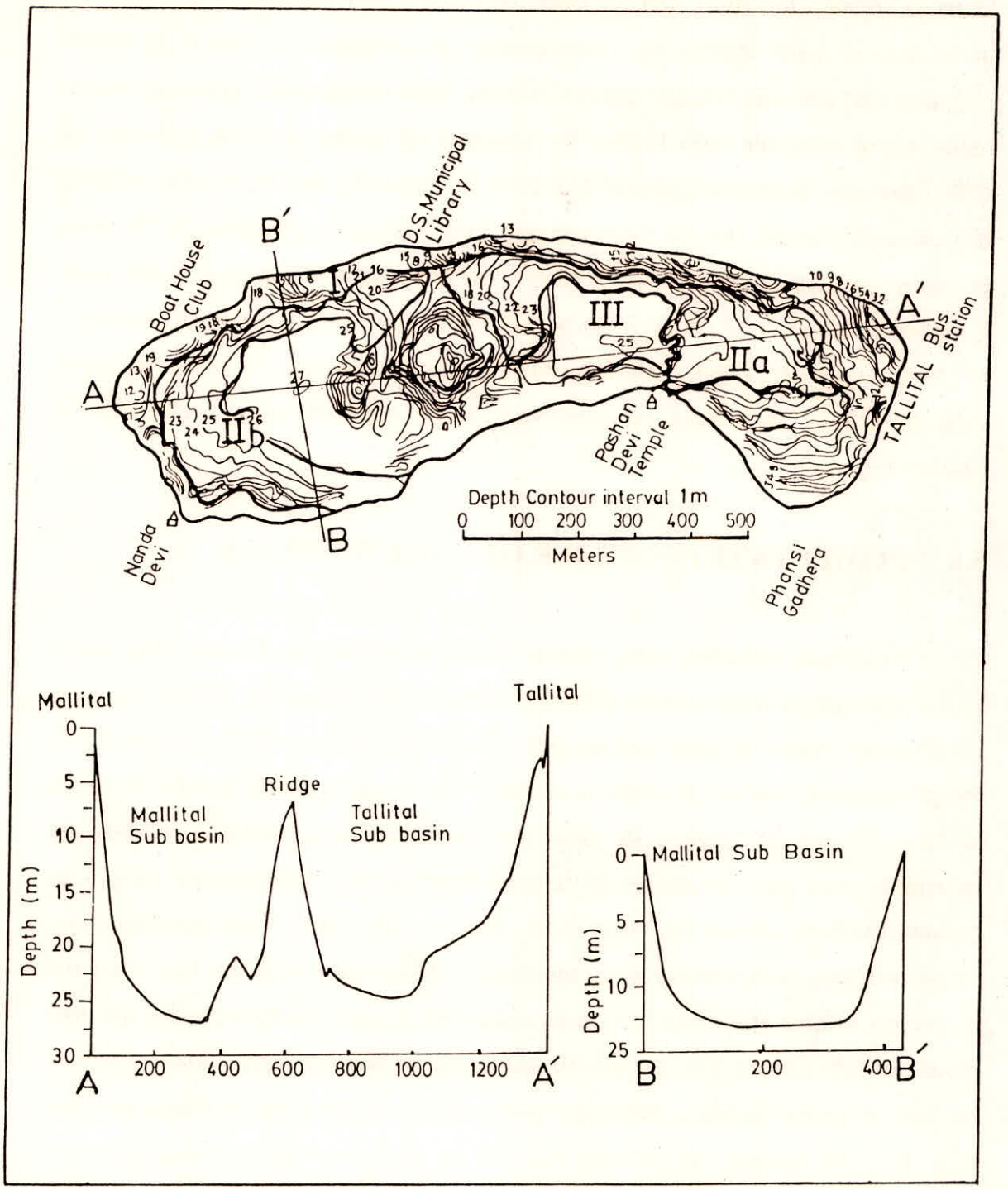


Fig. 5. Four different depositional zones of Lake Nainital with the cross sections showing the present bottom configuration of the lake.

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).

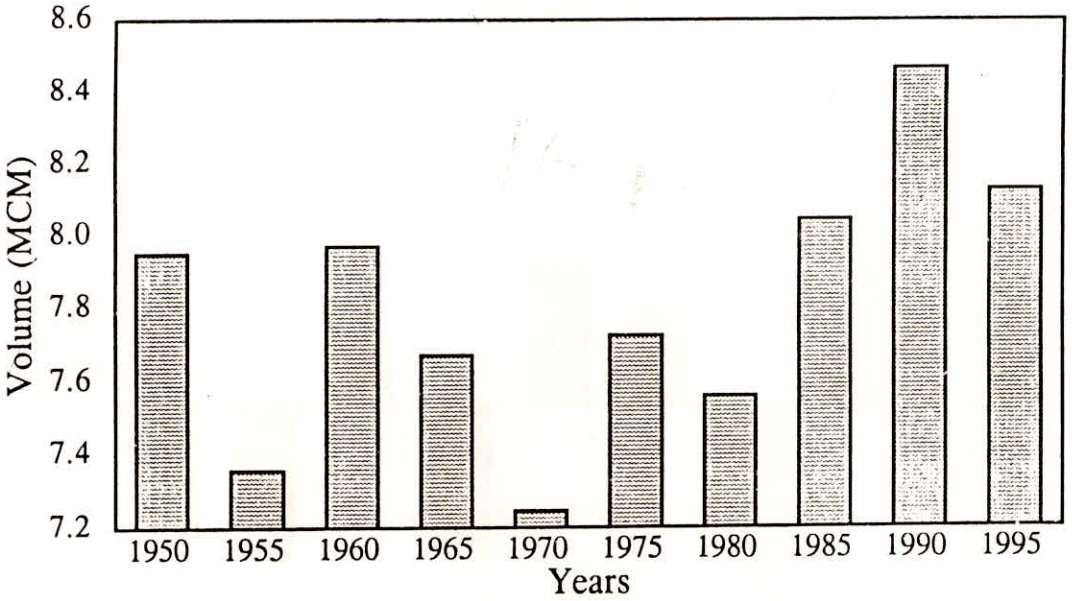


Fig. 6a. Volume of the lake based on the silting and scouring rates obtained in Lake Nainital computed for different time periods since 1960 using lake sounding data.

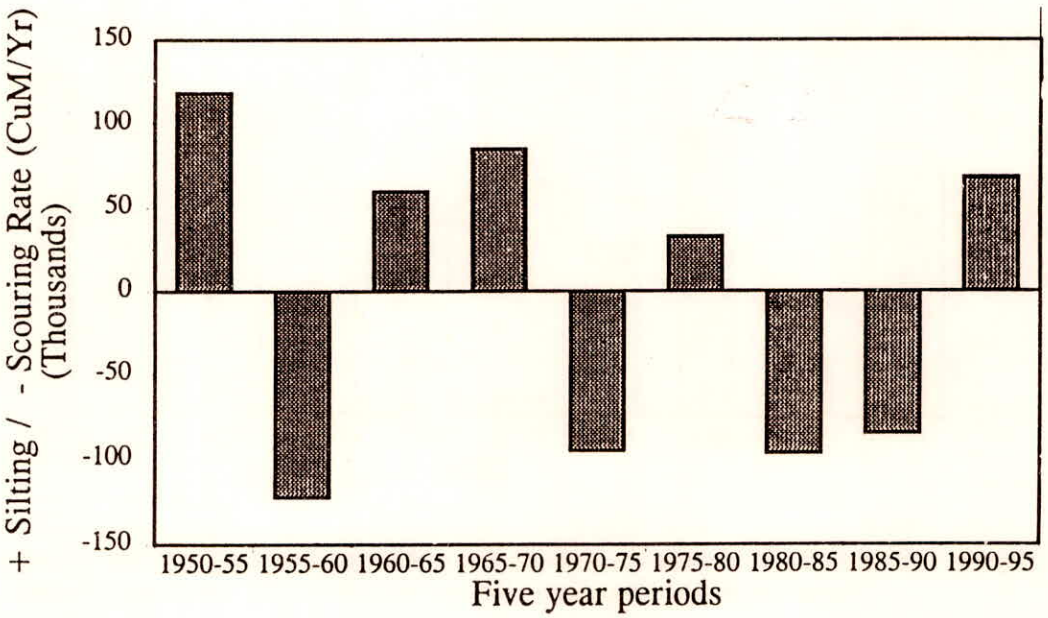


Fig. 6b. Volume of sediments accumulated in or scoured out based on the silting and scouring rates obtained in Lake Nainital computed for different time periods since 1950 using lake sounding data.

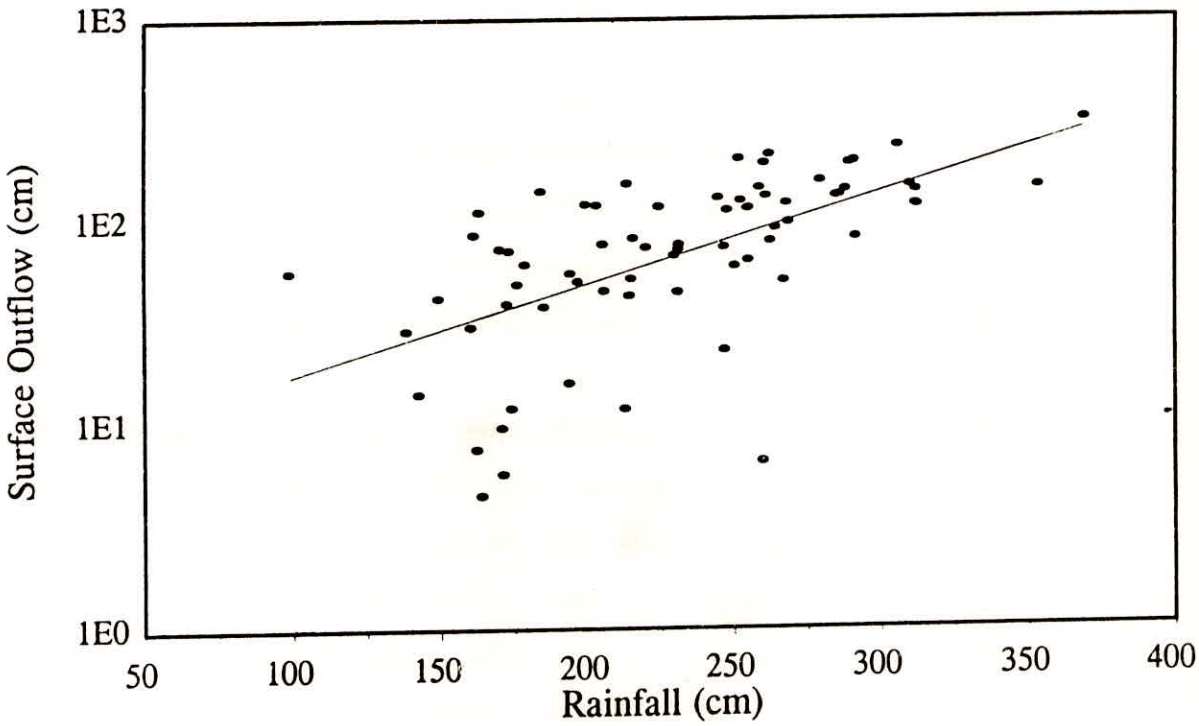


Fig. 7. Annual Rainfall - surface outflow relationship for Lake Nainital, worked out using long-term hydrological data.

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.

REFERENCES

Appleby, P.G. and Oldfield, F. Catena, 5, 1 (1978).

Appleby, P.G., Oldfield, F., Thompson, R. and Huttunen, P. Nature, 280, 53 (1979).

Ashley, G.M. and Moritz, L.E., 1979. Determination of lacustrine sedimentation rates by radioactive fall-out (^{137}Cs), Pitt Lake, British Columbia. Can. J. Earth Sci. 16:965-970.

Athy L.F. (1930) Density, porosity and compaction of sedimentary rocks. Bull. Amer. Assoc. Petrol. Geol. 14, 1-24.

Ball, V.,1878. On the origin of Kumaun lakes, Rec. Geol. Surv. Ind., II, pp. 174-182.

Balkaments, T. and Gregory, L.P., 1977. Profiles of ^{90}Sr and ^{137}Cs concentrations in selected New Zealand soils and their bearing on milk contamination levels. N.Z. J. Sci. 20: 425-431.

Bartarya, S.K., 1988. Geohydrological and Geomorphological Studies of Gaula River Basin, District Nainital with special reference to the problem of erosion, Unpublished Ph.D. Thesis, Kumaun University, Nainital, 266pp.

Battarbee, R.W., Digerfeldt, G., Appleby, P. and Oldfield, F. Arch. Hydrobiol. 89, 440 (1980).

Benninger, L.K., Aller, R.C., Cochran, J.K. and Turekian, K.K. Earth Planet. Sci. Lett., 47, 307 (1980).

Bergerioux, C., Rapin, F. and Haerdi,W. Radiochem. Radional. Lett., 45, 241 (1980).

Blais, J.M. and Kaiff J. (1995) The influence of lake morphometry on sediment focusing. Limnol.Oceanogr.40,582-588.

Bonyman, J., Duggleby, J. C., Kotler, L. H. and Molina-Ramos, J. 1972, Stronsitium-90 and Cesium-137 in the Australian environment during 1970 and some results for 1971, Defence Standard laboratories, Canberra, Australia, Report AWTSC No. 4.

Bortelson, G.C. and Lee, G.F., 1972. Recent sedimentary history of lake Mendota Wisconsin, Environ Sci Technol, 6, pp.798-808.

Brunskill, G.J., Ludam S.D., and Peng T.H. (1984) Fayetteville Green Lake, N.Y., U.S.A. VIII. Mass balance for ^{137}Cs in water, varved and non-varved sediment. Chem. Geol. 44, 101-117.

Byrnes, W.F., 1930. Technical Report on Hillside Safety, Kumaun Provincial Div.,Nainital, pp. 80.

Cambray, R.S., Fisher, E.M.R., Playford, K., Eakins, J.D. and Peirson, D.H. 1980. Radioactive fallout in air and rain: results to end of 1979, Report AERE-R-9672.

Campbell, B. L.,(1983), Applications of environmental Cesium-137 for the determination of sedimentation rates in reservoirs and lakes related catchment studies in developing countries, IAEA-TEDOC-298, Radioisotopes in Sediment Studies, pp. 7-30, Vienna.

Chow, V.T., 1964. Handbook of Applied Hydrology, Mc Graw-Hill Book Company, New York.

Cooper, M.B., Stanney, K.A. and Williams, G.A. Australian Radiation Laboratory Report ARL/TR039 (1981).

Crickmore M.J., Tazioli G.S., Appleby P.G., and Oldfield F. (1990) The use of nuclear techniques in sediment transport and sedimentation prolems. Technical Document in Hydrology. UNESCO, Paris.

Das, B.K., Singh, M., and Borkar, M.D., 1994. Sediment accumulation rate in the lakes of Kumaun Himalaya, India using ^{210}Pb and ^{226}Ra. Environ. Geol., 23: 114-118.

Davis, R.B., Hess, C.T., Norton, S.A., Hanson, D.W., Hoogland, K.D., and Anderson, D.S. 1984. ^{137}Cs and ^{210}Pb dating of sediments from soft-water lakes in New England (U.S.A.) and Scandinavia, a failure of 137Cs dating. Chem.Geol.44, 151-185.

Eakins, J.D. and Morrison, R.T. Int. J. Appl. Radiation Isotopes, 29, 531-6 (1978).

Eakins, J.D. 1983. The ^{210}Pb technique for dating sediments and some applications, IAEA-TECDOC-298,Radioisotopes in Sediment Studies. pp. 31-47. Vienna.

El-Daoushy, M.F.A.F., Doctorial dissertation at Uppsala University (1978) ISBN 91-554-0772-2.

Eyman, L.D. and Kevern, M.R., 1975. Cesium-137 and stable cesium in a hypereutrophic lake, Health Phys. 28: 549-555.

Gaggeler, H., Von Gunten, H.R. and Nyffeler,U. Earth Planet. Sci. Lett., 33, 119 (1976).

Goldberg, E.D. Geochronology with ^{210}Pb In" 'Radioactive Dating'. International Atomic Energy Lifency, Vienna (1963).

Hakanson L. (1977) The influence of wind, fetch and water depth on the distribution of sediments in Lake Venern, Sweden, Canadian J.Earth Sci. 14, 397-412.

Hashimi, N.H., Pathak, M.C., Jauhari, P., Nair, R.P., Sharma, A.K., Bhakuni, S.S., Bisht, M.K.S. and Valdiya, K.S., 1993. Bathymetric Study of the Neotectonic Nainital lake in Outer Kumaun Himalaya. Geol. Soc. Ind., 41: 91-104.

Hukku, B.M., Srivastava, A. K. and Jaitle, G.N., 1968. A geological Report on the Investigation of the Stability of the Hill-Slopes Around Nainital. Unpublished Progress Report, EGDivn.-NR, Geol. Surv. India.

Imboden, D.M. and Stiller, M. J. Geophys. Res., 87, 557 (1982).

Jauhari P. and Hashmi N.H. (1994) On the surfacial sediments of the fresh water Nainital Lake, Himaun Himalaya, India. Proc. Indian Nat. Sci Acad. 60,A.,No.5,675-682.

Jenne E.A. and Wahlberg J.S. (1968) Role of certain stream-sediment components in radio- ion sorption, U.S. Geol.Surv.Prof. Papers 433-F. 16 pp.

Jensen, J.M., Enge, W., Erlenkeuser, H. and Willkom, H. Nucl. Instrum. Meth. 147, 97 (1977).

Joshi L.V., Rangarajan C., and Gopalkrishnan S. (1969) Measurement of ^{210}Pb in surface, air and precipitation. Tellus, 21, 107-112.

Joshi, S.R. and Durham, R.W. Chem. Geol., 18, 381 (1978).

Kansanen P.H. and Jaakkola T. (1985) Assessment of pollution history from recent sediments in Lake Vanajavesi, southern Finland, I. Selection of representative profiles, their dating and chemostratigraphu, Annales Zoologici Fennici, 22, 13-55.

Koide M., Soutar A., and Goldberg E.D. (1972) Marine geochronology with Pb-210. Earth Planet.Sci.Lett. 14, 442-446.

Koide, M., Bruland, K.W. and Goldberg, E.D. Geochim. Cosmochim. Acta, 37, 1171 (1973).

Koide, M. and Bruland, K.W. Anal. Chim. Acta, 75, 1 (1975).

Krishnaswamy, S., Lal, D., Martin, J. M., and Meybeck, M., 1971. Geochronology of lake sediments, Earth Planet. Sci. Lett., 11:407-414

Krishnaswamy, S., Lal, D., Martin, J.M. and Meybeck, M. Earth Planet. Sci. Lett., 11, 407 (1971).

Krishnaswamy S., Lal D. (1978) Radionuclide Limnochrology. In Lakes: Chemistry, Geology, Physics, (ed. A.Lerman), pp. 153-173. Springer Verlag.

Krishnaswamy, S., Benninger, L.K., Alter, R.C. and Von Damm, K.L. Earth Planet. Sci. Lett., 47, 307 (1980).

Kusumgar, S., Agrawal, D.P. and Sharma, P., 1989. Radiocarbon chronology and magnetic susceptibility variation in Kumaon lake sediments, Radiocarbon, 31(3): 957-964.

Leland H.V. and Shukla S.S. (1973) Factors affecting distribution of lead and other trace elements in sediments of southern Lake Michigan. In Trace Metals and Metal-Organic Interactions in Natural Waters, (ed. P.C. SINGER), pp. 89-129. Ann Arbor Science, Ann Arbor, Mich.

Lewis, D.M. Geochim. Cosmochim. Acta, 41, 1557 (1977).

Livingston D. and Cambray R S (1978) Confirmation of Cs-137 dating by algal stratigraphy in Rosthene Mere. Nature 276, 259-261.

Mackereth, F.J.H. Phil. Trans. R. Soc. B 250, 165 (1966).

Mackereth, F.J.H., 1958. A portable core sampler for lake deposits, Limnol. Oceanogr. 3:181-191.

Mackereth, F.J.H., 1969. A short core sampler for subaqueous deposits, Limnol. Oceanogr. 14: 145-151.

Madsen, P.P. and Sorensen, J. J. Radional. Chem. 54, 39 (1979).

McCallan, M.E., O'Leary, B.M. and Rose, C.W. 1980. Redistribution of caesium-137 by erosion and deposition on an Australian Soil, Aust. J. Soil Res. 18: 119-128.

McHenry, J.R., Ritchie, J.C., and Gill, A.C., 1973. Accumulation of fall-out ^{137}Cs in soils and sediments in selected watersheds. Water Resour. Res., 9: 676-686.

McHenry, J.R. and Bubenzer, G.D., 1982. Field erosion estimated from ^{137}Cs activity measurements, Proc. Conference American Society of Agricultural Engineers, University of Wisconsin-Madison, June 27-30, Paper No. 82-2034.

Miller K M and Heit M. (1986) A time resolution methodology for assessing the quality of lake sediment cores that are dated by 137Cs. Limnol. Oceanogr. 31, 1292-1300.

Nozaki Y., Cochran J.k., and Turekian K.K. (1977) Radiocarbon and 210Pb distribution in submersible-taken deep-sea cores from project Famous. Earth Planet. Sci. Lett. 34, 167-173.

Oldfield F., Appleby P.G., and Thompson R. (1980) Paleoecological studies of lakes in the Highlands of Papua New Guinea, I. Chronology of sedimentation. J. Ecol. 68, 55-62.

Oldfield, F., Appleby, P.G. and Battarbee, R.W. Nature, 271, 339 (1978).

Oldfield, F. and Appleby, P.G. Empirical testing of ^{210}Pb dating models for lake sediments. In: Studies in Palaeolimnology and Palaeoecology (Ed. BIRKS, H.J.B.) Leicester University Press (in press).

Pennington, W., Freshwat. Biol. 3, 363. (1973).

Pennington, W., Cambray, R.S., Eakins, J.D. and Harkness, D.D. Freshwat. Biol., 6, 317. 1976.

Petit, D. Earth Planet. Sci. Lett., 23, 407 (1974).

Plato, P. and Goldman, G.C., 1972. Use of fall-out cesium-137 as a tracer to define the recent deltaic facies of a river, Radiat. Data Rep. 13: 653-657.

Plato, P., 1974. Use of rivers to predict accumulation in sediment of radionuclides discharged from nuclear power stations, Health Phys. 26: 489-496.

Plato, P. and Jacobson, A.P., 1976. Cesium-137 in Lake Michigan sediments: areal distribution and correlation with other man-made materials, Environ. Pollut. 10: 19-33.

Ravera, O. and Premazzi, G., 1971. A method to study the history of any persistent pollution in a lake by the concentration of ^{137}Cs from fall-out. Publication No. 679 (Biology Directorate), Commission of the European Communities.

Rawat, J. S., 1987. Morphology and morphometry of the Nainital lake, Kumaun, Lesser Himalaya. Geol. Soc. India, 30: 493-498.

Ritchie, J.C., McHenry, J.R. and Gill, A.C., 1974. Fallout ^{137}Cs in the soils and sediments of three small watersheds, Ecology (US) 55: 887-890.

Ritchie J.C. and McHenry J.R. (1978) Fall-out cesium-137 in cultivated and non-cultivated north central United States watersheds. J.Environ.Qual.7, 40-44.

Ritchie, J. C. and McHenry, J. R., 1985. A comparison of three methods for measuring recent rates of sediment accumulation. Water Resour. Bull., 21:99-103

Robbins, J. A. and Edgington, D. N., 1975. Determination of recent sedimentation rates in Lake Michigan using 210Pb and 137 Cs. Geochim. Cosmochim. Acta, 39: 285-304

Robbins, J.A., Krezoski, J.R. and Mosley, S.C. Earth Planet. Sci. Lett., 36, 325 (1977).

Robbins, J.A., Edgington, D.N. and Kemp, A.L.W. Quat. Res. 10, 256 (1978).

Schell W.R. and Nevissi A. (1983) Sedimentation in lakes and reservoirs. In Guidebook On Nuclear Techniques in Hydrology, Chap. 11, pp. 163-176. I.A.E.A.-Vienna.

Sharma, A.K., 1981. Structural Study of Area East of Nainital with Special Reference to the Hillslide Instability. Ph.D Thesis, Kumaun University, Nainital.

Sharma, A.K., 1987. Sedimentation in Nainital lake, Nainital, Aquaworld, Vol. II, No. 5, pp. 139-140.

Sholkovitz E.R. and Mann D.R. (1984) The porewater chemistry of $^{239,240}Pu$ and ^{137}Cs in sediments of Buzzards Bay, Massachusetts. Geochim. Cosmochim.Acta 48, 1107-1114.

Simpson, H.J., Olsen, C.R., Trier, R.M. and Williams, S.C., 1976. Man-made radionuclides and sedimentation in the Hudson River estuary, Science 194: 179-183.

Skei, J. Fluxes of pollutants to Norwegian fjord sediments based on ^{210}Pb. Symposium on 'Marine Chemistry into the Eighties', Sydney, Vancouver Island (1979).

Sly, P.G., 1978. Sedimentary processes in lakes, In: A. Lerman (Editor), Lakes: chemistry, geology and physics. Springer Verlag, pp.65-89.

Strong, W. L. and Cordes,L. D., 1976, A coring method for lake surface sediments, Can. J. Earth Sci. 13: 1331-1333.

US Health and safety laboratory, 1977, Environmental Quarterly, Appendix, July 1, Energy Research and Development Adminisration, Report HASL-321.

Valdiya, K.S., 1988. Geology and Natural Environment of Nainital Hills. Kumaun Himalaya. Gyanodaya Prakashan, Nainital, India.

Walling, D. E. and He, Q., 1993. Towards improved interpretation of ^{137}Cs profiles in lake sediments. In: (Eds. J. Mamanus and R.W. Duck) Geomorphology and Sedimentology, Wiley.

Wiebe, K. and Drennan, L., 1973. Sedimentation in reservoirs. In: Fluvial Processes and Sedimentation. Proc. Hydrology Symposium, University of Alberta, Edmonton. pp. 539-561.

Wise, S. University of London, King's College Report No. ULKC-OP-7 (1977).

APPENDIX - D

WATER QUALITY AND POLLUTION ASPECTS OF LAKE NAINITAL

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1.0 INTRODUCTION

The water quality of a lake depends upon various parameters which are influenced by a wide range of natural and man made operations. A lake may be characterized by morphometric, hydrological, chemical, biological and sedimentological parameters depending on its age, history, climate and water budget. Each lake develops its own response to these combined factors causing major variations of water quality in both time and space. The physico-chemical characteristics of a lake provide a first hand information about the pollution of the lake water. These characteristics include the measurement of pH, conductance, temperature, dissolved oxygen, dissolved inorganic carbon, turbidity, transparency, alkalinity, hardness, chloride, sulphate and nitrogen etc. The present report deals with the study of water quality aspects of Lake Nainital including its characterisation and comparison with other lakes in Kumaun region.

The behaviour of Nainital lake is subjected to a wide range of influences operating over three dimensions like other lakes. The water quality of the Nainital lake is mostly governed by the base flow and flow takes place through major drains including sediments. However, the continuous supply of various major and minor trace elements have created the deposits of these elements at the bottom which circulates every year during winter mixing. The circulation of these elements make the concentration of few elements beyond the permissible limits. Further, the Nainital lake has been showing signs of accelerated eutrophication due to human interference in the catchment area. Eutrophication is carried when the water of a lake is not able to purify itself because its dissolved oxygen is consumed in oxygen-demanding biochemical and chemical processes, thereby, developing anaerobic condition. The prolific growth due to the presence of phosphate and nitrate nutrients and overcrowding of algae and weeds and their eventual death and decay creates the same situation. One of the major causes of eutrophication of lake is the indiscriminate discharge of untreated domestic waste along with refuse and solid waste through 26 major drainage channels resulting in severe impairment of physical, chemical and biological quality of lake water.

The causes of deterioration of the Nainital lake are manifold. The infrastructural facilities such as water supply, sewerage, solid waste disposal, traffic and transportation and tourists facilities have fallen short of requirement. Due to this, the rain water fed channels serve as conduit to carry sewage overflow and also the solid waste, which are dumped into the channels which finally reach the lakes. Some of the springs contributing water to the lakes have dried up, and some are in the process of drying. On the other hand, the need of water is increasing day by day. Therefore, there is a strong need for the study of all aspects related with lakes for better management of lake recharge zones and to restore the health of the lakes Nainital.

The investigations conducted during the period 1994 to 1996 included water quality and eutrophication aspects of the lake besides the sedimentation and water balance studies. In this report the sampling strategy adopted, the analytical techniques followed at the laboratory, accuracy of the results are presented along with a comprehensive discussion on the sources and behaviour of selected elements in the lake. The causes for the hypereutrophic state of the lake, the limiting factor, and probable measures to check the eutrophication process have also been presented.

1.1 Study Area

Lake Nainital is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalayas (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 18.52 m. The lake is subdivided into two sub-basins by 100 m wide transverse underwater ridge, 7 to 20 m below the lake surface. The volume of the lake is 8.58 Mm^3. The average annual rainfall in the basin is 248.8 cm. The area of the lake basin is 4.7 km^2 out of which the surface area of lake is 0.46 Km^2 and that of Sukhatal sub-basin is 0.75 km^2. Therefore, the exclusive catchment area of Lake Nainital is 3.49 km^2. The landuse pattern of the entire lake basin is 48.4% forest, 18.3% barren, 19.3% built land and 10.4% water bodies.

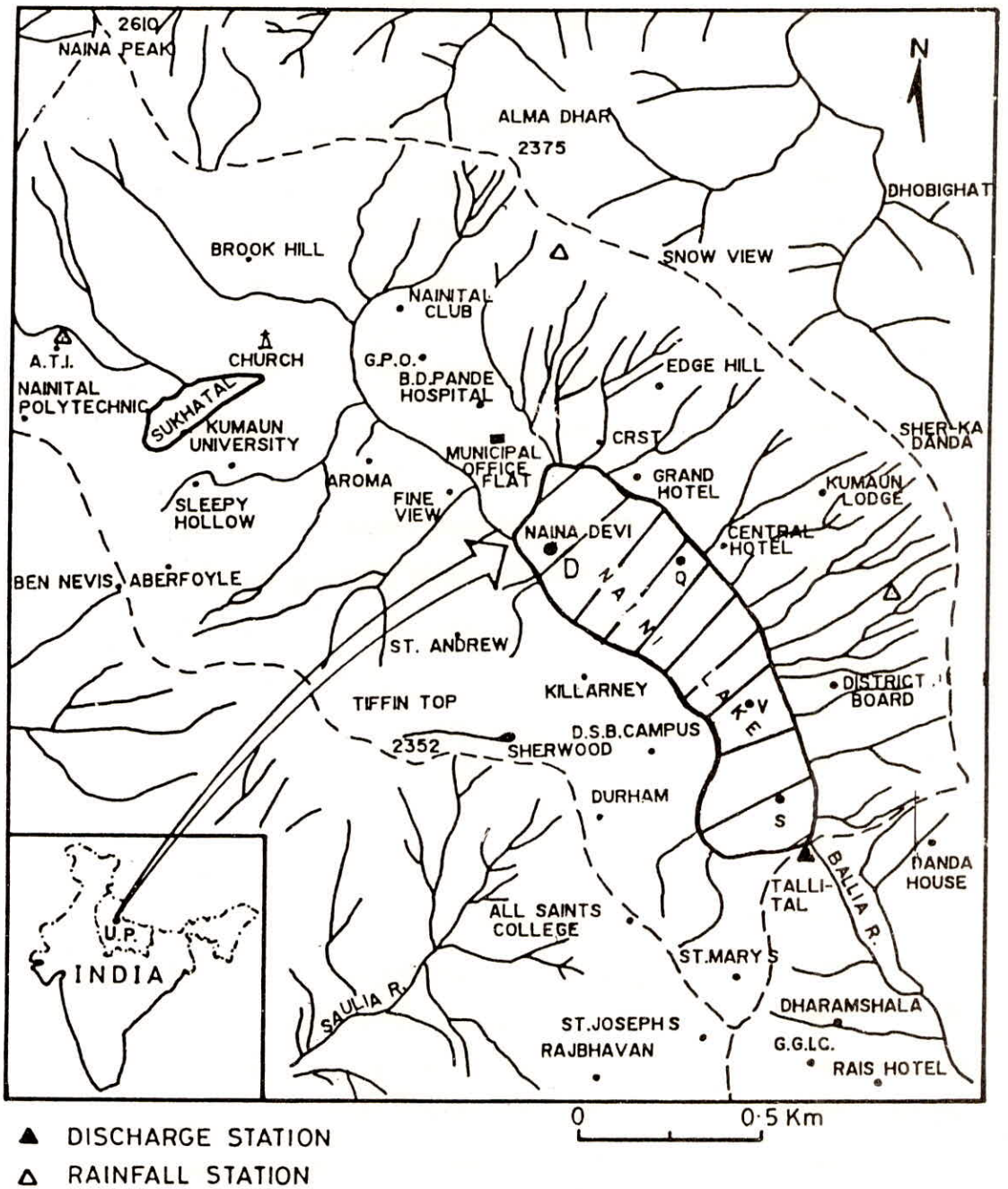


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

2.0 EARLIER STUDIES

2.1 Biological Characteristics

Biological analysis in Lake Nainital, have been carried out by various workers from time to time. In these studies, noticeable amount of phytoplankton, zooplankton, macrobenthos, fungi, actinomycetes, nematodes, insects, bacteria and photozoons have been isolated during different seasons. The colour of lake vary from light green to dark blue depending upon the population of phytoplankton and zooplankton. Algal blooming has become very common in Nainital lake which clearly indicates its eutrophication. These biological activities indicating the pollution level in the lake.

Pant et al. (1981) observed various species of phytoplankton among these microcystis species and others, which undergo blooming during summer and autumn months. The occurrence of oedogonium species and anabacna spiroides towards the upper end (north-west) of the lake as well as near the mouths of the two perennial open drains, suggested the existence of concentrated zone of pollution in the lake. The higher population density of plankton was encountered during the late spring and early autumn months.

Certain zooplanktons, such as bodo species, bursaria species, oxytricha species, spirostomum species, epistylis species, brachionus species and keratella species have been observed in appreciable numbers near and around the inlets of nalahs into the lake. The benthonic fauna was mainly constituted by low-oxygen tolerant and pollution-tolerant organism such as chironomus plumosus, tubifex tubifex, glossiphonia and weberi etc. They also observed population of 6105 indiv/m^3 of tubificid worms in certain months which could be taken as evidence of pollution.

The marked pollution of Nainital lake (Pant, et al., 1980) was also reflected by the absence of macrobenthic organisms below a depth of 7 m . It could be attributed to the completely anoxic conditions in the bottom water overlying the sediments for greater

part of the year, to accumulation of organic matters at the bottom with sediments are responsible for the production of toxic substances like (NH_3, CH_4, and H_2S) in the lake.

Sharma et al. (1982) observed the growth of phytoplankton often forming visual algal blooms except during the winter. The algal density becomes higher during March and August. The phytoplankton community was mainly constituted by green algae, with relatively lower proportions of diatoms and blue green algae. Thus the phytoplankton community in Nainital is truly characterized by blooms of blue green algae.

Purohit and Singh (1985) observed submerged macrophytes upto 6 m water depth in Nainital lake. Potamogeton pectinatus reached the maximum depth in Nainital lake and show high rate of production from April to May . Other species like hydrilla verticillata during rainy season and P. crispus during February-March (Late winter) have been observed in the lake. Besides species of many higher flung including Epicoccum, Cheetomium, Fusarium, Humicola, Lemonmiera, Lunulospora, Tetracladium, Triscelophorus and Tubercularia have been isolated from various decomposing domestic wastes present in drains and lake water (Khulbe et al., Khulbe and Bhargava, 1981; Khulbe, 1980). They have also isolated different kinds of bacteria from the lake water. Depending upon the colour, colonies pattern and shape of the bacteria, the sample showed 10 types of bacteria. Their number varied from 45 to 240/ml lake water. They have also noticed that tap water which supplied after filtration and chlorination by Water Works Department also show a considerable number of bacteria Escherichia coli and Salmonella sp. have been identified from the water samples which clearly indicate faecal (sewer) pollution.

2.2 Physico-chemical characteristics

Gupta and Pant (1983) carried out experiments for a period of 12 months from October 1977 to September 1978. They studied the variations of the contents of lake organic matters, phosphorous, nitrate- nitrogen (NO_3-N), cations (Ca, Na & K), trace metals (Mn, Cu, Zn & Co), pH and redox potential (Eh) including sediments in the

water samples collected from different depths of Nainital lake including mud-water interface. Their findings are: 1)With depth, clay, organic metals, cations redox potential go on increasing rapidly upto 9 m depth and almost negligible after 9 m depth, 2) Dissolved O_2 decreases while phosphate and NO_3-N increase with depth and much in hypolimnetic sample of overlying water and 3) Trace metals decrease with depth.

The sources of organic matter in the lake are (a) disposal of domestic wastes (including sewage) through open drains, (b) biologically derived organic matter (dead plankton, microphytes or dead fishes etc.) settling at bottom (c) randomly deposited faecal matters, broken tree leaves etc. falling into lake through surface runoff during rains by wind.

Pant et al. (1985), carried out some important investigations related with Physio-chemical limnology of Lake Nainital. They found that transparency is poor throughout the whole lake, with lowest in March and highest in June. Poor transparency is because of suspended regime matter (Mccombic) biological productivity in the form of algal blooming and in the form of plankton and in winter because of lake mixing. Also because of silting and low sunshine in rainy seasons.

More recently Gupta and Shukla (1997) have tried to relate the changes in physico-chemical and biological properties of Lake Nainital to human interference. But none of the above studies have taken into account the role of hydrology in the lake's present water quality status.

3.0 SAMPLING STRATEGY AND PROCEDURES

The water quality aspects of the Lake Nainital was monitored between February 1994 and July, 1996. Sampling was carried out during February, May, October and December, 1994; February, March, May, June, August, September, November and December, 1995; January, April and July, 1996. The number of samples collected from the lake varied from a minimum of 6 (June, 1995) and a maximum of 37 (March, 1995).

However, keeping in view the need for control points, the centre points of North and South basins (C2 and H2) were sampled regularly during all the sampling periods. Sampling at any point in the lake was carried out, generally, at three different depths viz., the surface, middle and bottom of the lake. During some sampling periods, sampling was carried out at every three meter depth interval, starting from surface to the bottom.

Apart from the analyses of lake waters as noted above other water sources in the surrounding region were also studied, since the lake has to be studied as part of the total ecosystem of the catchment rather than as an isolated water body. The samples of upstream springs considered to be representative of the local groundwater were also collected and analysed for establishing background water quality. To study the human impact on the lake environment it is imperative to have the knowledge of the quality of water that flows into the lake through the nalahs. Keeping this in view, apart from the lake, Springs located in the upstream side of lake and within the catchment, springs located on the downstream side of lake and outside the catchment, nalahs draining into the lake and the tube wells and open well located around the lake were also sampled. The water quality information on downstream springs issuing outside the catchment will give information on the possible links with the lake. The details of samples collected during the study period is given below:

Month	Lake	Nalahs	U/s Springs	D/s Springs	Wells	Total
Feb.,94	4	1	1	-	-	6
May, 94	9	1	1	-	-	11
Oct.,94	28	11	-	1	2	42
Dec.,94	11	1	1	6	1	20
Feb.,95	26	1	-	4	3	34
Mar.,95	37	2	7	4	1	51
May, 95	18	2	6	7	4	37

Month	Lake	Nalahs	U/s Springs	D/s Springs	Wells	Total
Jun.,95	6	-	-	7	-	13
Aug.,95	20	7	3	4	3	37
Sep.,95	20	6	4	5	5	40
Nov.,95	20	2	3	4	4	33
Dec.,95	19	-	2	2	2	25
Jan.,96	20	2	3	4	4	33
Apr.,96	27	2	3	4	5	41
Jul.,96	8	1	3	2	1	15
Total	**273**	**39**	**37**	**54**	**35**	**438**

In the year 1994, sampling was carried out during 4 months, which was considered to be representative of the four different seasons. However, realising the dynamics and the possible short hydraulic residence time of the lake water, the sampling was carried out during 8 months (as shown in the table) in the year 1995. In the last year of the investigations i.e. 1996, sampling was carried out in January, April and July with a view to complement the available information on the lake's quality.

The samples from the lake were collected using a depth sampler (Hydrobios make) of 2 L capacity with a built in thermometer of 0.2°C least count. The electrical conductivity (E.C.) and pH were measured in-situ using a 5-parameter field water testing kit. In the early stages the dissolved oxygen was also measured in the field. But later comparison with laboratory data showed the non-reliability of the field DO values. Hence, the in-situ measurements were restricted only to temperature, pH and E.C.

As stated above samples were collected from fixed points (Fig. 2). To understand the hydrodynamics of the lake and also the spatial variation of the water characteristics within the lake, samples were collected at every three meter depth, starting from the surface upto the bottom. The collected samples were mainly utilised for three different

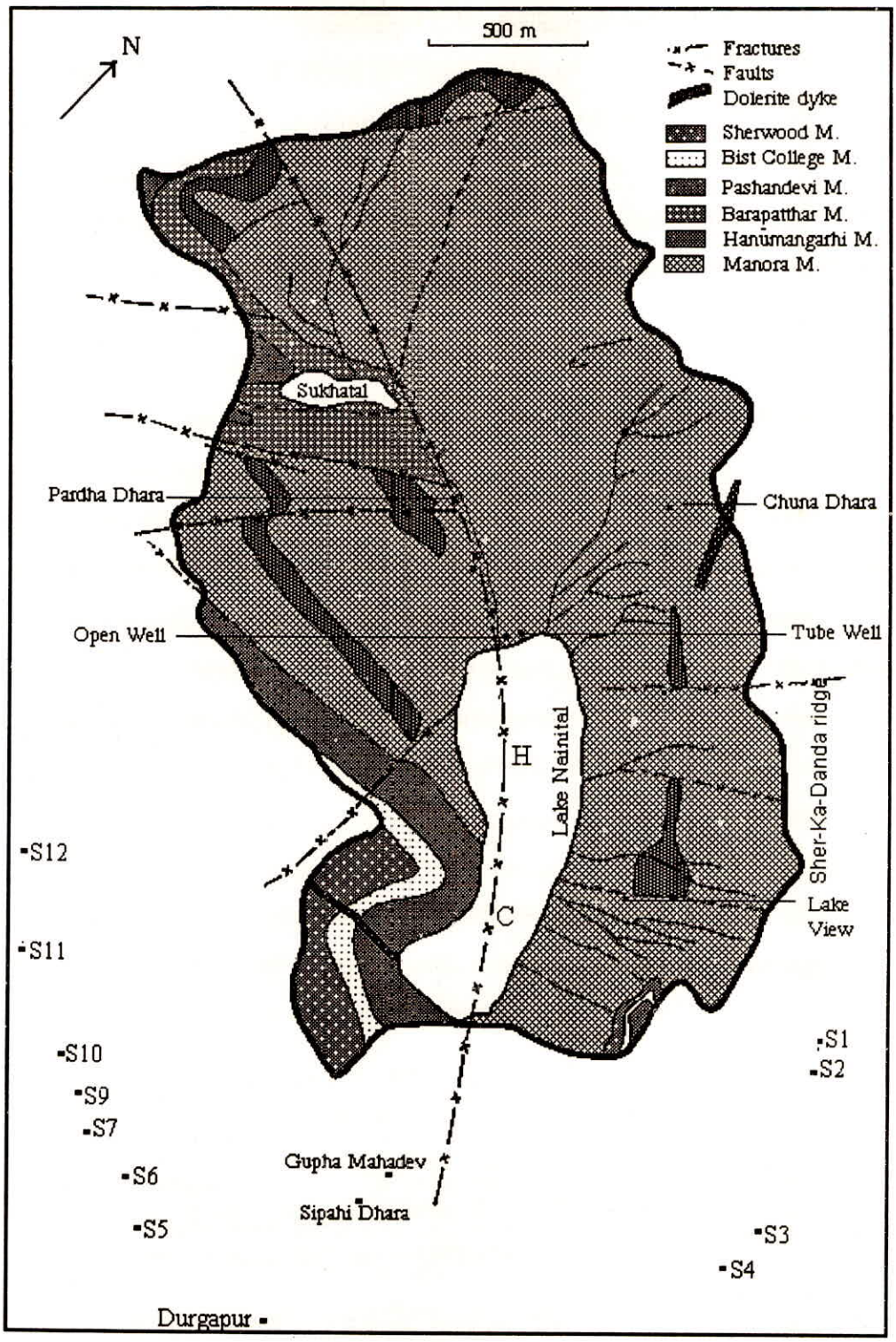


Fig.2 Geological map of Lake Nainital catchment showing locations of sampling points in lake and surrounding springs

aspects, viz. a) In-situ measurement of phsico-chemical characteristics, b) Isotope composition and c) water quality aspects. While insitu measurements and samples for isotope characteristics were made every three meters, samples for water quality of aspects were made only at three or four different depths viz. Epilimnion (0 m), Mesolimnion (6 - 9 m, depending on the season) and hypolimnion (1 to 4 m above the bottom, depending on the season).

The samples collected for the water quality aspects were first filtered using an 0.45 μm Whatman filter and preserved. Three different bottles were filled. The first one (1 L) was unpreserved for alkalinity, chloride and Orthophosphate - phosphorus determination. The second one (1 L) was preserved with Concentrated sulphuric acid for total hardness, and calcium hardness determinations. The third one (60 mL) was preserved with concentrated nitric acid for trace elements, Na, K and sulphate determinations. The samples were then transported to the National Institute of Hydrology laboratory at Roorkee, and were immediately analysed giving priority to those parameters that are to be determined using the unpreserved samples. Other parameters were analysed within a weeks time.

Apart from the above three bottles, one sample was collected from each sampling point for dissolved oxygen determination. The DO bottle of 300 mL capacity was filled upto the brim and preservatives were added according to winkler's method.

The samples for stable isotope analyses were collected at every three meters depth in 20 mL plastic vials and tightly sealed with tapes and were transported to Bhabha Atomic Research Centre (BARC), Mumbai. Samples were also collected for environmental tritium analyses and sent to BARC, during the month of December, 1994. The physico-chemical parameters that were analysed in the water samples include:

Field parameters	-	Temp., pH and E.C.
Major ions	-	Ca, Mg, Na, K, HCO_3, SO_4 and Cl
Trace elements	-	Sr, B, Pb, Mn, Zn and Fe



Preparation for Water Sampling from Nainital Lake in Progress



Water Sampling for Chemical Analyses in Progress from Lake Nainital

Nutrients	-	PO_4-P and NO_3-N
Others	-	DO, BOD, COD and Suspended solids
Stable isotopes	-	Oxygen-18 and Deuterium
Radio-isotopes	-	Environmental tritium

The methods followed at the NIH water quality laboratory for analyses of different parameters have been presented elaborately (National Institute of Hydrology, 1987) and are discussed briefly in what follows:

Chloride was estimated by argentometric method in the form of silver chloride. Alkalinity was determined by titrimetric method using phenolphthalein and methyl orange indicators. Total hardness and calcium hardness were determined by EDTA titrimetric method while magnesium hardness is calculated by deducting calcium hardness from total hardness. Calcium (as Ca) may be calculated by multiplying calcium hardness with 0.401 while magnesium (as Mg) by multiplying magnesium hardness with 0.243. Sodium and potassium were determined by flame-emission method using flame photometer.

Nitrogen in the form of nitrate was determined by using spectrometric methods. Phosphate was estimated by Stannous chloride method in the form of molybdenum blue while sulphate by turbidimetric method in the form of barium sulphate crystals. Trace elements were determined by atomic absorption or atomic emission methods.

4.0 ANALYSES OF DATA AND ACCURACY

It is an established fact that the sampling techniques, preservation methods and length of storage time before analysis have certain effect on the accuracy of the results. Under optimum conditions the results for major constituents of the water have an accuracy of $\pm$ 2% to $\pm$10 %. Solutes present in concentrations above 100 mg/L generally can be determined with an accuracy of better than $\pm$ 5%. For solutes present in concentration below 1 mg/L, the accuracy is not better than $\pm$ 10% and can be poorer. One way of determining the accuracy of major dissolved constituent values in

a reasonably complete chemical analysis of a water sample can be accomplished by checking anion - cation balance. Though this concept is chemically sound, in some waters it may be difficult to ascertain the forms of some of the ions reported in the analysis. Solutions that are strongly coloured, for example, commonly have organic anions that form complexes with metals and the usual analytical procedures will not give results that can be balanced satisfactorily. Another procedure for checking the accuracy is possible using specific conductivity and dissolved solids determinations. The total of milliequivalents per litre of either anions or cations multiplied by 100 usually agrees approximately with the electrical conductivity in μmhos/cm. A simple screening procedure for evaluating analyses for the same or similar source is to compare the results with one another. Groups of analyses from the same or similar sources in which all magnesium concentrations are similar but the calcium concentrations have a rather wide range may indicate the calcium and bicarbonate were lost by precipitation of calcite. This can occur during storage and also in the water circulation system before sampling. Considering the results of the repeat analysis and duplicate analysis of samples and electro-neutrality for estimating analytical accuracy, it is found that the overall accuracy of the analyses in the present study is within $\pm$ 5% error limit.

5.0 RESULTS

The results have been organised and presented in two different formats. The first set (Table 1 to Table 14b) gives sampling campaign wise results of the all the samples from different sources. The second set (Table 15 to Table 26) gives the results of samples collected from selected sources viz., the north and south basins of the lake (includes epilimnion and hypolimnion), Naina devi mandir drain, well located on the north bank of the lake, upstream springs (issuing from dolomite rock - Pardha dhara, from shales - alma spring, Chuna dhara or doctor house spring, and lake view spring), downstream springs (Gupha mahadev mandir spring or Sipahi dhara, and springs that issue outside the catchment). The second set of results are presented in a more comprehensive manner so that temporal variations can be assessed easily.

Table :1 Collected :9-10, Feb, 1994

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
C21	1		10	7.5	385	260	386	8		0	0			67	54
C28	20		8.5	8.6	366	285	338			0.19	0			53	32
H21	1		9.2	8.1	404	272	352			0.2	0			56	52
H28	20		8.8		416		336				0			51	51
DRAINS															
Naina D				8.1	455	290	420	2.8		0.02	2.85			69	60
SPRINGS															
Pardha S					520		356				3.5			58	52

Table :2 Collected :20-21, May, 1994

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
C21	0.00	5.60	19.90	8.60	600.00	133.00	372.00	1.00	110.00	0.00	0.00	9.90	4.50	46.10	62.50
C24	12.00	0.80	9.80	7.20	660.00	147.00	370.00	1.00	93.00	0.16	0.00	10.20	4.40	80.20	41.30
C28	21.00	3.90	17.20	8.00	610.00	140.00	344.00	1.00	110.00	0.08	0.00	10.20	4.60	54.10	50.80
E27	22.00	2.70	16.30	7.20	610.00	148.00	340.00	3.00	101.00	0.29	0.00	10.30	4.80	52.90	50.50
F21	0.00	5.10	19.60	8.50	600.00	128.00	373.00	5.00	119.00	0.04	0.00	9.40	4.60	48.90	61.00
F24	7.00	0.70	14.60	7.90	630.00	143.00	375.00	3.00	96.00	0.22	0.00	9.50	4.30	50.10	60.80
H21	0.00	5.40	18.60	8.60	600.00	132.00	365.00	4.00	112.00	0.02	0.00	10.00	4.80	45.70	60.90
H24	12.00	0.90	10.10	7.60	650.00	144.00	379.00	1.00	111.00	0.28	0.00	9.60	4.80	56.10	58.10
H28	21.00	0.80	9.20	8.00	660.00	130.00	391.00	3.00	78.00	0.10	0.00	10.10	4.70	58.50	59.50
DRAINS															
Naina D		2.80		7.50	1040.00	202.00	542.00	9.00	173.00	0.48	1.50	10.40	9.30	86.20	79.50
SPRINGS															
Pardha S		5.70		8.10	845.00	150.00	478.00	6.00	177.00	0.00	2.90	8.60	3.00	85.80	64.20

Table :3a Collected :03-05, Oct., 1994

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A16				7.10	652.00	266.00	280.00	12.00		0.40	2.30			45.70	40.30
A25				7.70	634.00	242.00	274.00	11.00		0.30	2.40			42.50	40.80
A35				7.70	620.00	220.00	318.00	11.00	98.00	0.17	1.70			48.10	48.10
C21	0.00	9.50	20.10	8.20	506.00	189.00	254.00	13.00	76.60	0.00	0.40			26.50	45.70
C22	3.00		19.60	8.20	520.00	188.00	252.00	14.00	78.20	0.00	0.30			28.10	44.20
C23	6.00		18.60	7.80	559.00	213.00	274.00	15.00	74.10	0.00	0.40			36.10	44.70
C24	9.00		13.50	7.30	629.00	247.00	326.00	13.00	79.00	0.25	1.60			52.10	47.60
C25	12.00	0.00	10.80	7.20	656.00	260.00	328.00	14.00	67.50	0.18	2.90			50.50	49.10
C26	15.00		10.00	7.10	662.00	242.00	330.00	13.00	77.40	0.10	3.20			52.10	48.60
C27	18.00		9.90	7.10	658.00	265.00	324.00	11.00	77.40	0.20	3.50			52.10	47.10
C28	21.00		10.20	8.30	673.00	258.00	330.00	11.00	72.40	0.10	3.70			52.90	48.10
C29	23.75	0.00	10.00	7.10	683.00	284.00	430.00	16.00		0.40	0.00			80.20	55.90
C39	23.50		9.90	6.90	669.00	260.00	282.00	13.00		0.40	3.10			49.70	38.40
D39				6.90	660.00	258.00	290.00	13.00		0.40	2.00			49.70	40.30
F21	0.00	9.60		8.10	521.00	180.00	252.00	13.00	117.70	0.00	0.20			27.30	44.70
F24	7.00	0.90		7.50	581.00	218.00	302.00	13.00	76.60	0.10	0.70			42.50	47.60
H110	24.52		9.60	6.80	946.00	200.00	518.00	16.00		0.10	2.30			120.30	52.90
H21	0.00	8.50	20.50	8.20	521.00	178.00	248.00	15.00	86.40	0.00	0.30			26.50	44.60
H22	3.00		20.20	8.10	505.00	174.00	244.00	14.00	84.80	0.02	0.40			30.50	40.80
H23	6.00		18.10	7.70	571.00	214.00	274.00	14.00	81.50	0.04	0.40			39.30	42.80
H24	9.00		12.90	7.80	657.00	246.00	320.00	16.00	76.60	0.30	1.80			54.50	44.70
H25	12.00		10.90	7.20	664.00	250.00	316.00	17.00	82.30	0.14	2.50			55.30	43.20
H26	15.00	0.00	10.00	7.20	667.00	260.00	314.00	15.00	76.60	0.20	3.30			55.30	42.80
H27	18.00		10.00	7.10	661.00	252.00	320.00	13.00	79.80	0.20	3.50			55.30	44.20
H28	21.00		9.80	7.20	683.00	266.00	322.00	13.00	83.10	0.20	4.30			55.30	44.70
H29	24.00	0.00		7.10	711.00	270.00	332.00	13.00	45.30	0.12	7.00			59.30	44.70
H210	26.05		9.70	6.90	772.00	270.00	400.00	14.00		0.60	0.00			80.20	48.60
H310				7.10	701.00	274.00	326.00	12.00	74.90	0.10	5.10			59.30	43.20

Table :3b Collected :03-05, Oct., 1994

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
DRAINS															
Nala 1				7.40	909.00	310.00	408.00	6.00	45.30	0.80	4.00			80.20	50.50
Nala 4				8.20	916.00	350.00	400.00	26.00	139.10	0.30	2.30			86.60	44.70
Nala 11				8.20	845.00	296.00	376.00		152.30	0.30	2.00			52.10	59.80
Nala 13				8.10	775.00	242.00	422.00	11.00	158.10	0.00	1.40			52.90	70.50
Nala 16				8.10	663.00	280.00	286.00			0.02	2.70			43.30	43.20
Naina D-		7.40		7.70	807.00	290.00	408.00	14.00	84.80	0.10	3.20			43.30	72.90
Naina D-				7.80	802.00	288.00	420.00	15.00	158.20	0.10	3.05			33.70	81.60
Alka				8.20	478.00	140.00	220.00	13.00	87.30	0.20	0.00			23.20	39.40
Stream 1				5.90	58.00	26.00	14.00	4.00	4.12	0.20	0.00			4.80	0.50
Stream 2				7.10	171.00	38.00	40.00	21.00	11.50	0.00	0.20			11.20	2.90
Stream 3				8.10	610.00	260.00	300.00	15.00	11.50	0.00	0.00			46.50	44.70
SPRINGS															
Suriya S				8.00	606.00	228.00	290.00	5.00	99.60	0.00	0.00			50.50	39.80
GW															
O. Well		1.80		7.50	640.00	238.00	210.00	15.00	70.80	0.11	1.80			62.60	13.10
Pump H				7.40	671.00	266.00	278.00		86.40	0.10	2.00			44.90	40.30

Table :4 Collected :14-20, Dec., 1994

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A35	11.50	0.00	10.60	7.80	601.00	260.00	404.00	12.00		0.55	0.00	14.00	3.60	70.00	56.00
C21	0.00	2.20	11.40	8.00	547.00	240.00	316.00	6.00		0.16	0.75	12.00	4.40	47.00	49.00
C24	7.50	0.70	11.00	8.10	547.00	230.00	306.00	10.00		0.21	0.80	11.80	4.20	43.00	48.00
C26	15.00	0.00	10.40	7.50	630.00	298.00	344.00	6.00		0.53	0.00	13.60	4.80	53.00	52.00
C29	22.80	0.00	10.00	7.70	652.00	324.00	356.00	8.00		0.90	0.00	11.60	3.60	63.00	49.00
F21	0.00	1.40	11.00	7.90	553.00	242.00	316.00	10.00		0.14	0.70	11.60	4.40	48.00	48.00
F24	7.00	3.00	10.80	7.90	550.00	244.00	314.00	6.00		0.19	0.70	14.00	4.40	47.00	48.00
H21	0.00	1.30	11.60	8.10	553.00	234.00	310.00	4.00		0.13	0.65	11.20	4.10	46.00	48.00
H24	7.50	0.90	10.90	8.10	562.00	164.00	314.00	8.00		0.18	0.65	11.20	4.20	46.00	49.00
H26	15.00	0.00	10.40	7.60	614.00	302.00	350.00	8.00		0.55	0.00	13.80	4.50	57.00	51.00
H210	25.00	0.00	9.80	7.60	680.00	350.00	354.00	8.00		0.15	0.00	11.60	4.50	51.00	55.00
DRAINS															
Naina D		5.30		7.60	822.00	328.00	434.00	4.00		0.43	2.00	12.20	7.40	71.00	62.00
SPRINGS															
Pardha S		4.90		7.70	716.00	174.00	320.00	6.00		0.06	3.30	13.60	3.60	71.00	35.00
S-3 S		8.10		8.20	654.00	228.00	384.00	8.00		0.00	0.00	12.80	1.50	83.00	43.00
S-5 S		7.70		8.10	288.00	174.00	168.00	0.00		0.01	0.00	6.40	0.70	34.00	20.00
S-9 S		6.60		7.90	562.00	268.00	348.00	0.00		0.03	0.15	5.20	1.70	55.00	52.00
S-12 S				8.30	1066.00	208.00	592.00	0.00		0.00	0.00	8.40	4.80	129.00	66.00
Gupha S		7.70		8.30	547.00	230.00	302.00	6.00		0.02	2.20	8.80	2.70	49.00	44.00
Sipahi S		6.40		8.10	560.00	238.00	310.00	6.00		0.03	2.30	9.20	3.00	46.00	48.00
GW															
Pump H		2.00		7.70	726.00	294.00	370.00	6.00		0.05	2.35	14.60	4.40	44.00	63.00

Table : 5 Collected :22-26, Feb , 1995

parame units	Depth m (bws)	DO mg/l mg/l	T °C	pH	EC mic. mho	Alk mg/l	H mg/l	Cl mg/l	S mg/l	P mg/l	N mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00	6.60	8.60	6.90	493.00		330.00	11.00	61.30	0.22	0.40	11.80	4.40	49.70	50.10
A35	12.00	3.40	7.90	7.10	504.00		328.00	13.00	102.10	0.23	0.50	12.40	4.60	54.50	46.70
C21	0.00	5.60	9.20	6.80	516.00		322.00	11.00	72.00	0.27	0.20	11.80	4.60	51.30	47.10
C25	12.00	5.00	8.20	6.90	503.00		324.00	1.00	90.10	0.29	0.60	11.20	4.70	48.90	49.10
C29	22.75	4.90	8.00	7.00	496.00		310.00	3.00	74.90	0.26	0.70	11.00	4.60	48.90	45.70
F11	0.00	7.00	10.20	6.80	532.00		316.00	11.00	94.30	0.25	0.00	11.20	4.60	49.70	46.70
F15	12.00	4.80	8.00	6.80	511.00		300.00	13.00	96.70	0.24	0.40	11.00	4.50	47.30	44.20
F17	18.50	3.50	8.00	6.80			318.00	2.00	92.60	0.22	0.40	13.40	4.80	48.10	48.10
H21	0.00	4.80	8.40	6.60	553.00		324.00	1.00	85.20	0.19	1.00	14.00	4.40	50.50	48.10
H25	12.00	5.40	8.00	6.70	511.00		326.00	9.00	87.70	0.16	0.50	14.40	4.30	46.50	51.00
H29	24.00	3.60	8.00	6.80	501.00		318.00	9.00	95.90	0.19	0.30	11.60	4.20	46.50	49.10
J11	0.00	5.10	8.30	6.60	507.00		330.00	27.00	63.40	0.25	0.60	11.20	4.70	48.90	50.50
J12	3.00	5.00	8.20	6.50	517.00		348.00	13.00	103.30	0.24	0.60	11.00	4.70	49.70	54.40
J13	6.00	5.30	8.20	6.40	516.00		354.00	19.00	113.20	0.28	0.60	9.20	4.60	48.90	56.40
J14	9.00	5.00	8.10	6.50	507.00		334.00	9.00	105.80	0.24	0.70	11.80	4.50	48.90	51.50
J15	12.00	4.90	8.20	6.50	506.00		334.00	19.00	105.40	0.25	0.60	11.10	4.60	44.90	54.00
J16	15.00	4.70	8.10	6.50	503.00		324.00	3.00	98.80	0.24	0.60	11.80	4.60	45.70	51.00
J17	16.00	5.10	8.10	6.40	503.00		322.00	15.00	99.60	0.26	0.60	14.20	4.50	47.30	49.60
DRAINS															
Naina D		6.00	11.00	7.00	490.00		350.00	22.00	125.10	0.35	2.90	15.20	6.40	20.10	72.90
SPRINGS															
S3 S		8.80					398.00	25.00	137.90	0.14	0.00	12.60	1.60	58.60	61.20
S5 S		7.70	15.00	6.90	300.00		234.00	15.00	142.80	0.00	0.00	4.30	0.40	36.90	34.50
Sariya S							366.00	7.00	81.50	0.00	0.50	2.70	2.20	59.30	52.90
km 11 S							334.00	5.00	117.30	0.00	0.00	7.00	1.40	40.90	56.40
GW															
O. Well		2.50	12.70	6.70	757.00		436.00	13.00	73.20	0.04	3.00	12.80	5.00	64.90	66.60
Pump							400.00	15.00	13.60	0.24	2.30	11.20	4.40	65.00	57.80
N Pump							428.00	17.00	26.70	0.06	3.80	11.00	5.90	68.20	62.70

Table :6a Collected: 22-23, March, 1995

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00	14.10	16.00	9.40	751.00	252.00	332.00	15.00	93.80	0.10	0.00	11.60	4.10	46.70	52.30
A32	3.00		12.00	9.00	741.00	268.00	340.00	15.00	95.50	0.16	0.00	11.60	4.10	48.10	53.60
A33	6.00		10.40	8.60	747.00	254.00	333.00	17.00	95.50	0.13	0.50	11.60	4.20	48.30	51.60
A34	9.00	0.46	8.40	8.10	709.00	270.00	343.00	18.00	101.30	0.23	1.30	12.60	4.20	52.00	51.90
A35	12.00	1.20	8.20	8.00	698.00	270.00	341.00	16.00	102.10	0.20	1.00	12.00	4.20	52.30	51.20
C21	0.00	11.10	16.00	9.40	888.00	260.00	326.00	16.00	95.50	0.16	0.00	13.60	4.20	42.40	58.40
C22	3.00		12.20	9.00	830.00	262.00	366.00	21.00	90.60	0.09	0.00	11.80	4.20	41.90	63.50
C23	6.00		9.40	8.30	795.00	260.00	343.00	16.00	105.40	0.18	1.15	12.20	4.20	47.40	54.50
C24	9.00	1.50	8.60	8.10	760.00	248.00	346.00	16.00	93.80	0.15	1.15	11.60	4.30	50.50	53.50
C25	12.00		8.20	8.10	773.00	268.00	335.00	16.00	88.10	0.19	1.25	11.00	4.20	45.70	53.70
C26	15.00		8.20	8.10	723.00	256.00	324.00	15.00	96.30	0.16	1.15	11.20	4.20	46.80	55.10
C27	18.00		8.20	8.00	772.00	252.00	345.00	12.00	88.90	0.19	1.25	10.20	4.20	47.50	55.10
C28	21.00		8.20	8.00	769.00	264.00	338.00	16.00	102.90	0.15	1.15	11.20	4.20	49.60	52.20
C29	22.50	0.36	8.20	8.10	711.00	260.00	337.00	18.00	88.90	0.19	1.05	11.20	4.10	48.30	52.70
F11	0.00		14.90	9.20	760.00	260.00	344.00	15.00	74.90	0.15	0.00	12.80	4.40	47.90	54.70
F12	3.00		12.60	8.80	766.00	278.00	349.00	17.00	76.60	0.15	0.00	12.60	4.50	52.50	53.10
F13	6.00		9.30	8.90	739.00	272.00	346.00	16.00	100.40	0.19	1.00	12.60	4.40	50.80	53.30
F14	9.00	1.70	8.60	8.50	717.00	272.00	335.00	16.00	93.80	0.22	1.25	12.60	4.50	45.70	53.70
F15	12.00		8.30	8.20	726.00	276.00	334.00	17.00	88.90	0.21	1.15	12.60	4.50	48.90	51.40
F16	15.00		8.20	8.00	716.00	272.00	337.00	17.00	105.40	0.20	1.30	12.20	4.50	47.20	53.30
F17	20.00	1.30	8.20	8.20	721.00	256.00	338.00	18.00	86.40	0.24	1.25	12.60	4.50	48.80	52.40
H21	0.00	15.50	15.40	9.10	740.00	238.00	306.00	16.00	101.30	0.16	0.00	13.40	4.50	37.00	52.00
H22	3.00		12.40	9.10	761.00	262.00	349.00	14.00	99.60	0.14	0.00	13.40	4.70	46.70	56.60
H23	6.00		9.60	8.70	721.00	254.00	330.00	14.00	98.80	0.19	0.70	14.60	4.60	49.20	50.30
H24	9.00		8.60	8.50	701.00	262.00	338.00	17.00	101.30	0.21	0.50	12.60	4.40	46.00	54.20
H25	12.00	1.80	8.30	8.30	751.00	256.00	343.00	12.00	135.00	0.21	0.70	13.00	4.50	51.20	52.40
H26	15.00		8.20	7.90		252.00	345.00	16.00	131.70	0.23	1.15	12.40	4.50	42.80	58.00
H27	18.00		8.20	7.80	723.00	286.00	349.00	13.00	102.10	0.22	1.10	12.60	4.50	45.90	57.10
H28	21.00		8.20	8.30	746.00	268.00	350.00	18.00	94.70	0.23	1.10	13.00	5.10	43.90	58.40
H29	24.00	1.40	8.20	8.40	861.00	236.00	352.00	19.00	121.80	0.26	1.15	12.20	5.20	41.70	60.20

Table :6b Collected :22-23, March, 1995

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Lake															
J11	0.00	14.50	16.00	9.30	892.00	260.00	368.00	15.00	96.30	0.16	0.00	11.60	4.40	51.50	58.30
J12	3.00		12.30	8.80	752.00	262.00	342.00	15.00	102.90	0.13	0.00	15.20	4.60	59.10	47.20
J13	6.00		10.00	8.70	766.00	268.00	344.00	15.00	97.10	0.19	0.30	11.60	4.20	54.10	50.80
J14	9.00	2.10	8.80	8.40	757.00	250.00	335.00	16.00	87.30	0.19	0.45	14.60	4.30	52.10	49.60
J15	12.00		8.30	8.20	740.00	264.00	341.00	16.00	79.90	0.21	1.00	13.60	4.40	48.90	53.10
J16	15.00		8.20	8.20	744.00	278.00	337.00	16.00	73.70	0.21	1.05	13.60	4.40	50.20	51.50
J17	16.50	1.90	8.20	8.10	711.00	260.00	338.00	17.00	76.60	0.22	0.15	12.80	4.40	49.70	52.00
DRAINS															
Naina D		3.40			999.00	366.00	464.00	27.00	194.30	0.10	2.35	19.00	8.70	57.50	77.90
Riksha D		4.10			1147.00	350.00	485.00	44.00	189.30	0.22	0.45	27.60	16.00	71.90	74.40
SPRINGS															
Pashan S		5.40			800.00	290.00	427.00	19.00	174.50	0.00	1.70	12.60	5.50	69.00	61.90
Arch S		6.80			871.00	268.00	413.00	18.00	180.30	0.00	2.80	10.20	3.80	65.50	60.70
Pardha S		4.60			818.00	296.00	432.00	23.00	176.20	0.03	4.15	12.40	4.50	61.10	67.90
L. View S					806.00	322.00	546.00	17.00	184.40	0.02	0.95	10.20	3.10	55.10	99.20
S2 S						254.00	264.00	17.00	106.20	0.03	0.40	9.60	2.60	42.00	38.80
S3 S						224.00	366.00	11.00	208.30	0.07	0.00	14.00	2.20	62.60	51.10
S5 S						182.00	185.00	9.00	84.80	0.03	0.00	3.40	1.00	36.70	22.70
Sariya S					806.00	260.00	387.00	16.00	149.80	0.05	0.00	1.60	2.60	49.60	64.00
Rais S					657.00	250.00	329.00	26.00	117.70	0.08	4.30	14.80	5.50	44.67	52.80
Sipahi S						244.00	354.00	13.00	149.80	0.00	2.10	9.00	3.80	46.40	57.90
Gupha S						236.00	328.00	16.00	133.20	0.03	2.10	10.60	3.00	45.90	57.90
GW															
Sukha					840.00	262.00	367.00	19.00	167.90	0.05	3.60	9.80	3.50	37.90	66.30

Table :7a Collected :29-31, May, 1995

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00	15.00	21.30	7.80	567.00	209.00	280.00	21.00	126.00	0.10		11.60	4.40	37.70	45.20
A34	9.00	1.70	10.00	7.60	637.00	245.00	340.00	11.00	97.00	0.40		9.60	4.70	40.10	58.30
A35	11.50	2.80	10.20	7.60	646.00	252.00	326.00	10.00	92.00	0.37		9.20	4.00	36.90	56.90
C21	0.00	13.90	21.10	7.80	570.00	206.00	280.00	9.00	85.00	0.12		9.60	4.60	32.90	48.10
C24	9.00	1.90	8.90	7.80	648.00	260.00	326.00	10.00	85.00	0.39		9.40	4.50	39.30	55.40
C29	21.85	0.00	8.50	7.40	649.00	253.00	332.00	9.00	97.00	0.78		11.00	4.60	40.90	55.90
E11	0.00	14.20	21.00	8.00	569.00	197.00	294.00	12.00	100.00	0.11		11.60	4.60	32.90	51.50
E14	9.00	4.90	9.20	7.50	639.00	254.00	336.00	11.00	90.00	0.42		12.40	4.80	40.10	57.30
E18	19.50	1.40	8.40	7.60	651.00	255.00	336.00	11.00	93.00	0.41		8.00	4.60	36.10	59.80
F11	0.00	13.40	21.00	7.80	570.00	229.00	304.00	15.00	90.00	0.12		11.20	9.00	34.50	52.90
F14	9.00	2.50	8.80	7.50	633.00	253.00	338.00	10.00	97.00	0.36		12.40	4.80	40.90	57.30
F18	20.00	3.40	9.00	7.40	640.00	252.00	334.00	15.00	86.00	0.42		10.00	4.70	44.10	54.40
H21	0.00	10.80	20.30	8.00	583.00	209.00	304.00	13.00	86.00	0.09		11.60	4.50	42.50	48.10
H25	12.00	2.50	8.60	7.20	647.00	248.00	346.00	11.00	99.00	0.49		10.20	4.50	44.10	57.30
H29	23.00	1.80	8.40	7.30	642.00	251.00	356.00	12.00	92.00	0.53		10.00	4.60	48.50	56.90
J11	0.00	5.50	20.50	7.80	568.00	208.00	286.00	17.00	93.00	0.13		12.20	4.80	33.70	49.10
J14	9.00	4.90	9.00	7.60	647.00	259.00	334.00	13.00	93.00	0.40		10.60	4.80	40.10	56.90
J17	15.90	1.10	8.50	7.40	644.00	234.00	358.00	17.00	94.00	0.29		11.00	4.40	42.50	61.20
DRAINS															
Riksha D		0.00	14.50	7.10	1549.00	360.00	504.00	82.00	126.00	0.68		72.00	35.00	38.50	99.10
Naina D		0.70	19.50	7.10	1054.00	234.00	472.00	45.00	150.00	1.71		32.00	16.00	49.70	84.60

Table :7b Collected :29-31, May, 1995

parame units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alk mg/l	Hardnes mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
SPRINGS															
Pardha S		15.30	15.00	7.30	821.00	234.00	304.00	13.00	170.00	0.03		13.60	3.30	28.90	56.40
Chuna S			14.50	7.50	943.00	231.00	356.00	21.00	170.00	0.06		13.00	5.60	32.10	67.10
Pashan S		3.30	16.00	7.30	722.00	252.00	324.00	18.00	176.00	0.11		11.60	3.90	32.10	59.30
Dr. H S			15.00	7.90	652.00	200.00	280.00	24.00	100.00	0.07		9.60	2.30	33.70	47.60
Sipahi S				7.70	632.00	230.00	312.00	18.00	99.00	0.07		9.60	3.00	36.90	53.50
Gupha S				8.00	602.00	159.00	246.00	11.00	130.00	0.03		8.00	2.50	34.50	38.90
S3 S				7.60	885.00	187.00	350.00	12.00	192.00	0.07		32.00	2.50	38.50	61.70
S4 S			15.00	7.10	525.00	83.00	248.00	20.00	150.00	0.09		10.80	2.90	35.30	38.90
S5 S			18.50	7.70	339.00	162.00	170.00	6.00	135.00	0.04		5.20	0.50	30.50	22.80
Sher S			19.50	7.60	443.00	209.00	270.00	12.00	123.00	0.01		1.40	0.70	32.10	46.20
L View S			14.50	7.60	851.00	266.00	356.00	23.00	165.00	0.04		8.60	2.30	28.90	69.00
Sariya S		1.10	16.80	7.50	698.00	217.00	314.00	15.00	126.00	0.03		2.00	2.10	30.50	57.80
Mangoli				7.80	347.00	123.00	126.00	6.00	10.00	0.23		4.60	2.20	28.90	13.10
GW															
O. Well		4.70	15.20	7.30	734.00	262.00	330.00	15.00		0.16		14.00	4.50	36.90	57.80
T. Well 1				7.60	799.00	210.00	312.00	16.00	134.00	0.04		13.60	4.60	30.50	57.30
T. Well 3				7.50	745.00	231.00	292.00	23.00	99.00	0.09		12.00	5.60	29.60	52.90
Sukha		5.60	13.50	7.40	764.00	210.00	300.00	17.00	135.00	0.03		12.00	3.20	38.50	49.60

Table :10b Collected :26-28,Sept.,1995

paramete units	Depth m (bws)	DO mg/l mg/l	Temp °C	pH	EC micromho	Alk mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	Phosphat mg/l	Nitrate mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
DRAINS															
Riksha D		3.00				306.00	418.00	32.00	125.30	0.24	3.74	36.60	12.60	33.30	81.40
Boat D						306.00	464.00	24.00	170.60	0.15	5.15	34.50	10.10	31.30	93.80
Alka D						362.00	480.00	30.00	162.80	0.16	1.59	27.40	8.70	36.90	94.30
Church D						354.00	468.00	24.00	135.60	0.27	2.60	23.30	7.90	48.90	84.10
Library D						290.00	402.00	30.00	136.90	0.03	1.62	17.10	4.60	35.30	76.30
Naina D		3.90				306.00	398.00	26.00	116.60	0.13	3.57	18.20	5.00	36.10	74.80
SPRINGS															
Dr. Hous						240.00	358.00	20.00	69.70	0.06	3.61	12.00	2.90	39.30	63.20
Takula		7.20				186.00	174.00	24.00	69.60	0.09	0.00	4.80	0.70	32.10	22.80
L-view						392.00	524.00	20.00	183.60	0.02	0.26	13.00	2.90	40.90	102.50
S-3						108.00	200.00	12.00	122.10	0.07	0.80	12.00	2.30	32.10	29.20
Chuna						330.00	476.00	24.00	149.90	0.02	4.32	22.30	7.80	40.10	91.40
Sariya						286.00	334.00	30.00	88.20	0.07	0.23	3.80	1.60	33.70	60.80
Pardha						290.00	372.00	26.00	134.40	0.04	3.57	14.10	3.70	37.70	67.60
Sipahi						236.00	314.00	18.00	134.30	0.08	3.79	13.00	3.50	36.90	53.90
Gupha		4.90				220.00	298.00	28.00	76.50	0.04	3.96	13.00	3.30	32.10	52.90
GW															
T-Well-1						314.00	452.00	24.00	138.20	0.09	4.86	22.30	5.20	36.10	87.90
Open						238.00	320.00	22.00	101.80	0.14	3.13	21.20	7.50	36.90	55.40
Jal San						268.00	368.00	24.00	113.60	0.13	3.06	18.20	5.30	36.10	67.50
T-Well-2						280.00	400.00	16.00	115.40	0.16	3.21	20.20	5.20	34.50	76.30
T-Well-3						358.00	468.00	46.00	113.80	0.05	3.58	37.60	13.40	33.70	93.30

Table :11a Collected :24-25, Nov., 1995

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00	9.14	14.00	7.50	579.00	234.00	376.00	10.00	96.00	0.00	0.50	14.80	3.60	57.70	56.40
A34	9.00	8.80	13.10	7.50	573.00	235.00	416.00	8.00	91.00	0.00	0.57	14.80	3.80	51.30	70.00
A35	12.00	0.00	10.50	7.20	624.00	263.00	442.00	6.00	86.00	0.29	2.48	16.90	4.60	63.30	69.00
C21	0.00	9.78	14.20	8.80	567.00	233.00	366.00	37.00	94.00	0.59	0.14	13.80	3.50	52.90	56.90
C25	12.00	0.00	10.20	7.50	644.00	258.00	410.00	20.00	88.00	0.41	0.00	17.90	4.50	77.80	52.50
C28	9.30	0.00	9.30	7.40	660.00	263.00	402.00	15.00	82.00	0.47	0.61	16.90	4.70	55.30	64.10
E11	0.00	9.17	13.60	8.10	583.00	230.00	382.00	14.00	92.00	0.56	0.65			54.50	59.80
E15	12.00	0.00	10.20	6.90	643.00	257.00	398.00	5.00	85.00	0.42	2.26	16.90	4.10	77.80	49.60
E17	18.00	0.00	9.20	7.30	633.00	254.00	428.00	12.00	84.50	0.53	2.99			75.40	58.30
F11	0.00	8.03	13.60	7.60	586.00	227.00	374.00	6.00	93.50	0.13	0.55	39.80	4.90	52.10	59.30
F15	12.00	0.00	10.00	6.80	650.00	266.00	420.00	8.00	91.50	0.30	2.46	16.90	4.70	69.80	59.80
F17	18.00	0.00	10.90	7.00	626.00	249.00	380.00	21.00	88.50	0.27	1.97	39.80	4.90	72.20	48.60
H21	0.00	9.26	13.60	7.80	580.00	219.00	364.00	21.00	92.00	0.01	0.52	39.80	4.90	56.90	53.90
H25	12.00	0.00	9.80	7.20	638.00	264.00	380.00	11.00	83.50	0.39	2.41	17.90	4.70	67.40	51.50
H28	21.00	0.00	9.20	6.90	654.00	267.00	414.00	14.00	79.50	0.49	4.18	19.00	4.80	77.80	53.50
J11	0.00		13.80	8.00	578.00	227.00	410.00	23.00	95.00	0.00	1.09	19.00	3.90	56.10	65.60
J15	12.00		10.00	6.80	652.00	266.00	430.00	17.00	85.50	0.33	2.50	25.20	4.90	77.80	57.30
J17	17.50		9.30	6.70	650.00	248.00	414.00	17.00	83.00	0.46	3.63	19.00	5.00	68.90	58.80

Table :11b Collected :24-25, Nov.,1995

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
DRAINS															
Riksha D				7.15	821.00	279.00	514.00	35.00	127.20	0.45	3.39	41.80	8.70	83.00	74.60
Naina D				6.98	796.00	288.00	495.00	16.00	132.60	0.23	4.20	23.10	5.80	88.60	66.60
SPRINGS															
Pardha S				8.00	701.00	269.00	467.00	10.00	122.00	0.00	3.29	20.00	2.90	70.20	70.90
Alma S				7.20	788.00	323.00	512.00	30.00	121.20	0.00	0.42	15.90	3.40	91.80	68.80
Lake S				8.30	834.00	332.00	555.00	16.00	137.40	0.13	0.84	13.80	2.10	149.20	44.50
S-4				8.60	475.00	86.00	302.00	13.00	140.40	0.00	0.69	31.50	1.80	53.70	40.80
Sipahi				8.50	582.00	228.00	370.00	10.00	80.50	-8.00	2.50	9.70	2.60	48.10	60.80
Gupha				8.60	566.00	222.00	347.00	9.00	82.50	0.03	2.93	10.70	2.30	49.30	54.40
Sariya S				7.40	586.00	249.00	419.00	10.00	90.50	-8.00	0.19	0.90	1.50	73.40	57.30
GW															
O. Well				7.10	708.00	237.00	439.00	19.00	111.50	0.15	2.85	15.90	3.50	70.60	63.90
Suk Wel				6.90	679.00	241.00	453.00	9.00	121.20	0.09	3.14			68.60	68.50
Jal Nigam				6.90	594.00	224.00	376.00	21.00	89.50	0.22	0.00	15.90	4.90	54.50	58.30
Jal Sans				7.50	693.00	270.00	423.00	21.00	104.50	0.12	1.97	16.90	3.60	56.10	68.30

Table :12 Collected :29-30, Dec,1995

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00		10.00	8.70	448.00	252.00	366.00	20.00	106.00	0.16	0.94	6.50	3.20	40.90	64.20
A34	9.00		9.80	8.30	469.00	254.00	358.00	28.00	93.50	0.16	0.87	9.20	3.80	52.10	55.40
A35	12.00		9.30	8.10	494.00	272.00	390.00	20.00	128.50	0.54	3.83	9.30	3.60	63.40	56.40
C21	0.00		10.60	8.10	450.00	254.00	372.00	10.00	49.00	0.17	0.92	8.80	3.10	53.70	57.80
C24	9.00		9.80	8.10	468.00	272.00	404.00	18.00	94.50	0.20	1.10	7.40	3.20	60.90	61.20
C28	21.00		9.40	7.70	497.00	300.00	422.00	22.00	87.00	0.58	4.99	9.20	4.40	66.60	62.20
E11	0.00		10.00	8.10	454.00	276.00	406.00	20.00	94.50	0.18	0.88	8.40	4.00	59.30	62.70
E17	18.00		9.80	8.10	458.00	272.00	338.00	20.00	90.50	0.11	0.89		3.30	44.10	55.40
F11	0.00		10.40	8.50	464.00	288.00	366.00	10.00	74.00	0.24	1.17	8.00	4.30	49.70	58.80
F14	9.00		9.80	8.30	464.00	276.00	356.00	14.00	76.50	0.17	0.94	8.10	5.80	52.90	54.40
F17	18.00		9.00	7.60	558.00	320.00	392.00	6.00	83.00	0.92	3.58	9.70	5.20	73.80	50.50
H21	0.00		10.00	8.20	457.00	316.00	376.00	8.00	93.50	0.14	0.93	9.80	6.20	52.10	59.80
H24	9.00		9.80	8.10	453.00	276.00	320.00	4.00	90.50	0.17	0.93	5.90	5.80	48.10	48.60
H27	18.00		9.00	7.80	522.00	300.00	374.00	4.00	72.50	0.80	3.21	6.80	6.70	60.20	54.40
J21	0.00		10.40	8.20	462.00	284.00	360.00	8.00	90.00	0.15	0.98	6.70	4.70	52.90	55.40
J24	9.00		10.00	8.00	459.00	284.00	318.00	12.00		0.19	0.89	6.50	4.80	41.70	52.00
J27	18.00		9.40	7.90	500.00	296.00	346.00	4.00	87.00	0.48	3.74	7.10	5.50	58.50	48.60
Y-TOP			10.00	8.10	463.00	288.00	368.00	8.00	90.50	0.32	1.89	5.40	3.60	52.90	57.30
Y-BOTT			9.80	8.00	449.00	276.00	332.00	10.00	96.00	0.15	1.84	6.30	4.30	45.70	52.90
SPRINGS															
Chuna S				8.20	625.00	360.00	498.00	22.00	162.00	0.06	3.28	8.00	7.00	100.30	60.30
L. View S				8.40	629.00	380.00	486.00	18.00	148.00	0.05	0.39	4.70	2.70	81.00	69.00
Sipahi S				8.30	434.00	288.00	324.00	10.00	122.00	0.04	2.25	4.60	3.20	48.90	49.10
Gupha S				8.30	468.00	280.00	350.00	16.00	75.00	0.04	2.46	4.30	2.90	46.50	56.90
GW															
Sukha				8.80	530.00	312.00	398.00	12.00	131.00	0.03	3.08	4.70	3.00	62.60	58.80
O. Well				8.00	548.00	364.00	432.00	20.00	138.50	0.07	2.33	5.80	3.60	72.20	61.20

Table :13a Collected :12-15,Jan, 1996

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31		0.00	9.80		454.00	260.00	402.00	20.00	94.50	0.16	0.95	7.10	4.70	60.90	60.80
A34			9.40		487.00	258.00	392.00	18.00	96.00	0.19	0.99	8.30	3.90	64.20	56.40
A35			9.20		502.00	292.00	414.00	32.00	114.00	1.47	1.88	9.50	4.20	57.70	65.60
C21		2.40	9.60		432.00	276.00	394.00	12.00	90.50	0.19	0.92	9.40	4.50	44.90	68.50
C24		2.90	9.20		462.00	264.00	398.00	20.00	88.00	0.18	1.07	9.20	4.30	39.30	72.90
C27		1.20	9.20		492.00	270.00	408.00	20.00	88.00	0.22	0.99	9.20	3.90	59.40	63.20
C29			9.20		515.00	284.00	412.00	12.00	118.00	0.50		9.90	3.60	28.10	96.00
E11		2.90	9.50		459.00	256.00	400.00	14.00	99.50	0.30	1.17	9.70	3.90	61.80	59.80
E14		2.80	9.40		464.00	264.00	376.00	12.00	102.50	0.16	0.95	9.20	3.70	61.80	53.90
E17		0.60	9.20		489.00	278.00	376.00	30.00	93.50	0.23	1.04	7.70	4.00	59.40	55.40
F11			9.60		471.00	268.00	392.00	20.00	98.50	0.16	1.26	7.90	5.00	50.50	64.60
F14			9.20		479.00	266.00	396.00	28.00	94.50	0.19	1.03	8.00	4.50	60.20	59.80
F17			9.20		485.00	280.00	420.00	14.00	106.00	0.21	0.16	7.90	4.50	58.60	66.60
H21		2.00	9.40		456.00	264.00	404.00	22.00	88.00	0.20	0.87	6.90	4.30	68.90	56.40
H24		1.80	9.20		473.00	266.00	402.00	20.00	97.00	0.15	0.89	7.70	4.20	55.30	64.20
H27		0.00	9.20		483.00	272.00	384.00	16.00	87.00	0.32	1.74	7.40	4.00	68.20	52.00
H29			9.20		515.00	314.00	400.00	22.00	116.50	0.70	3.62	7.40	5.20	73.00	52.90
J11		1.40	9.60		465.00	260.00	366.00	32.00	84.00	0.20	0.91	8.20	4.30	61.80	51.50
J14		2.60	9.20		460.00	266.00	364.00	30.00	145.00	0.21	1.02	7.40	3.90	53.70	55.90
J17		1.00	9.20		480.00	268.00	388.00	30.00	87.00	0.28	1.06	7.80	4.00		

Table :13b Collected :12-15,Jan, 1996

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
DRAINS															
Riksha D		8.60				298.00	502.00	24.00	94.50	0.56	4.18	9.60	6.60	47.30	93.30
Naina D		5.80				324.00	466.00	18.00	142.50	0.54	6.23	7.60	7.60	77.80	66.10
SPRINGS															
Chuna S						334.00	494.00	18.00	171.00	0.07	3.46	9.60	7.00	32.10	100.60
Pardha S						290.00	460.00	12.00	88.00	0.05	3.34	6.70	4.00	77.80	64.60
L. View S						374.00	522.00	2.00	144.00	0.04	0.69	5.20	5.20	53.70	94.30
Gupha S		8.40				240.00	356.00	14.00	97.00	0.07	2.27	4.70	2.90	46.50	58.30
Sipahi S						240.00	336.00	18.00	84.00	0.08	2.63	5.30	2.70	45.70	54.00
Sariya S						270.00	382.00	24.00	98.50	0.03	0.14	1.20	1.50	42.50	67.10
S5 S						204.00	202.00	6.00	15.00	0.03	0.00	2.10	0.00	36.90	26.70
GW															
O. Well		3.30				290.00	432.00	14.00	133.50	0.09	2.61	6.80	3.50	71.40	61.70
T. Well						332.00	462.00	22.00	122.00	0.08	3.40	5.00	5.30	77.80	65.10
T. Well 2						288.00	470.00	10.00	162.00	0.05	2.21	9.70	3.40	60.20	77.80
Sukha W						292.00	432.00	14.00	136.00	0.08	3.40	5.20	5.20	31.30	87.20

Table :14a Collected :27-30,Apr, 1996

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
LAKE															
A31	0.00	4.90	19.00		440.00	268.00	364.00	26.00	68.00					41.70	63.20
A34	9.00	2.60	10.00		410.00	304.00	340.00	14.00	72.00					38.50	52.30
A35	11.00	1.70	9.50		410.00	286.00	368.00	6.00	72.00					43.70	58.80
C21	0.00	4.70	19.00		440.00	242.00	336.00	10.00	73.00					37.70	58.80
C24	9.00	2.90	9.80		390.00	260.00	352.00	12.00	67.00					56.10	51.50
C27	18.00	2.00	9.00		370.00	256.00	348.00	18.00	70.00					52.10	53.00
C29	23.00		9.00		380.00	254.00	350.00	12.00	122.00					56.90	50.50
E11	0.00	2.90	19.80		460.00	244.00	326.00	12.00	73.00					56.90	44.70
E14	9.00	2.80	9.80		370.00	244.00	344.00	12.00	69.00					50.50	53.00
E17	18.00	0.60	9.00		360.00	256.00	360.00	18.00	71.00					57.70	52.50
F11	0.00		18.80		480.00	252.00	334.00	18.00	73.00					43.30	54.90
F14	9.00		9.80		420.00	268.00	350.00	12.00	69.00					62.60	47.10
F17	17.50		9.00		400.00	248.00	344.00	22.00	66.00					60.20	47.10
H21	0.00	4.10	18.80		490.00	260.00	348.00	16.00	69.00					46.50	56.40
H22	3.00		17.80		480.00	234.00	340.00	16.00	75.00					50.50	52.00
H23	6.00		12.40		440.00	258.00	354.00	10.00	69.00					52.90	53.90
H24	9.00	3.20	9.80		410.00	260.00	364.00	14.00	67.00					49.70	58.30
H25	12.00		9.20		400.00	254.00	344.00	16.00	65.00					47.30	54.90
H26	15.00		9.00		400.00	258.00	340.00	14.00	66.00					68.20	41.30
H27	18.00	1.60	9.00		400.00	252.00	346.00	14.00	65.00					52.90	52.00
H29	23.50	0.90	9.00		420.00	270.00	350.00	16.00	115.00					60.90	48.10
J11	0.00	4.60	19.30		490.00	244.00	346.00	14.00	68.00					40.10	59.80
J14	9.00	2.70	9.80		420.00	250.00	344.00	14.00	71.00					57.70	48.60
J17	16.00	2.00	9.20		410.00	250.00	328.00	20.00	64.00					41.70	54.40

Table :14b Collected :27-30,Apr, 1996

Parame units	Depth m (bws)	DO mg/l	Temp °C	pH	EC mic. mho	Alkalinity mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/i	P(PO-4) mg/l	N(NO-3) mg/i	Na mg/i	K mg/l	Ca mg/l	Mg mg/l
DRAINS															
Riksha D		8.20				362.00	480.00	46.00	128.80					92.20	60.80
Naina D		7.40				392.00	440.00	56.00	108.40					38.50	83.40
SPRINGS															
Chuna S						308.00	514.00	28.00	167.50					99.40	64.60
Pardha S						260.00	414.00	18.00	128.80					60.20	64.20
L. View S						334.00	522.00	22.00	132.00					61.00	69.00
Gupha S		8.40				224.00	324.00	24.00	83.70					36.90	56.40
Sipahi S						224.00	314.00	20.00	88.00					45.70	48.60
Sariya S						242.00	360.00	14.00	89.00					52.90	55.40
S5 S						174.00	204.00	18.00	21.50					38.50	26.20
GW															
O. Well		4.20				262.00	372.00	28.00	70.80					63.40	52.00
Pump 1						300.00	394.00	30.00	108.40					35.30	74.40
Pump 3						292.00	408.00	26.00	99.80					56.10	65.10
T.Well 3						278.00	398.00	26.00	131.00					36.90	74.40
Sukha W						268.00	424.00	18.00	126.70					51.30	71.90

Table 15 Lake south sub-basin - Epilimnion

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mh	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94		10.0	7.5	385.0	260.0	386.0	8.0		0.0	0.0			67.0	54.0
May-94	5.6	19.9	8.6	600.0	133.0	372.0	1.0	110.0	0.0	0.0	9.9	4.5	46.1	62.5
Oct-94	9.5	20.1	8.2	506.0	189.0	254.0	13.0	76.6	0.0	0.4			26.5	45.7
Dec-94	2.2	11.4	8.0	547.0	240.0	316.0	6.0		0.2	0.8	12.0	4.4	47.0	49.0
Feb-95	5.6	9.2	6.8	516.0		322.0	11.0	72.0	0.3	0.2	11.8	4.6	51.3	47.1
Mar-95	11.1	16.0	9.4	888.0	260.0	326.0	16.0	95.5	0.2	0.0	13.6	4.2	42.4	58.4
May-95	13.9	21.1	7.8	570.0	206.0	280.0	9.0	85.0	0.1		9.6	4.6	32.9	48.1
Jun-95	12.5	22.4	7.6	600.0	199.0	289.0	18.0	90.0	0.2		13.6	3.4	35.7	48.6
Aug-95	18.4	21.6	8.9	392.0	204.0	240.0	10.0	97.3	0.1	0.0	17.0	6.1	44.1	31.6
Sep-95	14.0	20.2	8.4	440.0	196.0	264.0	16.0	55.4	0.0	0.0	14.1	4.9	36.1	42.3
Nov-95	9.8	14.2	8.8	567.0	233.0	366.0	37.0	94.0	0.6	0.1	13.8	3.5	52.9	56.9
Dec-95		10.6	8.1	450.0	254.0	372.0	10.0	49.0	0.2	0.9	8.8	3.1	53.7	57.8
Jan-96	2.4	9.6		432.0	276.0	394.0	12.0	90.5	0.2	0.9	9.4	4.5	44.9	68.5
Apr-96	4.7	19.0		440.0	242.0	336.0	10.0	73.0					37.7	58.8
Jul-96	13.8		7.1	542.0	186.0	260.0	14.0						32.1	43.7

Table 16 Lake south sub-basin - Hypolimnion

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mh	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94		10.0	7.5	385.0	260.0	386.0	8.0		0.0	0.0			67.0	54.0
May-94	3.9	17.2	8.0	610.0	140.0	344.0	1.0	110.0	0.1	0.0	10.2	4.6	54.1	50.8
Oct-94	0.0	10.2	8.3	673.0	258.0	330.0	11.0	72.4	0.1	3.7			52.9	48.1
Dec-94	0.0	10.0	7.7	652.0	324.0	356.0	8.0		0.9	0.0	11.6	3.6	63.0	49.0
Feb-95	4.9	8.0	7.0	496.0		310.0	3.0	74.9	0.3	0.7	11.0	4.6	48.9	45.7
Mar-95	0.4	8.2	8.1	711.0	260.0	337.0	18.0	88.9	0.2	1.1	11.2	4.1	48.3	52.7
May-95	0.0	8.5	7.4	649.0	253.0	332.0	9.0	97.0	0.8		11.0	4.6	40.9	55.9
Jun-95	0.0	8.6	7.7	734.0	263.0	348.0	14.2	110.0	0.2		9.4	4.0	28.1	67.6
Aug-95	0.0	8.8	7.6	553.0	276.0	326.0	4.0	94.2	0.5	0.0	21.0	7.7	40.1	54.9
Sep-95	0.0	9.0	8.7	490.0	268.0	360.0	16.0	87.5	0.1	3.8	16.1	6.0	28.9	69.9
Nov-95	0.0	9.3	7.4	660.0	263.0	402.0	15.0	82.0	0.5	0.6	16.9	4.7	55.3	64.1
Dec-95	0.0	9.4	7.7	497.0	300.0	422.0	22.0	87.0	0.6	5.0	9.2	4.4	66.6	62.2
Jan-96	1.2	9.2		492.0	270.0	408.0	20.0	88.0	0.2	1.0	9.2	3.9	59.4	63.2
Apr-96	2.0	9.0		370.0	256.0	348.0	18.0	70.0					52.1	53.0
Jul-96	0.0		7.2	847.0	274.0	356.0	4.0						62.6	48.6

Table 17 Lake north sub-basin - Epilimnion

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mh	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94		9.2	8.1	404.0	272.0	352.0			0.2	0.0			56.0	52.0
May-94	5.4	18.6	8.6	600.0	132.0	365.0	4.0	112.0	0.0	0.0	10.0	4.8	45.7	60.9
Oct-94	8.5	20.5	8.2	521.0	178.0	248.0	15.0	86.4	0.0	0.3			26.5	44.6
Dec-94	1.3	11.6	8.1	553.0	234.0	310.0	4.0		0.1	0.7	11.2	4.1	46.0	48.0
Feb-95	4.8	8.4	6.6	553.0		324.0	1.0	85.2	0.2	1.0	14.0	4.4	50.5	48.1
Mar-95	15.5	15.4	9.1	740.0	238.0	306.0	16.0	101.3	0.2	0.0	13.4	4.5	37.0	52.0
May-95	10.8	20.3	8.0	583.0	209.0	304.0	13.0	86.0	0.1		11.6	4.5	42.5	48.1
Jun-95	10.5	23.6	7.8	608.0	194.0	285.0	3.0	120.0	0.12		10.8	3.8	26.5	53.2
Aug-95	17.1	22.2	8.9	392.0	204.0	248.0	0.0	87.3	0.2	0.0	19.0	7.2	32.1	40.1
Sep-95	16.3	20.2	8.5	440.0	180.0	266.0	28.0	92.7	0.4	0.0	14.1	5.0	38.5	41.3
Nov-95	9.3	13.6	7.8	580.0	219.0	364.0	21.0	92.0	0.0	0.5	39.8	4.9	56.9	53.9
Dec-95		10.0	8.2	457.0	316.0	376.0	8.0	93.5	0.1	0.9	9.8	6.2	52.1	59.8
Jan-96	2.0	9.4		456.0	264.0	404.0	22.0	88.0	0.2	0.9	6.9	4.3	68.9	56.4
Apr-96	4.1	18.8		490.0	260.0	348.0	16.0	69.0					46.5	56.4
Jul-96	16.7		6.9	651.0	198.0	252.0	10.0						33.7	40.8

Table 18 Lake north sub-basin - Hypolimnion

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94		8.8		416		336				0			51	51
May-94	0.80	9.20	8.00	660.00	130.00	391.00	3.00	78.00	0.10	0.00	10.10	4.70	58.50	59.50
Oct-94		9.80	7.20	683.00	266.00	322.00	13.00	83.10	0.20	4.30			55.30	44.70
Dec-94	0.00	9.80	7.60	680.00	350.00	354.00	8.00		0.15	0.00	11.60	4.50	51.00	55.00
Feb-95	3.60	8.00	6.80	501.00		318.00	9.00	95.90	0.19	0.30	11.60	4.20	46.50	49.10
Mar-95	1.40	8.20	8.40	861.00	236.00	352.00	19.00	121.80	0.26	1.15	12.20	5.20	41.70	30.20
May-95	1.80	8.40	7.30	642.00	251.00	356.00	12.00	92.00	0.53		10.00	4.60	48.50	56.90
Jun-95	0.00	8.60	8.20	717.00	262.00	348.00	4.20	97.00	0.80		9.00	3.60	42.50	58.80
Aug-95	0.00	8.80	7.60	542.00	262.00	326.00	44.00	97.00	0.40	2.40	19.00	7.90	32.30	59.30
Sep-95	0.00	9.40	5.00	490.00	282.00	352.00	12.00	93.40	0.13	3.34	16.10	5.50	32.10	66.10
Nov-95	0.00	9.20	6.90	654.00	267.00	414.00	14.00	79.50	0.49	4.18	19.00	4.80	77.80	53.50
Dec-95		9.00	7.80	522.00	300.00	374.00	4.00	72.50	0.80	3.21	6.80	6.70	60.20	54.40
Jan-96	0.00	9.20		483.00	272.00	384.00	16.00	87.00	0.32	1.74	7.40	4.00	68.20	52.00
Apr-96	0.90	9.00		420.00	270.00	350.00	16.00	115.00					60.90	48.10
Jul-96	0.00		7.10	825.00	284.00	394.00	8.00						61.80	58.30

Table 19 Naina Devi Drain

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94			8.1	455	290	420	2.8		0.02	2.85			69	60
May-94	2.80		7.50	1040.00	202.00	542.00	9.00	173.00	0.48	1.50	10.40	9.30	86.20	79.50
Oct-94			7.80	802.00	288.00	420.00	15.00	158.20	0.10	3.05			33.70	81.60
Dec-94	5.30		7.60	822.00	328.00	434.00	4.00		0.43	2.00	12.20	7.40	71.00	62.00
Feb-95	6.00	11.00	7.00	490.00		350.00	22.00	125.10	0.35	2.90	15.20	6.40	20.10	72.90
Mar-95	3.40			999.00	366.00	464.00	27.00	194.30	0.10	2.35	19.00	8.70	57.50	77.90
May-95	0.70	19.50	7.10	1054.00	234.00	472.00	45.00	150.00	1.71		32.00	16.00	49.70	84.60
Jun-95														
Aug-95	8.30				292.00	396.00	10.00	146.70	0.13	4.80			34.50	75.30
Sep-95	3.90				306.00	398.00	26.00	116.60	0.13	3.57	18.20	5.00	36.10	74.80
Nov-95			6.98	796.00	288.00	495.00	16.00	132.60	0.23	4.20	23.10	5.80	88.60	66.60
Dec-95														
Jan-96	5.80				324.00	466.00	18.00	142.50	0.54	6.23	7.60	7.60	77.80	66.10
Apr-96	7.40				392.00	440.00	56.00	108.40					38.50	83.40
Jul-96			7.80	1090.00	300.00	444.00	16.00						87.40	54.90

Table 20 Wells located at north bank of Lake Nainital

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94	1.8		7.5	640.0	238.0	210.0	15.0	70.8	0.1	1.8			62.6	13.1
Dec-94	2.0		7.7	726.0	294.0	370.0	6.0		0.1	2.4	14.6	4.4	44.0	63.0
Feb-95	2.5	12.7	6.7	757.0		436.0	13.0	73.2	0.0	3.0	12.8	5.0	64.9	66.6
Mar-95														
May-95	4.7	15.2	7.3	734.0	262.0	330.0	15.0		0.2		14.0	4.5	36.9	57.8
Jun-95														
Aug-95	5.0				284.0	416.0	46.0	120.5	0.2	4.2			44.1	74.3
Sep-95					238.0	320.0	22.0	101.8	0.1	3.1	21.2	7.5	36.9	55.4
Nov-95			7.1	708.0	237.0	439.0	19.0	111.5	0.2	2.9	15.9	3.5	70.6	63.9
Dec-95			8.0	548.0	364.0	432.0	20.0	138.5	0.1	2.3	5.8	3.6	72.2	61.2
Jan-96	3.3				290.0	432.0	14.0	133.5	0.1	2.6	6.8	3.5	71.4	61.7
Apr-96	4.2				262.0	372.0	28.0	70.8					63.4	52.0
Jul-96			7.6	692.0	216.0	268.0	10.0						44.1	38.4

Table 21 Well located at Sukhatal

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94														
Dec-94														
Feb-95														
Mar-95				840.0	262.0	367.0	19.0	167.9	0.1	3.6	9.8	3.5	37.9	66.3
May-95	5.6	13.5	7.4	764.0	210.0	300.0	17.0	135.0	0.0		12.0	3.2	38.5	49.6
Jun-95														
Aug-95														
Sep-95														
Nov-95			6.9	679.0	241.0	453.0	9.0	121.2	0.1	3.1			68.6	68.5
Dec-95			8.8	530.0	312.0	398.0	12.0	131.0	0.0	3.1	4.7	3.0	62.6	58.8
Jan-96					292.0	432.0	14.0	136.0	0.1	3.4	5.2	5.2	31.3	87.2
Apr-96					268.0	424.0	18.0	126.7					51.3	71.9
Jul-96														

Table 22 Pardha Dhara (U/s) located near Nainital Water works

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94				520.0		356.0				3.5			58.0	52.0
May-94	5.7		8.1	845.0	150.0	478.0	6.0	177.0	0.0	2.9	8.6	3.0	85.8	64.2
Oct-94														
Dec-94	4.9		7.7	716.0	174.0	320.0	6.0		0.1	3.3	13.6	3.6	71.0	35.0
Feb-95														
Mar-95	4.6			818.0	296.0	432.0	23.0	176.2	0.0	4.2	12.4	4.5	61.1	67.9
May-95	15.3	15.0	7.3	821.0	234.0	304.0	13.0	170.0	0.0		13.6	3.3	28.9	56.4
Jun-95														
Aug-95					250.0	396.0	16.0	144.0	0.1	4.6	18.0	3.7	39.3	72.4
Sep-95					290.0	372.0	26.0	134.4	0.0	3.6	14.1	3.7	37.7	67.6
Nov-95			8.0	701.0	269.0	467.0	10.0	122.0	0.0	3.3	20.0	2.9	70.2	70.9
Dec-95														
Jan-96					290.0	460.0	12.0	88.0	0.1	3.3	6.7	4.0	77.8	64.6
Apr-96					260.0	414.0	18.0	128.8					60.2	64.2
Jul-96														

Table 23 U/s springs issuing from calcareous shales (near Alma Cottage, Chuna Dhara or Dr. House)

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94														
Dec-94														
Feb-95														
Mar-95														
May-95		14.5	7.5	943.0	231.0	356.0	21.0	170.0	0.1		13.0	5.6	32.1	67.1
Jun-95														
Aug-95					208.0	302.0	28.0	86.0	0.0	3.5	12.0	2.2	33.7	52.9
Sep-95					330.0	476.0	24.0	149.9	0.0	4.3	22.3	7.8	40.1	91.4
Nov-95			7.2	788.0	323.0	512.0	30.0	121.2	0.0	0.4	15.9	3.4	91.8	68.8
Dec-95			8.2	625.0	360.0	498.0	22.0	162.0	0.1	3.3	8.0	7.0	100.3	60.3
Jan-96					334.0	494.0	18.0	171.0	0.1	3.5	9.6	7.0	32.1	100.6
Apr-96					308.0	514.0	28.0	167.5					99.4	64.6
Jul-96			8.1	923.0	340.0	408.0	2.0						73.0	54.9

Table 24 Lake view (U/s) Spring issuing from calcareous shales (near Lake View Cottage)

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94														
Dec-94														
Feb-95														
Mar-95				806.0	322.0	546.0	17.0	184.4	0.0	1.0	10.2	3.1	55.1	99.2
May-95		14.5	7.6	851.0	266.0	356.0	23.0	165.0	0.0		8.6	2.3	28.9	69.0
Jun-95														
Aug-95					250.0	418.0	16.0	99.8	0.1	1.8	14.0	2.6	38.5	78.2
Sep-95					392.0	524.0	20.0	183.6	0.0	0.3	13.0	2.9	40.9	102.5
Nov-95			8.3	834.0	332.0	555.0	16.0	137.4	0.1	0.8	13.8	2.1	149.2	44.5
Dec-95			8.4	629.0	380.0	486.0	18.0	148.0	0.1	0.4	4.7	2.7	81.0	69.0
Jan-96					374.0	522.0	2.0	144.0	0.0	0.7	5.2	5.2	53.7	94.3
Apr-96					334.0	522.0	22.0	132.0					61.0	69.0
Jul-96			7.9	1050.0	326.0	470.0	6.0						97.0	55.4

Table 25 S3 (D/s) Spring issuing in Kailakhan side.

Parameter units	DO mg/l mg/l	Temp °C	pH	EC mic. mho	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94														
Dec-94	8.1		8.2	654.0	228.0	384.0	8.0		0.0	0.0	12.8	1.5	83.0	43.0
Feb-95	8.8					398.0	25.0	137.9	0.1	0.0	12.6	1.6	58.6	61.2
Mar-95					224.0	366.0	11.0	208.3	0.1	0.0	14.0	2.2	62.6	51.1
May-95			7.6	885.0	187.0	350.0	12.0	192.0	0.1		32.0	2.5	38.5	61.7
Jun-95														
Aug-95					74.0	172.0	20.0	117.7	0.1	1.3	10.0	1.5	31.3	22.8
Sep-95					108.0	200.0	12.0	122.1	0.1	0.8	12.0	2.3	32.1	29.2
Nov-95			8.6	475.0	86.0	302.0	13.0	140.4	0.0	0.7	31.5	1.8	53.7	40.8
Dec-95														
Jan-96														
Apr-96														
Jul-96														

Table 26 Sipahi Dhara (D/s) Spring issuing from Dolomites

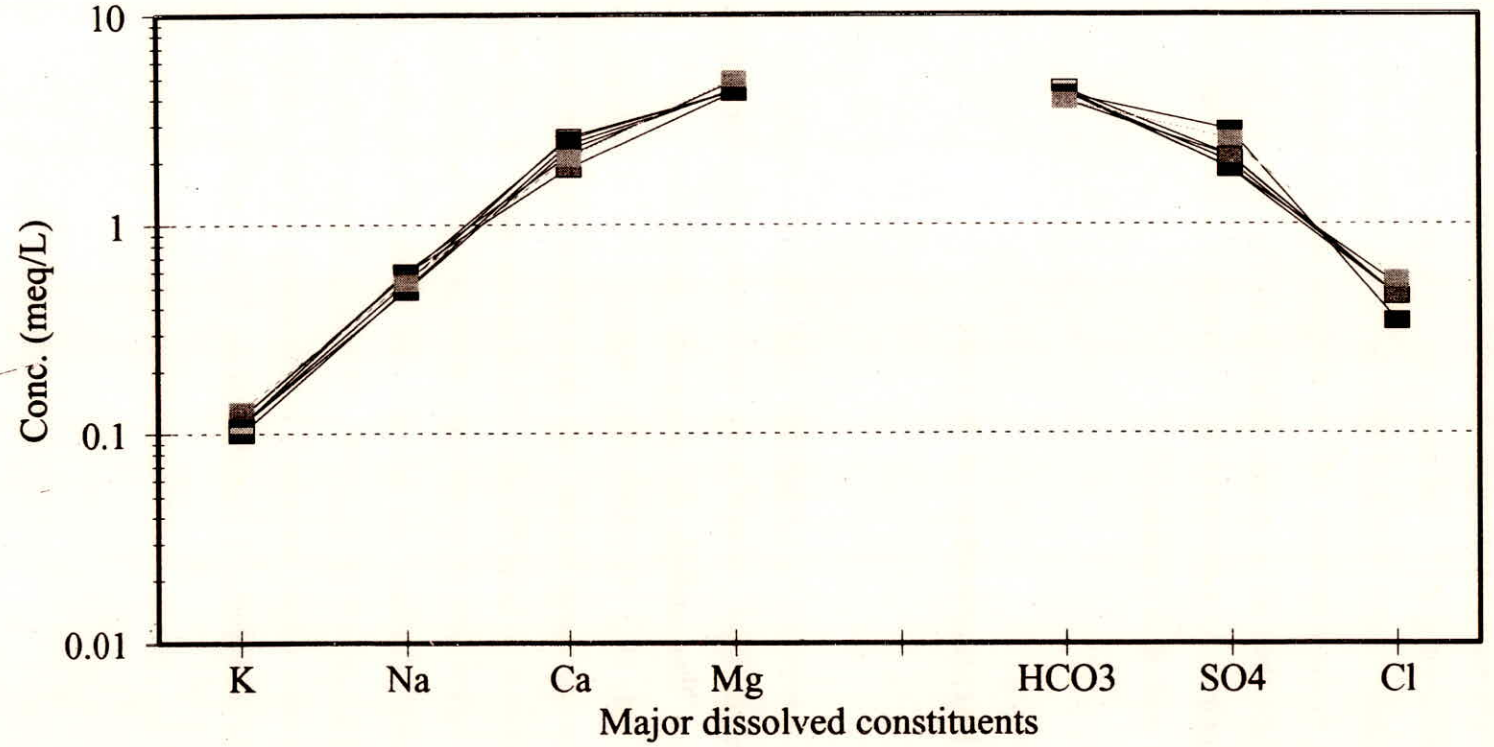
Paramete units	DO mg/l mg/l	Temp °C	pH	EC mic. mh	Alkalinit mg/l	Hardness mg/l	Cl mg/l	Sulfate mg/l	P(PO-4) mg/l	N(NO-3) mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Feb-94														
May-94														
Oct-94														
Dec-94	6.4		8.1	560.0	238.0	310.0	6.0		0.0	2.3	9.2	3.0	46.0	48.0
Feb-95														
Mar-95					244.0	354.0	13.0	149.8	0.0	2.1	9.0	3.8	46.4	57.9
May-95			7.7	632.0	230.0	312.0	18.0	99.0	0.1		9.6	3.0	36.9	53.5
Jun-95			8.2	676.0	236.0	327.0	0.0	100.0	0.1		8.0	2.6	43.3	53.2
Aug-95					218.0	302.0	20.0	81.8	0.1	4.5	20.0	4.5	36.1	51.5
Sep-95					236.0	314.0	18.0	134.3	0.1	3.8	13.0	3.5	36.9	53.9
Nov-95			8.5	582.0	228.0	370.0	10.0	80.5	-8.0	2.5	9.7	2.6	48.1	60.8
Dec-95			8.3	434.0	288.0	324.0	10.0	122.0	0.0	2.3	4.6	3.2	48.9	49.1
Jan-96					240.0	336.0	18.0	84.0	0.1	2.6	5.3	2.7	45.7	54.0
Apr-96					224.0	314.0	20.0	88.0					45.7	48.6
Jul-96			7.9	789.0	238.0	348.0	8.0						68.2	43.3

The results show that all the water sources in the study area are closely related and that they reflect the local geology. Since the study area is very small (less than 5 km^2) no significant variations in the water chemistry can be expected. This is reflected in the fingerprint plots for the lake (Fig. 3a to Fig. 3h) that all the samples behave in a similar fashion (with a little deviations due to the analytical errors). However, the springs that issue in the Kailakhan side, in Ratighat and Krishnapur show a slightly different characteristic than other springs (Fig. 4a to Fig. 4h), in that they have sulfate as the major anionic constituent rather than bicarbonate, which is the case with all other sources that were studied in the area.

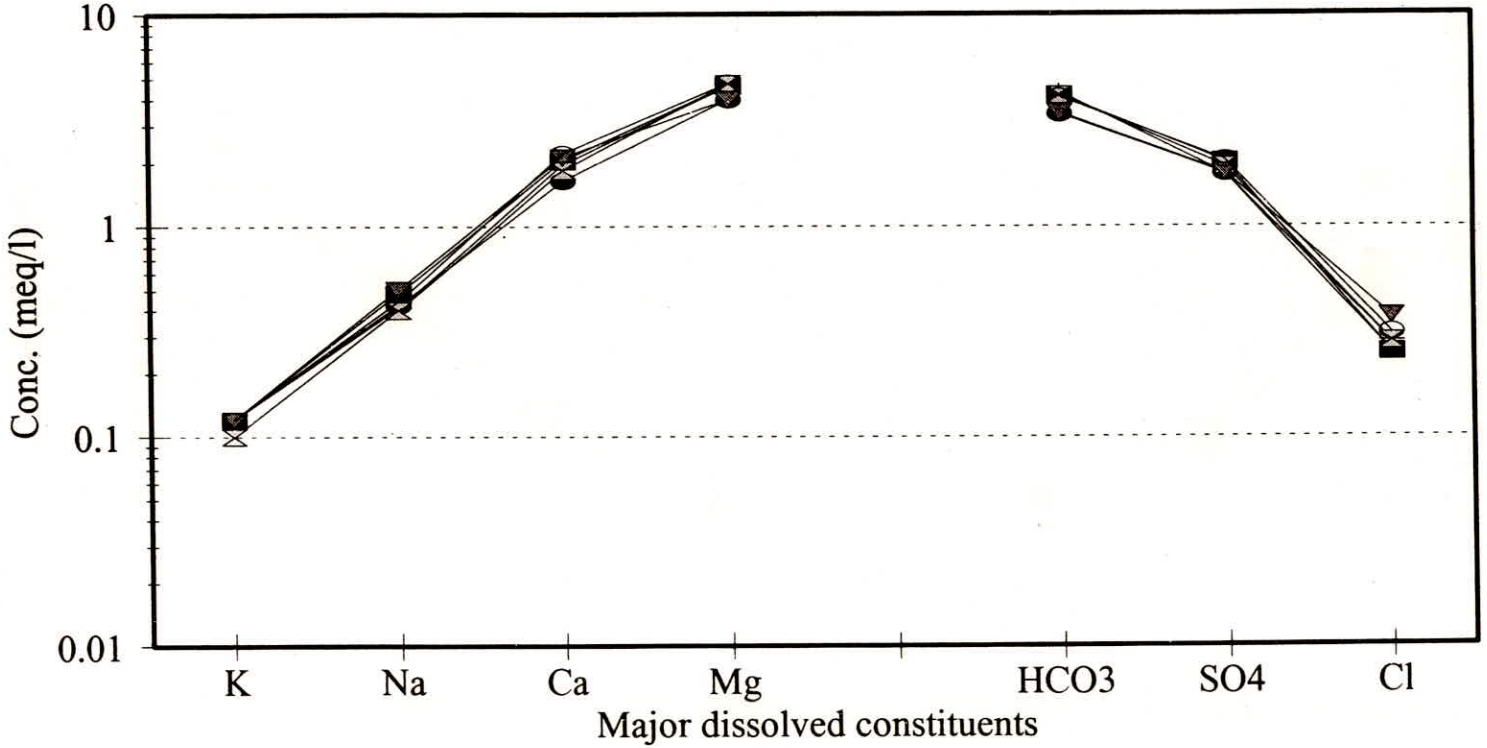
5.1 Characterisation of Waters

In general all the springs that issue within the catchment, the water flowing in the nalahs and the Lake Nainital water are of Magnesium-Bicarbonate type. However, the springs that issue outside the catchment, particularly S2, S3 and S4 located in the kailakhan side (Fig. 2) which were thought to be as leakages from the lake based on topography and stable isotope data (refer section on stable isotopes) are not of the same type of water as in Lake Nainital. These spring waters are of Magnesium-Sulphate type. This may be considered as indicative of the fact that the sources of these springs may not be the lake. Further, the springs that issue at Durgapur power house are also Magnesium-sulfate type. However, the springs Sipahi dhara, Gupha mahadev, Rais hotel (Reserve police lines), Sariyatal, Takula spring are all of magnesium bicarbonate type, same as the lake water. A summary of the water types of different sources are presented in Table 27.

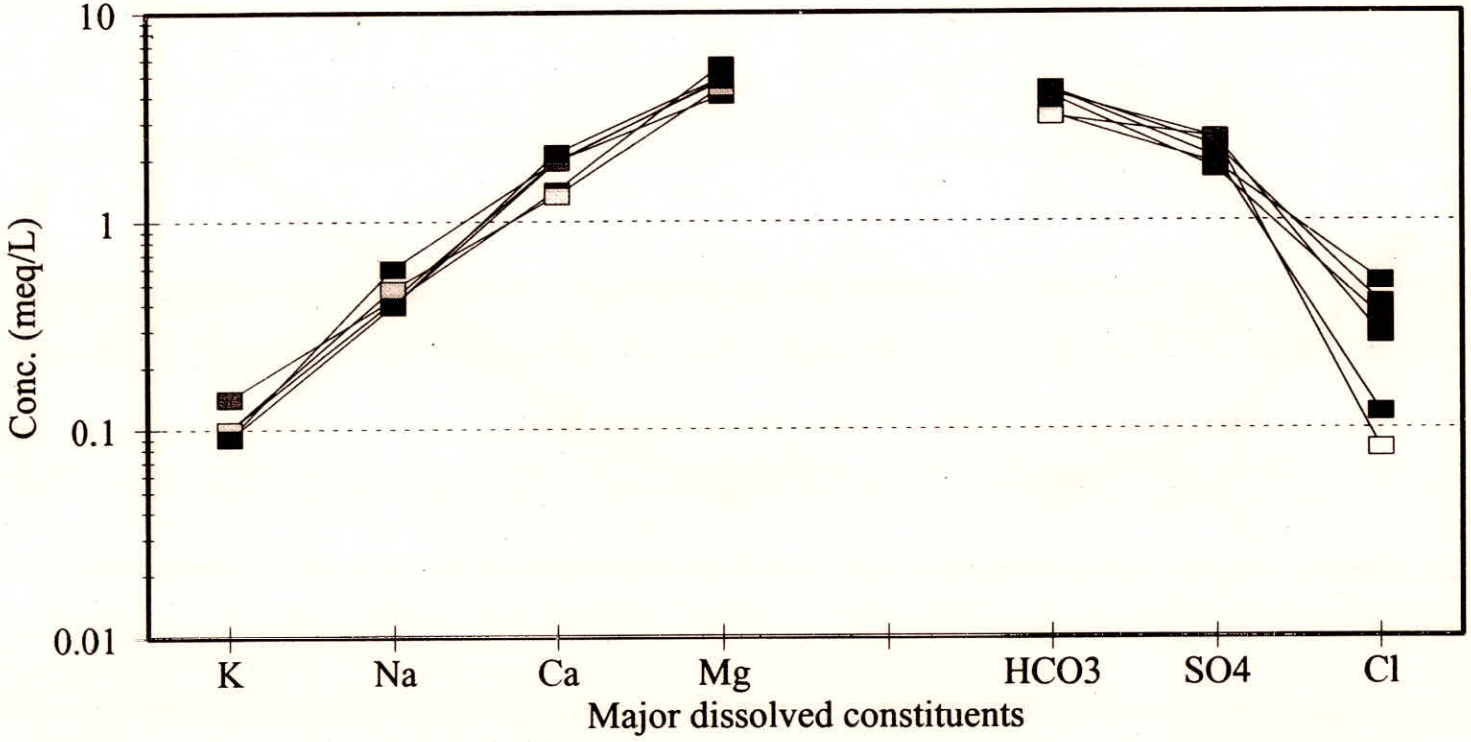
Figure 3a. Finger print plot showing water characteristics of Lake Nainital (March, 1995)



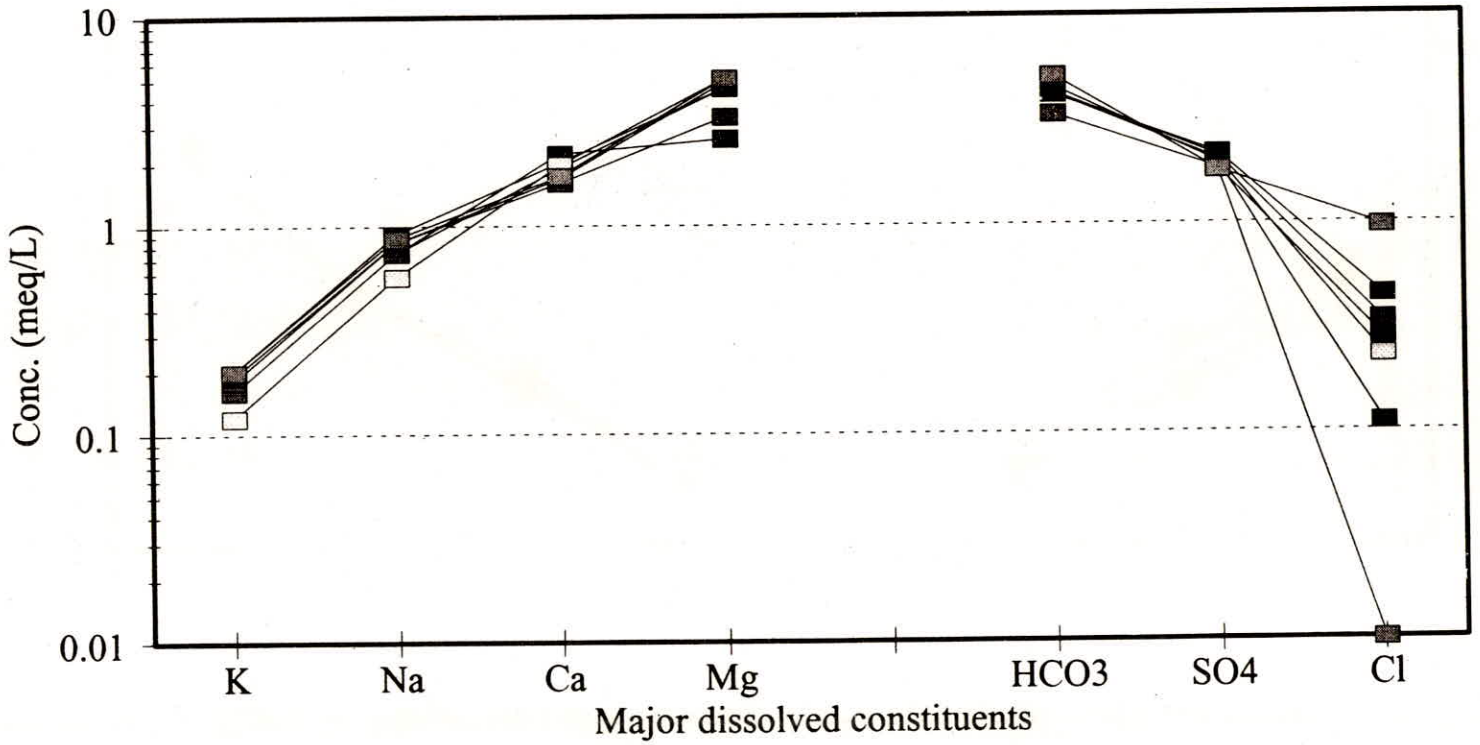
Fgure 3b. Finger print plot showing water characteristics of Lake Nainital (May, 1995)



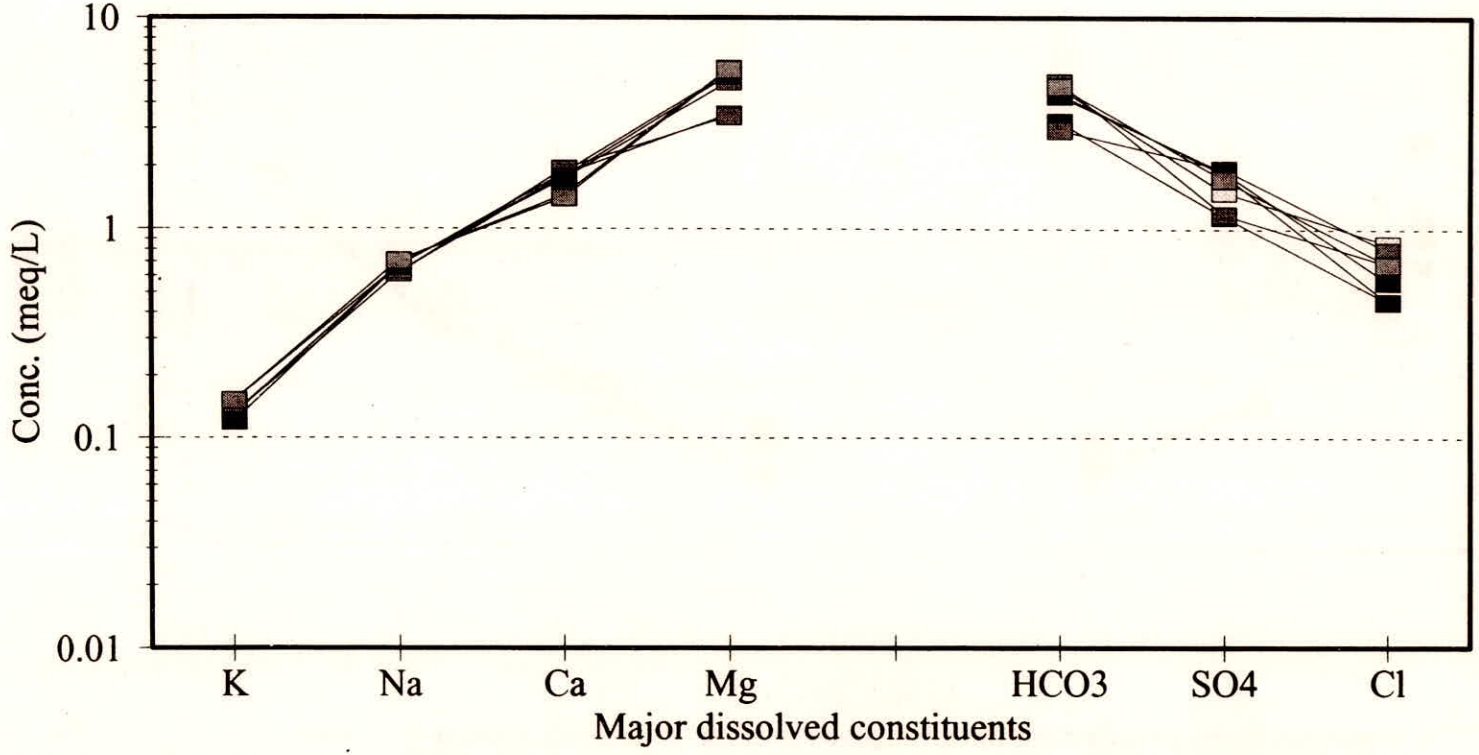
Fgure 3c. Finger print plot showing water characteristics of Lake Nainital (June, 1995)



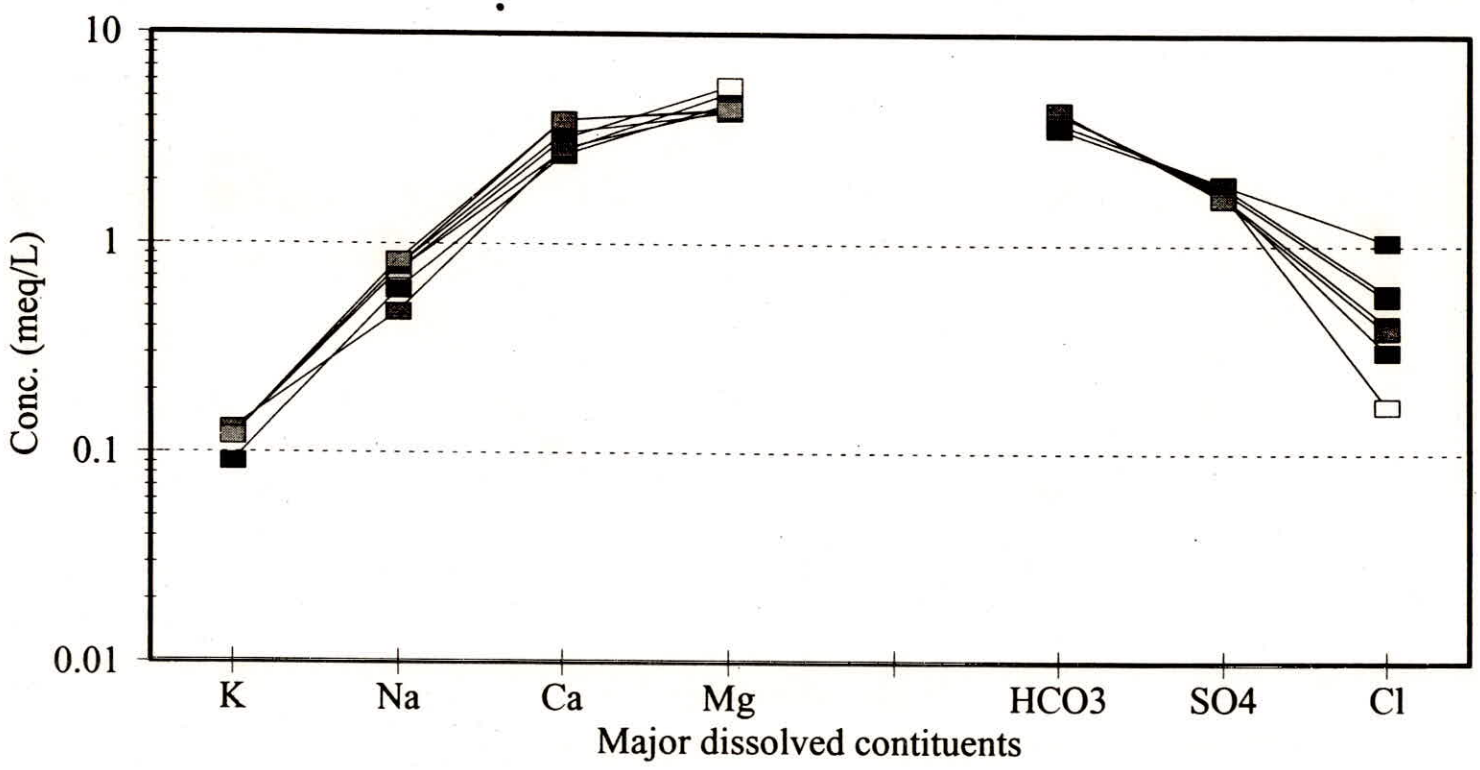
Fgure 3d. Finger print plot showing water characteristics of Lake Nainital (August, 1995)



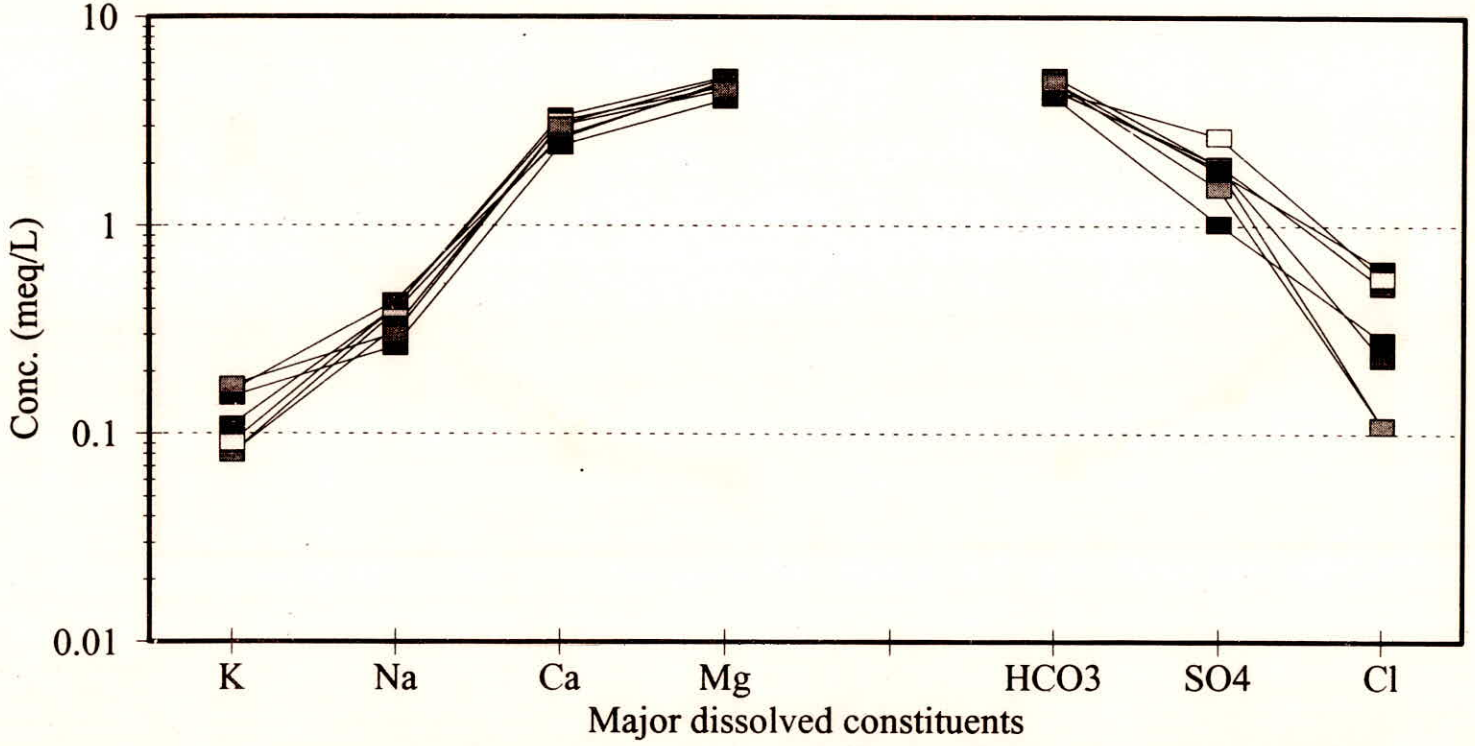
Fgure 3e. Finger print plot showing water characteristics of Lake Nainital (September, 1995)



Fgure 3f. Finger print plot showing water characteristics of Lake Nainital (November, 1995)



Fgure 3g. Finger print plot showing water characteristics of Lake Nainital (December, 1995)



Fgure 3h. Finger print plot showing water characteristics of Lake Nainital (January, 1996)

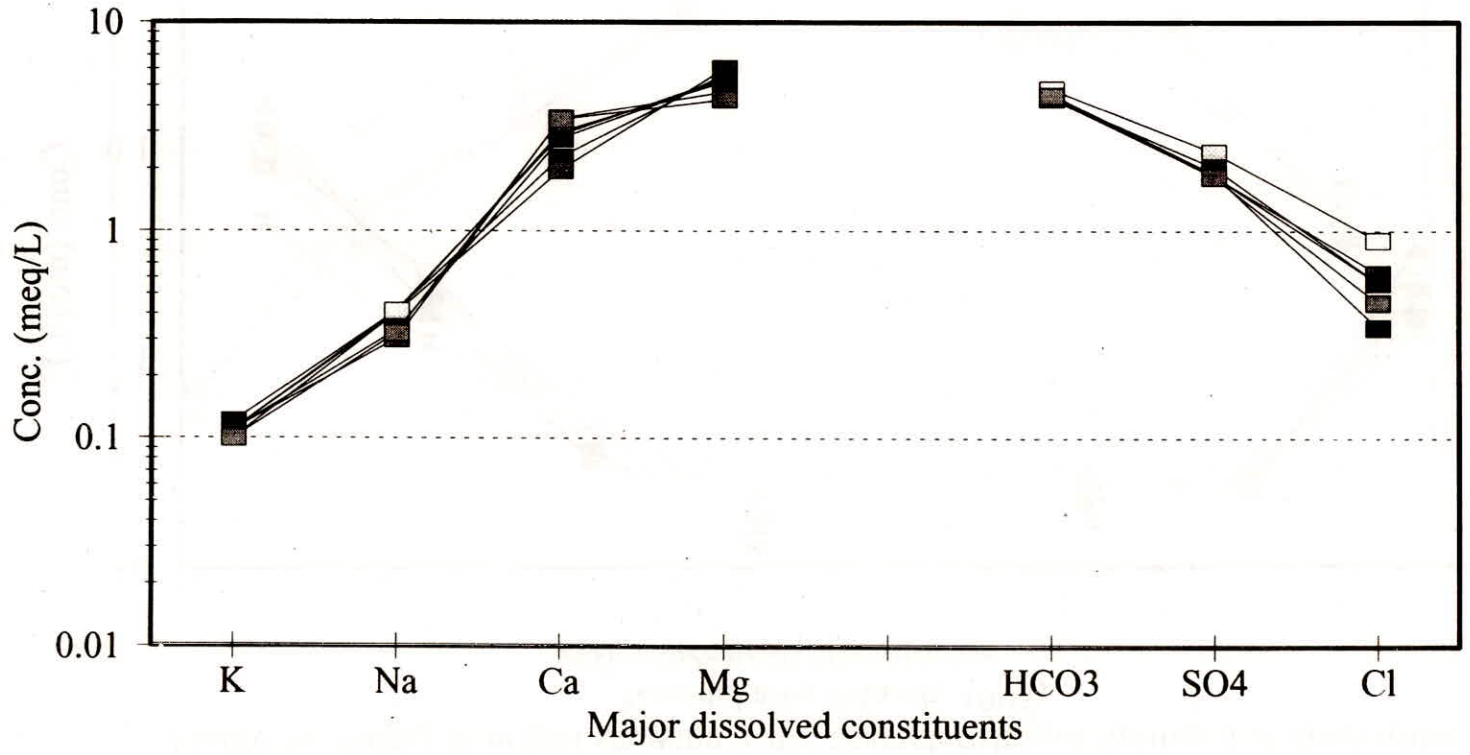


Figure 4c. Finger print plot showing water characteristics of Springs and drain water in Nainital area (June, 1995)

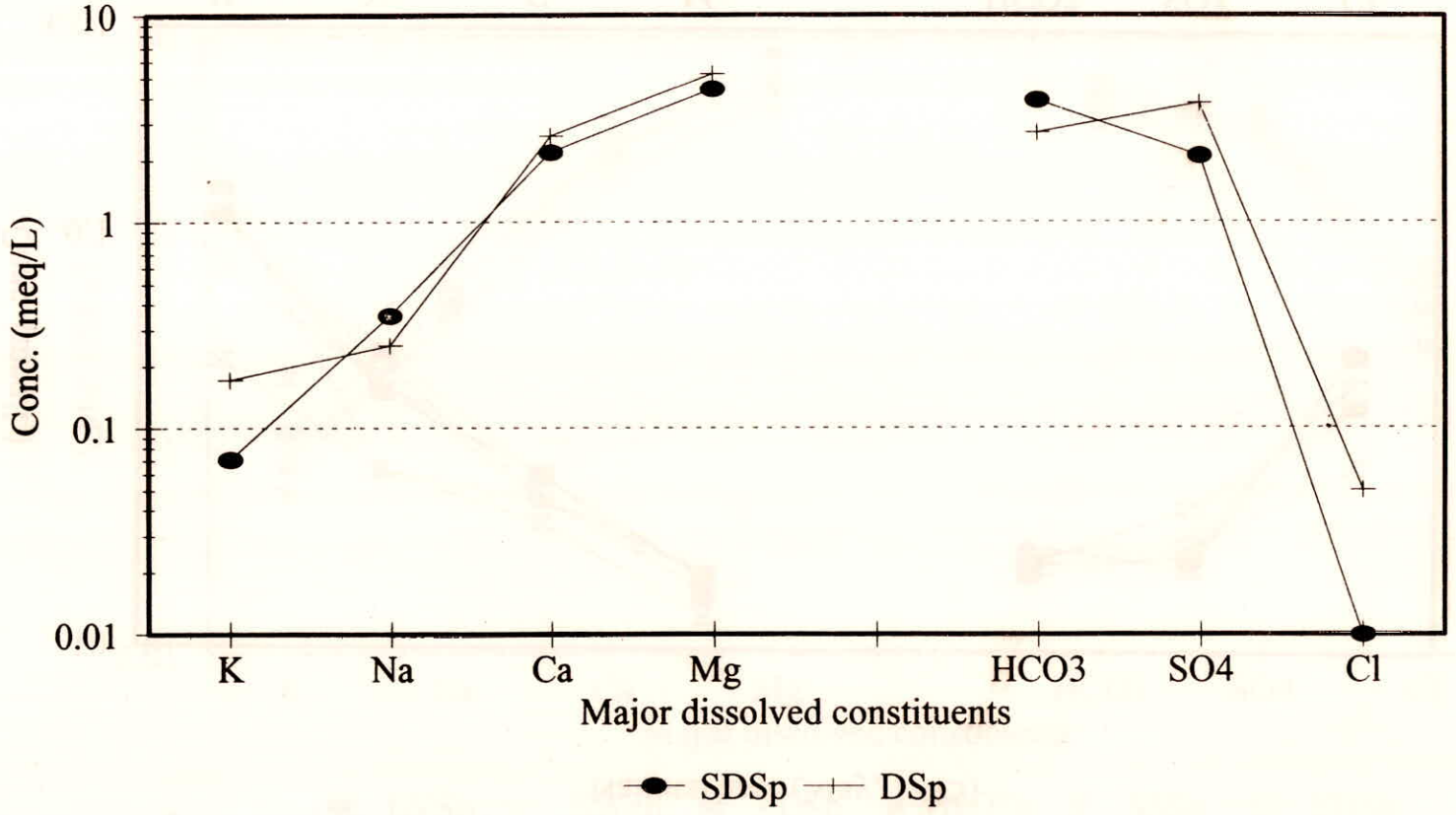


Figure 4d. Finger print plot showing water characteristics of Springs and drain water in Nainital area (August, 1995)

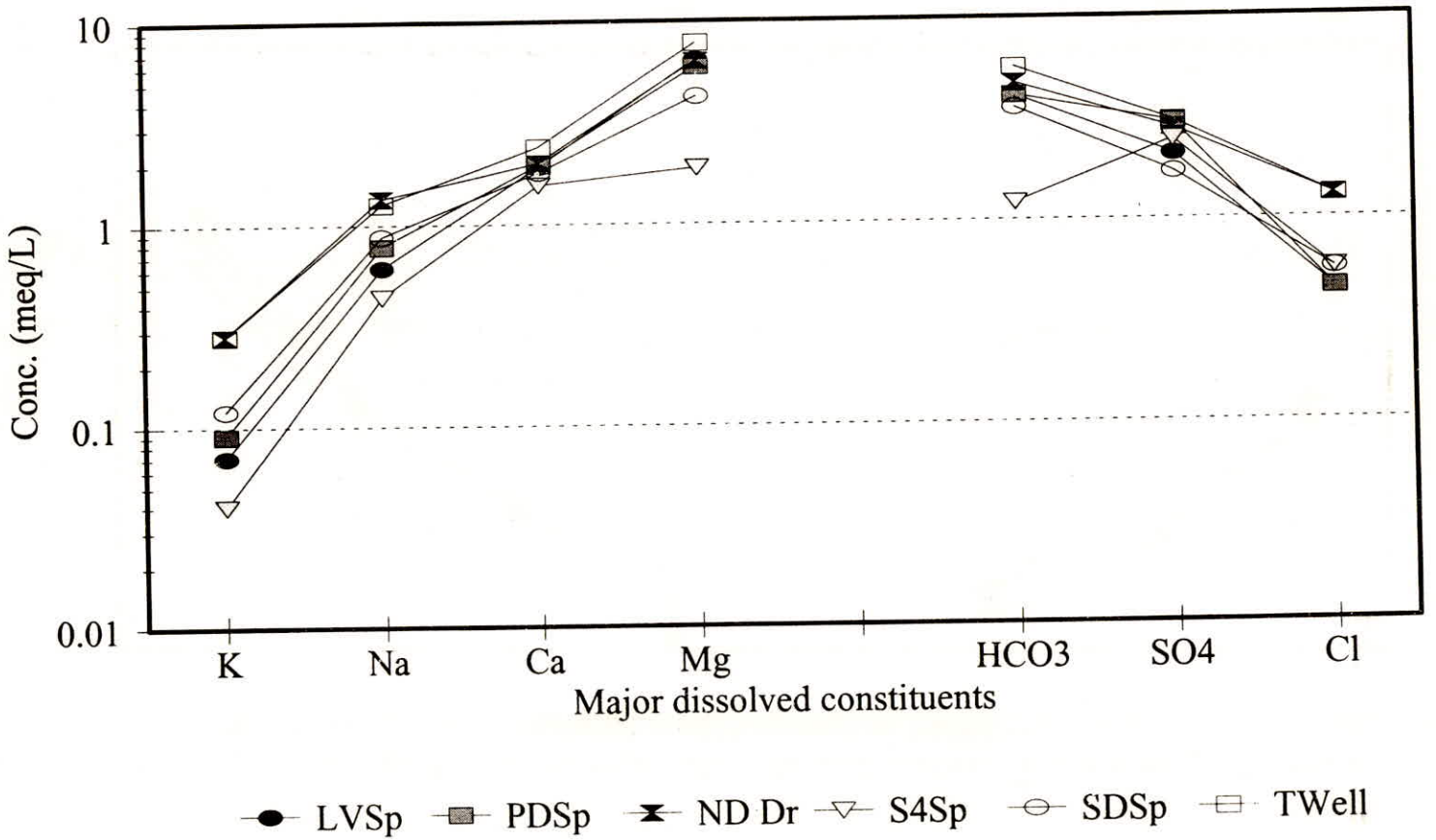


Figure 4e. Finger print plot showing water characteristics of Springs and drain water in Nainital area (September, 1995)

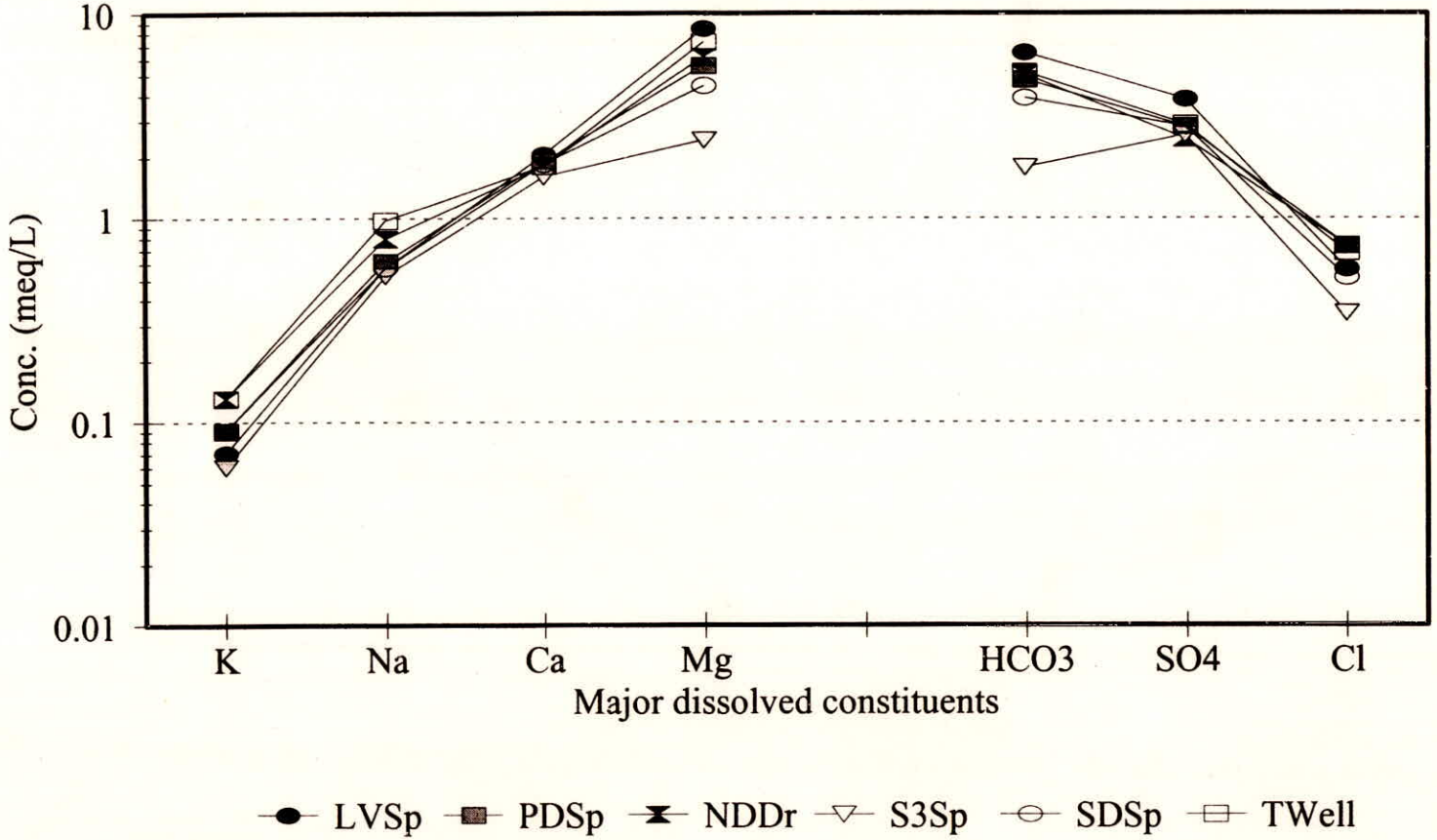


Figure 4f. Finger print plot showing water characteristics of Springs and drain water in Nainital area (November, 1995)

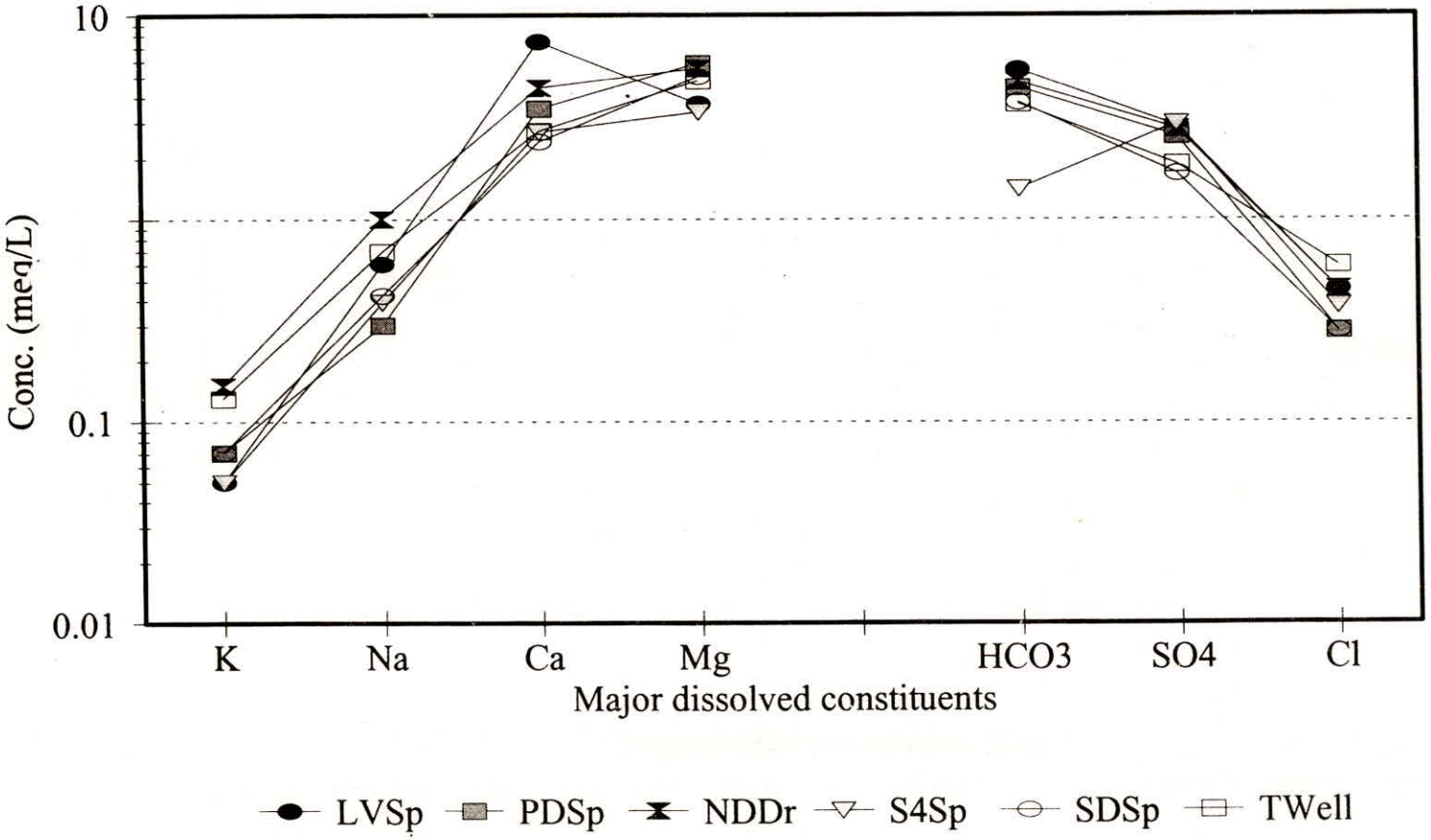


Figure 4g. Finger print plot showing water characteristics of Springs and drain water in Nainital area (December, 1995)

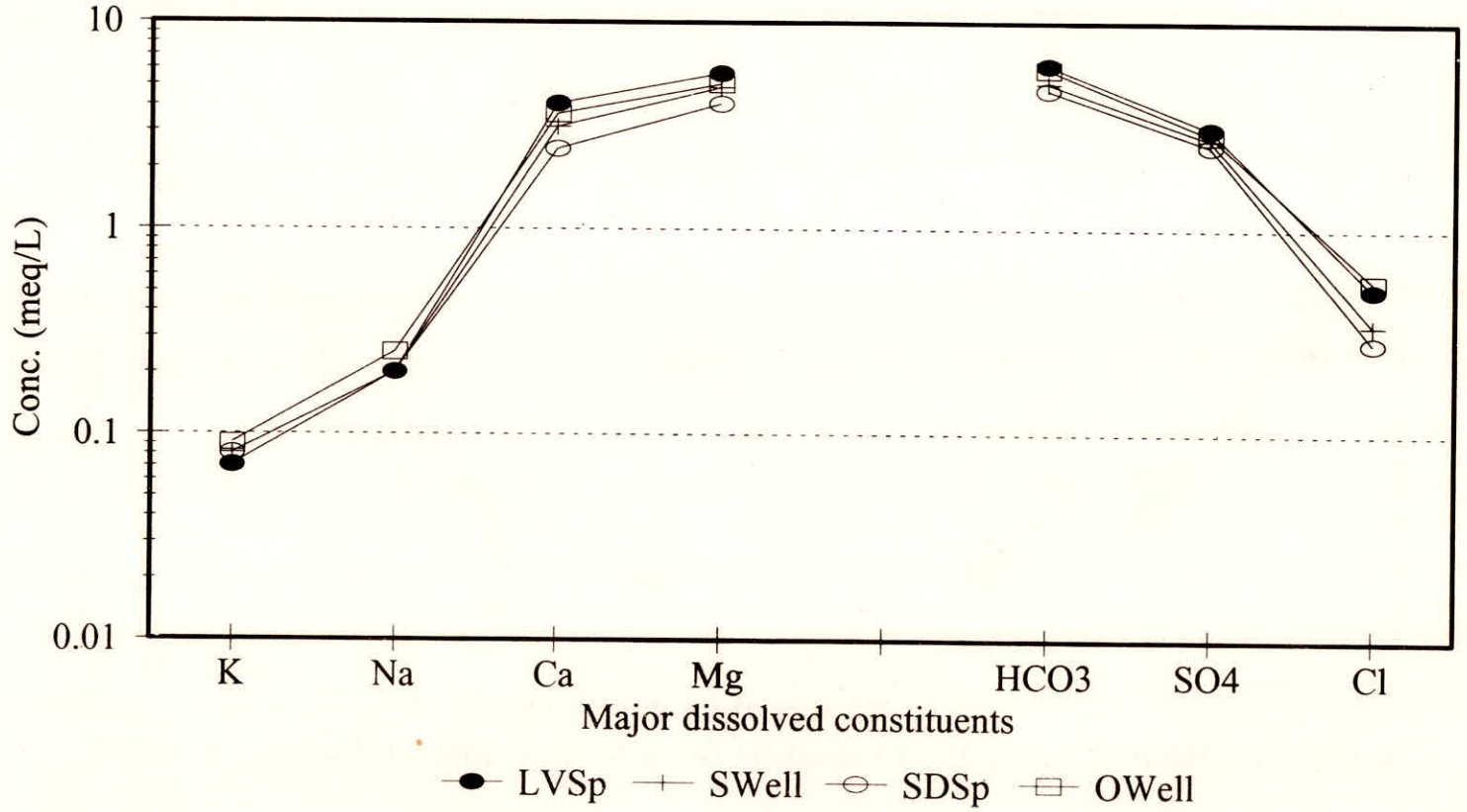
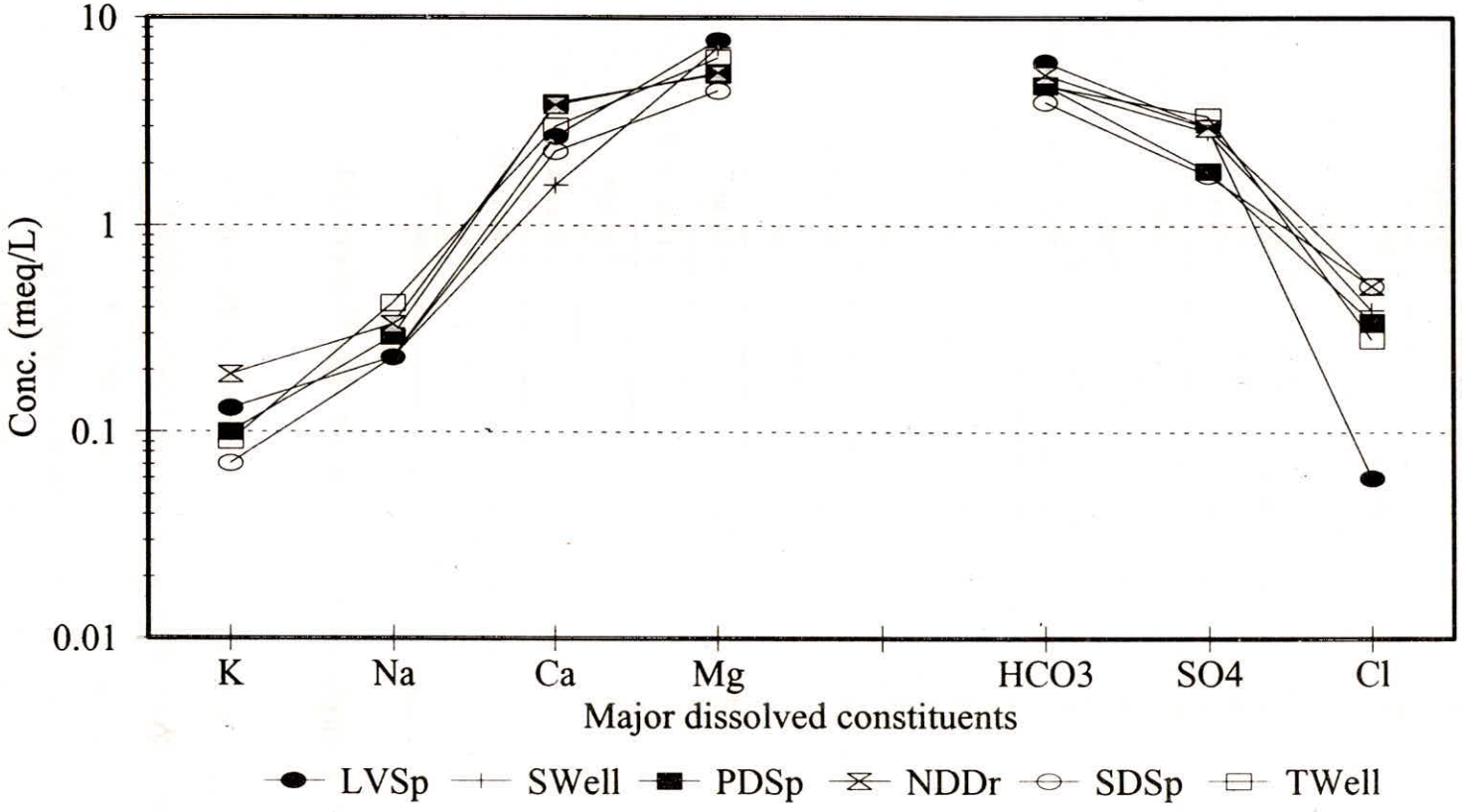


Figure 4h. Finger print plot showing water characteristics of Springs and drain water in Nainital area (January, 1996)



The above data can not be considered as representative of the whole lake, as the data pertains only to the surface waters. It however, gives an idea that the hardness has not significantly varied, during the past several years. This could be due to the reason that the residence time of lake waters is very low (refer section on water balance).

6.0 DISCUSSION

6.1 Electrical Conductance

Electrical conductance, or conductivity, is the ability of a substance to conduct an electric current. Specific electrical conductance is the conductance of a body of unit length and unit cross section at a specified temperature. This term is synonymous with volume conductivity and is the reciprocal of volume resistivity. The American Society for Testing and Materials defined electrical conductivity of water as the reciprocal of the resistance in mhos measured between opposite faces of a centimetre cube of an aqueous solution at a specified temperature. This definition further specifies that units for reporting conductivity shall be micromhos per centimetre at t°C. Because the definition already specifies the dimensions of the cube to which the measurement applies, the added precaution of including the length in the unit may not be essential and is often omitted in practice. The standard temperature for laboratory measurements is 25°C, but because other standard temperatures were used in the past it is important that the temperature of measurement be specified. Under the International System of Units (SI) the unit of conductivity is Siemens. The microsiemens (μS) is numerically the same as the micromho.

The specific conductance of the purest water that can be made would approach 0.5 μmho/cm, but ordinary single-distilled water or water passed through a deionizing exchange unit normally has a conductance of at least 1.0 μmho/cm. Carbon dioxide from the air in the laboratory dissolves in distilled water that is open to the air, and the resulting bicarbonate and hydrogen ions impart most of the observed conductivity. Rain water has ample opportunity before touching the Earth to dissolve gases from the air and

also may dissolve particles of dust or other airborne material. As a result, rain may have a conductance much higher than distilled water, especially near the ocean or near sources of atmospheric pollution.

The conductance of surface and ground waters has a wide range, of course, and in some areas may be as low as 50 μmho/cm where precipitation is low in solutes and rocks are resistant to attack. In other areas, conductances of 50,000 μmho/cm or more may be reached; this is the approximate conductance of seawater. Brine associated with halite may contain as much as ten times the dissolved-solids concentration of seawater. The accuracy of field measurements of conductivity made with good portable equipment and proper attention to temperature effects should be about the same as the accuracy of laboratory measurements if the temperature is near 25°C. Conductivity devices that have been permanently installed in the field require periodic maintenance to prevent electrode fouling and (or) other interferences that may cause erroneous readings and loss of record.

The EC in the lake waters vary from a minimum of 412 μS/cm to a maximum of 742 μS/cm. EC shows a larger temporal variation than hardness, and cannot easily be related to any hydrological process. However a first look indicates that the EC during the spring, summer and early part of the monsoon is controlled by surface runoff inputs and during later part of monsoon and winter by subsurface inputs. The higher EC and hence the total dissolved solids (TDS) in the month of March may be due to heavy snowfall during the preceding months and resultant melt water flowing into the lake, as sub-surface and also as interflow. Since the groundwater (lake view spring) is also high in TDS (with an EC of 800 μS/cm to 1050 μS/cm), the lake may infact be reflecting the characteristics of its major source.

The epilimnion is low in EC in both the sub-basins when compared to the hypolimnion. The lake waters show a comparatively low EC during the late winter period (February), which incidentally is the well mixed period. The EC ranges between 400 and 450 μS/cm. As noted above the EC is high during March (Spring season) and October and November (post monsoon) with an EC range of 700 to 800 μS/cm.

The Pardha dhara spring that issues from dolomite, in the Lake fault zone, has an average EC of 740 μS/cm (520 μS/cm to 850 μS/cm). This mean and range of EC closely resembles that of Sukhatal well. The springs that issue from calcareous shales (Alma spring, Chuna dhara and Doctor House spring) as well as Lake view spring has a mean of 825 μS/cm (625 μS/cm to 1050 μS/cm). This may be indicative of the fact that the aquifer that feed the springs in the shales which is recharged by natural infiltration process has a relatively higher EC. On the other hand the Pardha dhara which is thought to be having its source as the infiltrated waters of Sukhatal lake, a seasonal lake in upstream side shows comparatively lower EC. The perennial drain, the nalah that flows near the Naina devi mandir, shows an average EC of 840 μS/cm (460 μS/cm to 1090 μS/cm). The large range of EC is due to the fact that the nalah during February shows a strikingly lower EC, than other months. Hence the average is close to the higher side of the EC range. In general the nalah waters are high in EC. This is because of disposal of domestic effluent and the effluent from the mushrooming hotel industry into these nalahs. The common bathing facility constructed by the side of Nainital water works also leads to the increase in pollutants, which will be discussed in the lake eutrophication section.

The EC in the well waters (wells located on the northern bank of Lake Nainital), unfortunately, have not been measured regularly. However, the available data indicates that the variation in EC of well waters follow the pattern of lake epilimnion. This is also indicative of the fact that the water drawn through these wells are dominated by the seepage from the lake. These wells have an average EC of 675 μS/cm (640 μS/cm to 740 μS/cm). The well located on Sukhatal has an average EC. of 700 μS/cm (530 μS/cm to 840 μS/cm). While the average EC of the waters from both well groups are very close, the range of EC differs significantly.

6.2 Dissolved Oxygen

The equilibrium concentration of dissolved oxygen (DO) in water in contact with air is a function of temperature and pressure, and to a lesser degree, of the concentration

of other solutes. At 5°C in freshwater the equilibrium DO value is 12.75 mg/L. Values for DO in water analyses may be given in milligrams per litre or as a percentage of saturation at the temperature of measurement.

The higher forms of aquatic life require oxygen for survival, and the DO determination is used widely in evaluations of the biochemistry of streams and lakes. The DO concentration may be depleted by processes that consume dissolved, suspended, or precipitated organic matter, and values above equilibrium can be produced in systems containing actively photosynthesizing biota. The extent to which a supply of oxygen can be maintained in a polluted stream or lake depends in part on the hydraulic properties that influence rates at which atmospheric oxygen can be supplied in the water column; the stream can assimilate more organic or other oxidizable material without significant degradation when the rate is rapid than when it is slow.

Oxygen is supplied to ground water through recharge and by movement of air through unsaturated material above the water table. This oxygen reacts with oxidizable material encountered along the flow path of the water. Water containing measurable amounts of dissolved oxygen may penetrate long distances into the system if little reactive material is available. The principal reacting species are organic materials and reduced inorganic minerals such as pyrite and siderite. As time passes the oxidizable material in the aquifer will be removed or altered for long distances from the point of recharge. For various reasons, determining dissolved oxygen in ground water has not been a standard practice. The dissolved-oxygen concentration of a ground water could not be used as an indicator of organic pollution. Nor would it be significant in evaluating the usability of the water for ordinary purposes. The determination would require special sampling equipment and care and would normally need to be completed immediately after sampling. In part, because few analyses have included this constituent, there is a general impression that most ground waters contain little or no dissolved oxygen. Actually, the water that enters ground-water systems as recharge can be expected to contain oxygen at concentrations similar to those of surface water in contact with the atmosphere, unless the recharge has encountered oxidizable material below the

land surface. Buried organic matter or oxidizable minerals are plentiful enough in some systems to deplete oxygen quickly. It seems likely that significant concentrations of dissolved oxygen occur in ground water in many areas.

The epilimnion showed varying degrees of dissolved oxygen contents. In the winter and summer months the DO is much less than the saturated values and during the monsoon it is much higher than the saturated DO. The observed DO values above the saturated values during monsoon months could be related to the excessive biotic activities. This has also been reported by earlier workers (Pant et al., 1980; Gupta and Shukla, 1997). The Hypolimnion waters, on the other hand, was generally devoid of dissolved oxygen. DO in the bottom waters was observed only during late winter and early summer. The DO in February was 30%, and during March, April and May ranged between 7 and 12 %. Between June and January, DO was virtually absent and anoxic conditions prevailed in the bottom waters. This seriously hampers the decay of dead organic matter that settles to the bottom and also creates a reducing condition leading to release of unwarranted matter from the sediments.

6.3 Calcium

Calcium is the most abundant of the alkaline-earth metals and is a major constituent of many common rock minerals. It is an essential element for plant and animal life forms and is a major component of the solutes in most natural water. Calcium has only one oxidation state, Ca^{2+}. Its behaviour in natural aqueous systems is generally governed by the availability of the more soluble calcium-containing solids and by solution-and gas-phase equilibria that involve carbon dioxide species, or by the availability of sulfur in the form of sulfate. Calcium also participates in cation-exchange equilibria at aluminosilicate and other mineral surfaces. Solubility equilibrium models have been used widely in studying the chemical behaviour of calcium.

The most common forms of calcium in sedimentary rock are carbonates. The two crystalline forms, calcite and aragonite, both have the formula $CaCO_3$, and the mineral

dolomite can be represented as $CaMg(CO_3)_2$. Limestone consists mostly of calcite with admixtures of magnesium carbonate and other impurities. A carbonate rock is commonly termed dolomite if the magnesium is present in amounts approaching the theoretical 1:1 mole ratio with calcium. Other calcium minerals common in sediments include the sulfates gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$), and, more rarely, the fluoride, fluorite (CaF_2). Calcium is also a component of some types of zeolite and montmorillonite.

In sandstone and other detrital rocks, calcium carbonate commonly is present as a cement between particles or a partial filling of interstices. Calcium also is present in the form of adsorbed ions on negatively charged mineral surfaces in soils and rocks. Because divalent ions are held more strongly than monovalent ions at surface charge sites, and because calcium is generally the dominant divalent in solution, most such sites are occupied by calcium ions in the usual river or ground-water system.

Generally calcium is the predominant cation in river water. The pH of river water is influenced by many factors, especially by photosynthesizing organisms. These organisms commonly cause diurnal and seasonal fluctuations, with higher pH values on summer days and lower values at night and during other periods of low photosynthetic activity. The measured pH in river water is generally not well correlated with calcium and bicarbonate activities. Rivers in more arid regions, especially where some of the more soluble rock types are exposed, tend to have much higher dissolved-calcium concentrations. When river water is impounded in a storage reservoir, changes may occur in calcium content as a result of calcium carbonate precipitation. The increased pH near the water surface, caused by algae and plankton, may bring about supersaturation, and precipitation can occur on solid surfaces around the edges of the water body. The fresh water deposit called marl, which is formed in many lakes, is made up partly of calcium carbonate.

In closed basins, water can escape only by evaporation, and the residual water can be expected to change in composition after a fairly well defined evolutionary pattern.

The less soluble substances, including calcium carbonate, are lost first, followed by calcium sulfate. Equilibrium solubilities can be expected to control calcium concentrations in many ground-water systems. Unfortunately, many published chemical analyses of such waters are unsuitable for rigorous testing of calcite-solubility models owing to lack of accurate on site measurements for pH and alkalinity. However, if the acceptable uncertainty in saturation index calculations is broadened, the application of calcite equilibria to some of the ground-water analyses may be useful. Approximations of this kind often are of value in water-analysis interpretation.

Equilibrium with respect to gypsum is obviously to be expected in ground water from a gypsiferous aquifer. As the amount of other solutes increases, the solubility of gypsum will tend to increase owing to greater ionic strength and smaller activity coefficients. In a solution containing 2,500 mg/L of chloride and about 1,500 mg/L of sodium, the equilibrium concentration of calcium would be near 700 mg/L. These calculations presuppose nearly equivalent concentrations of calcium and sulfate. Frequently, this does not occur in natural water. When the solution is in equilibrium with gypsum, however, any increase in sulfate activity would be matched by a decrease in calcium as CaSO4 precipitates. Water that has been trapped underground for a long time could be altered from its original composition by selective permeability of strata for different solutes, by the bacterial reduction of sulfate and other dissolved ions, and by adsorption or desorption of dissolved ions, as well as by chemical solution or precipitation of minerals. Water that is strongly influenced by irrigation return flow may approach simultaneous equilibrium with both calcite and gypsum.

The calcium content in both top and bottom waters show a seasonal variation. It ranges from a minimum of around 30 mg/L during late summer (June) and a maximum of around 60 mg/L during winter. This could probably be related to the precipitation of calcite during summer months, when the lake shows a steady reduction in Ca content. The increase in Ca during the advent of winter may be linked to either dissolution of precipitated calcium carbonate (which is highly unlikely) or a large subsurface inflow which is high in Ca. The calcium content in Nalah inflow waters is in general low during

February, August and September. This indicates that the surface inflow during the snow melt period and during monsoon season is low in Ca content. The Ca content ranges from a minimum of 20 mg/L to a maximum of 90 mg/L.

6.4 Magnesium

Magnesium is an alkaline-earth metal and has only one oxidation state of significance in water chemistry, Mg^{2+}. It is a common element and is essential in plant and animal nutrition. In some aspects of water chemistry, calcium and magnesium may be considered as having similar effects, as in their contributions to the property of hardness. The geochemical behaviour of magnesium, however, is substantially different from that of calcium. Magnesium ions are smaller than sodium or calcium ions and can be accommodated in the space at the centre of six octahedrally coordinated water molecules, an arrangement similar to that described for aluminium. The hydration shell of the magnesium ion is not as strongly held as that of aluminium ions, but the effect of hydration is much greater for magnesium than for the larger ions of calcium and sodium. The tendency for precipitated crystalline magnesium compounds to contain water or hydroxide is probably related to this hydration tendency.

Sedimentary forms of magnesium include carbonates such as magnesite and hydromagnesite, the hydroxide brucite, and mixtures of magnesium with calcium carbonate. Dolomite has a definite crystal structure in which calcium and magnesium ions are present in equal amounts. The magnesium ion, Mg2+, will normally be the predominant form of magnesium in solution in natural water. It has been shown that the complex MgOH+ will not be significant below about pH 10. The ion pair MgSO4(aq) has about the same stability as the species $CaSO_4$(aq), and magnesium complexes with carbonate or bicarbonate have approximately the same stability as the similar species of calcium. The sulfate ion pair and the bicarbonate complex will be significant if the solution contains more than 1,000 mg/L of sulfate or bicarbonate. Before it reaches saturation with respect to either dolomite or calcite, a water passing through dolomite should dissolve equal molar amounts of calcium and magnesium.

Magnesium content of the surface waters varies from a minimum of 30 mg/L to a maximum of 60 mg/L. The minimum values are associated with higher surface inflow during monsoon season. the maximum values are associated with winter overturn process. The bottom waters are slightly higher in its Mg content. It ranges from 45 mg/L to 70 mg/L. The minimum values are observed during winter season, most probably related to the lake's winter overturn process, as noted above. The maximum values in the hypolimnion are observed during late monsoon period. This could probably be associated with the large subsurface inflow from the dolomite aquifers. The magnesium content in Nalah inflow waters is minimum during winter. The Mg content ranges from a minimum of 60 mg/L to a maximum of 85 mg/L.

6.5 Sodium

Sodium is the most abundant member of the alkali-metal group of the periodic table. The other naturally occurring members of this group are lithium, potassium, rubidium, and cesium. In igneous rocks, sodium is slightly more abundant than potassium, but in sediments, sodium is much less abundant. The amounts of sodium held in evaporite sediments and in solution in the ocean are an important part of the total. All the alkali metals occur in the 1+ oxidation state and do not participate in redox processes. Sodium ions have a radius somewhat greater than 1 angstrom and are not strongly hydrated.

When sodium has been brought into solution, it tends to remain in that status. There are no important precipitation reactions that can maintain low sodium concentrations in water, in the way that carbonate precipitation controls calcium concentrations. Sodium is retained by adsorption on mineral surfaces, especially by minerals having high cation-exchange capacities such as clays. However, the interaction between surface sites and sodium, and with monovalent ions generally, is much weaker than the interactions with divalent ions. Cation-exchange processes in fresh water systems tend to extract divalent ions from solution and to replace them with monovalent ions.

According to an estimate, about 60 % of the body of igneous rock in the Earth's outer crust consists of feldspar minerals. The feldspars are tectosilicates, with some aluminium substituted for silica and with other cations making up for the positive-charge deficiency that results. The common feldspars are orthoclase and microcline and the plagioclase series ranging in composition from albite to anorthite. Some sodium may be present, substituting for potassium in orthoclase and microcline. Potassium feldspar is resistant to chemical attack. However, species containing sodium and calcium are somewhat more susceptible to weathering; they yield the metal cation and silica to solution and commonly form a clay mineral with the aluminium and part of the original silica. Human activities can have a significant influence on the concentrations of sodium in surface water and ground water. The use of salt for deicing highways in winter and the disposal of brine pumped or flowing from oil wells, for example, have had direct, noticeable regional effects. Somewhat less directly, the reuse of water for irrigation commonly leaves a residual that is much higher in sodium concentration than was the original water.

Pumping of ground water, which alters hydraulic gradients, can induce lateral movement of seawater into fresh-water coastal aquifers. Water associated with evaporite formations generally has a very high sodium concentration. Anthropogenic effects on sodium concentrations are demonstrated by high sodium concentration of residual drainage.

The Na ion is not a major constituent in the lake waters, when compared to Ca and Mg. The Na ranges from 10 mg/L to 20 mg/L. There is single well defined peak during the monsoon season. However the rising limb of the peak in surface waters is less sharply defined than that of the bottom waters. The Na+ in content Drain waters ranges between 13 mg/L to 33 mg/L. The peak observed during summer (in the month of May) may be a resultant of polluted sewage flow. The effluent from the nearby hotel industry could be probable reason for this spike during May.

6.6 Potassium

Potassium is slightly less common than sodium in igneous rock but more abundant in all the sedimentary rocks. In the ocean the concentration of potassium, though substantial, is far less than that of sodium. Sodium tends to remain in solution rather persistently once it has been liberated from silicate-mineral structures. Potassium is liberated with greater difficulty from silicate minerals and exhibits a strong tendency to be reincorporated into solid weathering products, especially certain clay minerals. In most natural water, the concentration of potassium is much lower than the concentration of sodium.

Another important factor in the hydrochemical behaviour of potassium is its involvement in the biosphere, especially in vegetation and soil. Potassium is an essential element for both plants and animals. Maintenance of optimum soil fertility entails providing a supply of available potassium. The element is present in plant material and is lost from agricultural soil by crop harvesting and removal as well as by leaching and runoff acting on organic residues. The principal potassium minerals of silicate rocks are the feldspars orthoclase and microcline, the micas, and the feldspathoid leucite. The potassium feldspars are resistant to attack by water. Presumably they are altered to silica, clay, and potassium ions by the same process as other feldspars, only more slowly. In sediments, the potassium commonly is present in unaltered feldspar or mica particles or in illite or other clay minerals. Evaporite rocks may locally include beds of potassium salts and constitute a source for high potassium concentration in brines. Average content of potassium in living plants is near 0.3 percent. Concentrations in dry plant material and in ash are substantially greater. Wood ashes have been used by humans as a potash source for many centuries.

In dilute natural waters in which the sum of sodium and potassium is less than 10 mg/L, it is not unusual for the potassium concentration to equal or even exceed the sodium concentration. However, in most other fresh-water aquifers, if the sodium concentration substantially exceeds 10 mg/L the potassium concentration commonly is

half or a tenth that of sodium. Concentrations of potassium more than a few tens of milligrams per litre are decidedly unusual except in water having high dissolved-solids concentration or in water from hot springs.

The K content in the Lake surface waters ranges from 3.5 mg/L to 7 mg/L. As in the case of Na ions, the K content also shows a peak in monsoon season. The south basin is comparatively low in K content, and the North basin is slightly higher. This could be due to the reason that most of the surface inflow is through the Nalahs draining the larger part of the catchment. In the hypolimnion, the picture is not too different from that of Epilimnion, in K content, except that the range of variation is slightly larger, i.e., it ranges from 4 mg/L to 8 mg/L. In the bottom waters also the K shows a definite peak during monsoon season. The potassium content is, in general, one third to one fourth of the sodium content. The K+ content in Drain waters varies from a minimum of 4 mg/L to maximum of 16 mg/L. The peak, as in the case of sodium, is observed during the May, the month of maximum tourist influx.

6.7 Alkalinity

The properties of alkalinity and acidity are important characteristics of natural and polluted waters and are almost always included in the chemical determinations. However, these properties differ in important ways from most of the other determinations reported in the analysis. Both are defined as capacity functions - that is, the capacity of the solution to neutralize acid or base. Both properties may be imparted by several different solute species, and both are evaluated by acid-base titration, to appropriate end points. Systems having these properties are commonly referred to by chemists as buffered systems.

Most quantities determined in chemical analyses are intensity functions-that is, they are actual concentrations of a particular dissolved species at the time of analysis. The measurement of pH provides values of concentrations of H+ and OH- in solution. These species contribute, of course, to acidity or alkalinity, but within in pH range

commonly seen in natural water they are minor constituents. The principal solutes that constitute alkalinity are imparted to natural water during its passage in liquid form through the hydrologic cycle. They reflect the history of the water, as an imprint left by these encounters. The properties of alkalinity or acidity also evaluate the potential of the solution for some kinds of water-rock interaction or interaction with other material the water may contact.

Most natural waters contain substantial amounts of dissolved carbon dioxide species, which are the principal source of alkalinity and can conveniently be evaluated by acid titrations. Undissociated dissolved carbon dioxide contributes to acidity rather than to titratable alkalinity and can also be determined by titration using a basic solution. The alkalinity of a solution may be defined as the capacity for solutes it contains to react with and neutralize acid. The property of alkalinity must be determined by titration with a strong acid, and the end point of the titration is the pH at which virtually all solutes contributing to alkalinity have reacted. The end-point pH that should be used in this titration is a function of the kinds of solute species responsible for the alkalinity and their concentrations. However, the correct titration end point for a particular solution can be identified from the experimental data when the species involved are unknown. It is the point at which the rate of change of pH per added volume of titrant acid is at a maximum. The best values for the end points for a particular sample depend on ionic strength and temperature. Analytical procedures may specify a pH value between 5.1 and 4.5, or that of the methyl-orange end point (about pH 4.0-4.6). Sometimes, however, an alkalinity above the phenolphthalein end point (about pH 8.3) is also specified. Thus one may find terms such as methyl-orange alkalinity, or its equivalent, total alkalinity, and phenolphthalein alkalinity.

Several different solute species contribute to the alkalinity of water as defined above, and titration with acid does not specifically identify them. The property of alkalinity can be expressed in quantitative terms in various ways. The most common practice is to report it in terms of an equivalent amount of calcium carbonate. It could also be expressed in milliequivalents per litre, where meq/L is 1/50 times mg/L CaCO3.

In almost all natural waters the alkalinity is produced by the dissolved carbon dioxide species, bicarbonate and carbonate, and the end points mentioned above were selected with this in mind. Analyses in current geochemical literature, follow the convention of reporting titrated alkalinity in terms of the equivalent amount of bicarbonate and carbonate.

The more important noncarbonate contributors to alkalinity include hydroxide, silicate, borate, and organic ligands, especially acetate and propionate. Rarely, other species such as NH4OH or HS- may contribute significantly to alkalinity. If alkalinity is expressed in milliequivalents per litre, or as CaCO3, the contributions from these species will affect the cation-anion balance of the analysis only if some of them are determined by other methods and are thus included in the balance computation in two places. Except for waters having high pH (greater than about 9.50) and some others having unusual chemical composition, especially water associated with petroleum and natural gas or water having much dissolved organic carbon, the alkalinity of natural waters can be assigned entirely to dissolved bicarbonate and carbonate without serious error.

The principal source of carbon dioxide species that produce alkalinity in surface or ground water is the CO2 gas fraction of the atmosphere, or the atmospheric gases present in the soil or in the unsaturated zone lying between the surface of the land and the water table. The CO2 content of the atmosphere is near 0.03 percent by volume. Soil-zone and unsaturated-zone air can be substantially enriched in carbon dioxide, usually owing to respiration by plants and the oxidation of organic matter. In some natural systems there may be sources of carbon dioxide other than dissolution of atmospheric or soil-zone CO2. Possible major local sources include biologically mediated sulfate reduction and metamorphism of carbonate rocks.

Carbon dioxide species are important participants in reactions that control the pH of natural waters. Reactions among the alkalinity-related species, aqueous CO2, H2CO3(aq.), HCO3-, and CO3 2-, and directly pH related species, OH- and H+, are

relatively fast and can be evaluated with chemical equilibrium models. Rates of equilibration between solute species and gaseous CO2 across a phase boundary are slower, and water bodies exposed to the atmosphere may not be in equilibrium with it at all times. The oceans are a major factor in maintaining atmospheric CO2 contents. It may be of interest to note that carbonic acid, H2CO3, is conventionally used to represent all the dissolved undissociated carbon dioxide. In actuality, only about 0.01 percent of the dissolved carbon dioxide is present in this form. We will use the H2CO3 convention in discussing these systems, however, as the choice of terminology has no practical effect on final results.

In more calcareous environments, the circulation of water rich in carbon dioxide may produce solutions that are highly supersaturated with respect to CaCO3 when exposed to air. Such solutions may deposit large quantities of calcium carbonate as travertine near their points of discharge. The bicarbonate concentration of natural water generally is held within a moderate range by the effects of carbonate equilibria. The concentration in rainwater commonly is below 10 mg/L and sometimes is much less than 1.0 mg/L, depending on pH. Most surface streams contain less than 200 mg/L, but in ground waters somewhat higher concentrations are not uncommon. Concentrations over 1,000 mg/L occur in some waters that are low in calcium and magnesium, especially where processes releasing carbon dioxide (such as sulfate reduction) are occurring in the ground-water reservoir. The alkalinity in the Lake surface waters ranges from 180 to 300 mg/L, and in general is higher during winter. The hypolimnion waters have alkalinity ranging from 240 to 320 mg/L. In this layer also the alkalinity is higher during winter, and a small peak is also observed during monsoon season.

6.8 Sulfur

The chemical behaviour of sulfur is related strongly to redox properties of aqueous systems. In the most highly oxidized form, the effective radius of the sulfur ion is only 0.20 angstrom and it forms a stable, four-coordinated structure with oxygen, the SO4 2- anion. The reduced ion, S 2-, forms sulfides of low solubility with most metals.

Because iron is common and widely distributed, the iron sulfides have a substantial influence on sulfur geochemistry. The element is essential in the life processes of plants and animals.

Sulfur is widely distributed in reduced form in both igneous and sedimentary rocks as metallic sulfides. Concentrations of these sulfides commonly constitute ores of economic importance. When sulfide minerals undergo weathering in contact with aerated water, the sulfur is oxidized to yield sulfate ions that go into solution in the water. Hydrogen ions are produced in considerable quantity in this oxidation process. Pyrite crystals occur in many sedimentary rocks and constitute a source of both ferrous iron and sulfate in ground water.

Oxidation of pyrite and other forms of sulfur also is promoted by humans: the combustion of fuels and the smelting of ores are major sources of sulfate for natural water. Organic sulfides also may undergo oxidation in natural soil processes or in organic waste treatment. Sulfate occurs in certain igneous-rock minerals of the feldspathoid group, but the most extensive and important occurrences are in evaporite sediments. Calcium sulfate as gypsum, $CaSO4.2H20$, or as anhydrite, which contains no water of crystallization, makes up a considerable part of many evaporite-rock sequences. Barium and strontium sulfates are less soluble than calcium sulfate but are relatively rare. Sodium sulfate is formed in some closed-basin lakes, as noted in the discussion of sodium occurrence.

Moderately low sulfate concentrations are typical of rainfall in relatively unpolluted areas. Although sulfur oxides are probably a major factor in producing rainfall having a low pH, the correlation between acidity and sulfate concentration is not always close. In some areas nitrogen oxides may be more important contributors. Sulfate concentrations below the level expected in present-day rainfall occur in ground waters that have undergone sulfate reduction. Sometimes such waters contain noticeable concentrations of dissolved hydrogen sulfide, but in many places they do not. Waters showing the effects of sulfur gases are common in some geothermal areas. Effects of

pyrite oxidation on ground waters is sometimes more subtle, as the iron so released may be precipitated or lost by cation exchange and the sulfate may be reduction as the water moves through the aquifer.

When an area of low rainfall and accumulated solutes is reclaimed by irrigation, the increased water supply tends to leach away the solutes, and they appear in drainage water or return flow. The process is an acceleration of natural leaching and will increase the dissolved-solids concentrations and loads in the residual water of the affected area for a considerable period. Even where the soil is fairly free from soluble salts, the sulfate concentrations and chloride concentrations of the residual water draining from an irrigated area are generally much higher than they were in the original water supply, owing to water lost by evapotranspiration.

The sulfate in the epilimnion waters range from 40 to 100 mg/L. The south basin shows a large variation and no definite seasonal trend. On the other hand the north basin shows a single peak during June. And generally the SO_4 content is around 90 mg/L. In the hypolimnion waters the SO_4 ranges from 70 to 120 mg/L. In the south basin the peak is observed during June and in the north basin the main peak is observed during March and subsidiary peak during August. These are probably related to inflows. The sulfate content in drain waters varies between 120 mg/L to 200 mg/L. The maximum value is observed in the month of March, and minimum during monsoon season.

6.9 Chloride

The element chlorine is the most abundant of the halogens. Others in this group of elements are fluorine, bromine, and iodine. The geochemical behaviour of chlorine reflects the volatility of the element and the fact that compounds of chlorine with common metallic elements, alkali metals, and alkaline earth metals are readily soluble in water. Although chlorine can occur in various oxidation states ranging from Cl^{1-} to Cl^{7+}, the chloride form is the only one of major significance in water exposed to the atmosphere.

A significant fact illustrating the geochemical behaviour of this element is that more than three-fourths of the total amount present in the Earth's outer crust, atmosphere, and hydrosphere is in solution in the ocean as Cl^- ions. Chloride forms ion pairs or complex ions with some of the cations present in natural waters, but these complexes are not strong enough to be of significance in the chemistry of fresh waters. They may be of more significance in seawater and brine. Chlorine gas dissolves readily in water and has a somewhat stronger and more rapid oxidizing effect than does dissolved oxygen. The element has long been used as a disinfectant or biocide in purification of water supplies. Organic solutes are attacked also, as are other easily oxidized species, and the biological sterility of the solution after the reactions have been completed is readily ascertainable by testing for the presence of free chlorine. It is common practice in water-supply technology to maintain a few hundred micrograms per litre residual of free chlorine in solution throughout the distribution system.

Although some of the oxidized chlorine species, once formed, are fairly stable, they are not found in significant concentrations in any natural water. The presence of chlorine residuals in treated water may influence laboratory tests for some other ions, however. Chloride is present in the various rock types in concentrations lower than any of the other major constituents of natural water. Among the chloride-bearing minerals occurring in igneous rock are the feldspathoid sodalite and the phosphate mineral apatite. Minerals in which chloride is an essential component are not very common, and chloride is more likely to be present as an impurity. On the whole, it must be concluded that igneous rocks cannot yield very high concentrations of chloride to normally circulating natural water. Considerably more important sources are associated with sedimentary rocks, particularly the evaporites.

Chloride may be present in resistates as the result of inclusion of connate brine and in cementing material and is to be expected in any incompletely leached deposit laid down in the sea or in a closed drainage basin. When porous rocks are submerged by the sea at any time after their formation, they become impregnated with soluble salts, in which chloride plays a major role. Fine-grained marine shale might retain some of this

chloride for very long periods. In all these rock types, the chloride is mostly present either as sodium chloride crystals or as a solution of sodium and chloride ions.

The behaviour of chloride in the hydrosphere can be represented by a cycle, one considerably simper than the cycles of carbon and sulfur. Chloride is present in rain and snow owing primarily to physical processes that entrain marine solutes in air at the surface of the sea. Some of the entrained chloride also reaches the land and its fresh water by dry fallout. Leaching of evaporites and return of connate water to circulating ground water are important routes by which marine chloride is returned to the sea. Humans use salt in many ways, and the return of this material to the sea by various routes can have important local effects on natural-water composition.

The chemical behaviour of chloride in natural water is tame and subdued compared with the other major ions. Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few vital biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes. Chloride ions move with the water through most soils with less retardation or loss than any of the other tracers (such as tritium) that had actually been incorporated into the water molecules. This conservative behaviour should not be expected where movement is through compacted clay or shale, however.

Chloride is present in all natural waters, but mostly the concentrations are low. In most surface streams, chloride concentrations are lower than those of sulfate or bicarbonate. Exceptions occur where streams receive inflows of high-chloride ground water or industrial waste or are affected by oceanic tides. Rainwater close to the ocean commonly contains from one to several tens of milligrams per litre of chloride, but the concentrations observed generally decrease rapidly in a landward direction. Air masses containing sodium chloride particles may move inland and drop out salt by mechanisms other than by washing out in rainfall. The most common type of water in which chloride

is the dominant anion is one in which sodium is the predominant cation. Waters of this type range from dilute solutions influenced by rainfall near the ocean to brines near saturation with respect to sodium chloride. The determination of chloride is commonly assumed to be one of the simplest and most dependable procedures in water analysis. However, a commonly used procedure, the Mohr titration, which uses a standard silver nitrate solution with chromate to indicate the end point, has fundamental limitations that have not always been adequately recognized. The optimum range of concentration for this procedure is from about 20 to about 5,000 mg/L. Accuracy and precision of the Mohr procedure are inadequate for determining concentrations of chloride below about 10 mg/L unless the sample is concentrated by evaporation of a large aliquot, and this entails a risk of contamination.

The Cl has a range from 3 to 7 mg/L, in the epilimnion. The chloride shows a distinct single peak during August, and reduces during post monsoon period. This is probably indicative of outflow, since Cl^- is conservative in nature. The bottom waters have Cl^- ranging from 2.5 mg/L to 30 mg/L. The variation is more pronounced in the south basin rather than the north. There are two distinct peaks observed in the north basin, during March and during August. The Cl- content in drain waters ranges from 5 mg/L to 45 mg/L. The maximum value is observed during May. This behaviour is similar to the cations Na+ and K+.

6.10 Nitrogen

Aqueous geochemical behaviour of nitrogen is strongly influenced by the vital importance of the element in plant and animal nutrition. It is present in the atmosphere, hydrosphere, and biosphere at oxidation states covering the full range from N^{3-} to N^{5+}. Most of the Earth's atmosphere is nitrogen gas.

The crustal rocks of the Earth contain about one-fourth of the total nitrogen present in the crust, atmosphere, hydrosphere, and biosphere and that nearly three-fourths in the atmosphere. Amounts in the hydrosphere and biosphere are much smaller.

A much larger quantity may be present in the mantle at depths below 16 km. Amounts there are not known with certainty, nor are they significant in the biochemical cycle of the element. Chemical and biological processes that transfer nitrogen to and from the lithosphere, atmosphere, hydrosphere, and biosphere represent the nitrogen cycle. A very large amount of scientific investigation of the nitrogen cycle has been done, and the related literature is voluminous. The importance of these processes in governing concentrations, form, and behaviour of nitrogen in water is obvious, and they merit brief consideration. Processes by which N_2 gas is changed in oxidation state and converted to chemical compounds containing nitrogen are referred to in general as nitrogen fixation. A substantial energy input is required because the two atoms in molecular N_2 are very strongly bound to each other. Biological fixation is accomplished by blue-green algae and certain related organisms that have the capacity of photosynthesis, and by certain species of bacteria that use other organic material as energy sources. The latter may grow symbiotically on roots of some species of higher plants, notably legumes. Inorganic fixation occurs naturally in the atmosphere, but amounts produced in this way are small. Lightning discharges produce nitric oxides and were thought at one time to be a major factor in producing nitrate nitrogen in rainwater.

Man's influence on the nitrogen cycle includes production and use of synthetic fertilizers such as ammonia and other nitrogen compounds. Some of this fixed nitrogen escapes to the hydrosphere. Nitrogen in reduced or organic forms is converted by soil bacteria into nitrite and nitrate. This process is commonly termed nitrification. The nitrogen used by plants is largely in the oxidized form. Nitrate in anaerobic systems can be reduced by other strains of bacteria to nitrous oxide or nitrogen gas. Biochemists refer to this process as denitrification. Nitrogen oxides are present in the atmosphere, in part, from combustion of fossil fuel. Coal and petroleum generally contain about 1 percent nitrogen. A part of this is converted to nitrogen oxides on burning and escapes to the atmosphere. Gasoline and diesel engines and most other combustion devices also emit nitrogen oxides that are synthesized by high-temperature fixation of atmospheric nitrogen.

Nitrogen oxides in the atmosphere undergo various chemical alterations that produce h+ and finally leave the nitrogen as nitrate. These processes can lower the pH of precipitation in the same way sulfur oxides do. Ammonia nitrogen is generally present in rainfall also. Nitrogen occurs in water as nitrite or nitrate anions (NO_2^- and NO_3), in cationic form as ammonium (NH_4^+), and at intermediate oxidation states as a part of organic solutes. Some other forms such as cyanide (CN^-) may occur in water affected by waste disposal. The differences in chemical properties among these species obviously is substantial. Ammonium cations are strongly adsorbed on mineral surfaces. Anionic species such as nitrate are readily transported in water and are stable over a considerable range of conditions. Above a pH of 9.20 the form of most dissolved ammonium ions will be $NH_4OH(aq)$, an uncharged species. The nitrite and organic species are unstable in aerated water and are generally considered to be indicators of pollution through disposal of sewage or organic waste. The presence of nitrate or ammonium might be indicative of such pollution also, but generally the pollution would have occurred at a site or time substantially removed from the sampling point. Ammonium and cyanide ions form rather strong soluble complexes with some metal ions, and certain types of industrial waste effluent may contain such species.

Excessive concentrations of nitrate in drinking water may cause methaemoglobinaemia in small children. Concentrations in excess of 20 mg/L, equivalent to 88 mg/L of NO_3^- evidently present this hazard (IS:10500). Occurrence of nitrate and nitrite in water has been studied rather extensively because of the public health relationship. Concentrations of nitrate that approach or exceed 44 mg/L NO_3^- are not uncommon in many rural water-supply wells. This nitrate is attributed to drainage from nearby septic tanks and cesspools. Farm animals produce considerable amounts of nitrogenous organic waste that tends to concentrate in places where large number of animals are confined.

The sources of reduced forms of nitrogen in natural water presumably are similar to the sources of nitrate, and the state of oxidation of nitrogen probably is controlled by biochemical processes. Although the reduced forms normally would be transformed to

is most probably due to uptake by the aquatic biota. The PO_4-P in the bottom waters ranges from 100 to 900 μg/L. The presence of PO_4-P in bottom waters is very significant in Winter, May and to a less extent in August. The higher quantity of SRP in the bottom waters during winter is probably due to release from the sediments during winter overturn.

The minimum SRP content in the nalahs is 200 μg/L. The maximum value is a whopping 1750 μg/L. The maximum value is observed during May. The main source of this SRP is then the anthropogenic activities, such as washing and bathing, etc. along the nalah, particularly near the Nainital water works.

6.12 Lead

Lead is comparable in abundance to cobalt and is rather widely dispersed in sedimentary rocks. Its natural mobility is low, however, owing to the low solubility of lead hydroxy carbonates and phosphate. The adsorption of lead on organic and inorganic sediment surfaces and the coprecipitation of lead with manganese oxide also tend to maintain low concentration levels in surface and ground water. Certain of the uses of load by humans have tended to disperse the element widely through the environment. In the 1920's, addition of tetraethyl lead was found to promote more efficient combustion of gasoline used in automobile engines. Leaded petrol permitted a higher compression of the fuel-air mixture, which in turn increased the power output. The lead content of the fuel is emitted as an aerosol in exhaust gases, and the quantities so dispersed increases greatly as the number of automobiles in use grow.

Lead pipe once was commonly used to convey drinking water and is still present in many old buildings. Water that has a pH below neutrality or is poorly buffered may dissolve considerable amounts of lead from such pipe, and may also obtain lead from solder used to join copper pipe and fittings. The extent of these effects is not well known, because few chemical analyses are available for water taken from consumer taps. The upper limit for lead in drinking water in India is 100 μg/L (IS:10500).

Concentrations of lead in rain and snow range from 100 μg/L or more in areas subject to substantial air pollution down to 1.0 μg/L or less in more remote areas. Dry fallout and rainout of particulate lead is probably a factor of major importance in the circulation of the element, especially in areas of heavy automobile traffic. Washing of this material into streams during runoff events is a potential source of dissolved lead in river water.

Occasional concentrations of dissolved lead in excess of 10 μg/L have been reported at many river-sampling stations elsewhere in the developed countries but the records indicate that most of the lead that was present was in particulate form. The lead content in the lake is above the limit prescribed in the ISI standards. It ranges from 120 μg/L to 160 μg/L. Though this is unhealthy for human consumption, this may not be treated as pollution related, as the background concentration in the area is also above 100 μg/L. The upstream springs representing the local groundwater also have lead values comparative to that of lake waters. This could be probably from dissolution of certain lead bearing minerals present in the catchment rock formations (upto 100 μg/L) and anthropological activities.

6.13 Manganese

The chemistry of manganese is somewhat like that of iron in that both metals participate in redox processes in weathering environments. Manganese, however, has three possible valence states in such environments rather than two (2+,3+, and 4+) and can form a wide variety of mixed-valence oxides. The 3+ species are unstable in that they may disproportionate. That is, two Mn^{3+} ions may interact spontaneously to produce one Mn^{2+} and one Mn^{4+} ion, and these products are more stable thermodynamically than the original Mn^{3+} species. This ability has a number of interesting ramifications in the chemistry of the element in natural water.

Manganese is an undesirable impurity in water supplies, mainly owing to a tendency to deposit black oxide stains. The recommended upper limit for manganese in public water supplies in India is 500 μg/L (IS:10500). It is an essential element for both

plant and animal life forms. Small amounts commonly are present in dolomite and limestone, substituting for calcium. When divalent manganese is released to aqueous solution during weathering, it is somewhat more stable toward oxidation than is ferrous iron. Generally, however, if it is in contact with the atmosphere, it will be precipitated, at sites where pH is high enough, as a crust of manganese 4+ oxide. These encrustations generally contain a substantial quantity of coprecipitated iron and, under some conditions, significant amounts of other metal ions as well, especially cobalt, lead, zinc, copper, nickel and barium. A particularly favourable substrate for manganese oxide precipitation is a previously existing manganese oxide surface. Thus the deposit may become thicker with time and form nodules around some central nucleus, as on the bottoms of certain lakes and at many localities on the ocean bottom. Small, discrete particles of oxide or coatings on other particles are widely distributed in stream sediments and soils. Coatings of manganese oxides in streambeds occur in many places. These coatings generally do not become very thick, owing to mechanical erosion and changes in water properties. In some areas manganese oxide may accumulate with other material in the form of a bog.

In lakes and reservoirs where thermal stratification develops, the bottom sediments may become anoxic and manganese oxide previously deposited may be reduced and dissolved. Water drawn from the deeper part of the supply reservoir may at times contain significant concentrations of dissolved Mn^{2+}. Reduction of manganese oxides at depth in buried sediment may be a factor in accumulations of manganese nodules in many environments. Diffusing Mn^{2+} can be redeposited as oxide when it reaches the surface of the sediment layer and encounters oxygenated water. Manganese is an essential element in plant metabolism, and it is to be expected that organic circulation of manganese can influence its occurrence in natural water. Specific mention of manganese accumulation in tree leaves appears in published literature. Some species of trees are much more effective accumulators than others. Aquatic plants are noted to be accumulators of manganese. Manganese in plant parts that die back or are shed becomes available for solution in runoff and soil moisture. The importance of this source of manganese in river water is not completely known, although some studies show the

effects of fallen leaves on the water quality of a small streams could be important at times.

The Mn content in lake waters hovers around the limit as per Indian Standards for domestic water supply. The Mn has been observed to exceed during the months of April (550 μg/L) and July (650 μg/L) and very close to the maximum limit during November and December. The Mn values are below the limits during January (300 μg/L), during which period the Chuna dhara, an upstream spring was very high in Mn content (5.7 mg/L). Some other sources which was high in Mn content during this period are Sukhatal groundwater well (1.56 mg/L), Sipahi dhara, a downstream spring (2.32 mg/L) and Sariyatal (2.79 mg/L).

7.0 EUTROPHICATION

The process of eutrophication is defined as the loading of inorganic and organic dissolved and particulate matter to lakes at rates sufficient to increase the potential for high biological production that leads to a decrease in the capacity of the lake. The above definition is a holistic and accurate one against the general description where eutrophication is referred as loading of inorganic plant nutrients (such as Phosphorous and Nitrogen) and the high production of algae that may occur as a consequence of increased nutrient concentration.

Lakes are considered to undergo a process of ageing which has been characterized by three qualitatively defined conditions. The initial condition of a lake is termed oligotrophic and is normally associated with deep lakes, where the waters at the bottom of the lake are cold and have relatively high levels of dissolved oxygen throughout the year. The waters and bottom sediments of the lake usually contain only small amounts of organic matter. Productivity in terms of the population levels of phytoplankton, rooted aquatic plants, zooplankton, and fish is usually low. Species diversity is often quite high and chemical water quality is good.

The eutrophic condition of a lake represents the opposite end of the ageing process. Eutrophic lakes may be either shallow or deep. They are characterized by high concentrations of suspended organic matter in the water column and by relatively large sediment depths with high organic contents particularly in the upper layers of the sediment. Biological productivity is high and the diversity of biological populations may be somewhat limited. Coarse (non-game) fish may predominate due to elevated bottom water temperatures and/or depressed water quality. Dissolved oxygen concentrations of bottom waters are usually depressed and in extreme cases of eutrophication may reach zero during summer periods. Generally water quality is low and can result in impairment of beneficial water usages such as water supply, contact recreation, and/or boating.

The characteristics of a eutrophic lake is that it will have frequent blue-green algal blooms, coloured water (green/brown), very low or absence of dissolved oxygen in the bottom waters and fairly high fish productivity. Silt is a major source of sorbed nutrients and organic matter in a eutrophic lake and silt loading directly contributes to reduction of lake's capacity. It is important to note that the term eutrophic does not mean bad, but it is only a descriptive of the state or condition of the lake. The problems of potable water treatment and its safety are directly related to the degree of eutrophication of the lake. According to Martin (1993) some organic molecules either loaded to or produced within the lake, produce mutagenic or carcinogenic compounds when chlorinated for drinking purposes. Surface water with a blue-green algal bloom may be unfit for human consumption as they may contain toxins released form algae. These toxins are lethal to cattle and have been shown to produce human gastro-intestinal problems.

A third lake condition is mesotrophic which is defined as an intermediate state between oligotrophic and eutrophic. Mesotrophic lakes have intermediate levels of biological productivity and can have some reductions in bottom dissolved oxygen levels. Lakes in this category generally have water quality which is adequate for most beneficial uses but may be deteriorating toward the eutrophic state.

The boundaries between the three stages are not rigidly defined and may vary with regions of the nation and with beneficial uses of lake waters. Therefore, attempts have been made to establish a trophic state index (TSI) as a function of commonly measured water quality variables. The different trophic classification schemes are shown below which are largely followed (US EPA-NES trophic state delineation).

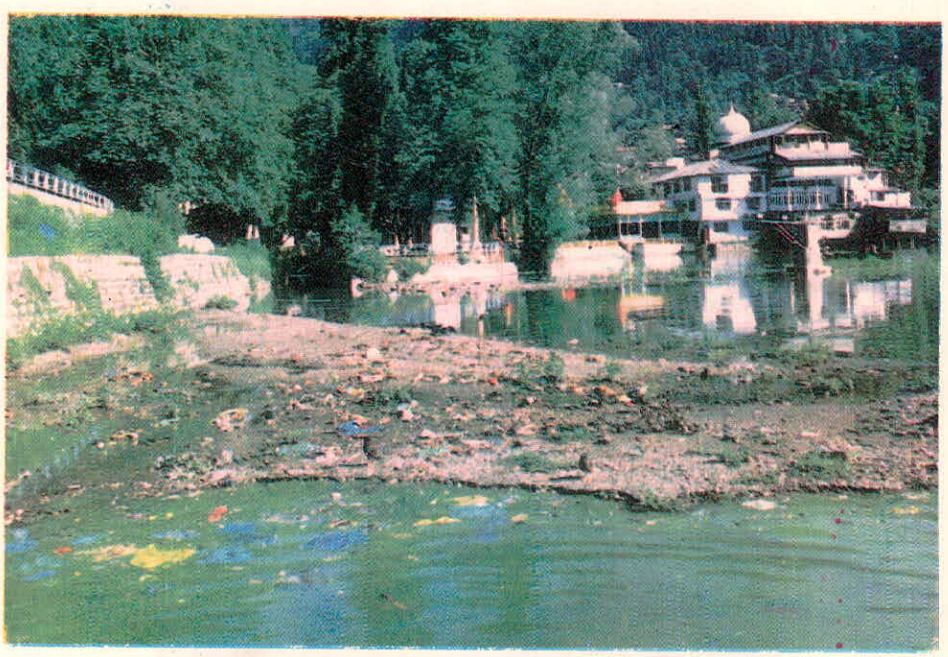
Water Quality Variable	Oligotrophic	Mesotrophic	Eutrophic
Total phosphorus (μg/1)	< 10	10-20	> 20
Chlorophyll (μg/1)	< 4	4-10	> 10
Secchi depth (m)	> 3.7	2-4	< 2
Hypolimnetic oxygen (% saturation)	> 80	10-80	< 10

7.1 Basic Processes

7.1.1 Loads

Nutrient levels in lakes are controlled by external sources to the lake and in-lake processes. External sources of nutrients include municipal and industrial point sources, stream inputs, atmospheric sources, urban drainage, groundwater, agricultural drainage, and other non-point sources surrounding the lake. In-lake processes include sediment release, biological recycling, and nitrogen fixation.

Municipal and industrial point sources may discharge both nitrogen and phosphorus directly into lakes or to streams that eventually drain into lakes. Existing monitoring data should be used or a monitoring network should be developed to provide reliable estimates of nutrient inputs. Source strength of municipal discharges can vary diurnally and seasonally. Total municipal load usually tends to increase over the years due to population growth.



A View of Pollutants and Sediment Deposits in Lake Nainital near Naina Devi Drain



A View of Pollution being Created by the Trees in Lake Nainital

produced numerical estimates of nutrient loss which can be used to compare sediment release to other lake inputs. Biological decomposition occurs throughout the water column to make the nutrients laced in organic detritus available for phytoplankton. In addition, phytoplankton and zooplankton secrete and excrete soluble and insoluble nutrient forms.

Nitrogen fixation may be a significant source of nitrogen in lakes with limiting concentrations of nitrogen. During nitrogen fixation, blue-green algae and some macrophytes are able to reduce molecular nitrogen to nitrogen at the ammonia oxidation level. The ability of selected algae and macrophytes to fix nitrogen is frequently cited as one of the reasons due to which phosphorus is considered to be the limiting nutrient in most lakes.

7.1.2 Nutrients

. As mentioned above, the two nutrients of greatest concern are nitrogen and phosphorus. In addition to these nutrients, phytoplankton require carbon dioxide and a host of minor elements (potassium, sodium) and trace elements (iron, manganese, cobalt, copper, zinc, boron, and molybdenum) and organic growth factors. Silica is an important nutrient for diatoms, as it forms the basis for their skeletal structure.

Phosphorus in lake inputs and the lake itself can be found in dissolved inorganic and/or organic and particulate forms. Dissolved inorganic forms include the free orthophosphate and the condensed phosphates (pyro, meta, and poly). Orthophosphate is immediately available to phytoplankton growth. Dissolved organic phosphorus includes nucleic acids, nucleotides, and phospholipids, among others. The phosphate part of these molecules must be cleaved by exoenzymes to release phosphorus for uptake. Particulate phosphorus includes algae, bacteria, detritus, and silt, etc.

Analytical testing for phosphorus in water can identify orthophosphate, dissolved and particulate condensed phosphates, and dissolved and particulate organic phosphorus.

Total phosphorus is just the sum of all phosphorus species. Levels of total phosphorus in lakes can range from as low as a few μg/1 to as high as a few mg/1. These levels are usually reported for elemental phosphorus; in some instances data are reported as phosphates and appropriate conversion is required. Levels of dissolved orthophosphate expressed in terms of elemental phosphorus range from below detection limits to a few hundred μg/1.

Nitrogen can exist in several different forms in lakes and their inputs. Nitrogen in its most reduced state is found in ammonia and various organic nitrogen forms such as purines, pyrimidines, nucleic acids, etc. Ammonia is immediately available for phytoplankton uptake. Organic nitrogen forms (both dissolved and particulate) may need to be broken down to ammonia for uptake. Some amino acids are immediately available. Other common nitrogen forms include the more oxidized and soluble, nitrate and nitrite. Nitrate is immediately available for uptake but requires the organism to expend more energy to employ this source of nitrogen than for utilization of ammonia.

Measurements of nitrogen compounds are usually reported in terms of elemental nitrogen. In lakes, the sum of the oxidized forms of nitrogen and ammonia may range from 10 μg/1 and above. The concentration of organic nitrogen may range up to several mg/1.

7.1.3 Phytoplankton

The specific growth rate of phytoplankton is controlled by the levels of important nutrients, light and temperature. Overall phytoplankton growth in an area is controlled by this specific growth rate and the effects of death, respiration, settling, zooplankton grazing, and vertical and horizontal transport.

Phytoplankton are one of two main primary producers found in lakes. Primary producers are able to utilize light, carbon dioxide and nutrients to synthesize new organic material. The other primary producers are the rooted or floating aquatic plants

(macrophytes). These plants are generally restricted to shallow waters. Phytoplankton are free-floating and transported by currents. In most cases, phytoplankton are more important than are rooted aquatic vegetation in the basic food production of the lake ecosystem, although their relative importance depends on the specific characteristics of the pond/lake in question.

Phytoplankton can be characterized in terms of species, size, composition, growth rates, and pigmentation, among others. Groups of phytoplankton species include diatoms, green algae, nitrogen-fixing blue-green algae and non-nitrogen-fixing blue-green algae. The standing crop of phytoplankton in lakes has been characterized in terms of overall cell counts, individual species counts, mass, and chlorophyll a. Phytoplankton mass has also been characterized after drying, ashing, and weighing. A problem with this determination is that all biomass in a lake water sample, including bacteria, detritus and zooplankton, will also be measured as phytoplankton. Other processes affecting phytoplankton levels are respiration and death. Respiration is a biochemical process that occurs continuously day and night and results in consumption of some portion of the photosynthetically fixed carbon in the system. Hydrolysis of the phytoplankton cell follows death.

Factors affecting phytoplankton growth in a particular volume include advective and dispersive transport, settling, and zooplankton grazing. There are a number of factors that can limit phytoplankton growth. For the purposes of modifying the productivity of a lake, it is important to identify those limiting factors which can be controlled. Very little can be done to control the intensities or concentrations of light, temperature and the various trace elements and organic growth factors. Because some control can be exerted over the concentrations of nitrogen and phosphorus in lakes, considerable effort has been exerted to define the effects of these nutrients. While nitrogen contributions from point sources are controllable, the greater solubility of nitrogen compounds in non-point sources makes control difficult. The ability of blue-green algae to fix nitrogen from the atmosphere also reduces the importance of nitrogen control. In addition, control of nitrogen alone may cause a shift from green to blue-green algae, thereby reducing the

the total load of SRP to the lake has been computed. It is clearly seen from Fig. 5 that the annual areal loading to the lake in the present scenario is around 1150 mg/m^2. If the nalah waters are excluded then the annual areal loading reduces to 450 mg/m^2. That is, if the nalah waters are diverted away from the lake then the loading is reduced by a significant 60%. The nalah diversion measure will not seriously affect the water availability in the lake, as the channel flow during non-monsoon season is just 1.00 m., while the total surface inflow during monsoon season is 3.89 m.

7.4 Chlorophyll, Phosphorus & Secchi Depth Relationships

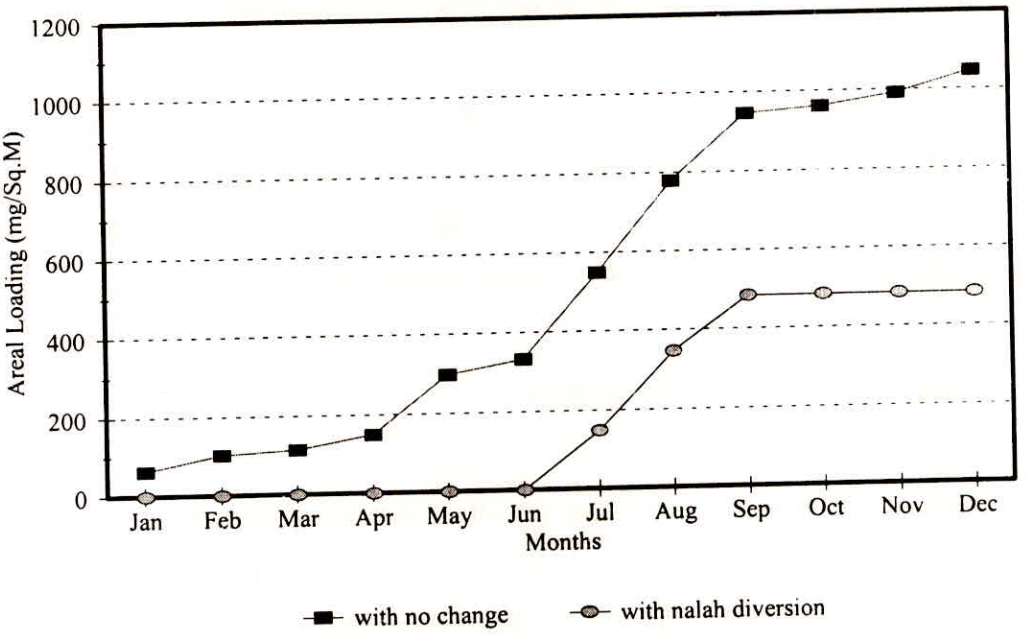
Strong relationships between chlorophyll-a and total phosphorus have been shown by Sakamoto (1966), Dillon and Rigler (1974), Jones and Bachmann (1976), Carlson (1977), Rast and Lee (1978), Bartsch and Gakstatter (1978), Smith and Shapiro (1981), Smith (1982), Lambou et.al. (1982) and Ryding (1983).

Several investigators have also proposed the use of empirical relationships between secchi depth and chlorophyll - a to predict changes in transparency to be expected from changed chlorophyll-a levels. The following are the relationships found for the lakes of Kumaun region (Shewa, 1998).

log Chlor	=	-0.259 + 0.844 log TP	[r = 0.93]	(1)
log SD	=	0.822 - 0.444 log Chlor	[r = 0.83]	(2)
log SD	=	1.072 - 0.450 log TP	[r = -0.95]	(3)

The correlation coefficient obtained in the present investigation indicate a strong relationship between chlor and TP. Hence, it can be argued that the factors which may affect the chlor-TP relationship are uniform in the lakes of Kumaun region. The factors include availability of light, biological availability of phosphorus, limitation of phytoplankton growth by nutrients other than phosphorus, domination of aquatic flora by vascular plants, temperature, lake hydraulic retention time, lake morphometry, grazing of phytoplankton and the presence of toxic substances.

Fig. 5. Cumulative annual external SRP loading in Lake Nainital



Using the equations developed for the lakes (Eq. 1 & 2), a nomogram combining chlor, TP and SD has been constructed (Shewa,1998) and presented in Fig. 6. This nomogram can be used as a predictive tool for the Kumaun lakes particularity for winter conditions.

As far as the chlor-SD relationship is concerned, Lorenzen (1980) contended that a constant chlor-SD relationship can result in misleading projections. Lorenzen stated that, when chlor concentrations are high, the SD and light extinction coefficient are largely controlled by chlor concentration and when chlor concentration are low, the SD and light extinction coefficient are largely controlled by light absorbing particles other than chlor. In the data presented for lake Naukuchiatal in which chlor values are very low, the SD observed is not reasonable and the comment given by Lorenzen can be attributed to the observation of SD values in lake Naukuchiatal. The SD values of Naukuchiatal were therefore not utilized while developing the relationships.

7.5 Trophic Status of the Lakes

As mentioned earlier, eutrophication refers to nutrient enrichment that promotes the growth of aquatic plants. At least 19 elements (all of which can be found dissolved in water) are essential for life in a water body although some of them are needed in minute traces (Hino, 1994). Five of them are required in large amounts: carbon, hydrogen, oxygen, nitrogen and phosphorus in proportions of approximately 106:181:45:16:1. The first three (C, H & O) are readily available either in water (H_2O) or dissolved carbondioxide (CO_2) and thus never become a long - term limiting factor in aquatic plant growth. However, the concentration of nitrogen and phosphorus, dissolved in natural waters are much lower and they are usually the limiting factors for the growth of aquatic plants.

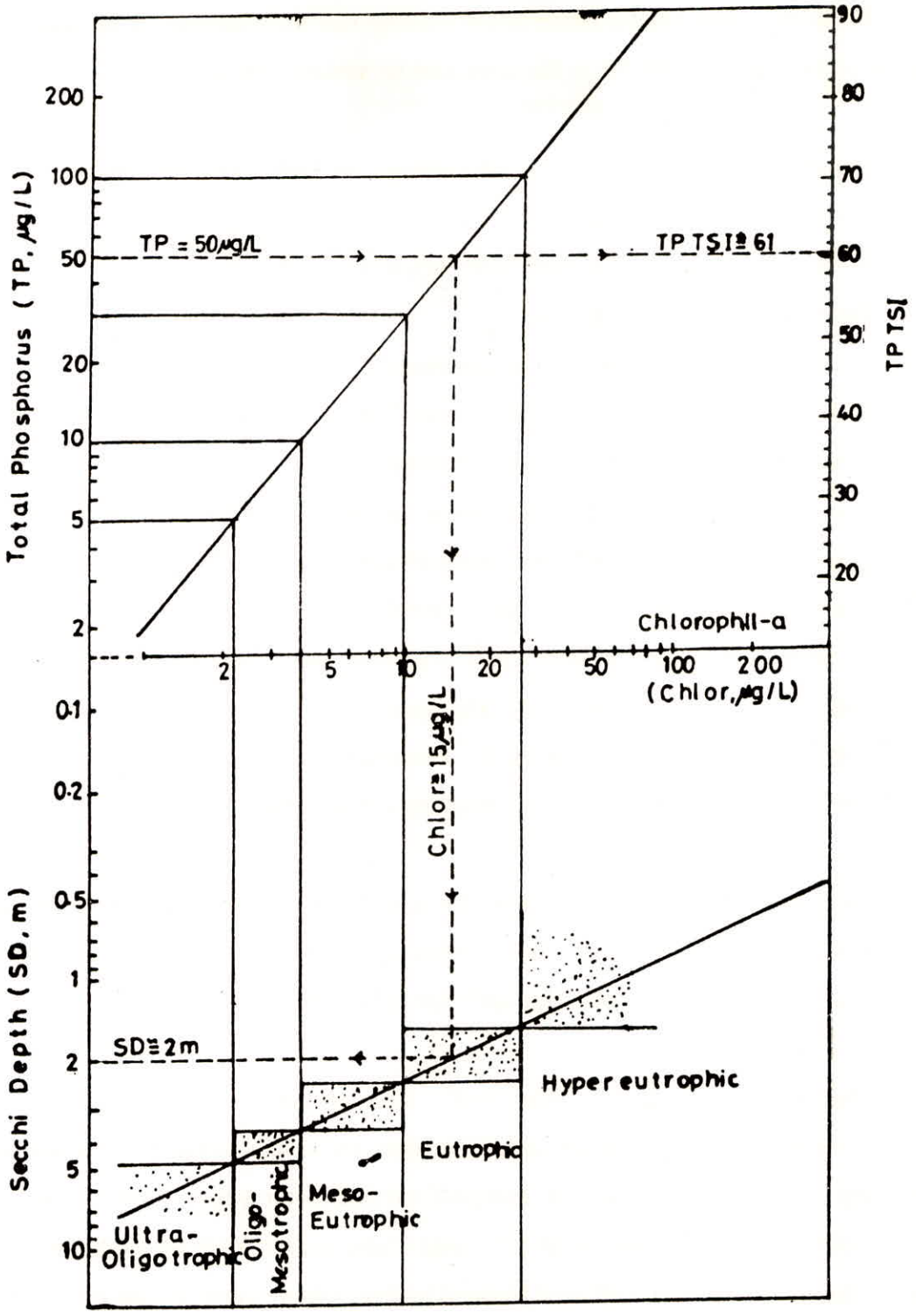


Fig. 6 Nomogram for determiningthe trophic status of Kumaun lakes combining Chlorophyll-a, Total Phosphorous and Secchi Depth

From the observations made while visiting the surroundings of the lakes, the sources of the nutrients (P&N) in the lakes can be summarized as below:

1. Direct addition of solid waste and sewage to rain water fed channels which ultimately reach to the lakes
2. Storm runoff from agricultural land, township and forest
3. Debris from surrounding hills
4. Litter from the vegetation in the catchment
5. Defecation of excreta of some local and floating population in the catchments.
6. Randomly deposited faecal matter of animal origin
7. Rooted aquatic plants which can release nutrients when they die and decompose
8. Even though it is insignificant, nutrients can be expected from the atmosphere (dust, debris carried by wind) and precipitation falling on the lake.
9. In addition to the above listed external sources, the release of nutrients from the sediments can not be ruled out. The source of all the sediments is soil erosion from croplands, overgrazed lands, construction sites, deforested areas, bare patches around schools, homes, shopping centres, roads etc.

To denote the nutrient status of or else to describe the effects of the nutrients on the general water quality of the lakes, three descriptive terms which are broadly classified as oligotrophic, mesotrophic and eutrophic were used.

Oligotrophic (Greek for "little food") lakes are usually characterized by low nutrient concentrations in the water, a diverse plant and animal community, a low level of primary productivity and biomass, and good over all water quality for most uses. By contrast, eutrophic (Greek for "well fed") lakes have a high level of productivity and biomass, frequent occurrence of algal blooms, anoxic bottom water, enhanced growth of littoral zone aquatic plants, and poor water quality for many uses. Mesotrophic is the transition state between oligotrophic and eutrophic.

Specific boundary values of total phosphorus, chlorophyll-a, and secchi depth for these tropic conditions have been provided by various authors. There are limitations, however, to 'fixed' values to delineate lake trophic conditions; some over lap is inevitable i.e., some waters are classified in one trophic condition based on one parameters and in other trophic condition based on a second parameter (Ryding 1989).

In the present study the tropic status of the 5 lakes has been determined based on the boundary values of total phosphorus given by Wetzel (1975), which were modified from Vollenweider (1968). The general relationships of lake productivity to average concentrations of eplimnetic total phosphorus is given in the following Table:

General level of productivity	Total phosphorus (μg/l)
Ultra - oligotrophic	< 5
Oligo - mesotrophic	5 - 10
Meso - eutrophic	10 - 30
Eutrophic	30 - 100
Hypereutrophic	> 100

The lakes in Kumaun region can, therefore, be classified in the tropic states as given below (Shewa, 1998):

Lake	Average total phosphorus (μg/l)	Tropic state
Nainital	127.25	Hypereutrophic
Bhimtal	26.43	Meso-eutrophic
Khurpatal	16.17	Meso-eutrophic
Sattal	6.67	Oligo-mesotrophic
Naukuchiatal	3.00	Ultra-oligotrophic

Several investigators have also developed a numerical tropic state index in an attempt to remove the subjectivity inherent in the terms oligotrophic, mesotrophic and

eutrophic. Total phosphorus, chlorophyll - a and Sechhi depth relationships were used by Carlson (1977) to develop a numerical Tropic State Index (TSI) which is probably the most commonly used (Cooke et.al. 1993).

Carlson used transformations to log 2 to interrelate these indices with in a scale of 0 to 100 (applicable to any lake). For comparison representative values for TP, chlor and SD calculated from these equations are given in the following Table. The range from 40 to 50 is most often associated with mesotrophy.

TSI	Sechhi depth (m)	Surface phosphorus (μg/l)	Surface chlorophyll (μg/l)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.12
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1183

The Carlson TPTSI is used for determining tropic state index of the lakes and the values are given below:

Lake	Average total phosphorus (μg/l)	Tropic state Index (TSI)
Nainital	127.25	74
Bhimtal	26.43	51
Khurpatal	16.17	44
Sattal	6.67	32
Naukuchiatal	3.00	20

8.0 MEASURES FOR AMELIORATION OF LAKE WATER QUALITY

There are several methods in vogue for the arresting the progressive eutrophication of surface water bodies. A few of the major and widely reported methods are given below. However, the applicability of any one or more methods for ameliorating water quality of Lake Nainital had to be adopted on the basis of cost effectiveness.

8.1 Phosphorous inactivation

Internal release of phosphorous (P) may be a significant source that could delay recovery of lake quality. Sediment P release can be controlled by adding aluminium salts to the water having problem, resulting in an aluminium hydroxide floc that settles to the sediment surface forming a barrier to further release, even if anoxia persists. This is a powerful, effective and popular technique. Sediment oxidation through enhanced denitrification and resulting improved complexation with iron is included with P inactivation.

8.2 Dilution and Hypolimnetic Withdrawal (siphoning)

Dilution involves the addition of low nutrient water to reduce lake nutrient concentrations and can be effective where external or internal sources are not controlled. Flushing simply removes algal biomass and may be accomplished with large volume of water even if nutrient concentration is high. Nutrient enriched hypolimnetic waters may be preferentially removed through siphoning, pumping or selective discharge through sluices / gates instead of low nutrient surface water. This has been shown to be effective at accelerating P exports, reducing surface P concentrations, and improving hypolimnetic oxygen content in many cases.

Presently, the lake water is being drained during the rainy season from the upper portion of the lake by opening the lake sluice gates to control only the water level in the lake but not to control the eutrophication level. The lake water in the upper portion is comparatively less polluted and unknowingly, we are draining the less polluted water from the lake. This is a great loss to the natural purification capability of the lake. Therefore, the water from the lake bottom should be drained in rainy season by constructing a siphon system at Tallital Dat region replacing the present practice. The details of this system can be discussed if Authorities are interested.

8.3 Artificial Circulation / Hypolimnetic Aeration

Although a potential exists for control of internal loading from anoxic hypolimnia (especially with iron addition), that potential has not been adequately demonstrated as yet to place this technique under algae control. This technique is used to prevent or eliminate thermal stratification through the mixing action of the rising column of air bubbles. However, it is highly effective at increasing dissolved oxygen in the hypolimnion without destratifying the lake. But most importantly it can cause light to limit algal growth in situations where nutrients are uncontrollable and can neutralise the factors favouring dominance while blue-green algae. This is usually accomplished with an air lift device, which brings cold hypolimnetic water to the surface, where gases are exchanged, followed by its return to deep water.

This procedure can improve lake or reservoir discharge quality, allow a cold water fishery to reestablish, provide a daytime refuge for zooplankton (from a warm water fishery), and eliminate problems with iron and manganese in potable water supplies. This technique can be applied in case of Lake Nainital. In fact one proposal has already been received by NIH, Roorkee from the University of Lund , Sweeden to apply this technique on Lake Nainital. But, presently it is only at its initial stage.

8.4 Adding Copper Sulphate

This has been a commonly used treatment for lakes and water supply reservoirs suffering from algal biomass and taste and odour problems, for at least a century. It is included because it is commonly practised, rather than because it is advocated. This method can be used to control algal biomass in case of Lake Nainital.

8.5 Trapping and Retention of Sediment at the entry points

In order to restrict the entry of sediments into the lake in future, a wall of atleast 1.5 ft. height should be constructed at the entry point into the lake of such drains through which maximum sedimentation is occurred or a sediment trap structure should be set-up in the drains along the side of Mall road including Naina Devi Drain. These structures should be cleaned periodically without fail, otherwise the situation as prevails with Naina Devi drain and Riksha Stand drain will be occurred where the similar exercise has been tried but due to non-cleaning of sediments deposited due to obstruction of wall, the levels of drains have been up lifted and there is no any benefit of construction of such walls. However, the drains which run through out the year with little discharge can have the provision of a small size net (strong enough) at the lower side of the wall to allow water to enter into the lake during non-monsoon periods.

8.6 Sediment Removal

This technique can be multipurpose, resulting in control of both algae and macrophytes. It is an effective procedure and is frequently recommended for deepening shallow lakes for macrophytes control, curtailing internal nutrient loading by eliminating the enriched sediment layer or eliminating sediments contaminated with toxic substances. It has a significant advantage over nutrient inactivation in that the source is removed rather than simply covered over.

It has been observed that most of the sediment deposition takes place near the debauching points of drains which later on slide to the deeper section. Although, the slide rate of the sediment is very less, the sediments will be deposited at a faster rates at the shallower parts of the lake, as being taking place in the present, the capacity of surface area and ultimately the lake will reduce tremendously. Therefore, the deposited sediments should be removed from these areas every year during the period of summer when the lake level reduced and these areas become dry. This can bring the lake area to its original with in few years, if the removal of sediments is continued at least for a period of 10 years. Therefore, there is a need to evolve a programme to remove the sediments deposited at the banks and nearby areas in the past few decades.

The first major step for the revival of the lake would be to divert the nalahs, especially the perennial ones viz. the Naina devi mandir drain and the rickshaw stand drain. These drains, as shown and discussed above are carriers of large quantity of nutrients and other pollutants. The diversion of the drains have to effected in such a way that the surface inflow during monsoon season can be let into the lake and during other seasons be stopped from reaching the lake. This may be achieved by constructing boundary drains bordering the lake, operated by appropriate gates. This arrangement will also be useful in checking the sediment inflow to the lake.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The dissolved oxygen in the top 3 meter zone varies from 18.4 mg/1 (maximum) in rainy season, (observed in the month of August 1995) to 1.3 mg/1 (minimum) in winter (observed in the month of Dec.1994). The D.O. value below 9m is negligible.

The mean annual of total dissolved solids in epilimnion (top 3 meter zone) is 484 MT, in mesolimnion (3-9 meter zone) 1059 MT, and hypolimnion, below 9m depth is 2022 MT. Anoxic condition exists in the hypolimnion region for most part of the year. During annual turnover, the D.O. is around 2-3 mg/l in the hypolimnion region. Epilimnion however is sufficiently rich in D.O. except during winter. Therefore, it is

contemplated that the bottom water is more mineralised (and hardened) and chemically polluted than the water in the top zone.

Only Nitrate nitrogen and orthophosphate have been found as the major pollutants for Lake Nainital. Phosphate concentration increases during water turnover. This is probably released from the sediments. NO_3-N is observed in higher concentration in winter. From the available data, it appears that PO_4-P is the limiting factor. If the phosphate content of the inflow could be controlled by suitable measures, the trophic state of the lake could be ameliorated.

The major inorganic ion, calcium seems to be brought into the lake in dissolved form. This is possible as the ground water component is significant in the lake water balance. The Ca is brought in by the over saturated (with respect to Ca) groundwater tends to precipitate as Calcite between May and August or co-precipitate with Mg to form dolomite. But this aspect has not been investigated in detail, as this is outside the purview of the present objectives.

Sulphate is also present in significant concentration in the lake. The quality of springs indicate that the source for sulphate could be dissolution of minerals like gypsum. The presence of gypsum in the rock formations has been reported by various geologists. Sodium and potassium vary within very narrow range. Chloride is also not significant. Max. concentration observed in the lake is of the order of 40 mg/l, that too only once in the entire study period.

Poisonous elements like As (Arsenic) and Pb (Lead) have been detected in the sediments in considerable amounts. The over all dissolved oxygen level also reduced tremendously during winter in the lake water. The mixing of bottom and top layers water is more dominant during the period from mid December to mid January. It further intensifies during more colder years. Therefore, due to reduced D. O. level and mixing of poisonous elements in the water, the fish mortality is observed in Nainital lake almost every year but, more in colder years.

The average water quality of the lake derived using volume weights of point data is shown alongwith IS:10500 standard for domestic water supply in Table 29. The limits for both class A (without treatment) and class C (with treatment) are indicated. The pH is well within the prescribed range. The DO is very low during winter and just near the required limit in February. During other months the observed lake value fall much below the prescribed level. The TDS has been calculated as a function of electrical conductivity. The accepted calibration factor for waters not too high in sulfate is 0.59. During March, April and May, the TDS values are very close to the set standard.

The lake water is classified as hard water. The total hardness frequently exceeds the prescribed limit of the IS:10500. Except during July in all other months the Hardness of the lake water exceeds 300 mg/L. This hardness, as described above, is due to natural factors. Nitrate-Nitrogen, Chloride and Sulfate values are well within the maximum limit set for the domestic water supply. However, the trace elements Mn exceeds the limit of 0.5 mg/L during April and July. The Pb value exceeds 0.1 mg/L during all the five observation months. This may not be directly linked to anthropogenic activities. Because the Pb values in upstream springs such as Alma cottage, Chuna dhara are also above 0.1 mg/L. Therefore, the sources of Pb in lake waters may be the geological formations in the catchment area. The trace elements Zn, Co, Cu, and Fe are well within the limits, with some of these elements being non-traceable or below detection limits in the entire lake during the study period.

The public awareness programme including the tourists' should be organised at all levels in order to avoid the pollution problem and each tourist or a group of tourists should be provided written instructions regarding 'what to do and what to not do' in order to avoid unwanted pollutants and waste materials reaching into the lake. It should be clearly indicated that the suitable penalty will be imposed, if the instructions are not followed strictly. The nominal charges of the instruction booklet etc. can be charged to the tourists themselves while delivering it to the tourist at the time of entry into the city. The same instructions should be applicable to the residents of the town of Nainital strictly.

Table 29. The Water quality of Lake Nainital as compared to IS:10500 standard

				0.69*ec	Total						
Parameter		pH	DO	TDS	Hardness	Mn	Cl	SO4	NO-3	Pb	Zn
			mg/L	mg/L	mg/L						
Class-A		6.5-8.5	6	500	300	0.5	250	400	20	0.1	15
Class-C		6.5-8.5	4	1500			600	400	50	0.1	15
Lake	#Samples	[Volume Weighted Means]									
Jan	20	-	1.0	330	394	0.30	21	99	0.7	0.12	0
Feb	18	6.7	5.0	350	325		11	91	0.5		
Mar	37	8.4	2.7	500	340		16	97	0.9		
Apr		8.0	3.6	470	334	0.55	14	95		0.16	0
May	18	7.6	4.5	430	329		12	94			
June	6	8.0	3.4	460	326		10	104			
July		8.2	2.8	400	309	0.65	13	100		0.16	0
Aug	20	8.4	2.2	330	292		16	96	0.9		
Sep	20	7.2	3.2	350	338		23	85	1.2		
Oct	28	7.5	3.1	440	309		14	60	1.9		
Nov	18	7.6	4.4	420	396	0.49	15	90	1.3	0.14	0
Dec	19	8.1	0.9	330	367	0.42	13	84	1.8	0.15	0

Lot of unauthorised residences have come up all along Naina Devi Drain/ Pardha dhara spring including Bhutiya Market whose sewerage is not connected with the main sewerage system of the city. The pollutants are also reaching to the lake through Rickshaw Stand drain. Therefore house/kitchen waste are reaching the lake continuously through Naina Devi and Rickshaw stand drains causing a major pollution threat to lake water. As an immediate measure, the flow from these drains should be diverted during non-monsoon seasons when the flow is comparatively less but highly polluted. However, it will be better for the good health of Lake Nainital that the sewerage and kitchen waste disposal from the unauthorised construction and leakage from the sewerage lines be tackled on top priority.

Some amount of poisonous elements like arsenic, mercury, chromium and lead are reaching into the lake only due to the anthropological activities. The possible sources may be the laboratories where such chemicals are being used for some testing/educational purposes and later on these are being disposed off into the drains meeting to the lake or at places from were these elements reach to the lake during the rainy season. The main sources of lead may be the paint which is used on large scale for the painting of boats and other belongings/buildings. Therefore, efforts are required to spread the message to take care in this respect by the concerned people for disposing such chemicals carefully at the places/drains which do not have direct and indirect access to the lake. As already stated that the Phosphorous is a limiting factor in case of Lake Nainital, therefore, it is essential to control the external as well as internal recycling of phosphorous to control the increasing order of eutrophication in the lake. In addition, the sediment entry reduce the lake capacity alongwith the increase of different types of pollutants.

REFERENCES

Bartsch, A.F. and J.H. Gakstatter. (1978) "Standard methods - for the examination of water and waste waters, 19th edition.

Carlson, R.E. (1977). "A tropic state index for lakes", Limnol. Oceanogr., 22:361-369.

Cooke, G.D., E.B. Welch, S.A. Peterson and P.R. Newroth. (1993). "Restoration and management of lakes and reservoirs", Lewis Publishers, Boca Raton, Florida.

Dillon, P.J. and F.H. Rigler. (1974). "The phosphorus-chlorophyll relationships in lakes", Limnol. Oceanogr. 19(4):767-773.

Gupta, P.K. and Pant, M.C., 1983. Chemical Composition of Surface Sediments in a Eutrophic Lake: Nainital (UP India), Environmental Pollution (Series B), 6, pp. 95-107.

Gupta, P.K. and Pant, M.C. 1986. Analysis of the İnshore Macrozoobenhic Community in Lake Nainital U.P., India, Int. Revue ges . Hydrobiol., 761, No.1, pp. 115-125.

Gupta, P.K. and Pant, M.C. 1989. Sediment Chemistry of Lake Bhimtal U.P. India, int. Revue ges. Hydrobiol., 74, No.6, pp. 679-687.

Gupta, P.K. and Pant, M.C. 1990. Distribution and seasonal abundance of benthic macroinvertebrates in lake Nainital, U.P., India, Int. Revue ges. Hydrobiol., 75, No.4, pp. 493-506.

Hino, M. (1994). "Water quality and its control", A.A. Balkema Publishers, Rotterdam, Netherlands.

Hutchinson, G.E., 1975. A treatise on limnology, Vol.1, No.2, Chemistry of Lakes, New York, John Wiley.

Jauhari, p. and Hashmi, N.,1994. On the surficial sediments of the fresh water Nainital lake, Kumaun Himalaya, India, Proc. Indian Natn. Sci. Acad., 60, No.5, pp. 675-682.

Jones, P.J. and R.W. Bachmann. (1976). "Prediction of phosphorus and chlorophyll levels in lakes", J. Water Pollut. Control Fed., 48(9): 2176-2182.

Kemp, A.L.W., Gray, C.B.J. and Mudrochova, A., 1972.Changes C, N, P and S in the last 140 years in three cores from lakes Omrio, Erie and Huron, In: Allen H.E. and Karmer J.R. (Eds), Nutrients in natural waters, New York, Wiley, pp. 251-279.

Khulbe, R.D., and Durgapal, A., 1994. Sweage mycoflora in relation to Pollutants in Nainital, Kumaun Himalaya, Poll. Res., 13, No. 1, pp. 53-58.

Lambou, V.W., S.C. Hern, W.D. Taylor and L.R. Williams. (1982). "Chlorophyll, phosphorus, secchi disk and trophic state", Water Resources Bulletin, American Water Resources Assoc., 18(5): 807-813.

Lorenzen, M.W. (1980). "Use of chlorophyll secchi disk relationships", Limnol. Oceanogr., 25:371-372.

Mortimer, C.H., 1941. The exchange of dissolved substances between mud and water in lakes, II. J. Ecol. 29, 280-329.

Mortimer, C.H., 1942. The exchange of dissolved substances between mud and water in lakes, II. J. Ecol., 30, 147-201.

National Institute of Hydrology (1987) Physico-chemical analyses of water and waste water, User's Manual, UM-26, NIH, Roorkee, India.

Pant, M.C., Gutpa, P.K. Pande, J. Sharma P.C. and Sharma A.P.; 1981, Aspects of Water Pollution in Lake Nainital, U.P., India, Environmental Conservation, Vol.8, No.2, pp. 113-117.

Pant, M.C. Sharma, P.C. and Sharma, A.P., 1983. Physio-chemcial Limnology of Lake Nainital, Kumaun Himaloaya (U.P.) India, Acta Hydrochim. Hydrobiool. 13, No.3, pp. 331-340.

Pant, M.C., Sharma, P.C., Sharma A.P. and Gupta, P.K. 1985. Lake Nainital: An Ecological perspective, In: Singh J.S. (eds) Environmental Regeneration in Himalaya Concept and Strategies, Gyonodeya Prakashan, Nainital. pp. 339-347.

Purohit, R., 1988. Relationship between physico-chemical featuresa of water sediment and macrophytic crop of the Lake Nainital, Kumaun Himalaya, in. Khulbe R.D. (eds) Perspective in Aquatic Biology, papyrus Publishying House, New Delhi, pp. 177-186.

Purohit, R. and Singh S.P., 1981. Seasonal variation in physio-chemical limnology of shalolow zones of Nainital lake, Western Himalaya (India), Proc. Indian Natn. Sci. Acad., B. 47, No.2, pp. 194-203.

Purohit, R. and Singh, S.P. 1985. Submerged macrophytic Vegetation in relation to eutrophication level in Kumaun Himalaya, Environmental Pollution (Series A), 39, pp. 161-173.

Purhohit, R., Singh, S.P. and Upreti, N. 1986. Effect of non-removal of the macrophytic biomass on the characteristics of water and plant community in Lake Nainital, U.P., India, Int. Revue ges. Hydrobiol., 71, No.2, pp. 245-257.

Rast, W. and G.F. Lee. (1978). "Summary analysis of the North American (US portion) OECD eutrophication project: nutrient loading lake response relationships and tropic state indices", USEPA, Corvallis Environmental Research Laboratory, Corvallis, OR 454, pp. EPA-600/3-78-008.

Ryding, S.O. (1983). "Mass-balance studies to, within and from drainage basins: A new approach for water monitoring programmes (in Swedish)", Nordic Co-operative Organization for Applied Research (NORD FORSK), Helsinki, Finland, pp. 149-162.

Ryding, S.O. and W. Rast. (1989). "The control of eutrophication of lakes and reservoirs", The Parthenon Publishing Group, Paris.

Sakamoto, M. (1966). "Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth", Arch. Hydrobiol., 62: 1-28.

Stumm, W. and J.J. Morgan. (1970). "Aquatic chemistry", John Wiley & Sons, Inc., NewYork, pp. 429- 436.

Smith, V.H. (1982). "The nitrogen and phosphorus dependence of algal biomass in lakes: Empirical and theoretical analysis", Limnol. Oceanogr., 27:1101-1112.

Smith, V.H. and J. Shapiro (1981). "Chlorophyll - phosphorus relations in individual lakes, their importance to lake restoration strategies", Environ. Sci. Tech., 15:444-451.

Sawyer, C.N., 1947. Fertilization of lakes by agricultural and urban drainage, J. New England Water Works Asso., 61, pp. 109-127.

Sharma, A.K., 1981 Structural Study of Area East of Nainital with Special reference to the Hillslide Instability, Unp. Ph.D. Thesis, Kumaun University, Nainital, pp.126.

Sharma, A.P., Jaiswal, S., Negi, N. and Pant, M.C., 1982. Phytoplankton Community analysis in lakes of Kumaun Himalaya, Arch. Hydrobiol. 93, pp. 173-193.

Shewa, W. A. (1998) Eutrophication analysis of lakes of Kumaun region. M. E. Dissertation (unpublished), Dept. of Civil Engineering, Univ. of Roorkee, Roorkee.

Vollenweider, R.A., 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to nitrogen and phosohorus as factors in eutrophication, organisation for Economic Cooperation and Development, Directorate of Scientific Affairs, Paris Report, pp.220.

Vollenweider, R.A. (1968). "Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to the phosphorus as factor in eutrophication", Organ. Econ. Coop. Dev., Paris, Tech. Report No. DAS/CSI/68.27, pp. 159.

Wetzen, R. (1975). "Limnology", Saunders Publishing Co., Philadelphia, pa.

APPENDIX - E

HYDRODYNAMICS OF LAKE NAINITAL AND HYDROMETEOROLOGICAL CHARACTERISTICS

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PART-I HYDRODYNAMICS OF LAKE NAINITAL

1.0 INTRODUCTION

The term hydrodynamics in lake studies includes the processes such as turbulence characteristics of horizontal currents, seiches, thermal regime, veritical exchange and eddy diffusion in case of vertically stratified lakes and water retention time (τ). The need for the knowledge of hydraulics of lakes arises when one is interested to know the fate of pollutants or any unwanted material is introduced into the lake. However, the actual field data required are often not available to fully understand and model the processes listed above. In the present study carried out in Lake Nainital, an attempt has been made to understand the thermal regime of the lake. The thermal regime of a lake is of great significance, as temperature influences the chemical & biochemical reaction rates. It also acts as a tracer of mass transport in the water column, so that heat balance may be considered as a primary tool for estimating vertical mixing rates. The effect of minimal vertical mixing that takes place during stratified period is very important in mass balance computations. When two-layer models are adopted for the tracer mass balance computation (or nutrient budgeting) the exchange of tracers between the layers through vertical diffusion has to be accounted. This is facilitated by first computing the vertical exchange and diffusion coefficients. This can be achieved from the data on lake's thermal regime.

2.0 STUDY AREA

Lake Nainital is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalayas (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 18.52 m. The lake is subdivided into two sub-basins by 100 m wide transverse underwater ridge, 7 to 20 m below the lake surface. The volume of the lake is 8.58 Mm^3. The average annual rainfall in the basin is 248.8 cm. The area of the lake basin is 4.7 km^2 out of which the surface area of lake is 0.46 Km^2 and that of Sukhatal sub-basin is 0.75 km^2. Therefore,

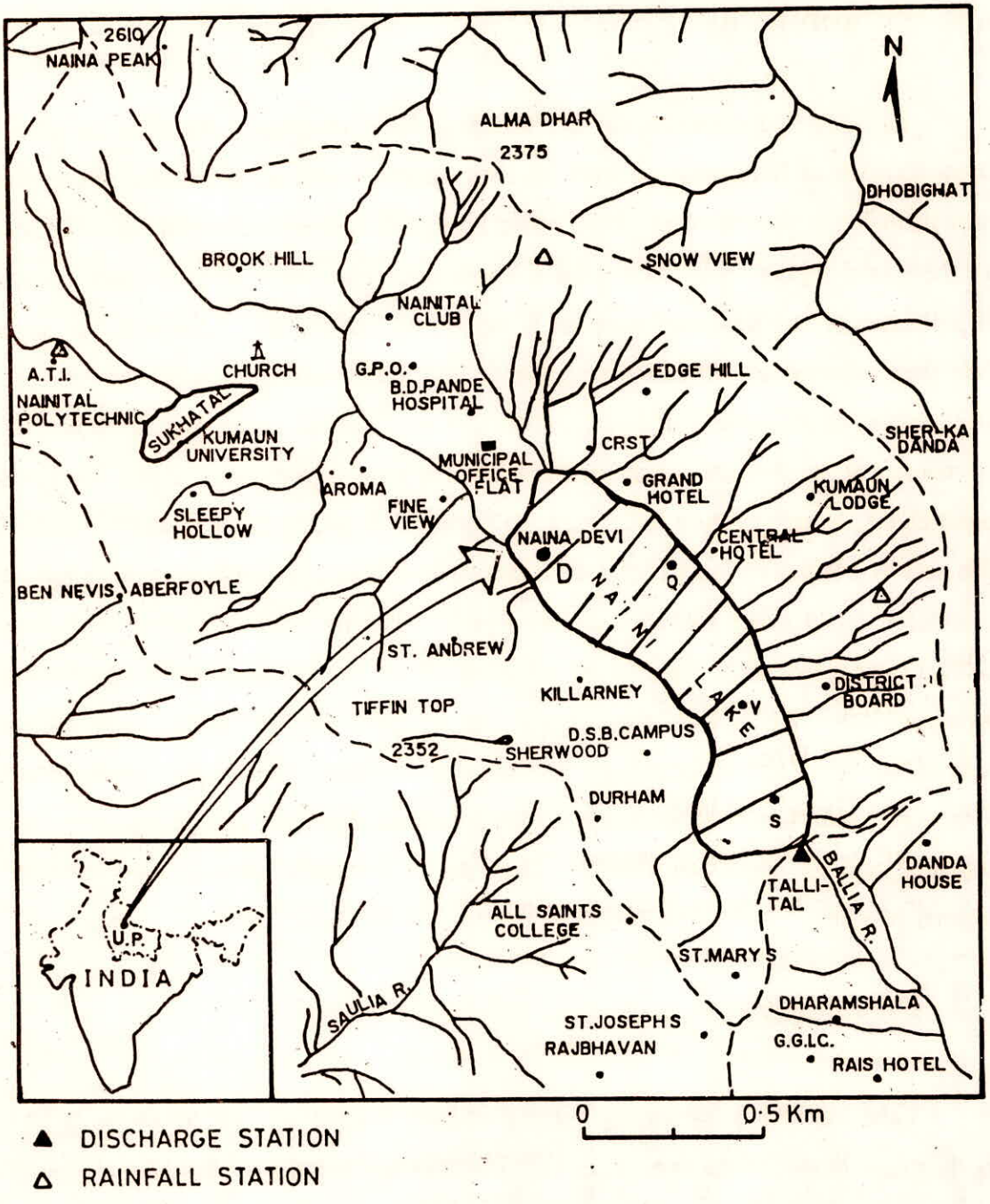


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

the exclusive catchment area of Lake Nainital is 3.49 km^2. The landuse pattern of the entire lake basin is 48.4% forest, 18.3% barren, 19.3% built land and 10.4% water bodies.

3.0 THERMAL REGIME OF LAKE NAINITAL

The thermal regimes of lakes is basically a result of heat & momentum transfer across the surface of the lake and also due to the force of gravity acting on density differences with in the lake. In general the heat transfer at the surface tends to raise the temperature during summer and lower during winter. Therefore, the temperature difference at the top and bottom give rise the mixing currents, but in summers these currents make a small depth cycle while during winter when the top layers become cooler in comparison to deeper, the sinking process starts which has greater mixing effects. Thus, the lakes of medium depth undergoes a complete mixing process and remains well mixed during winters while stratified during summers. This phenomenon is a consequence of several meteorological & other factors. The mixing and stratification behaviour of lakes is discussed below.

The depth versus temperature plots at different times of the year depict the seasonal changes in the temperature distribution in the lake. During winter, the lake may be considered as well mixed as there is negligible difference in the temperature of surface and the bottom waters. During spring, as á consequence of rise in air temperature thermal stratification is established. With the advent of summer and increase in solar radiation, the stratification is intensified. The mixing due to wind action, if any, is confined only to the surface layer (called epilimnion). The water of the bottom layer (called hypolimnion) remains cut off from the influence of wind. At this juncture the lake is said to be stably stratified. The layer that separates epilimnion and hypolimnion layers is called mesolimnion or metalimnion. This middle layer is also called thermocline. It is to be noted at this point that the term thermocline is also frequently used in the literature to denote the plane that passes through the points of maximum decrease in temperature with depth.

The stable stratification that persist during monsoon tends to become unstable during late monsoon and early winter, due mainly to falling air temperature resulting in net heat loss from the lake. During this period strong vertical mixing (convection) takes place. The process of convection, coupled with the increased action of wind results in the deepening of surface layer (sinking of thermocline) and complete mixing of lake takes place. This final phenomenon is called "winter overturn". Therefore, a moderately deep mountainous lakes undergoes two distinct stages namely complete mixed stage and a stratified stage of minimal vertical mixing.

The metabolism, physiology and behaviour of aquatic organism are related directly to the temperature of the aquatic environment. Extreme temperature restrict the growth and distribution of the plants, animals and microbes. Because of high specific heat of water, the temperature of large volumes of water change slowly. Therefore, large lakes tend to moderate the local climates. The temperature is one of the main causes of motion and mixing of lake's water therefore, the thermal structure, stratification of water masses and circulation patterns of lakes and reservoirs have profound effects on the nutrient cycling (spread of pollutants) and the distribution of dissolved gasses and the biota. For these and other reasons, the thermal structure and heat content of a lake must be known with some degree of accuracy in limnological studies..

The temperature of lake water at different depth were measured at centre points of southern and northern sub-basins of the lake viz. C2 and H2 as shown in Fig. 1. The temperatures were measured using a thermometer (0.2°C least count), that is fixed inside the standard water sampler. Measurements were made at every 3m depth starting from the water surface.

The thermal characteristics of Lake Nainital are presented in Tables 1(a) and 1(b) and are shown in Figures 2(a) and 2(b). The surface water temperatures ranges from 9.2°c to 22.4°c to in the South basin, while in the North basin, it ranges from 8.4°C to 23.6°c. The temperature in the bottom waters of South basin ranges from 8°c to 9.4°c, and in North basin from 8°c to 9.2°c. The lake is thermally well mixed during the period

Table 1a Temperature observed at north sub-basin of Lake Nainital

Point	H21	H22	H23	H24	H25	H26	H27	H28	H29
Depth (m)	0.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0
Jan.	9.4	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
Feb.	8.4	8.2	8.1	8.1	8.0	8.0	8.0	8.0	8.0
Mar.	15.4	12.4	9.6	8.6	8.3	8.2	8.2	8.2	8.2
Apr.	18.8	17.8	12.4	9.8	9.2	9.0	9.0	9.0	9.0
May	18.6	18.2	15.8	10.2	10.1	9.8	9.8	9.2	
Jun.	23.6	21.2	14.0	9.5	8.8	8.8	8.6	8.6	8.6
Jul.	22.2	22.0	18.0	10.4	9.8	9.8	9.4	9.2	9.2
Aug.	22.2	20.2	18.4	11.0	9.2	9.0	8.8	8.8	8.4
Sep.	20.2	19.3	20.0	11.7	10.0	9.4	9.4	9.0	8.9
Oct.	20.5	20.2	18.1	12.9	10.9	10.0	10.0	9.8	7.5
Nov.	13.6	13.6	13.4	13.2	9.8	9.3	9.3	9.2	
Dec.	11.6	11.0	11.0	11.0	10.8	10.4	10.2	9.0	9.8

Table 1b Temperature observed at south sub-basin of Lake Nainital

Point	C21	C22	C23	C24	C25	C26	C27	C28	C29
Depth (m)	0.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0
Jan.	9.6	9.4	9.4	9.2	9.2	9.2	9.2	9.2	9.2
Feb.	9.2	8.2	8.2	8.2	8.2	8.1	8.1	8.0	8.0
Mar.	16.0	12.2	9.4	8.6	8.2	8.2	8.2	8.2	8.2
Apr.	19.0	18.0	12.6	9.8	9.2	9.2	9.0	9.0	9.0
May	19.9	18.9	14.8	10.4	9.8	9.4	9.4	9.4	
Jun.	22.4	21.4	14.4	9.4	9.0	8.8	8.7	8.6	
Jul.	22.0	22.0	17.8	10.0	10.0	9.8	9.6	9.6	9.4
Aug.	21.6	20.0	18.4	11.6	9.4	9.2	9.0	8.8	8.8
Sep.	20.2	18.8	17.8	12.4	9.7	9.2	9.2	9.0	9.0
Oct.	20.1	19.6	18.6	13.5	10.8	10.0	9.9	10.2	10.0
Nov.	14.2	13.2	13.3	13.2	10.2	9.4	9.4	9.3	9.2
Dec.	11.4	11.2	11.0	10.8	10.8	10.4	10.2	10.2	10.0

Fig. 2a. Temperature variation in north sub-basin of Lake Nainital

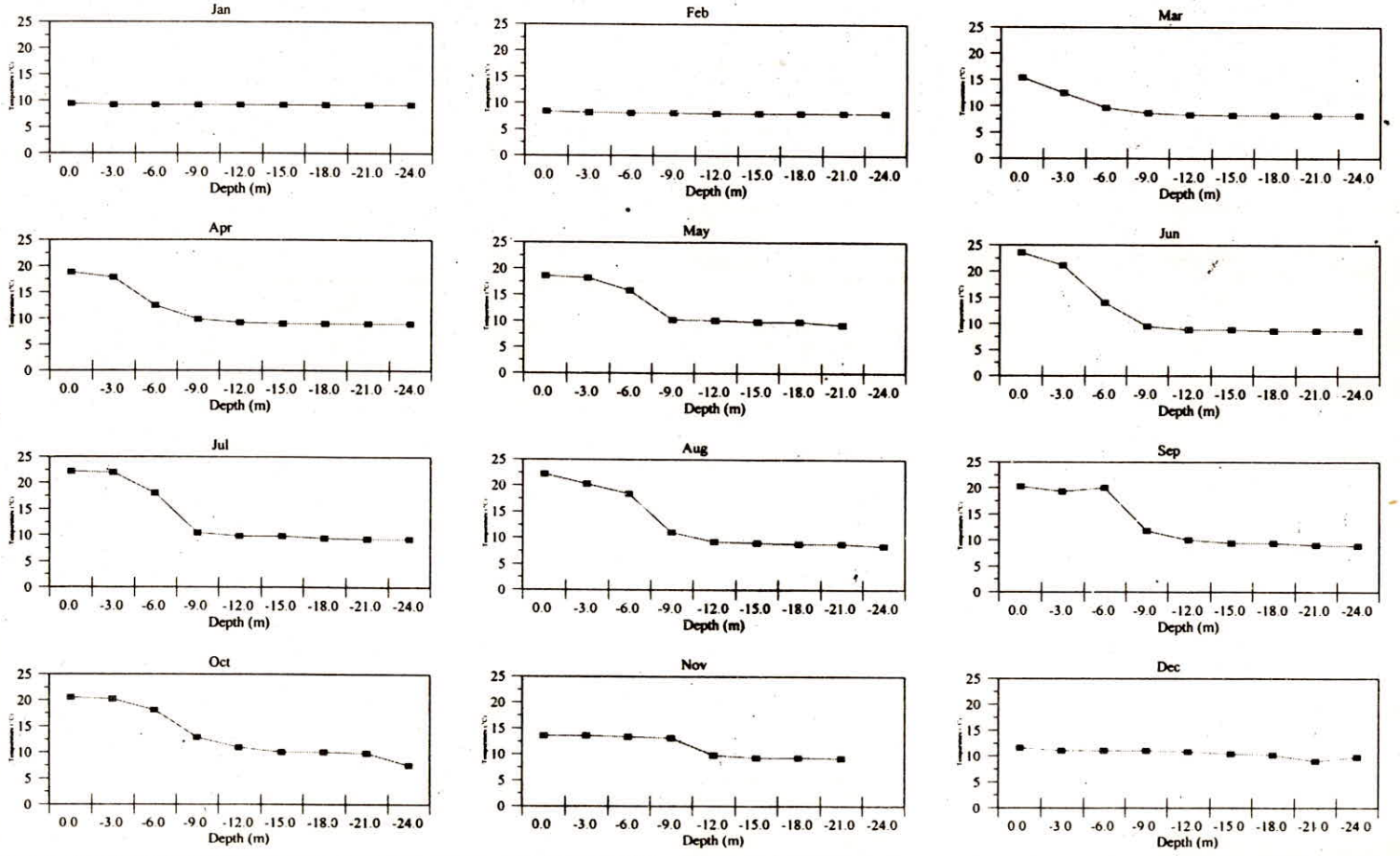
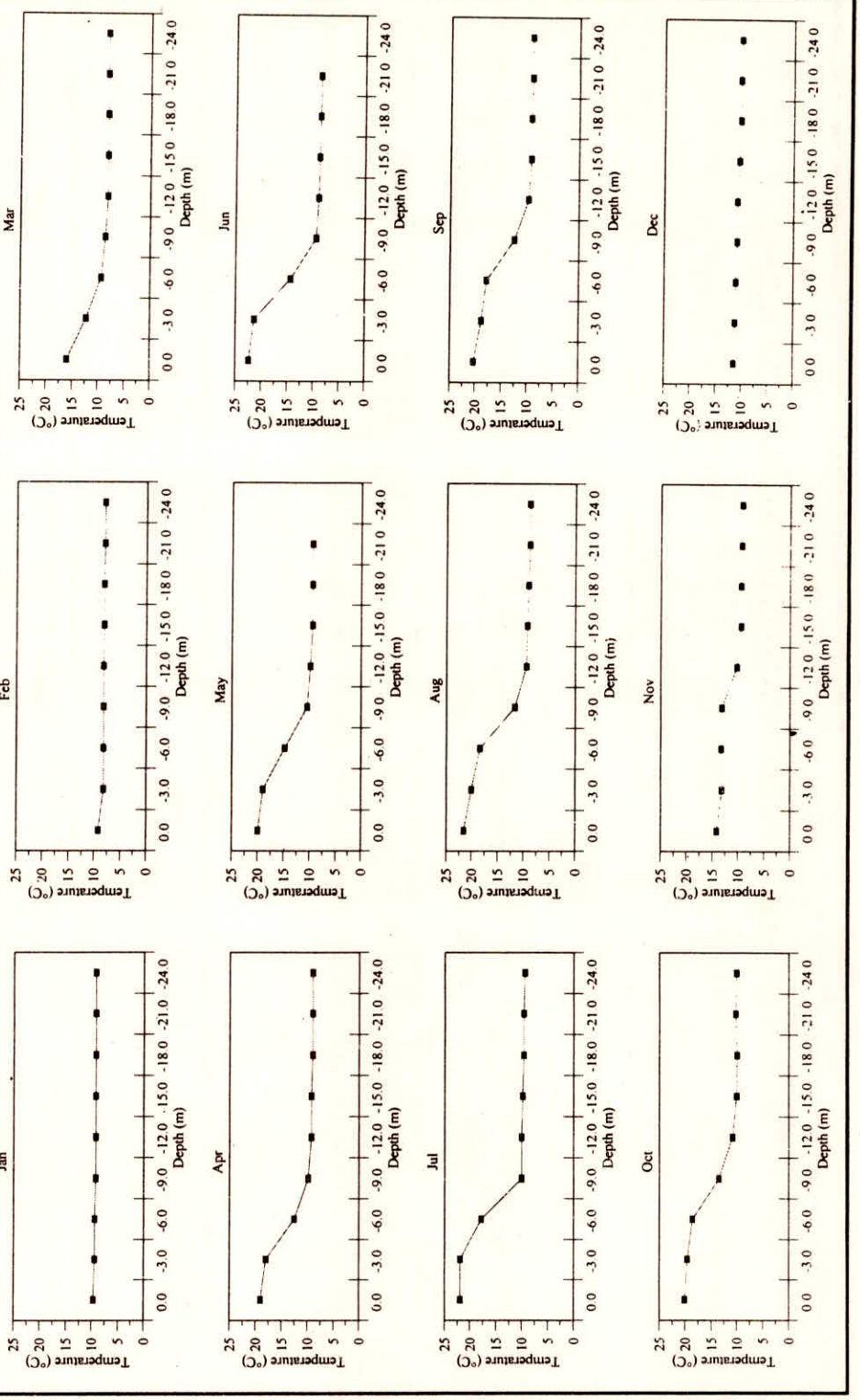


Fig. 2b. Temperature variation in south sub-basin of Lake Nainital



December to February. However the minor difference between the top and bottom waters are observed in December. During January the difference between epilimnion and hypolimnion water is just 0.4 °C. The lake continues to loose energy and in February the minimum temperature condition is observed in the entire column of lake waters. The thermocline develops during march and the onset of stratification is seen to develop in the month of April. The stratification intensifies during May. The vertical temperature difference was maximum during June when the thermocline was at 7.5 m below surface. The stratification continues so upto November, when, the thermocline sinks to the bottom. And the thermocline disappears totally during the third week of December and the winter turn over takes place. It has been reported that algal blooms are associated with this process, as the nutrients from hypolimnion, hitherto unavailable to the biota in the surface waters, is released as a consequence of turnover. It can be seen from Figures 1a and 1b, that the development of thermocline is first observed in March at 3m depth and later, it starts to sink and is observed at a depth of 13.5 m in November, before completely disappearing by the end of November.

3.1 Vertical Exchange Coefficient

The vertical exchange coefficient across the thermocline can be estimated by using the following equation (Reckhow & Chapra, 1983):

$$V_t = \frac{V_h}{2A_t\Delta_t}\,\frac{T_h^{n+1} - T_h^{n-1}}{T_e^n - T_h^n} \qquad (1)$$

Where V_t = vertical exchange coefficient (m/d)

V_n = volume of hypolimnion (m^3)

A_t = area of thermocline (m^2)

Δ_t = time interval between temperature measurement (d)

$T_h^{n+1}, T_h^n, T_h^{n-1}$ = temperature of hypolimnion at times n+1, n, n-1 (°C)

T_e^n = temperature of epilimnion at time n (°C)

The vertical diffusion coefficient (E_t) can be computed from the following equation (Reckhow & Chapra, 1983):

$$E_t = V_t \, Z_t \, \frac{10^4}{86400} \qquad (2)$$

Where E_t = vertical diffusion coefficient (cm^2/sec)

V_t = vertical exchange coefficient (m/d)

Z_t = thickness of thermocline (m)

The coefficients thus evaluated are useful for gaining information on influence of groundwater on the hydrology of a lake by adopting stable isotope mass balance technique, which is described in the subsequent sections on environmental isotopes. The estimation of vertical exchange cofficient has been made using the methods decribed above and using the observed data, and is given in Table 2.

Table 2: Vertical exchange coefficients estimated from lake temperature data

Month	Vertical exchange Coefficient (m/d)	Remarks
January	0	well mixed
February	0	well mixed
March	0.017	
April	0.007	
May	0.005	
June	0.004	
July	0.003	
August	0.007	
September	0.008	
October	0.005	
November	0.031	
Deecmber	0	well mixed

Apart from the above vertical exchange coefficients derived from the temperature data, the following important parameters have been studied to define the hydrodynamic characteristics of Nainital lake.

i) Electrical Conductivity
ii) Stable isotopes
iii) Environmental tritium

4.0 ELECTRICAL CONDUCTIVITY

Electrical conductance, or conductivity, is the ability of a substance to conduct an electric current. Specific electrical conductance is the conductance of a body of unit length and unit cross section at a specified temperature. This term is synonymous with volume conductivity and is the reciprocal of volume resistivity. The American Society for Testing and Materials defined electrical conductivity of water as the reciprocal of the resistance in mhos measured between opposite faces of a centimetre cube of an aqueous solution at a specified temperature. This definition further specifies that units for reporting conductivity shall be micromhos per centimetre at t°C. Because the definition already specifies the dimensions of the cube to which the measurement applies, the added precaution of including the length in the unit may not be essential and is often omitted in practice. The standard temperature for laboratory measurements is 25°C, but because other standard temperatures were used in the past it is important that the temperature of measurement be specified. Under the International System of Units (SI) the unit of conductivity is Siemens. The microsiemens (μS) is numerically the same as the micromho.

The specific conductance of the purest water that can be made would approach 0.5 μmho/cm, but ordinary single-distilled water or water passed through a deionizing exchange unit normally has a conductance of at least 1.0 μmho/cm. Carbon dioxide from the air in the laboratory dissolves in distilled water that is open to the air, and the resulting bicarbonate and hydrogen ions impart most of the observed conductivity. Rain

water has ample opportunity before touching the Earth to dissolve gases from the air and also may dissolve particles of dust or other airborne material. As a result, rain may have a conductance much higher than distilled water, especially near the ocean or near sources of atmospheric pollution.

The conductance of surface and ground waters has a wide range, of course, and in some areas may be as low as 50 μmho/cm where precipitation is low in solutes and rocks are resistant to attack. In other areas, conductances of 50,000 μmho/cm or more may be reached; this is the approximate conductance of seawater. Brine associated with halite may contain as much as ten times the dissolved-solids concentration of seawater.

The accuracy of field measurements of conductivity made with good portable equipment and proper attention to temperature effects should be about the same as the accuracy of laboratory measurements if the temperature is near 25°C. Conductivity devices that have been permanently installed in the field require periodic maintenance to prevent electrode fouling and (or) other interferences that may cause erroneous readings and loss of record.

The EC in the lake waters vary from a minimum of 412 μS/cm to a maximum of 742 μS/cm. EC shows a larger temporal variation than hardness, and cannot easily be related to any hydrological process. However a first look indicates that the EC during the spring, summer and early part of the monsoon is controlled by surface runoff inputs and during later part of monsoon and winter by subsurface inputs. The higher EC and hence the total dissolved solids (TDS) in the month of March may be due to heavy snowfall during the preceding months and resultant melt water flowing into the lake, as sub-surface and also as interflow. Since the groundwater (lake view spring) is also high in TDS (with an EC of 800 μS/cm to 1050 μS/cm), the lake may infact be reflecting the characteristics of its major source.

The epilimnion is low in EC in both the sub-basins when compared to the hypolimnion. The lake waters show a comparatively low EC during the late winter period

(February), which incidentally is the well mixed period. The EC ranges between 400 and 450 μS/cm. As noted above the EC is high during March (Spring season) and October and November (post monsoon) with an EC range of 700 to 800 μS/cm.

The overall variation in EC in the lake with depth and time at North and South basin centre points are given Tables 3(a) and 3(b) and shown in Figures 3(a) and 3(b). The EC ranges from 432 μS/cm to 888 μS/cm in the surface water in South basin and from 392 μS/cm to 740 μS/cm in the North basin surface water. The range is between 496 μS/cm and 711 μS/cm in the South basin bottom waters and the electrical conductivity for the North basin bottom water ranges from 510 μS/cm to 861 μS/cm. The surface electrical conductivity has been observed to be lower during monsoon and higher during winter. The vertical profiles of the electrical conductivity value closely followed the thermal regime of the lake. It becomes higher in winter because during winter turnover, bottom water mixes with surface water. The variation of temperature and electrical conductivity clearly indicate the seasonal mixing and stratification of lake.

5.0 STABLE ISOTOPES

The variation of stable isotopes, particularly $\delta^{18}O$ gives a more clear picture on the hydrodynamics of the lake. The advantage of using the stable isotopes of oxygen is that they are conservative in nature and also forms part of the water molecule itself. The samples for stable isotope analyses were collected from the lake in 20 ml plastic vials and tightly sealed. The collected samples were analysed by Stable Isotope Ratio Mass Spectrometer at the Isotope Division, Bhabha Atomic Research Centre, Mumbai, India. The samples were analysed using the CO_2 equilibration method for $\delta^{18}O$. The procedure followed for the isotope analyses at the BARC laboratory has been presented in detail by Navada and Kulkarni (1989). The measurement precision for $\delta^{18}O$ was ± 0.1 ‰. All the isotope data presented in this report correspond to Vienna - Standard Mean Oceanic Water.

Table 3a Observed electrical conductivity at north sub-basin of Lake Nainital

Point	H21	H22	H23	H24	H25	H26	H27	H28	H29
Depth (m)	0.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0
Jan.	460.0			470.0			480.0		520.0
Feb.	550.0	540.0	510.0	500.0	510.0	510.0	500.0	510.0	500.0
Mar.	740.0	760.0	720.0	700.0	750.0	740.0	720.0	750.0	800.0
Apr.	470.0	480.0	440.0	410.0	400.0	400.0	400.0	410.0	420.0
May	550.0	540.0	510.0	450.0	470.0	490.0	500.0	500.0	530.0
Jun.	610.0			620.0					720.0
Jul.									
Aug.	390.0	420.0	450.0	530.0	540.0	540.0	540.0	540.0	570.0
Sep.	440.0	490.0	430.0	510.0	510.0	520.0	490.0	500.0	510.0
Oct.	520.0	510.0	570.0	660.0	660.0	670.0	660.0	680.0	710.0
Nov.	580.0				640.0			650.0	
Dec.	480.0	480.0	490.0	490.0	530.0	540.0	530.0	540.0	570.0

Table 3b Observed electrical conductivity at south sub-basin of Lake Nainital

Point	C21	C22	C23	C24	C25	C26	C27	C28	C29
Depth (m)	0.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0
Jan.	432.0	441.0	454.0	462.0	474.0	485.0	492.0	508.0	515.0
Feb.	516.0	486.0	502.0	513.0	503.0	514.0	482.0	480.0	496.0
Mar.	888.0	830.0	795.0	760.0	773.0	723.0	772.0	769.0	711.0
Apr.	440.0	420.0	400.0	380.0	370.0	370.0	370.0	360.0	380.0
May	570.0	570.0	550.0	540.0	490.0	510.0	520.0	500.0	500.0
Jun.	600.0			670.0				730.0	
Jul.	542.0	566.0	703.0	830.0	828.0	820.0	829.0	841.0	847.0
Aug.	392.0	415.0	445.0	538.0	540.0	544.0	541.0	546.0	553.0
Sep.	440.0	500.0	430.0	500.0	500.0	490.0	480.0	490.0	490.0
Oct.	510.0	520.0	560.0	630.0	660.0	660.0	660.0	670.0	680.0
Nov.	567.0	572.0	560.0	592.0	644.0	645.0	655.0	660.0	598.0
Dec.	450.0	430.0	460.0	490.0	580.0	600.0	610.0	782.0	988.0

Fig. 3a Variation of electrical conductivity in north sub-basin of Lake Nainital

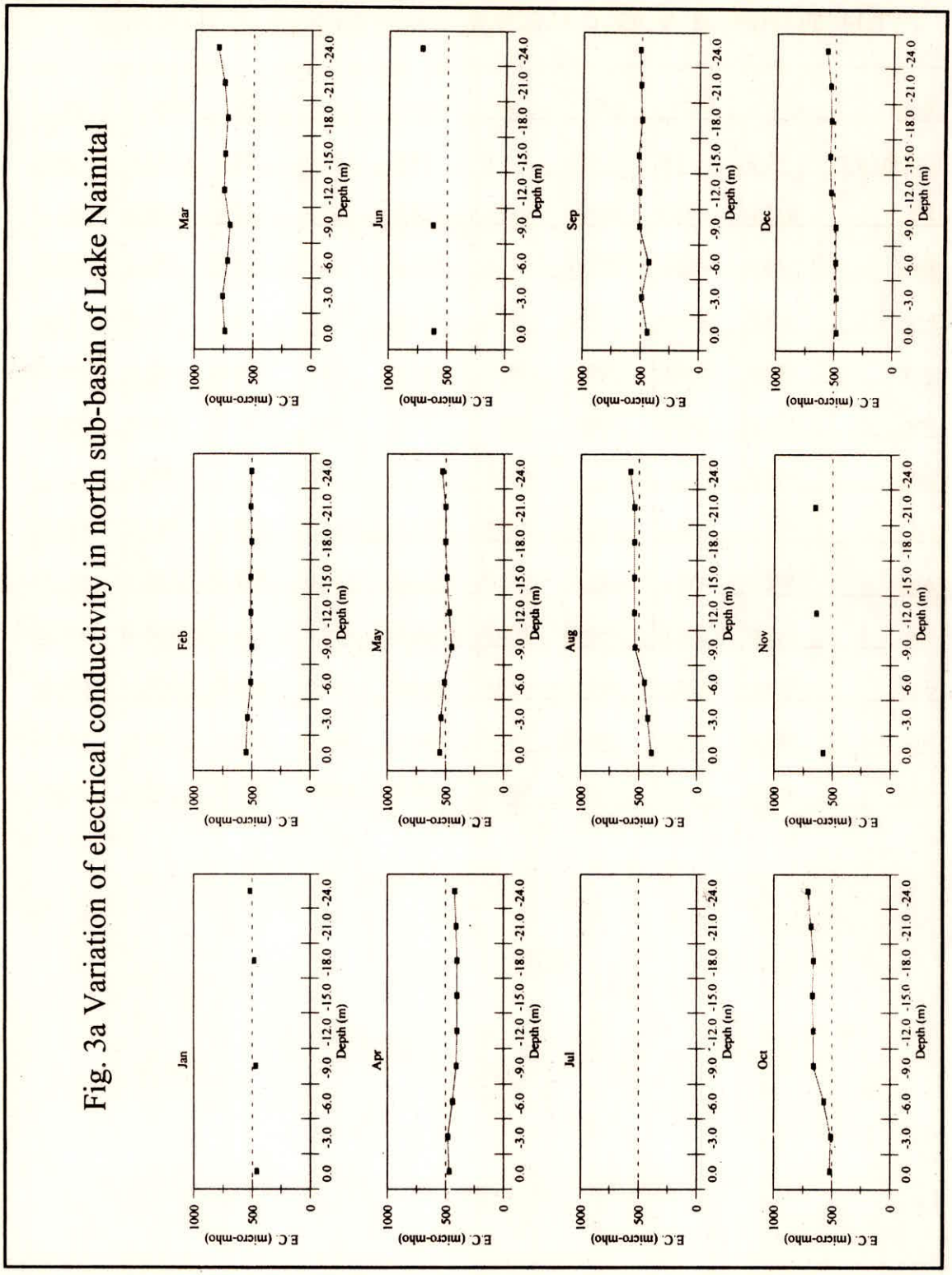
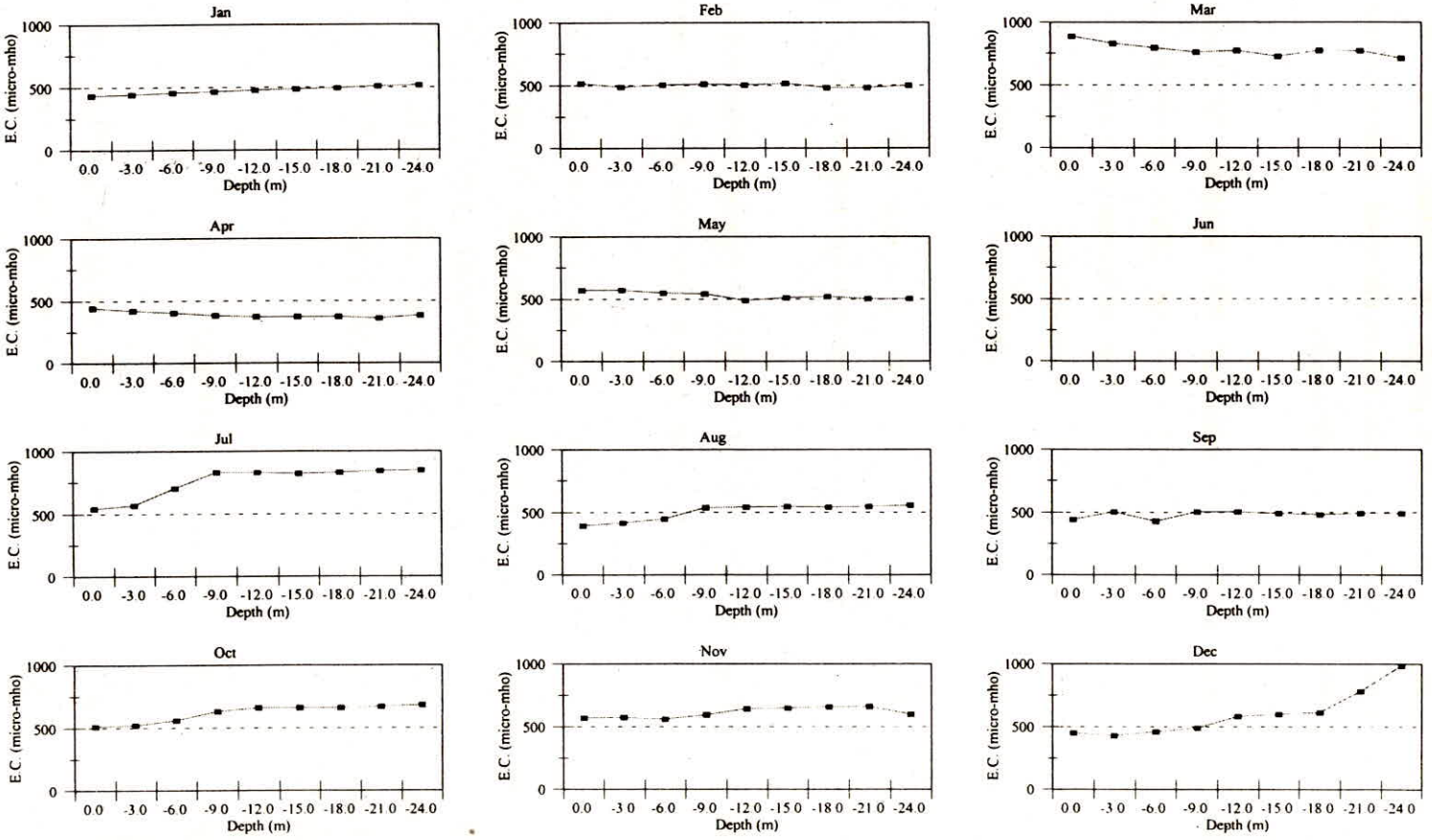


Fig. 3b Variation of electrical conductivity in south sub-basin of Lake Nainital



a. During May (summer) 1994, when the isotopic enrichment due to evaporation in the surface layers takes place, the surface value was -6.21‰, which is significantly higher than the values observed in the mesolimnion or hypolimnion (-7.26‰ & -7.77‰ respectively).

b. During October (post monsoon) 1994, when the thermocline was at a depth of approximately 10.5 m below the lake surface, the isotope values indicate that the diffusion, does takes place. That the thermocline was not a effective barrier for mixing. The values of $\delta^{18}O$ observed were -6.62‰, -6.94‰ and -6.81‰ in the epilmnion, mesolimnion and hypolimnion, respectively.

c. During December (winter) 1994, the isotope values observed were -9.63‰, and -9.75‰ for the surface and bottom water respectively.

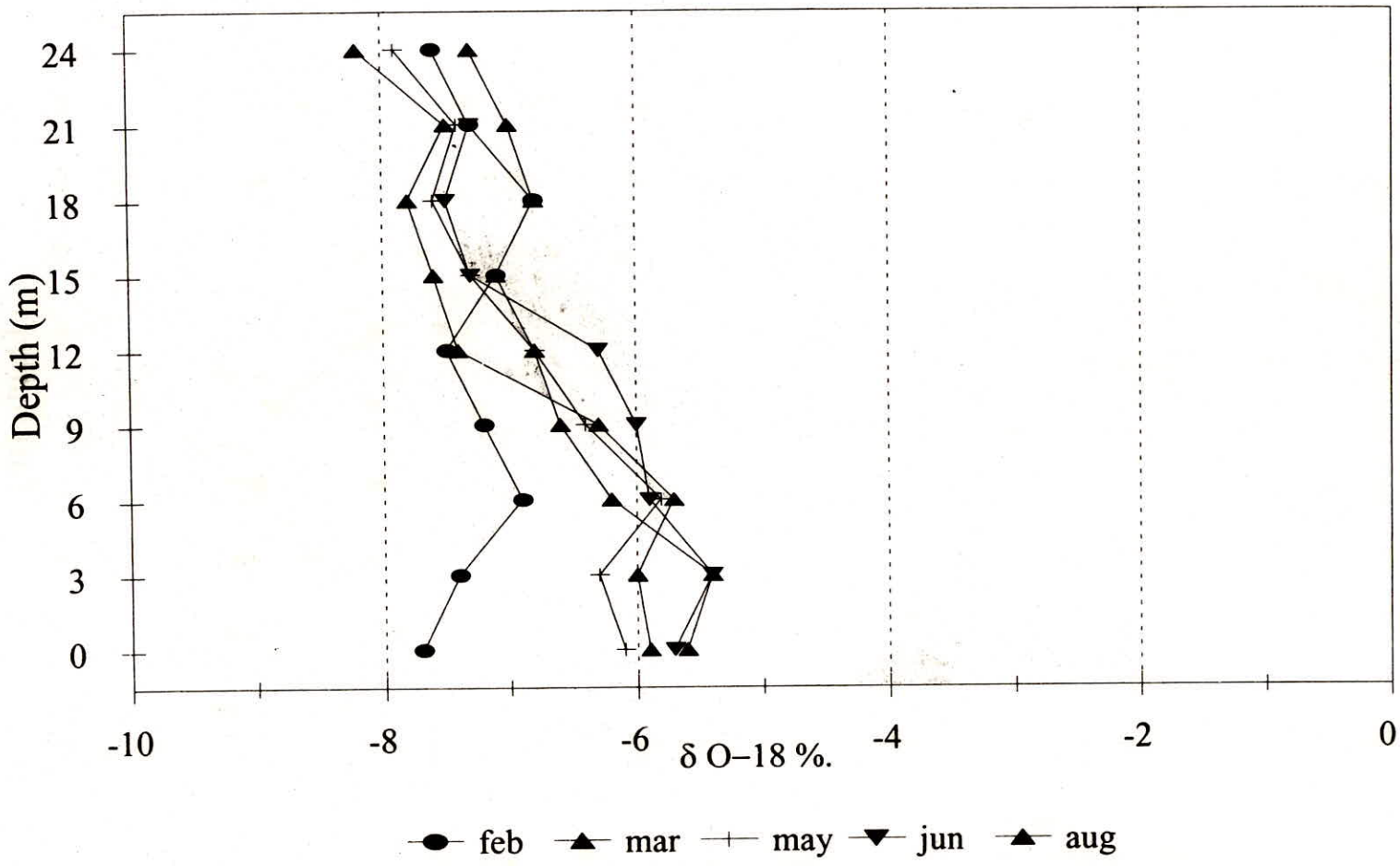
d. During February (winter) of 1994, a depleted values have been observed in both surface and bottom of the lake (-8.15‰ and -8.09‰, respectively).

Though the values given above are to be used with caution, in the absence of substantiative data, it is clear that except for May, during the other periods for which partial results are presented above, the diffusion takes place across the thermocline. The lake is well mixed during winter. The wide range in the isotopic values indicate a short residence time for the lake. The vertical variation of $\delta^{18}O$ and δD in different months are shown in figuers 4a and 4b.

6.0 ENVIRONMENTAL TRITIUM

The dynamics of a lake can be studied using tritium water balance model. If a lake is considered isotopically well mixed then, the tritium content of the lake outflow (both surface and subsurface) is equal to that of the lake; usually this is a case for a water body wherein mixing is fast relative to the residence time of water. Assuming that the lake is at hydrological steady state, the tritium balance corresponding to the basic

Fig. 4a Variation of stable isotope (O-18) with depth in Lake Nainital



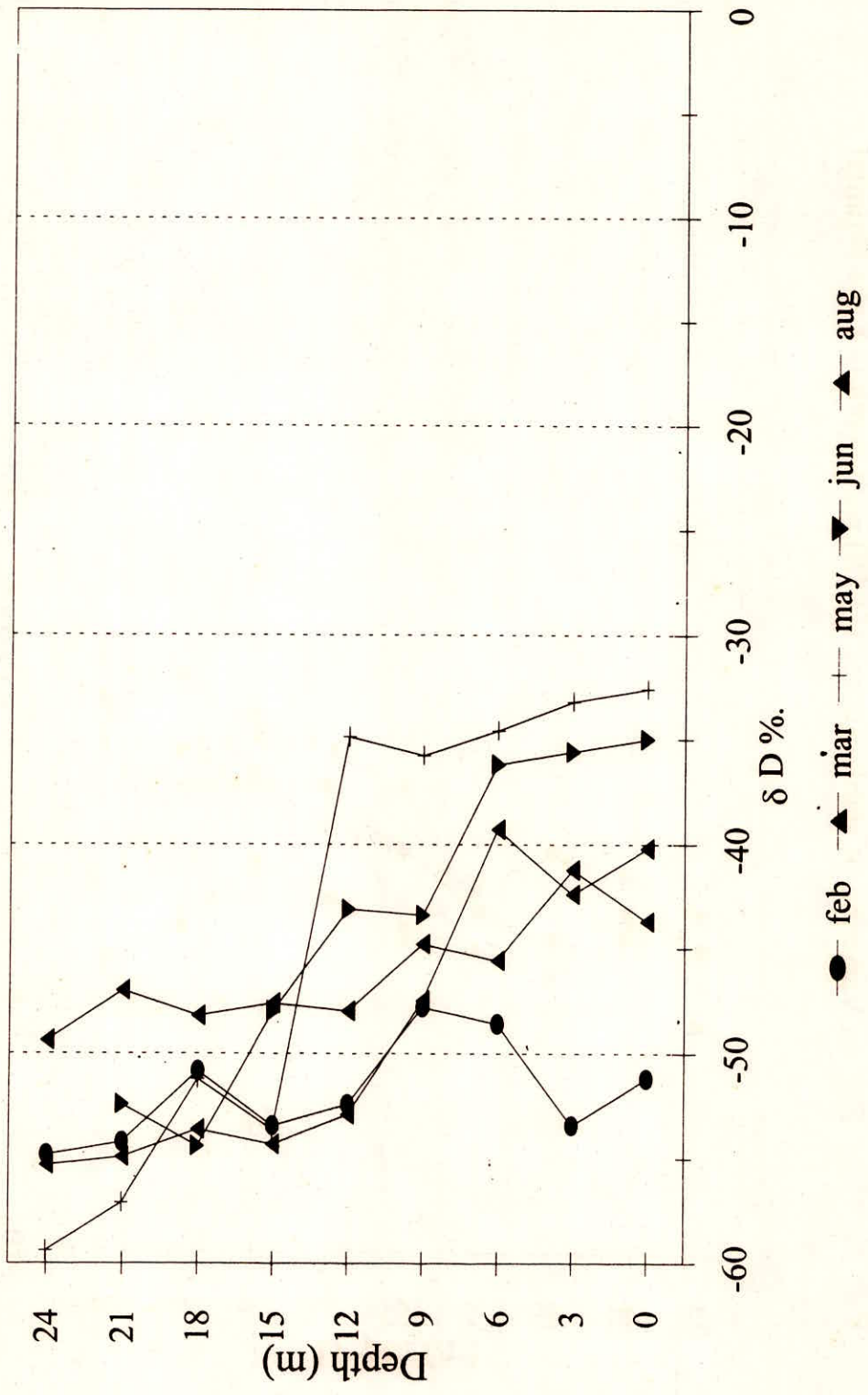


Fig. 4b Variation of stable isotope (D) with depth in Lake Naimital

water balance of a lake can be written as:

$$V dT_L/dt = T_S S_i + T_{SS} SS_i + T_P P_i - T_L S_o - T_L SS_o - T_E E_o - T_L . \lambda . V \qquad (3)$$

where T represents the respective tritium content of the water balance components (in tritium units, TU) and the last term being the decay term (where λ is the radioactive decay constant of tritium = 0.0557 a^{-1}) . T_E given in the above equation can be defined as,

$$T_E = (\alpha . T_S - h . T_A)/\{ \alpha_K (1-h)\} \qquad (4)$$

where, h is the relative humidity, T_A is the tritium content of water vapour over the lake, α is the equilibrium fractionation factor for tritium between liquid and vapour phases (=0.9), T_L is the tritium content of the lake water and α_K is the kinetic fractionation factor (=1.1). The change produced by evaporation and molecular exchange can be positive or negative, depending on the relative tritium content of lake water and precipitation. If the eqn. 3 is divided by volume V, we get

$$dT_L/dt = T_S K_{Si} + T_{SS} K_{SSi} + T_P K_{Pi} - T_L K_{So} - T_L K_{SSo} - T_E K_{Eo} - T_L . \lambda . \qquad (5)$$

where K represents the ratio of the volume of water that enters or leaves the water in different forms to that of the lake volume. For a steady state system (i.e., no increase or decrease of volume with time) , the water retention time (τ) is defined as the inverse of some of either K_{Si} , K_{SSi} and K_{Pi} or of K_{So} , K_{SSo} and K_{Eo} . Since, the lake volume is assumed to be a constant, it can be obtained that;

$$K_{Si} + K_{SSi} + K_{Pi} = K_{So} + K_{SSo} + K_{Eo} \qquad (6)$$

In addition, the tritium content in water vapour over the lake may be assumed to be in equilibrium with local meteoric water ($T_A = \alpha T_P$) which may be considered a reasonable assumption incase of a mid continental temperate zone lake. If we assume piston flow of groundwater,

$$T_{G,t} = T_{P,t-\tau}\ e^{-\lambda\tau} \qquad (7)$$

where $T_{G,t}$ is the tritium content of the groundwater at any time t and $T_{P,t-\tau}$ is the tritium content of the precipitation at a time $t-\tau$ (where τ is the residence time of ground water). Now discretising eqn. 5 in a time step of one year, we get,

$$T_{L,t} - T_{L,t-1} = T_{p,t}.K_{pi} + T_{s,t}.K_{so} + T_{p,t-\tau}.e^{-\lambda\tau}.K_{ssi} - [\{-\alpha T_{L,t} - h.\alpha.T_{p,t}\}/\{\alpha_k(1-h)\}].KE_O - T_{L,t}.K_{sso} - T_{L,t}.K_{so} - T_{L,t}\lambda \qquad (8)$$

In case, the lake catchment is not comparatively large in size, $T_{S,t} = T_{P,t}$, i.e., the stream or channel water undergo negligible change in their tritium content during their travel from the catchment to the lake in the form of atmospheric exchange. Therefore, the above equation can be arranged to get,

$$T_{L,t}.[1+\alpha.K_{EO}/\{\alpha_k(1-h)\} + K_{sso} + K_{so} + \lambda] = T_{L,t-1} + T_{p,t-\tau}.e^{-\lambda\tau}.K_{ssi} + T_{p,t}[K_{pi} + K_{si} + \{h.\alpha.K_{EO}/\alpha_k(1-h)\}] \qquad (9)$$

Using eqn. 6, the most difficult water balance components, namely K_{SSo} and K_{SSi}, in the above equation are expressed in terms of T as, $K_{sso} = (1/T) - K_{so} - K_{EO}$ and that $K_{SSi} = (1/T) - K_{Si} - K_{Pi}$ respectively. Therefore,

$$T_{L,t}[1-K_{EO}\{1-\alpha/\{\alpha_k(1-h)\}\} + (1/T) + \lambda] = T_{L,t-1} + T_{p,t}[K_{pi} + Ks_i + h.\alpha.K_{EO}/\{\alpha_k(1-h)\}] + T_{p,t-\tau}.e^{-\lambda\tau}\{(1/T) - K_{si} - K_{pi}\} \qquad (10)$$

The tritium contents of precipitation, spring water, surface runoff, lake water (at different depths and locations) and the water which is either drained or flowout in the form of streams are measured at different times. The tritium contents in the vapours can be obtained by using eqn. 4. By using the above equations and the different measured values of tritium contents, not only the values of SS_i and SS_o can be measured but the residence time of groundwater as well as residence time of water in the lake can be

computed which may be of great importance to understand the hydrological behaviour of the lake and for its management.

The above model has been tried considering lake as a single box (well mixed). The environmental tritium content of Lake Nainital was 11.2 TU during December, 1994. The environmental tritium content of rainfall was interpolated from the IAEA data for New Delhi and Kabul (Afghanistan) stations for the period from 1963 to 1993. The environmental tritium content of rainfall for the year 1994 was actually measured at the Lake basin. The model output indicates that for a mean residence time of the lake water of 2.1 years, the mean residence time of groundwater in the basin is 3 years. However, it requires further verification considering lake as a two box model, as the Lake Nainital remains stratified for 8 months in a year. The environmental tritium analyses of lake water and groundwater for different periods including the develoment of two-box model is under progress, and the results may be reported later on.

7.0 WATER RETENTION TIME

The water retention time (τ) of a lake is defined as the ratio of total annual outflow / inflow to the total volume of the lake and can be computed if values of all the inflow or outflow components are known. In case of Lake Nainital the volume of the lake is 18.52 m. The total outflow during the years 1994 and 1995 are 9.48 m and 10.76 m, respectively (NIH,1999, Report on Water Balance of Lake Nainital). The water retention time during the years 1994 and 1995 are then 1.95 years and 1.72 years, respectively.

PART-II HYDROMETEOROLOGICAL CHARACTERISTICS

1.0 HYDROMETEOROLOGICAL INSTRUMENTS INSTALLED IN THE LAKE CATCHMENT

In order to study the nature of variation of various hydrometeorological parameters, one data acquisition system with 13 sensors was installed at the Naini lake site. Some of these sensors were installed inside the lake using a buoy (drum type). The details of the data acquisition system and sensors installed are given below while the installation of the sensors etc have been shown in Fig. 5 and 6. The various sensors attached with the DAS are as follows .

(i) Water level - A 10 m
(ii) Water level - B 30 m
(iii) Sedimentation (g)
(iv) Relative humidity (%)
(v) Rainfall (mm)
(vi) Evaporation (mm)
(vii) Water temperature (°C)
(viii) Under water solar radiation
(ix) Air temperature - A (°C)
(x) Air temperature - B (°C)
(xi) Wind velocity (km/hr)
(xii) Wind direction (Degree)
(xiii) Solar radiation (W/m)
(xiv) Soil moisture (%)

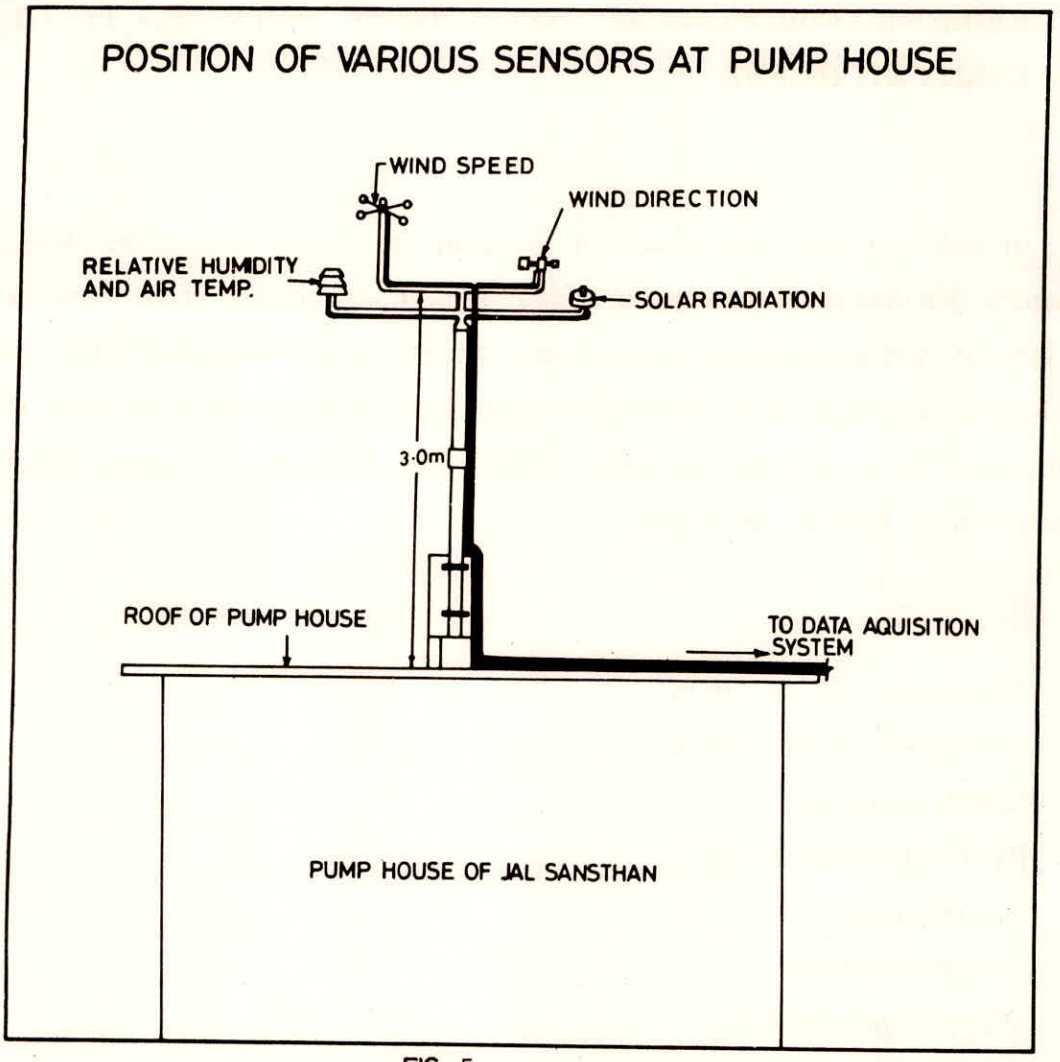

POSITION OF VARIOUS SENSORS AT PUMP HOUSE
WIND SPEED
WIND DIRECTION
RELATIVE HUMIDITY
AND AIR TEMP.
SOLAR RADIATION
3·0m
ROOF OF PUMP HOUSE
TO DATA AQUISITION
SYSTEM
PUMP HOUSE OF JAL SANSTHAN

FIG. 5

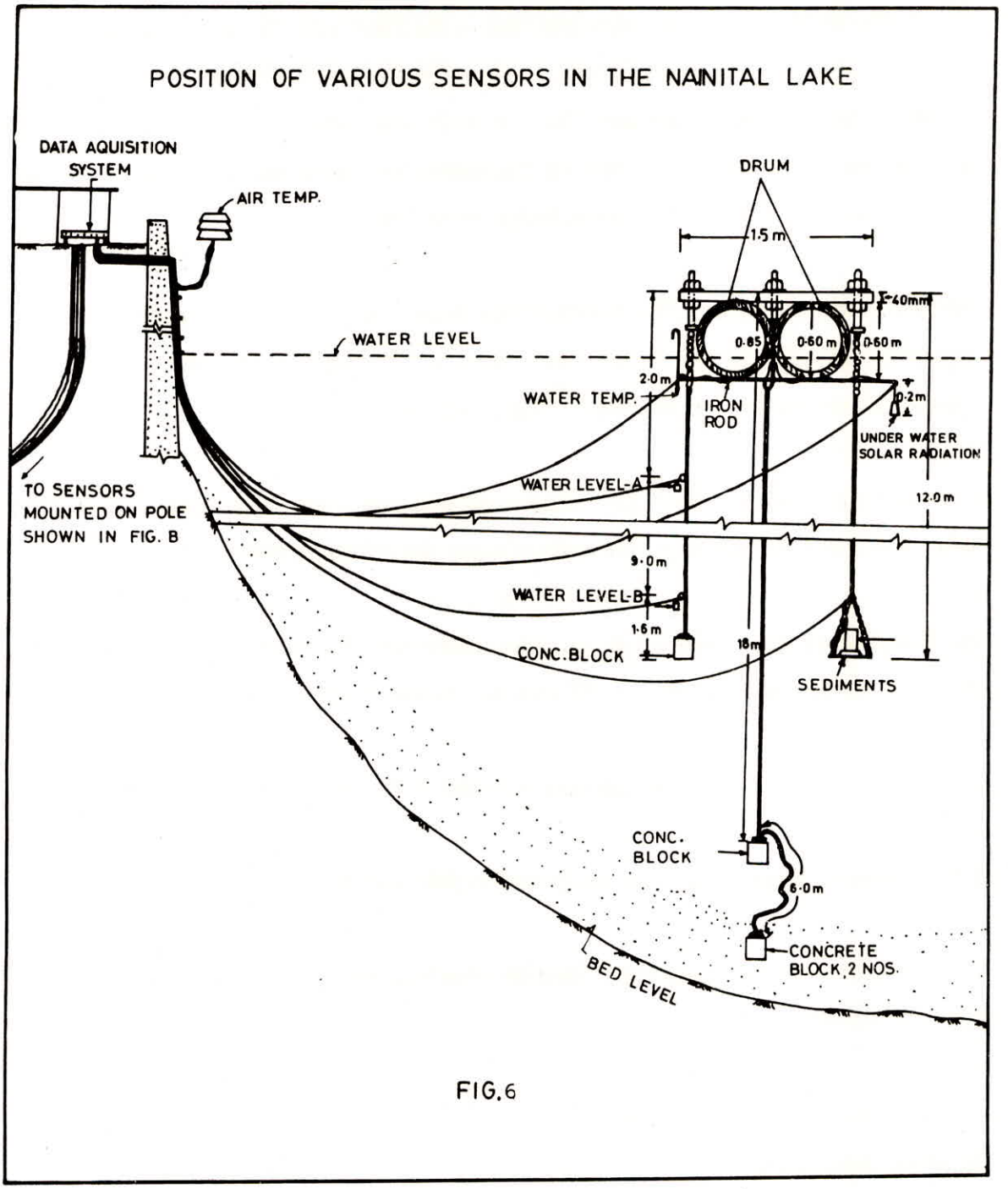

POSITION OF VARIOUS SENSORS IN THE NAINITAL LAKE
DATA AQUISITION SYSTEM
AIR TEMP.
DRUM
1.5 m
40mm
WATER LEVEL
0.85
0.60 m
0.60 m
2.0 m
WATER TEMP.
IRON ROD
0.2m
UNDER WATER SOLAR RADIATION
TO SENSORS MOUNTED ON POLE SHOWN IN FIG. B
WATER LEVEL-A
12.0 m
9.0 m
WATER LEVEL-B
1.6 m
CONC. BLOCK
18m
SEDIMENTS
CONC. BLOCK
6.0 m
CONCRETE BLOCK, 2 NOS.
BED LEVEL

FIG. 6

1.1 Sensors installed inside the lake

The following sensors were installed in the Lake with the help of a buoy.

(i) Water level (A) & (B) sensors: The two water level sensors having maximum range of 10 m and 30 m range of water level fluctuation were installed at a depth of 2 m and 11 m below the water surface respectively for this study.

(ii) Sedimentation sensor: The sedimentation sensor having a bucket for weighing the sediment deposited on that bucket was placed at 12m depth from water surface. The capacity of the bucket was to collect 1 kg of sediment.

(iii)Water temperature sensor: This sensor was attached to the buoy & was kept at 0.5m below the water surface to get the surface water temperature continuously.

(iv) Under water solar radiation sensor: This sensor was also placed at 0.5m depth under the water surface attached with a MS rod, which was fitted to the buoy.

The positions of various sensors installed in the lake are shown in Fig.-6.

1.2 Sensors installed at lake bank and in lake catchment

The following sensors were fitted on a 6m high pole from the Lake water surface at the Jal Sansthan office.

(i) Wind velocity (Km/ph) sensor
(ii) Wind direction sensor
(iii) Relative humidity sensor
(iv) Air temperature sensor
(v) Solar radiation sensor

Apart from the above, the rainfall sensor was connected with the data acquisition system at the Lake shore, just 3m above the Lake water surface, to get precipitation data along with the evaporation sensor. The soil moisture sensor was installed near the Lake shore on the ground by digging two holes 1m apart & 1 feet deep and placing the sensor plates in it for continuous record of soil moisture. One more air temperature sensor was placed 2 m above the normal lake water surface near the Lake shore to get a continuous record of air temperature above the Lake water surface.

One stevenson screen fitted with dry bulb and wet bulb thermometers and maximum - minimum thermometer was installed at the Jal Sansthan Pump House roof. One evaporimeter manually operated was also installed in addition to the one attached to the DAS as described above.

The positions of various sensors mounted at the pole are shown in Fig.- 5. In addition to the above sensors, following instruments were also installed at various locations in the lake catchment.

(a) Automatic water level recorders:

Two water level recorders were installed on both ends of the Lake to get Lake water fluctuations for water balance studies. One water level recorder was fixed at the western end of the Lake behind the Gurudwara, Mallital while the other was installed at the eastern end of the Lake near the bus stand, Tallital. The third water level recorder was fixed at the Naini drain (nalah No.23) in addition to a staff gauge installed nearby to get the total inflow in the Lake through the drain.

(b) Raingauge network:

Three self recording rain gauges (SRRG) were installed in the Naini Lake catchment. Sites were selected on the basis of slopes, safety of equipment and accessibility of sites. Out of the three SRRGs, one was installed at Ratan Cottage near

Birla Vidya Mandir, the second at Alma Cottage and the third at ATI Building in the Ardwell Camp.

2.0 LONG TERM HYDROMETEOROLOGICAL RECORD

In order to study the Hydrometeorological characteristics of Nainital lake and the surrounding region, a continuous monitoring of the above parameters was carried out at the lake shore and at other locations in the nearby area. The data of few meteorological parameters have also been collected from other organisation like, UP PWD, Nainital and Observatory etc.

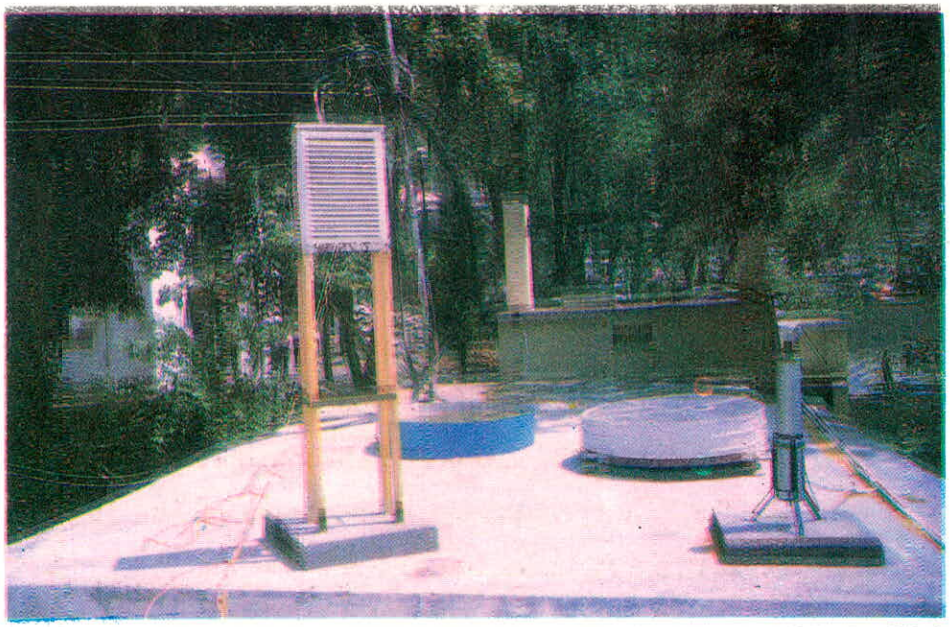
Long term meteorology data is not available for the lake site. However, reliable data on several parameters are available for the Manora site, which located at about 2 km south of Lake Nainital and at an elevation of 1951 m above msl. The daily maximum and minimum data for temperature, relative humidity and atmospheric pressure, daily sunshine hours, daily rainfall are available for the period 1966 to 1995. The hourly wind velocity data is available for the period 1982 to 1996. The data has been obtained from UP State Observatory and the same has been processed for deriving such information required for the estimation of potential evapotranspiration. This information is required for the computation of rainfall-runoff relationship, the details of which are presented in the water balance part.

2.1 Air Temperature

From the 30 year averages of monthly mean temperature, it is observed that the hottest month is May and the coldest month is January in the Nainital region. The maximum temperature in January is 8°C and during May is 21.5°C. The highest monthly mean temperature in the 30 year period has been observed in the month of May 1974 (25.6°C) and the lowest temperature in the month of Jan. 1975 (4.2°C). The average values are presented in Tables 4(a) to 4(c) and in Fig. 7.



A View of Datalogger with Various Sensors Installed at Mallital Bank of Lake Nainital



A View of Different Sensors Installed at the Mallital Bank of Lake Nainital

Table 4a: Mean Monthly Air Temprature with Standard Deviation (in °C) [1966-75]

	1966		1967		1968		1969		1970		1971		1972		1973		1974		1975	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	7.37	3.29	7.94	3.18	6.61	2.73	9.69	3.57	7.36	3.40	6.82	3.65	9.48	3.63	8.34	3.54	6.59	3.85	4.24	2.83
Feb	10.41	3.85	11.77	3.97	8.75	3.55	12.39	4.27	8.67	3.81	10.22	4.28	7.64	4.07	10.02	4.04	7.74	4.58	8.39	3.91
Mar	12.89	4.26	12.33	3.91	13.73	4.04	18.06	5.39	14.09	4.99	15.40	5.10	16.44	5.02	14.10	4.85	14.75	5.46	14.56	4.73
Apl	18.14	4.36	17.79	4.15	18.65	4.77	18.86	4.75	20.75	5.65	17.75	4.98	17.79	5.04	21.59	5.93	20.53	5.60	20.70	5.45
May	23.61	4.39	22.62	4.27	23.07	5.93	21.44	4.82	21.02	5.19	18.35	4.73	24.03	5.84	20.98	6.27	25.62	5.90	22.20	6.15
Jun	23.37	3.85	22.60	4.30	19.63	3.75	23.79	5.27	18.06	4.08	18.93	3.02	23.46	5.38	18.23	3.18	22.85	5.30	20.19	4.08
Jul	20.80	3.32	18.52	2.21	19.57	2.59	20.13	2.31	20.68	3.40	18.46	2.33	19.97	3.23	19.50	2.73	19.90	2.82	18.13	2.95
Aug	19.90	2.28	21.28	2.02	19.37	2.90	19.10	2.43	20.14	2.60	18.65	2.24	18.88	2.82	18.78	2.92	20.10	2.42	18.07	2.46
Sep	19.17	3.50	19.33	2.94	19.08	3.46	16.68	2.54	20.22	3.28	18.83	3.50	17.66	3.28	18.13	2.79	19.27	3.39	16.26	2.66
Oct	16.55	3.64	16.18	4.34	17.07	4.84	15.94	4.45	16.67	3.78	16.28	3.82	15.76	3.87	15.84	3.58	16.91	4.06	15.37	4.63
Nov	12.84	4.04	13.24	4.06	13.10	3.88	12.96	3.48	12.43	4.26	11.58	3.68	12.53	3.57	12.11	3.78	11.80	4.22	11.24	4.26
Dec	9.65	2.82	10.52	2.98	10.41	3.40	9.56	3.71	9.86	3.77	9.38	3.52	10.97	3.50	8.58	3.76	7.28	3.46	8.87	3.89

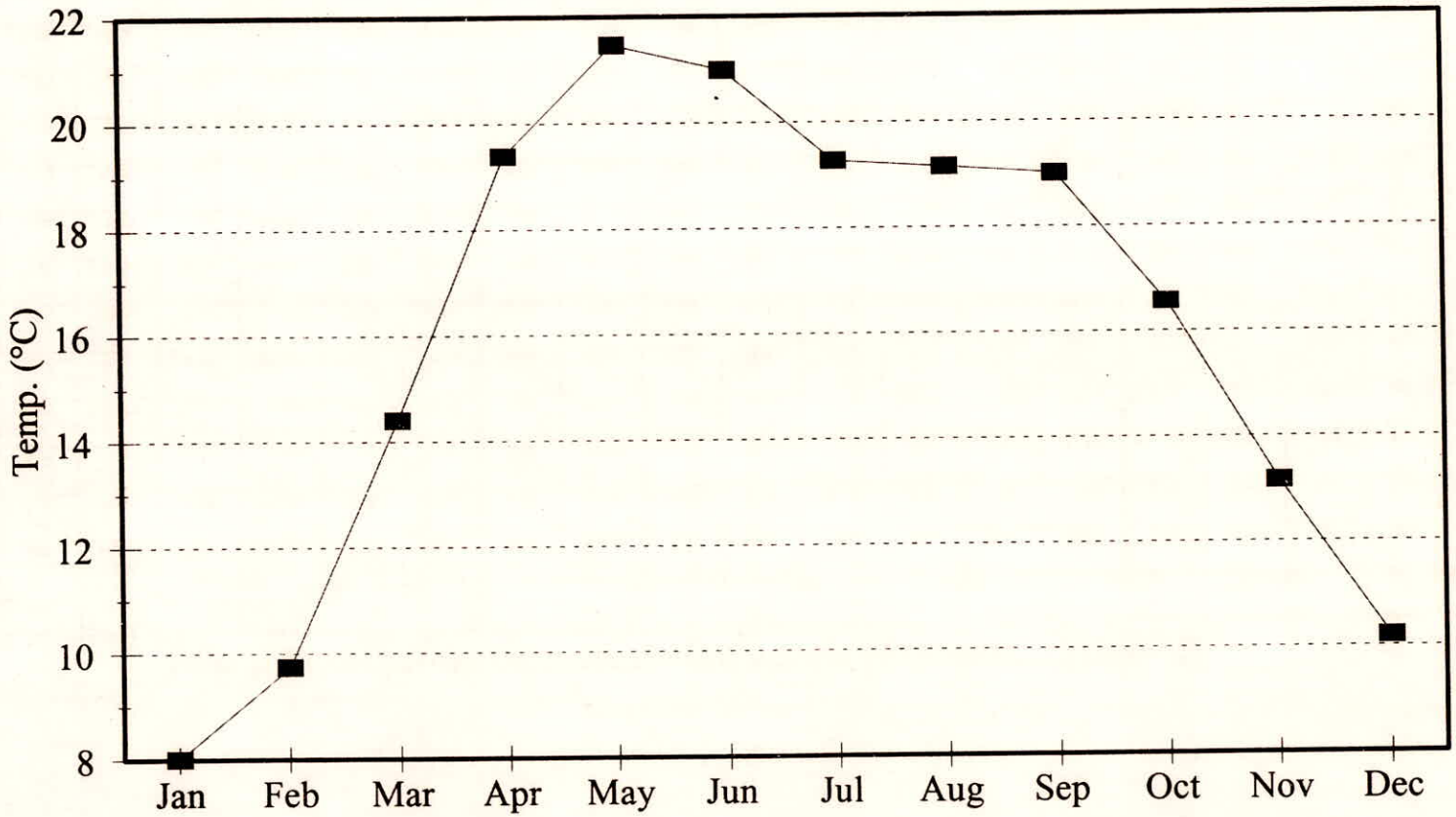
Table 4b: Mean Monthly Air Temprature with Standard Deviation (in °C) [1976-85]

	1976		1977		1978		1979		1980		1981		1982		1983		1984		1985	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	7.45	3.60	8.87	3.56	7.37	4.56	8.70	3.75	9.48	5.00	7.23	3.80	9.07	4.45	7.15	4.06	6.23	4.25	7.85	3.82
Feb	10.08	3.75	7.98	4.54	9.42	4.26	7.96	4.23	11.02	4.83	10.96	4.72	8.49	4.54	7.36	4.23	8.25	4.37	11.49	4.94
Mar	13.49	4.64	13.60	5.10	11.95	5.08	13.39	5.37	13.93	5.09	12.60	4.57	12.14	5.30	13.49	5.38	16.16	5.77	17.54	5.17
Apl	18.79	4.63	14.30	5.23	19.44	6.03	20.59	6.14	21.46	5.74	18.18	5.56	17.63	5.84	15.77	5.23	19.01	5.88	20.85	5.74
May	21.35	4.67	14.43	5.17	24.62	6.09	22.03	6.13	23.84	6.29	20.23	5.62	19.94	5.25	19.38	4.80	23.48	5.79	23.43	6.06
Jun	19.41	4.38	19.85	4.59	21.74	4.23	22.66	5.41	21.20	4.20	22.48	5.54	21.58	5.40	22.06	4.83	20.57	3.38	22.75	5.57
Jul	18.49	2.32	17.43	1.72	19.94	3.38	20.37	3.48	20.09	2.78	19.84	3.03	21.11	3.92	20.09	3.35	19.87	3.13	17.62	1.83
Aug	17.51	2.69	17.66	2.03	19.42	2.97	20.60	3.89	20.05	2.82	20.12	3.46	20.50	3.60	19.88	3.01	19.44	2.87	18.03	1.60
Sep	17.84	3.54	17.87	2.88	18.53	3.65	19.79	4.84	18.91	3.49	18.98	3.88	20.03	4.91	18.93	3.11	18.71	4.09	17.06	1.93
Oct	17.23	5.69	16.39	4.66	17.16	4.97	17.76	5.47	16.27	4.65	17.66	5.76	17.24	5.47	16.32	4.75	17.20	5.02	15.06	2.39
Nov	15.01	4.42	13.82	4.77	12.40	4.37	15.53	4.83	13.43	4.52	12.77	4.92	11.98	5.15	12.52	5.50	12.83	4.62	13.24	2.66
Dec	10.90	3.85	8.82	3.98	10.39	4.13	9.68	4.22	10.88	3.87	9.16	5.09	10.71	4.87	9.00	4.79	10.97	4.03	11.10	3.15

Table 4c: Mean Monthly Air Temprature with Standard Deviation (in °C) [1986-95]

	1986		1987		1988		1989		1990		1991		1992		1993		1994		1995	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	9.39	3.26	8.94	3.58	11.09	2.99	7.51	3.35	7.94	2.75	8.66	3.23	8.86	4.01	8.16	3.70	9.70	4.70	7.32	4.50
Feb	10.13	3.05	11.11	3.32	11.64	3.00	8.66	3.30	11.67	3.19	11.53	2.17	9.33	4.17	11.53	4.47	8.90	4.63	8.80	4.84
Mar	13.84	2.82	14.43	2.90	14.31	2.85	13.13	3.08	17.56	3.38	14.81	3.75	14.73	4.04	12.21	4.23	17.14	4.95	15.53	4.50
Apl	17.83	3.01	18.47	3.40	21.15	3.03	18.03	3.68	18.20	3.53	18.54	2.75	19.53	4.49	19.19	4.71	19.32	5.70	19.54	4.79
May	18.19	3.12	19.04	2.85	21.99	3.28	18.94	2.84	20.37	2.98	22.35	2.07	19.95	4.61	21.04	3.86	21.28	4.72	25.07	3.45
Jun	20.52	2.35	23.10	2.74	20.55	2.85	18.43	1.87	18.27	2.47	19.54	1.55	20.98	3.94	18.54	3.72	20.59	3.17	23.67	4.00
Jul	18.47	1.69	19.52	2.19	18.50	1.44	18.49	2.20	18.20	2.82	18.91	1.23	17.63	2.97	18.72	2.85	18.94	3.14	20.28	3.56
Aug	18.69	1.78	18.86	2.07	19.02	1.89	17.90	2.15	17.63	2.90	19.10	2.41	19.42	3.06	18.88	2.98	18.70	3.23	19.67	3.83
Sep	17.52	2.03	18.92	2.06	18.68	2.23	17.33	2.83	16.29	3.71	18.70	0.93	18.36	3.55	19.23	5.45	-	-	18.98	3.88
Oct	15.37	2.48	16.69	2.95	19.12	2.70	13.73	3.98	14.53	4.27	18.23	0.85	16.58	3.82	17.44	3.85	-	-	17.80	5.33
Nov	13.63	2.69	15.34	3.29	15.29	3.44	9.79	2.93	11.03	3.78	13.02	1.84	14.02	4.60	15.33	4.55	14.36	4.75	15.64	6.53
Dec	8.53	3.48	13.87	3.98	11.78	3.99	12.54	2.48	-	-	7.50	3.50	11.36	4.12	12.10	4.83	10.49	4.86	11.06	5.62

Fig. 7 Variation of 30 year average monthly mean air temperature at Manora (Nainital)



2.2 Relative Humidity

On the basis of 30 year relative humidity data, it could be said that the least humid month is April and the most humid month is August. The RH is below 55% for all the months except during monsoon season. During the monsoon months the mean RH ranges between 60 and 80%. However, the standard deviation in the RH is higher during non-monsoon months indicating the larger variability during this period. The average RH values are presented in Tables 5(a) to 5(c) and in Fig. 8.

2.3 Sunshine Hours

The length of the sunshine hours is maximum during April and May and minimum during July and August. This can be expected because of the cloudy conditions that prevail during monsoon months. The sunshine hours data is very important, if solar radiation data for the site is not available. The ratio of actual to maximum possible sunshine hours (based on latitude) is used for calculating the incident short wave radiation from the solar radiation received at the upper atmosphere. The latter data can be easily computed using the latitude information. Methods for such computation are many and are available in standard text books. The average Sunshine hours data are presented in Tables 6(a) to 6(c) and in Fig.9.

2.4 Atmospheric Pressure

The average atmospheric pressure in Nainital region ranges from 810 to 820 mbar. The atmospheric pressure data is used for calculating the weighting factor Δ, which is used in many evaporation or potential evapotranspiration estimation methods. The average AP values are presented in Tables 7(a) to 7(c) and in Fig. 10.

Table 5a Mean Monthly Relative Humidity with Standard Deviation (in %)[1966-75]

Months	1966		1967		1968		1969		1970		1971		1972		1973		1974		1975	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	36.70	21.59	62.52	25.23	58.87	29.13	41.63	21.27	40.48	21.06	44.47	27.95	41.26	22.74	49.93	27.27	43.93	26.41	59.09	23.91
Feb	53.77	25.70	46.48	25.08	60.01	24.20	59.45	21.02	47.25	33.36	51.86	35.54	47.41	22.72	55.22	20.15	53.95	14.73	57.22	31.15
Mar	43.85	21.35	45.15	18.92	54.33	31.85	36.94	16.96	39.97	29.10	40.29	25.42	32.95	18.66	57.60	4.92	57.58	20.78	57.39	21.79
Apr	38.10	9.37	48.10	23.33	45.80	19.16	43.72	14.83	40.26	17.84	47.98	22.22	36.08	13.32	51.41	2.70	32.87	16.97	24.00	12.19
May	30.01	10.28	62.60	14.66	39.43	19.02	-	-	33.27	21.37	41.53	25.24	16.02	8.18	53.19	4.55	37.60	21.05	39.21	17.15
Jun	28.01	4.73	56.20	25.17	58.48	22.00	40.16	24.80	42.00	21.34	25.72	9.18	51.79	19.87	67.69	13.45	53.07	26.73	32.32	20.79
Jul	49.82	13.68	73.27	3.03	50.28	12.03	79.28	11.72	67.32	14.38	34.15	9.50	63.24	10.98	62.58	17.84	41.81	12.77	-	-
Aug	76.25	9.08	80.61	3.35	53.40	10.27	75.90	11.23	61.03	11.42	66.17	10.77	61.59	11.17	69.50	19.27	40.40	11.77	-	-
Sep	65.39	15.22	74.17	22.57	58.72	16.60	48.77	13.47	71.80	19.57	56.37	24.57	48.26	18.29	45.79	12.10	40.43	20.73	-	-
Oct	49.05	22.30	64.17	29.24	40.02	23.93	38.58	23.71	52.00	25.45	43.92	28.82	50.87	24.78	40.66	25.92	63.56	27.90	-	-
Nov	50.23	22.69	52.26	29.15	45.76	27.97	50.88	29.45	56.66	33.10	44.65	34.58	28.95	22.25	48.53	29.53	55.00	28.86	-	-
Dec	44.96	28.70	63.63	32.05	37.98	25.47	44.45	29.85	46.95	33.50	53.07	30.14	35.60	25.18	45.68	33.74	59.80	30.43	-	-

Table 5b Mean Monthly Relative Humidity with Standard Deviation (in %)[1976-85]

Months	1976		1977		1978		1979		1980		1981		1982		1983		1984		1985	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	-	-	62.08	16.97	-	-	-	-	61.48	29.65	65.13	27.40	67.81	25.10	60.32	28.81	59.20	28.63	57.58	28.35
Feb	62.48	18.52	51.35	10.55	-	-	-	-	65.09	22.64	55.68	23.91	65.16	28.70	61.54	26.07	63.46	23.09	45.71	26.61
Mar	62.18	18.82	53.55	9.64	-	-	-	-	55.43	22.03	57.58	22.68	65.11	26.15	48.98	23.11	50.07	22.50	49.74	18.16
Apr	42.69	14.21	68.81	11.89	-	-	47.48	16.28	33.21	11.90	58.00	19.23	49.88	19.98	52.80	21.00	41.42	14.68	37.38	16.92
May	43.27	13.66	78.15	9.80	-	-	50.67	14.94	39.87	16.50	66.58	21.94	51.17	17.41	59.45	19.42	50.18	14.95	49.27	18.85
Jun	70.82	10.68	-	-	-	-	74.95	12.58	82.95	12.62	66.07	17.80	70.98	21.18	54.28	15.45	80.57	12.83	69.67	20.30
Jul	-	-	-	-	-	-	86.84	8.97	90.55	6.45	87.89	7.34	83.17	9.93	83.26	11.81	85.85	8.05	89.52	6.12
Aug	-	-	-	-	-	-	74.84	12.20	84.02	9.11	87.63	7.85	90.00	8.68	81.63	10.05	80.93	10.50	86.50	6.60
Sep	72.69	11.01	-	-	-	-	61.07	22.61	73.14	15.54	77.08	16.68	73.45	16.13	78.43	11.50	68.75	14.28	79.52	10.78
Oct	-	-	-	-	-	-	64.10	21.55	62.48	24.83	55.10	25.84	57.32	25.71	58.58	22.97	48.73	20.40	67.38	22.38
Nov	61.30	23.91	-	-	-	-	61.13	21.77	64.77	27.30	61.03	30.80	59.33	27.42	57.94	26.44	50.68	20.46	49.85	32.05
Dec	58.00	27.06	-	-	-	-	67.18	25.18	60.06	28.25	59.48	31.23	51.81	26.10	55.28	31.83	47.29	19.55	57.21	26.79

Table 5c Mean Monthly Relative Humidity with Standard Deviation (in %)[1986-95]

Month	1986		1987		1988		1989		1990		1991		1992		1993		1994		1995	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	84.69	8.90	52.95	20.16	44.35	24.13	52.06	32.32	60.68	9.55	65.03	26.26	55.60	25.82	56.91	23.91	58.13	22.63	59.89	27.63
Feb	85.77	8.73	51.33	16.88	43.43	17.57	42.98	29.52	63.48	13.34	63.92	23.50	58.65	30.70	64.72	22.24	56.50	26.79	58.63	25.29
Mar	68.73	22.50	40.54	16.35	39.60	14.98	39.20	21.52	40.45	19.23	60.19	21.65	43.56	18.47	50.83	20.61	46.90	21.02	50.21	18.21
Apr	71.77	26.13	47.35	14.42	32.02	7.92	22.72	14.52	62.57	23.90	44.75	14.52	33.92	10.24	41.59	13.00	43.98	13.54	30.70	8.57
May	56.87	31.77	41.65	12.06	38.50	14.95	66.24	20.60	66.10	15.06	46.60	16.71	42.64	14.93	49.66	20.21	52.31	18.82	39.28	9.28
Jun	56.23	27.13	56.72	17.02	66.27	11.17	84.95	9.35	83.77	7.47	71.36	19.61	60.43	16.40	66.30	15.37	69.10	11.48	61.38	12.71
Jul	42.33	18.33	78.97	14.51	89.06	5.65	86.66	7.37	82.13	7.95	78.21	10.32	83.71	8.87	83.50	9.38	83.74	9.06	82.26	10.33
Aug	-	-	79.27	10.57	84.50	11.12	81.76	11.82	86.82	8.85	78.90	8.16	84.21	8.15	81.89	10.95	85.82	7.82	85.48	8.35
Sep	-	-	65.98	19.61	67.41	16.76	53.98	28.88	68.65	18.98	71.09	14.83	69.57	16.76	83.80	7.83	-	-	77.87	15.40
Oct	-	-	57.89	26.69	53.10	30.76	54.77	27.00	64.73	26.08	56.45	23.09	58.53	19.53	50.94	23.23	-	-	58.12	20.69
Nov	-	-	49.35	25.88	56.15	27.38	44.30	18.91	62.57	22.73	59.28	30.44	64.29	23.76	52.50	20.45	54.89	19.61	54.97	24.43
Dec	-	-	46.83	25.17	57.74	26.48	31.75	17.08	-	-	70.88	24.38	55.38	26.24	48.71	22.67	53.45	17.24	58.90	25.94

Fig. 8 Variation of 30 year average monthly mean relative humidity at Manora (Nainital)

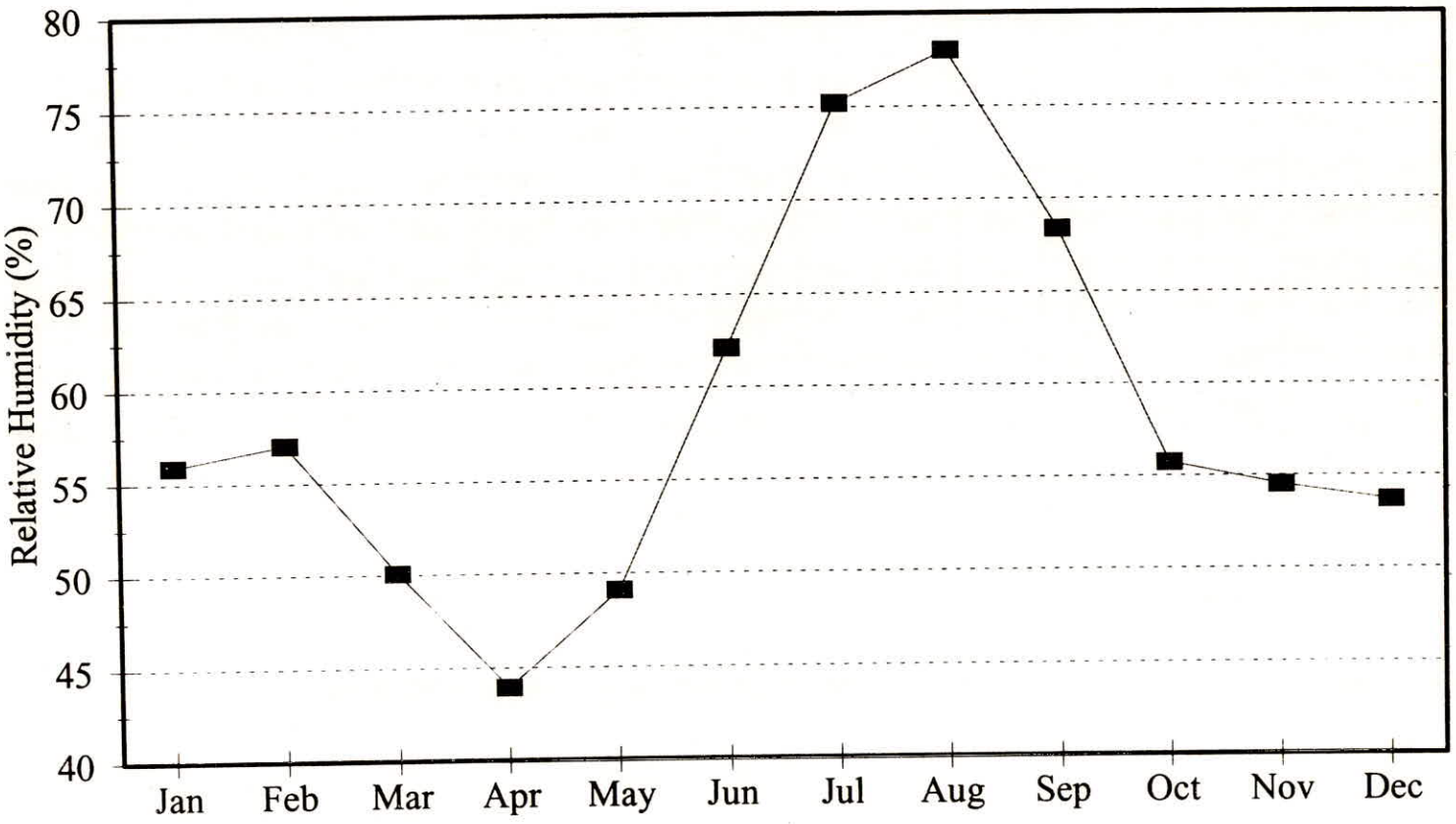


Table 6a Mean Monthly Sunshine with Standard Deviation (in hrs.) [1966-75]

	1966		1967		1968		1969		1970		1971		1972		1973		1974		1975	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	7.37	2.44	8.18	1.43	4.69	2.94	7.13	2.61	6.34	2.87	6.93	2.89	5.96	3.41	5.74	3.00	6.88	2.89	4.85	2.83
Feb	6.25	3.52	8.77	1.88	7.33	3.21	8.32	2.30	6.49	3.07	7.96	2.83	7.10	3.17	6.78	3.01	7.72	2.80	6.65	2.78
Mar	7.88	2.52	6.73	3.21	7.14	3.06	8.91	2.15	8.10	2.10	8.95	1.90	8.12	2.55	8.01	2.69	6.93	3.14	8.22	2.51
Apl	8.73	2.78	9.57	2.48	4.91	3.37	7.55	2.89	9.59	2.32	5.79	3.66	9.33	2.17	10.14	1.41	9.44	1.56	8.99	1.94
May	9.66	2.70	10.97	1.80	10.25	2.10	7.64	3.82	8.91	3.43	5.68	3.47	9.83	2.29	8.77	2.60	9.56	2.11	9.59	2.43
Jun	4.53	4.47	6.95	3.91	2.38	2.58	6.59	2.91	4.11	3.22	3.04	1.68	6.82	3.29	3.85	3.31	7.07	3.10	6.87	3.80
Jul	4.26	3.79	1.66	1.93	1.98	2.24	2.22	2.03	3.73	3.17	1.93	1.61	4.66	2.58	2.77	2.43	3.02	2.54	2.96	1.88
Aug	2.23	2.06	1.82	1.81	2.44	2.53	2.59	2.70	2.27	1.89	1.55	1.26	3.43	2.25	3.12	2.19	2.95	2.53	3.34	2.93
Sep	5.98	3.18	3.05	2.68	3.66	3.10	3.22	2.81	3.32	1.51	5.22	2.80	5.03	2.96	2.95	2.00	4.34	2.26	3.02	2.38
Oct	8.93	1.95	8.83	2.01	8.14	2.26	7.03	2.82	6.02	2.74	6.46	3.11	7.06	3.11	5.73	2.95	6.23	2.98	6.47	2.49
Nov	8.77	1.67	7.15	2.69	7.08	2.71	4.55	0.86	9.38	0.48	6.23	2.04	6.61	2.72	8.26	1.85	9.24	0.63	8.44	1.25
Dec	8.24	1.80	5.48	3.29	7.52	2.82	7.61	2.11	8.17	1.88	7.24	1.89	7.28	2.21	8.06	1.95	6.28	2.46	7.11	1.80

Table 6b Mean Monthly Sunshine with Standard Deviation (in hrs.) [1976-85]

	1976		1977		1978		1979		1980		1981		1982		1983		1984		1985	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	5.93	2.70	-	-	-	-	-	-	7.54	2.02	5.34	2.88	5.37	3.95	8.63	0.56	7.45	1.92	1.80	2.12
Feb	6.57	2.94	-	-	-	-	-	-	7.72	2.60	6.33	3.27	5.58	3.16	7.71	2.95	7.41	2.84	1.57	1.49
Mar	7.13	2.51	-	-	-	-	-	-	7.13	3.10	6.25	3.31	7.08	3.20	7.07	2.45	9.52	1.75	2.17	2.01
Apl	8.28	2.73	-	-	-	-	-	-	10.40	1.87	9.16	2.41	8.55	3.56	-	-	8.62	2.51	4.74	3.61
May	8.83	3.59	-	-	-	-	-	-	10.18	2.14	8.47	3.05	8.48	3.93	-	-	9.67	3.44	8.53	1.83
Jun	5.60	3.44	-	-	-	-	-	-	4.93	3.31	7.27	4.47	7.04	3.69	-	-	3.44	2.43	6.50	3.28
Jul	2.32	2.27	-	-	-	-	-	-	2.08	2.10	1.66	2.95	4.75	3.94	-	-	3.02	1.96	7.47	2.73
Aug	2.41	1.77	-	-	-	-	-	-	2.74	2.30	2.84	2.23	2.16	2.60	-	-	2.10	1.80	7.16	3.27
Sep	2.71	2.18	-	-	-	-	-	-	4.97	3.41	4.10	2.51	6.01	3.37	-	-	4.33	3.17	7.28	3.34
Oct	-	-	-	-	-	-	-	-	6.92	2.60	8.79	1.77	7.54	2.54	-	-	7.90	1.94	9.03	2.13
Nov	7.24	2.57	-	-	-	-	-	-	8.03	1.75	7.30	2.85	6.74	2.81	7.75	1.69	6.74	2.16	8.34	3.45
Dec	7.55	3.36	-	-	-	-	-	-	7.35	2.69	7.81	2.02	8.05	1.15	7.42	2.50	6.41	2.46	6.54	5.11

Table 6c Mean Monthly Sunshine with Standard Deviation (in hrs.) [1986-95]

	1986		1987		1988		1989		1990		1991		1992		1993		1994		1995	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	2.15	2.64	7.10	2.53	6.92	2.73	2.63	1.77	5.04	2.36	7.01	2.50	5.76	2.71	6.98	3.11	6.78	2.99	6.52	2.83
Feb	2.23	2.26	7.51	2.55	6.47	2.69	7.65	2.89	5.81	3.13	6.63	2.66	6.98	1.85	7.87	1.89	7.33	2.37	6.71	2.36
Mar	4.24	2.83	7.91	2.86	8.54	3.16	8.98	1.82	9.17	2.63	7.49	2.73	7.60	2.44	7.30	3.28	8.62	3.46	8.61	2.90
Apl	5.95	2.79	10.19	2.45	9.95	1.83	10.89	1.26	6.23	3.21	9.23	3.04	9.05	1.98	8.64	3.50	9.23	2.80	4.85	3.26
May	6.77	2.66	-	-	9.69	2.45	5.06	3.23	6.38	4.15	7.51	2.79	9.29	2.36	9.47	2 88	8.56	2.54	9.83	2.19
Jun	5.46	3.18	-	-	5.79	3.56	3.76	3.05	2.04	1.33	4.24	3.00	6.95	3.57	8.72	2.79	6.13	4.05	2.81	1.49
Jul	5.44	3.85	3.42	3.35	1.66	1.46	2.65	1.63	2.96	1.91	1.90	1.51	0.24	0.14	3.02	2.28	2.81	1.66	3.76	2.47
Aug	-	-	2.88	2.26	3.65	2.94	3.64	2.15	2.92	1.90	2.02	2.30	1.71	1.71	2.76	1.86	1.72	1.51	3.00	2.26
Sep	-	-	4.65	3.40	4.65	2.42	8.78	2.16	7.79	2.31	5.50	3.08	4.16	2.52	2.65	1.81	-	-	4.94	2.42
Oct	-	-	7.16	2.77	9.09	1.74	8.88	1.69	8.16	2.46	8.28	1.91	6.90	2.11	8.75	1.82	-	-	8.29	2.02
Nov	-	-	8.39	1.85	9.01	1.38	7.45	2.51	6.89	2.61	5.76	2.04	7.30	1.95	9.21	0.64	8.36	2.02	8.94	1.48
Dec	-	-	7.68	2.46	6.47	2.74	8.68	1.84	-	-	5.55	0.92	8.16	1.68	8.77	1.62	8.22	1.80	7.67	1.81

Fig. 9 Variation of 30 year average monthly mean sunshine hours at Manora (Nainital)

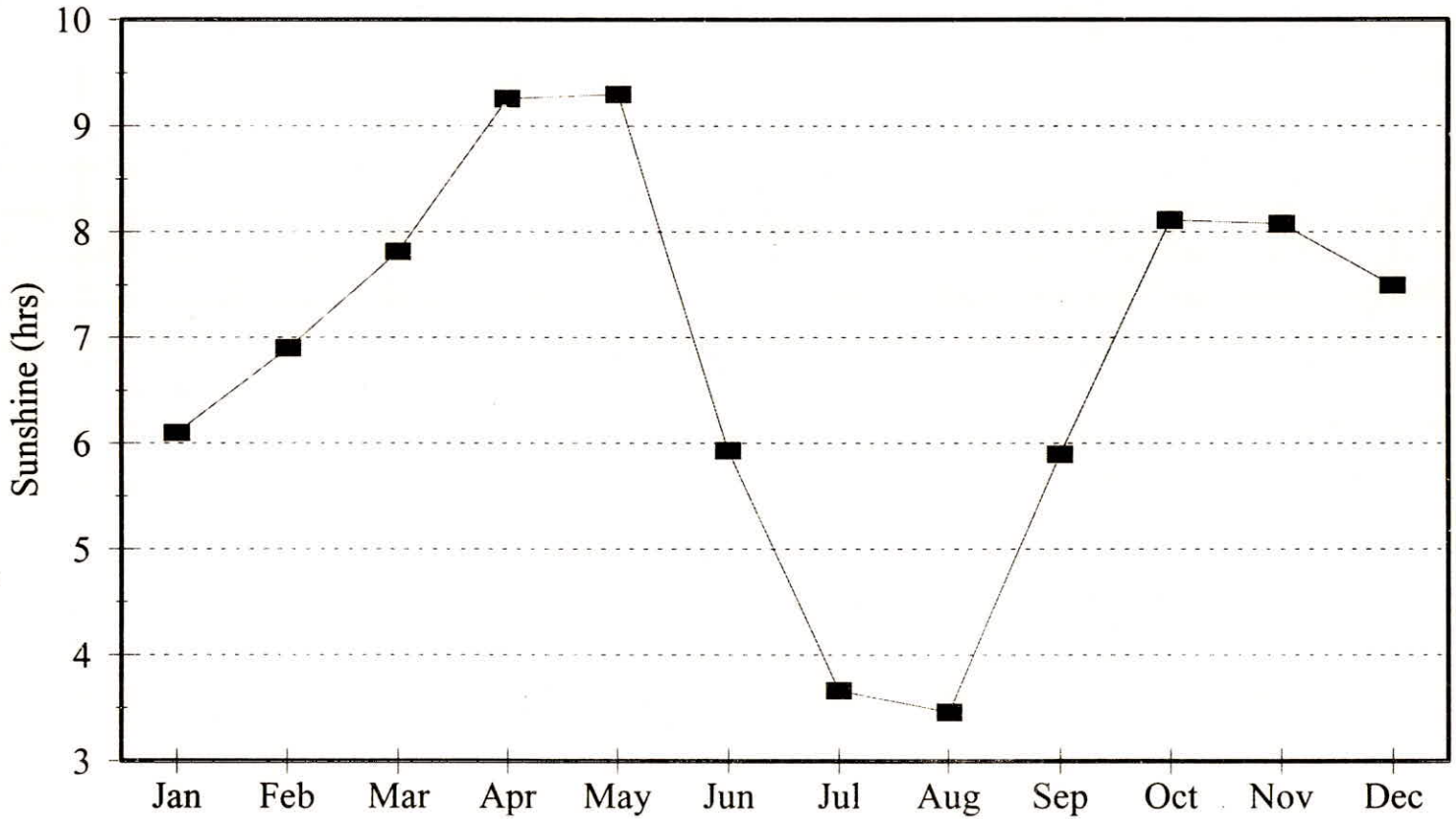


Table 7a Mean Monthly Atmospheric Pressure with Standard Deviations (in mbars) [1966 - 75]

Months	1966		1967		1968		1969		1970		1971		1972		1973		1974		1975	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Jan	-	-	-	-	-	-	-	-	-	-	804.46	0.37	805.24	0.47	804.32	0.42	814.50	0.23	810.27	0.23
Feb	-	-	-	-	-	-	-	-	-	-	804.48	0.36	805.26	0.46	804.80	0.58	814.22	0.22	810.85	0.23
Mar	-	-	-	-	-	-	-	-	-	-	804.51	0.38	805.01	0.56	804.63	0.60	814.13	0.26	811.87	0.16
Apl	-	-	-	-	-	-	-	-	-	-	804.90	0.30	804.85	0.53	805.53	0.48	813.88	0.25	811.61	0.21
May	-	-	-	-	-	-	-	-	-	-	804.87	0.42	805.05	0.53	805.18	0.40	812.87	0.27	811.54	0.36
Jun	-	-	-	-	-	-	-	-	-	-	804.55	0.37	805.16	0.53	805.18	0.47	811.99	0.28	810.25	0.18
Jul	-	-	-	-	-	-	-	-	-	-	805.03	0.42	804.71	0.52	804.48	0.52	811.76	0.24	810.46	0.14
Aug	-	-	-	-	-	-	-	-	-	-	805.23	0.43	803.97	0.47	804.19	0.46	811.67	0.60	811.09	0.17
Sep	-	-	-	-	-	-	-	-	-	-	805.09	0.37	804.17	0.48	804.93	0.44	811.65	0.22	810.88	0.15
Oct	-	-	-	-	-	-	-	-	-	-	805.14	0.49	804.82	0.52	805.33	0.48	811.35	0.64	810.90	0.17
Nov	-	-	-	-	-	-	-	-	-	-	805.45	0.47	804.50	0.57	815.54	0.21	810.93	0.43	810.86	0.14
Dec	-	-	-	-	-	-	-	-	-	-	805.05	0.50	804.03	0.40	814.68	0.45	810.81	0.55	811.00	0.17

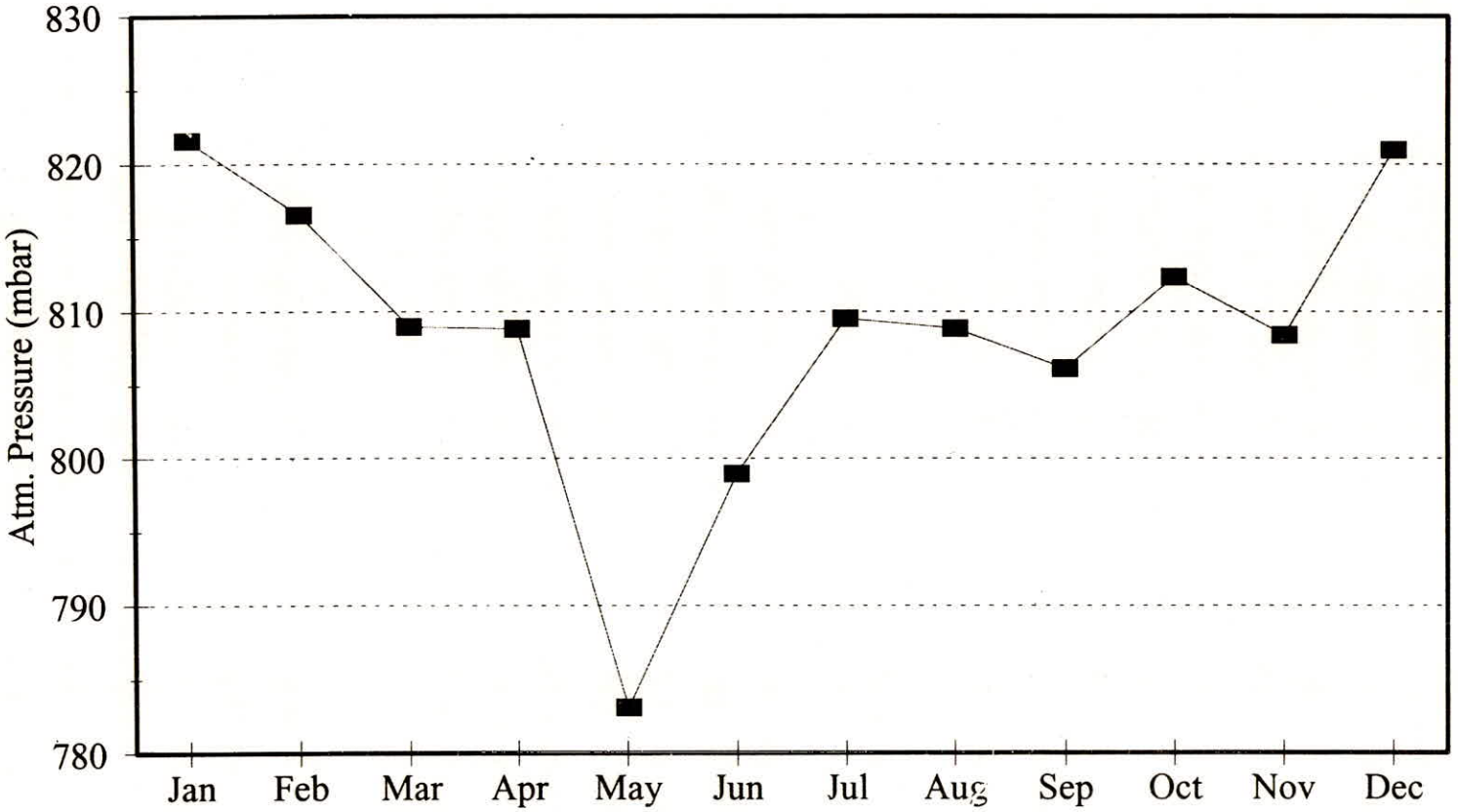
Table 7b Mean Monthly Atmospheric Pressure with Standard Deviations (in mbars) [1976 - 85]

Months	1976		1977		1978		1979		1980		1981		1982		1983		1984		1985	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	810.97	0.16	810.29	0.23	812.25	0.73	813.78	0.88	812.22	1.42	813.06	1.39	814.12	1.17	813.45	1.50	811.53	1.28	812.26	1.29
Feb	811.57	0.13	810.19	0.24	812.98	0.72	810.69	0.46	812.12	1.26	813.56	1.47	811.63	1.36	812.83	1.37	811.62	1.22	809.10	1.55
Mar			810.30	0.23	810.94	0.86	810.94	0.73	812.66	1.41	812.91	1.48	812.27	1.54	812.11	1.34	812.61	1.24	811.91	1.45
Apl	810.37	0.16	810.06	0.19	812.05	0.80	812.13	0.93	812.73	1.35	812.69	1.07	811.53	1.43	811.53	1.33	811.47	1.42	810.88	1.53
May	810.26	0.16	810.36	0.26	809.66	0.64	810.85	0.72	812.50	1.32	811.49	1.23	812.99	1.21	811.44	1.13	809.72	1.03	810.61	1.39
Jun	809.67	0.17	809.83	0.22	807.78	0.81	808.73	0.91	809.48	1.14	808.83	0.92	809.58	0.74	809.83	1.19	808.06	0.93	807.81	1.21
Jul	810.21	0.16	807.70	0.47	808.06	0.69	808.08	0.61	807.97	1.03	807.45	0.95	809.27	0.78	809.64	1.02	808.61	1.02	-	-
Aug	810.26	1.14	809.11	0.46	808.39	0.61	808.56	0.70	808.97	1.05	808.16	1.00	808.78	1.00	810.04	1.11	809.43	0.91	-	-
Sep	810.01	0.24	811.67	0.34	810.48	0.79	811.89	0.69	811.72	1.12	812.55	1.17	811.72	1.20	811.53	1.15	812.58	1.00	-	-
Oct	810.40	0.23	815.65	0.61	814.77	0.64	814.40	0.45	813.07	1.17	815.01	0.99	816.50	1.27	814.31	1.03	814.42	0.96	-	-
Nov	810.49	0.21	815.36	0.88	814.03	0.88	815.62	0.68	815.27	1.27	814.73	0.64	814.93	1.45	816.56	1.11	812.43	1.05	-	-
Dec	810.43	0.18	813.97	0.99	815.38	0.62	814.98	0.87	813.85	1.32	814.74	1.06	814.75	1.69	814.00	1.15	812.52	0.96	-	-

Table 7c Mean Monthly Atmospheric Pressure with Standard Deviations (in mbars) [1986 - 95]

Months	1986		1987		1988		1989		1990		1991		1992		1993		1994		1995	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Jan	808.66	1.04	813.65	1.06	812.27	1.44	810.20	1.54	809.39	1.45	812.93	1.40	813.63	1.32	811.62	1.31	812.19	1.47	812.78	1.55
Feb	809.93	1.09	814.12	1.37	811.53	1.47	811.13	1.55	811.31	1.40	814.01	1.39	810.14	1.41	812.19	1.31	811.11	1.48	812.37	1.37
Mar	812.10	1.13	812.60	1.25	810.20	1.54	811.92	1.41	810.22	1.46	813.67	1.62	812.51	1.44	811.75	1.53	812.56	1.46	813.40	1.21
Apl	813.96	1.31	812.82	1.33	812.38	1.43	810.90	1.37	809.79	1.31	812.99	1.41	813.07	1.41	813.25	1.42	812.50	1.45	-	-
May	814.71	1.21	813.17	1.35	810.18	1.55	809.31	1.18	808.06	1.20	812.26	1.44	811.24	1.49	811.31	1.34	811.56	1.44	812.26	1.20
Jun	813.96	1.51	810.18	1.35	809.17	1.28	808.59	1.16	807.24	1.06	810.20	1.22	809.82	1.11	810.17	1.08	808.60	1.07	809.61	1.11
Jul	811.75	1.75	808.87	1.05	808.06	1.06	809.46	1.02	812.16	1.06	808.27	0.97	609.51	1.04	809.69	0.85	808.94	1.11	809.27	1.34
Aug	-	-	810.13	1.22	808.48	1.05	811.10	1.23	812.79	1.19	809.16	1.25	810.34	1.00	810.19	1.23	809.92	1.05	810.06	1.54
Sep	-	-	812.52	1.13	810.88	1.31	813.66	1.23	814.96	1.18	811.62	1.22	811.68	1.13	811.11	0.98	-	-	811.96	1.32
Oct	-	-	813.52	1.37	812.79	1.23	814.40	1.28	815.37	1.26	812.40	1.06	813.26	1.28	814.04	1.17	-	-	814.48	1.28
Nov	-	-	813.47	1.37	814.66	1.40	812.71	1.33	814.57	1.38	814.33	1.24	814.59	1.29	814.13	1.14	815.43	1.33	813.86	1.48
Dec	-	-	814.26	1.35	813.64	1.53	811.99	1.31	-	-	814.19	1.04	813.85	1.16	813.69	1.32	814.40	1.38	814.15	1.35

Fig. 10 Variation of 30 year average monthly mean atmospheric pressure at Manora (Nainital)



2.5 Wind Velocity

The wind velocity plays a crucial role in the lake evaporation and catchment evapotranspiration processes. The information on wind velocity is required in hourly basis, since the variability of wind velocity in nature is fairly large. The average wind velocity (u) in km/hr at Manora is shown in Fig. 11. The u is maximum in April/May and minimum during the period Oct.-Feb. It in general ranges from 9 km/hr to 16 km/hr. The observations are made at 10 m height above ground level. Appropriate conversions can be made for getting information on wind velocity at 2 m height, as this is required in certain evapotranspiration estimation methods. The average wind velocity values are presented in Tables 8(a) & 8(b).

2.6 Rainfall

The average annual rainfall for the 30 year period is 2385 mm. The annual rainfall during the 30 year period ranges from a minimum of 1588 mm (1991) to a maximum of 2946 mm (1975). From the 30 year average, it is seen that the monsoon rainfall contributes around 86 % and non-monsoon rainfall contributes around 14 %. The average monsoon and non-monsoon rainfall for the 30 year period is shown in Fig. 12. This shows the monsoon rainfall plays an important role in the hydrology of the Nainital area. The average annual rainfall values are presented in Tables 9(a) to 9(c) and in Fig. 13.

Analysis of one hundred one year annual rainfall data avaliable for Lake Nainital basin (UPPWD) indicates that the mean annual rainfall in the basin is 248.8 cm, with a maximum of 390.98 cm in 1910 and a minimum of 136.7 cm in 1991. An interpretation of the rainfall pattern with time at Nainital (PWD data), indicates a general decline in annual rainfall in the last 40 years. However, the correlogram (Fig. 14) shows that there is no definite trend of annual rainfall in the basin. Therefore the visible decline in the total annual rainfall (Fig.15) need not cause any alarm.

Fig. 11 Variation of 15 year average monthly mean wind velocity at Manora (Nainital)

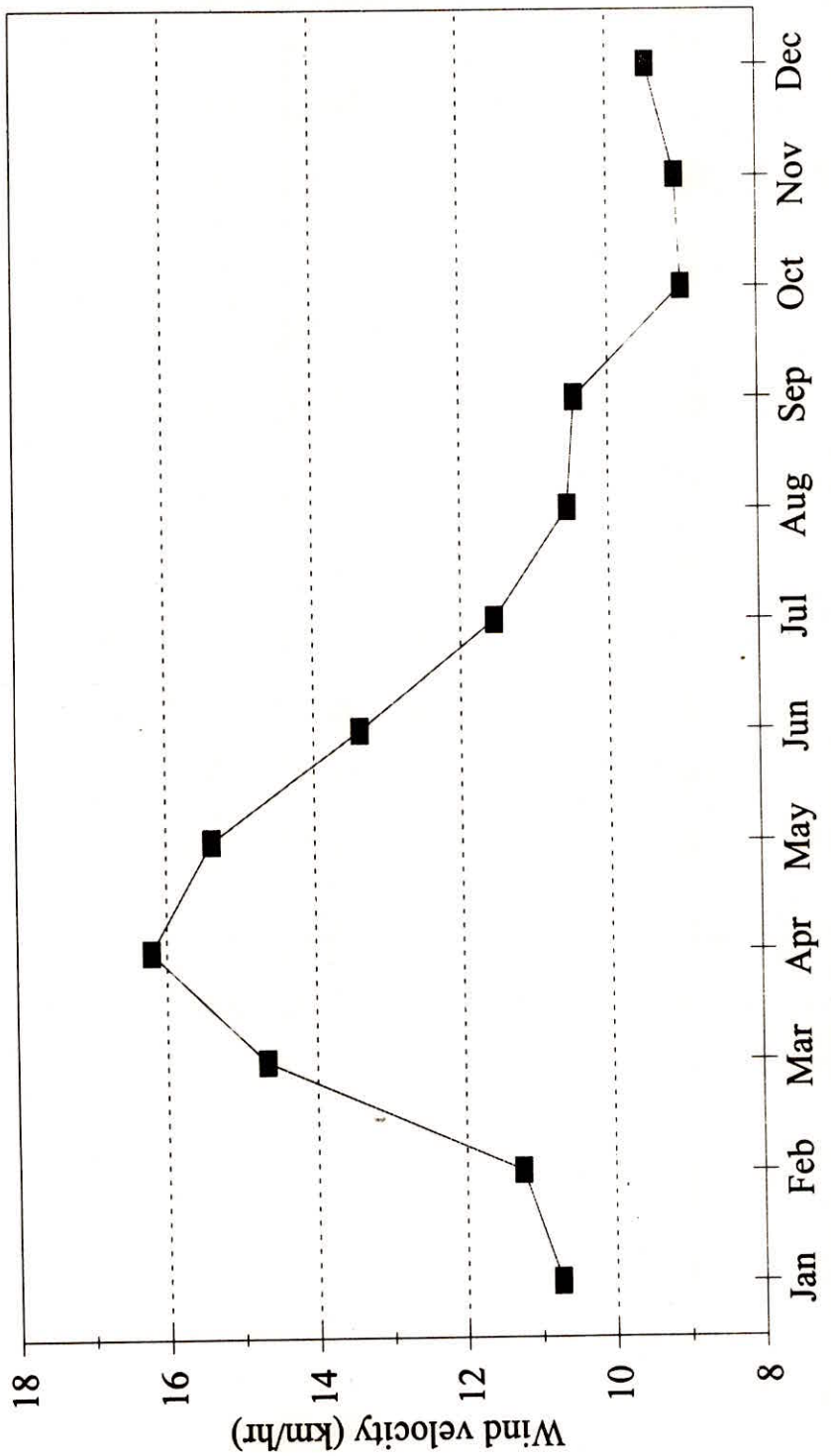


Table 8a Mean wind velocity (km/hr) at Manora [1982-1988]

	1982	1983	1984	1985	1986	1987	1988
Jan		7.58	8.89	6.88	10.34	9.82	9.85
Feb		8.15	8.37	11.26	10.57	11.27	10.20
Mar		10.74	12.08	17.16	15.54	16.01	15.81
Apr		11.14	14.40	18.87	16.53	16.37	13.81
May	9.95	11.36	15.33	14.21	13.89	18.13	20.15
Jun	12.57	11.22	11.42	12.10	13.22	16.65	14.21
Jul	9.95	7.54	8.93		11.62	17.68	16.11
Aug	6.28	6.74	6.58	8.64	10.34	14.30	14.78
Sep	10.58	7.88	8.58	9.76	12.17	11.89	12.67
Oct	7.36	6.50	8.25	9.70	7.13	12.40	8.45
Nov	8.38	5.90	8.30	10.92	9.07	7.77	8.54
Dec	9.64	7.41	11.44	10.89	9.71	8.67	9.75

Table 8b Mean wind velocity (km/hr) at Manora [1989-1996]

	1989	1990	1991	1992	1993	1994	1995	1996
Jan	10.30	19.26			12.92	11.50		8.44
Feb	15.85	12.98			11.56	12.26		7.78
Mar	15.94	10.79			14.64	17.97		
Apr	19.87	21.09			15.25	14.79		
May	14.07	13.86			20.99	17.34		15.02
Jun	13.72	15.96				12.69		9.33
Jul	14.06	9.93			11.40	10.14	9.71	7.71
Aug	9.56	11.83			14.81	10.97	11.76	8.14
Sep	10.27	9.16			10.97	10.19	11.37	7.42
Oct	9.90	9.49		11.37	10.01		7.59	6.25
Nov	13.04	11.13		8.93	10.79		6.25	7.09
Dec	10.30	10.69			9.18		6.47	7.25

Fig. 12 Variation of monsoon and non-monsoon rainfall at Manora (1951 m above msl)

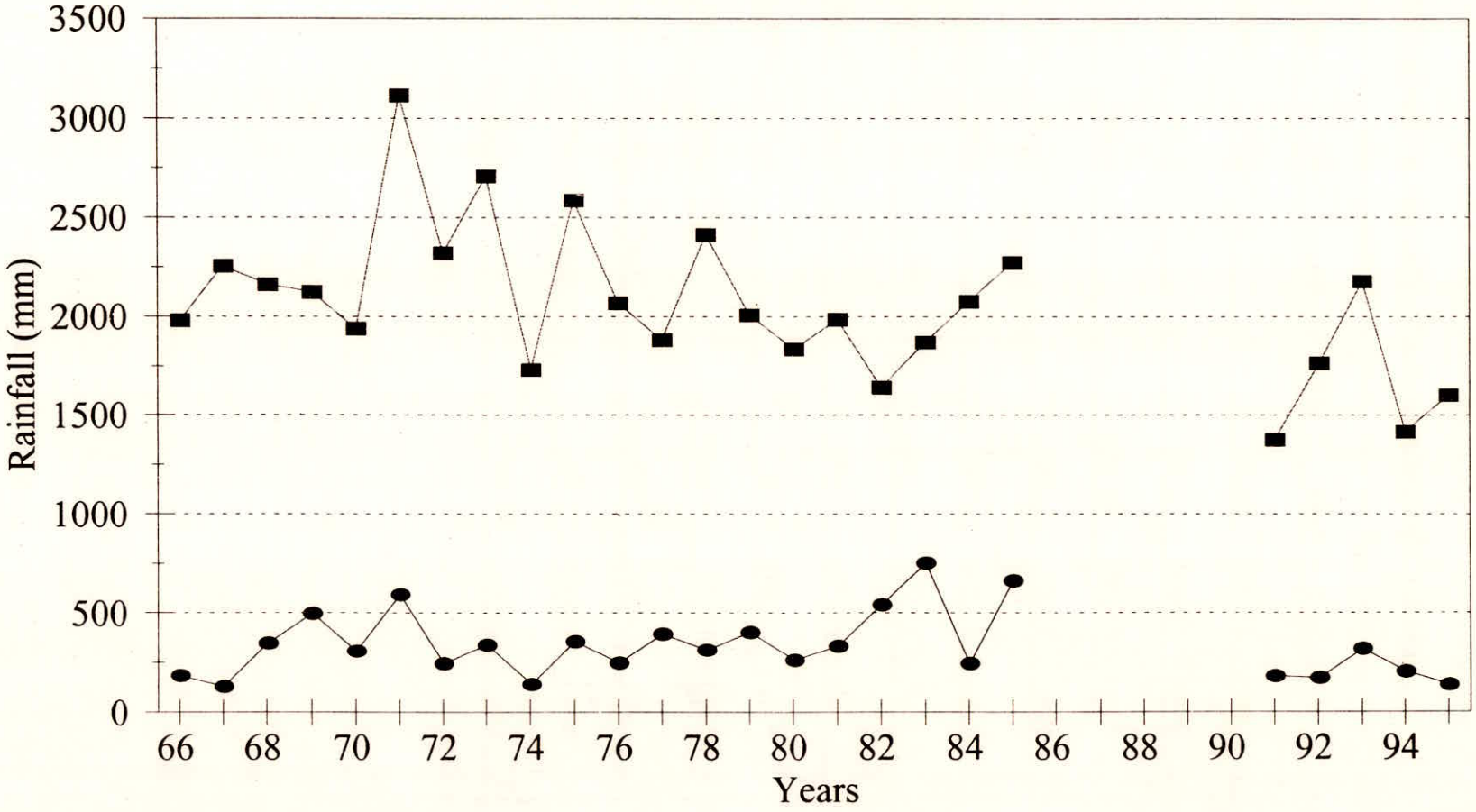


Table 9a Monthly Rainfall (mm) [1966-75]

	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1966-75	
Jan	17.58	0.00	189.13	32.50	115.30	59.50	21.50	55.00	12.50	219.50	72.25	
Feb	80.69	0.00	59.00	35.00	17.00	96.50	112.00	12.50	22.00	40.00	47.47	
Mar	3.29	30.04	41.50	55.00	34.10	23.00	15.70	20.50	27.50	37.00	28.76	
Apl	1.01	13.97	14.00	7.23	0.00	34.50	24.50	0.00	0.00	0.00	9.52	
May	62.50	9.40	0.00	234.50	120.70	220.00	2.00	65.50	12.50	12.00	73.91	
Jun	343.67	226.56	618.40	89.84	570.40	703.50	227.70	924.00	360.50	372.50	443.71	
Jul	849.43	546.04	683.70	446.20	766.60	945.40	882.00	613.50	646.60	1005.00	738.45	
Aug	664.38	1089.76	608.50	848.79	418.00	995.00	502.00	612.50	580.50	511.50	683.09	
Sep	121.92	392.86	251.00	739.59	184.47	469.00	709.00	558.50	142.50	699.00	426.78	
Oct	9.00	9.50	34.97	127.00	20.28	138.50	51.70	184.50	5.00	50.00	63.05	
Nov	6.00	0.00	0.00	6.50	0.00	19.00	15.00	0.00	0.00	0.00	4.65	
Dec	4.00	68.00	9.00	0.00	0.00	1.00	3.00	1.00	62.50	0.00	14.85	
Total	2163.47	2386.13	2509.20	2622.15	2246.85	3704.90	2566.10	3047.50	1872.10	2946.50	2606.49	

Table 9b Monthly Rainfall (mm) [1976-85]

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1976-85
Jan	24.00	69.50	18.50	94.17	28.50	22.00	56.00	109.50	34.50	25.50	48.22
Feb	101.60	8.50	68.50	90.30	47.00	19.50	40.30	16.50	122.00	2.00	51.62
Mar	27.50	2.50	125.00	46.50	80.00	100.50	147.50	43.50	10.00	3.50	58.65
Apl	24.00	107.43	13.00	16.00	11.00	14.00	77.00	206.50	16.00	14.50	49.94
May	67.50	121.80	16.50	52.00	10.00	83.00	138.00	167.00	18.50	37.50	71.18
Jun	311.50	178.70	391.40	557.00	402.00	487.00	116.00	327.50	556.90	196.50	352.45
Jul	621.30	700.61	702.40	568.00	576.50	754.50	552.00	503.00	896.00	673.80	654.81
Aug	1021.00	638.30	794.50	828.00	406.50	525.10	789.50	410.00	391.00	1005.70	680.96
Sep	113.50	364.32	524.50	54.50	451.00	216.90	183.50	629.00	232.00	396.00	316.52
Oct	2.00	37.80	16.80	48.00	29.50	0.00	23.75	172.00	0.00	515.50	84.54
Nov	0.00	0.00	41.50	30.00	0.50	61.50	2.10	0.00	3.50	0.00	13.91
Dec	0.00	47.00	15.05	25.00	56.50	33.50	56.00	37.50	40.50	63.00	37.41
Total	2313.90	2276.46	2727.65	2409.47	2099.00	2317.50	2181.65	2622.00	2320.90	2933.50	2420.20

Table 9c Monthly Rainfall (mm) [1986-95]

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1986-95
Jan						0.00	43.00	50.00	87.00	22.50	40.50
Feb						56.50	16.00	56.00	55.50	90.00	54.80
Mar						42.20	3.50	94.50	0.00	21.50	32.34
Apl						40.00	10.00	42.50	45.50	-	27.60
May						15.50	28.50	76.00	15.50	-	27.10
Jun						216.00	292.50	127.00	284.50	-	184.00
Jul						328.00	570.50	580.00	632.50	695.30	561.26
Aug						617.00	618.50	375.00	499.50	720.20	566.04
Sep						217.00	285.50	1097.00	0.00	188.20	357.54
Oct						26.50	22.50	0.00	0.00	0.00	9.80
Nov						0.00	0.00	0.00	0.00	0.00	0.00
Dec						0.00	50.00		1.50	5.50	14.25
Total						1558.70	1940.50	2498.00	1621.50	1743.20	1872.38

Fig. 13 Variation of 30 year average monthly rainfall at Manora (Nainital)

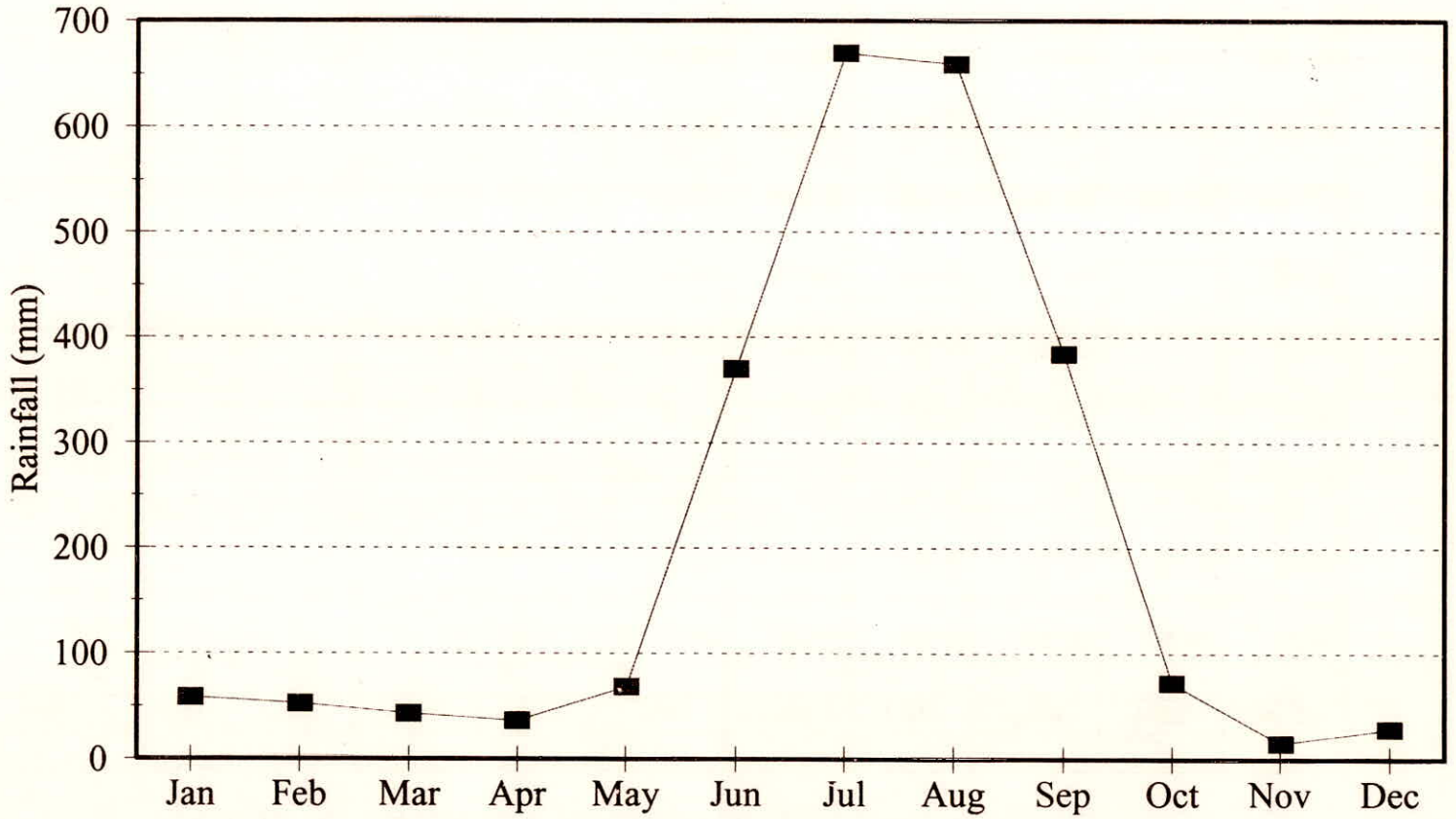


Fig. 14 Correlogram for Lake Nainital catchment annual rainfall

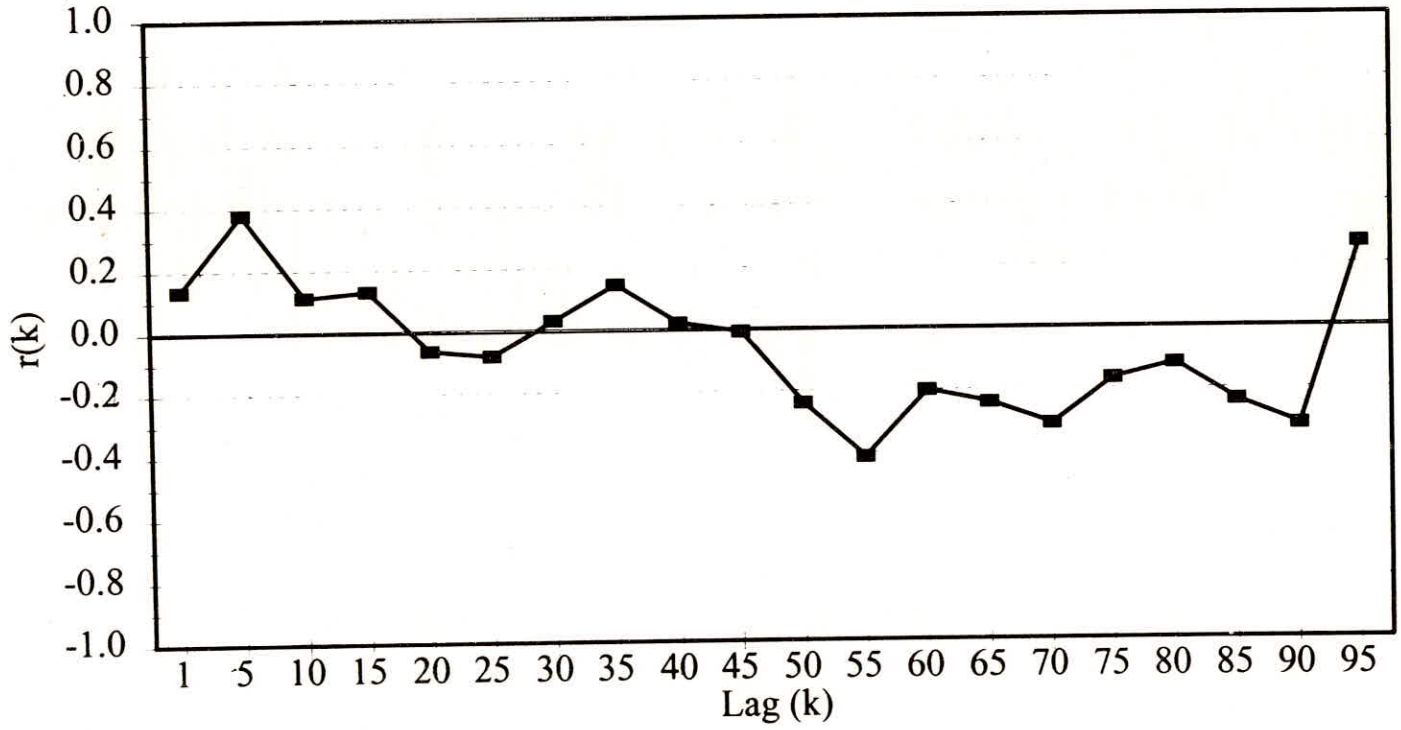
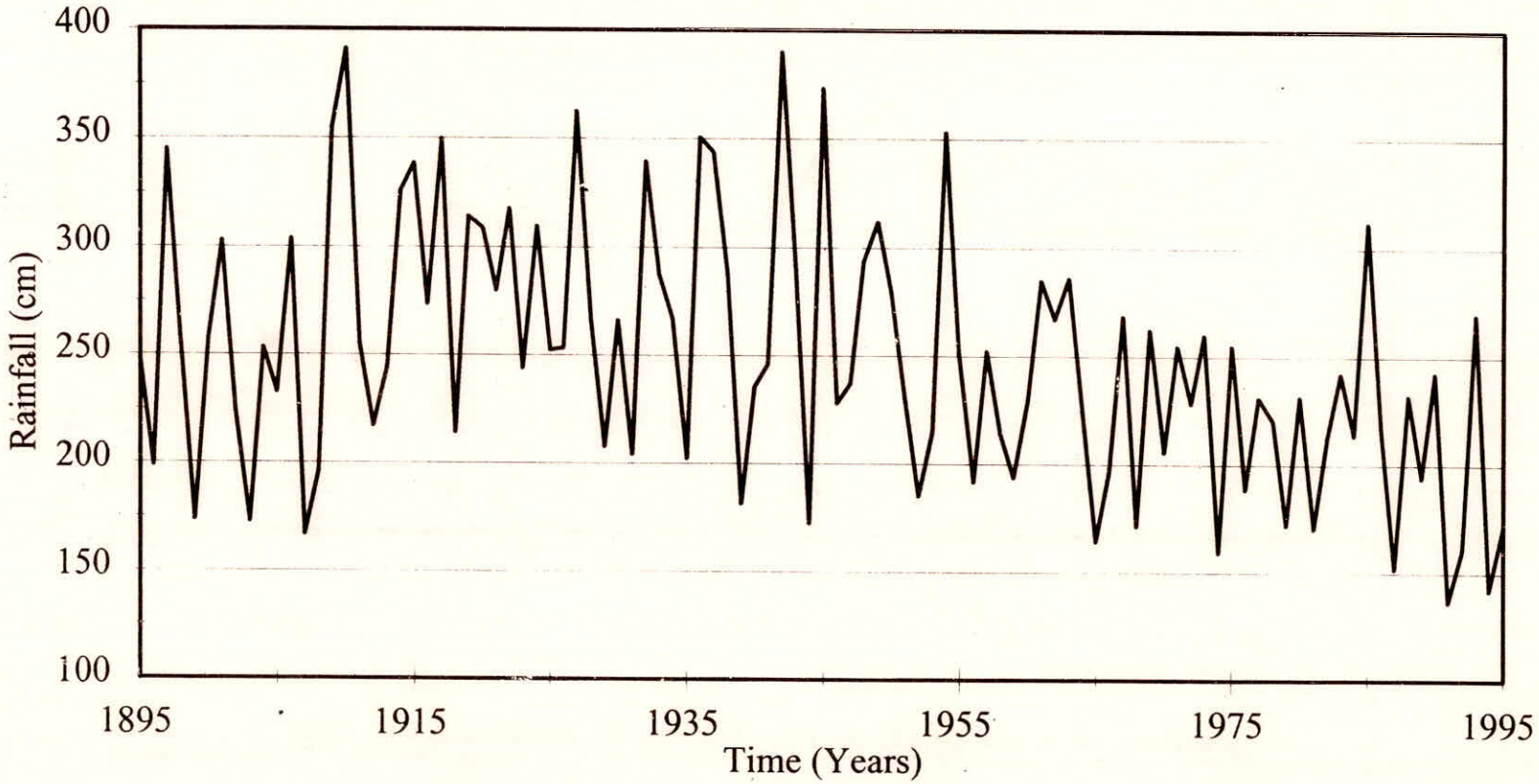


Fig. 15 Variation of annual rainfall in Lake Nainital basin for the period 1895 to 1995



2.7 Potential Evapotranspiration

The potential evapotranspiration in the Nainital catchment has been computed by the following methods:

1. Penman
2. Christiansen
3. Makkink
4. Jensen & Haise

The results are presented in Table 10 and for comparison shown in Fig.16. It is seen that the PET estimated by Penman method is higher than the estimates made by other methods. The Pan evaporimeter results are also shown in Fig. 16.

2.8 Actual Evapotranspiration

One of the most widely used approaches for estimating the actual evapotranspiration makes use of the potential evapotranspiration (estimated using meteorological data) and the relative soil water content. This approach has been adopted in this study. The actual evapotranspiration was computed using the following equation (Dingman, 1993).

$$ET_A = ET_P * \left(\frac{\theta - AWP}{AFC - AWP} \right) \qquad (11)$$

Where ET_A = Actual evapotranspiration (mm)

ET_P = Potential evapotranspiration (mm)

θ = Soil moisture content

AWP= Average Wilting Point

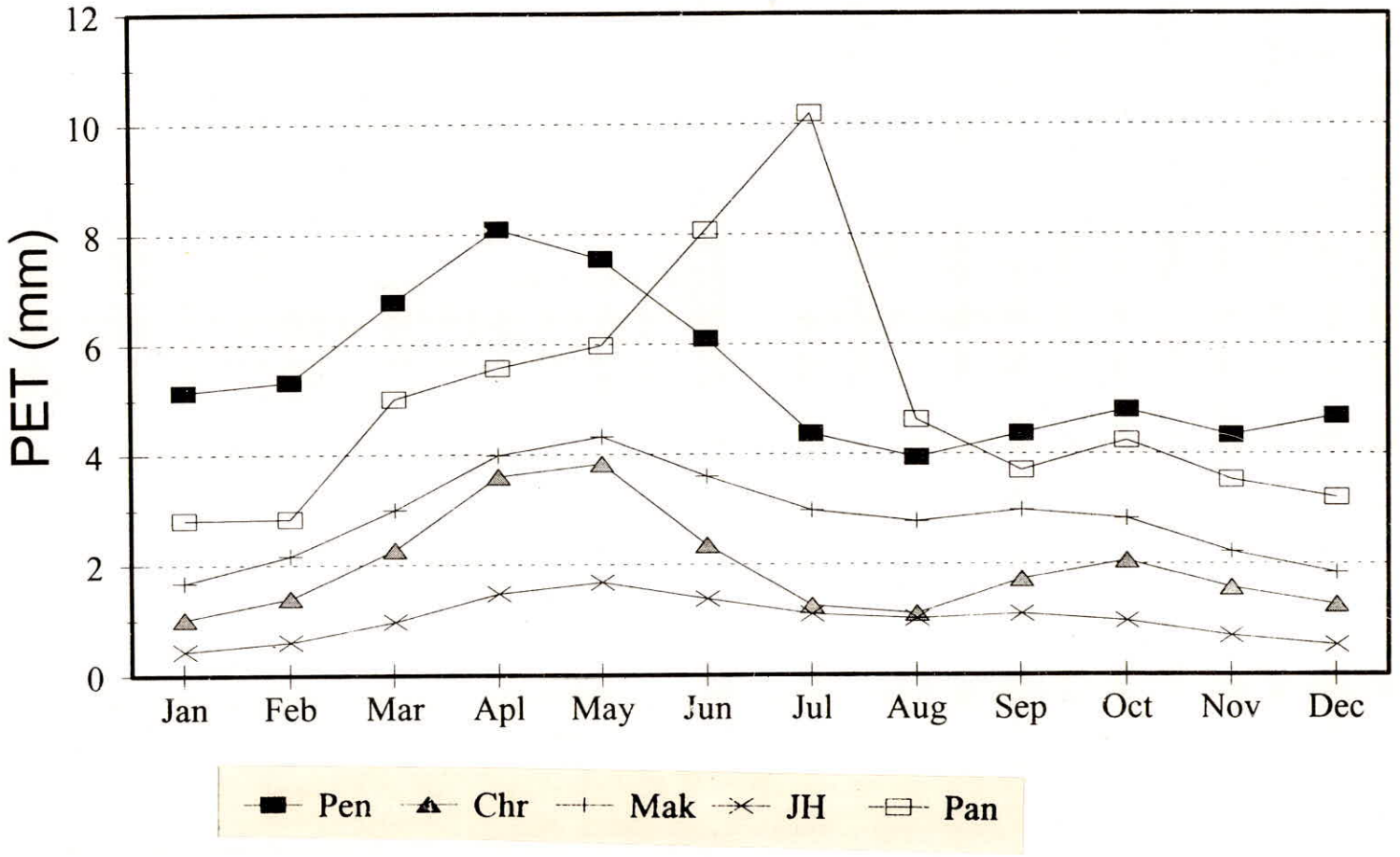
AFC = Average Field Capacity

Table 10: Potential evapotranspiration calculated using longterm average meteorological data by different methods

	Penman	Christ	Makking	Jen-Haise	Pan
	mm/day	mm/day	mm/day	mm/day	mm/day
Jan	5.14	1.02	1.67	0.43	2.81
Feb	5.32	1.39	2.17	0.60	2.83
Mar	6.78	2.27	2.99	0.97	5.02
Apl	8.09	3.59	3.98	1.46	5.57
May	7.55	3.83	4.32	1.67	5.98
Jun	6.10	2.35	3.60	1.38	8.08
Jul	4.37	1.25	2.98	1.09	10.19
Aug	3.93	1.10	2.78	1.02	4.63
Sep	4.38	1.72	2.98	1.09	3.70
Oct	4.81	2.06	2.82	0.97	4.24
Nov	4.34	1.56	2.23	0.69	3.53
Dec	4.69	1.26	1.83	0.52	3.20

Pen Chr Mak JH Pan

Fig. 16 Comparison of potential evapotranspiration calculated by different methods using long term meteorological data



Soil samples collected from different parts of the lake basin were subjected laboratory investigations to determine the field capacity and wilting point. The pressure plate apparatus (Eijelkamp make) was used for determining the moisture retention characteristics of the soil samples. Saturated samples were placed in the pressure plate apparatus and pressures that correspond to the wilting point (15 bars) and field capacity (0.15 bar) were applied till reaching equilibrium. Samples were then removed from the pressure chambers and weighed on a high precision electronic balance to record the moist weight of the samples. The weighed samples were then placed in a oven at 105°C for 24 hours and dried. The dry weight was then recorded. The moisture retention of the soil samples were then determined using the moist and dry weights of the samples. The results of the laboratory investigation are presented in Table 11.

Table 11: Moisture retention characteriscts of soil samples collected from different sites in Lake Nainital catchment.

Site	Field Capacity (0.15 bars)		Wilting Point (15 bars)	
	soil moisture content	Average	soil moisture content	Average
Alma Cottage	0.3122	0.3125	0.1958	0.1997
	0.3093		0.2004	
	0.3159		0.2029	
Ayarpatta - 1	0.2090	0.2035	0.0865	0.0856
	0.1990		0.0846	
	0.2020			
Ayarpatta - 2	0.1952	0.1996	0.1139	0.1146
	0.1987		0.1159	
	0.2049		0.1141	
Staff House	0.3540	0.3489	0.2416	0.2446
	0.3466		0.2391	
	0.3460		0.2532	
Catchment average	F.C.	0.2661	W.P.	0.1611

The actual evapotranspiration calculated using the PET values and soil moisture retention characteristics are shown in Fig. 17. The soil moisture variation with time has also been estimated by modified SCS-CN procedure (Soni, 1987). The soil moisture thus computed is shown along with the observed soil moisture in Fig. 18. The difference in the values are due to: a) the computed soil moisture pertains to the dominant soil type in the catchment namely the clay loam topping the calcareous shales and other rock type, while the observations are made at the coarser soil at the flats (due to logistical problems the soil moisture sensor could not be located at an apt site in the catchment) and b) the in-situ calibration of the soil moisture sensor could not be carried out, and had to rely on the factory calibrations. However, the pattern of soil moisture variation is very similar in both observed and computed values (Fig. 18).

Fig. 17 Variation of Potential evapotranspiration (Penman eqn.) and Actual evapotranspiration (soil moisture retention method) for Lake Nainital basin. Data pertaining to the year 1995.

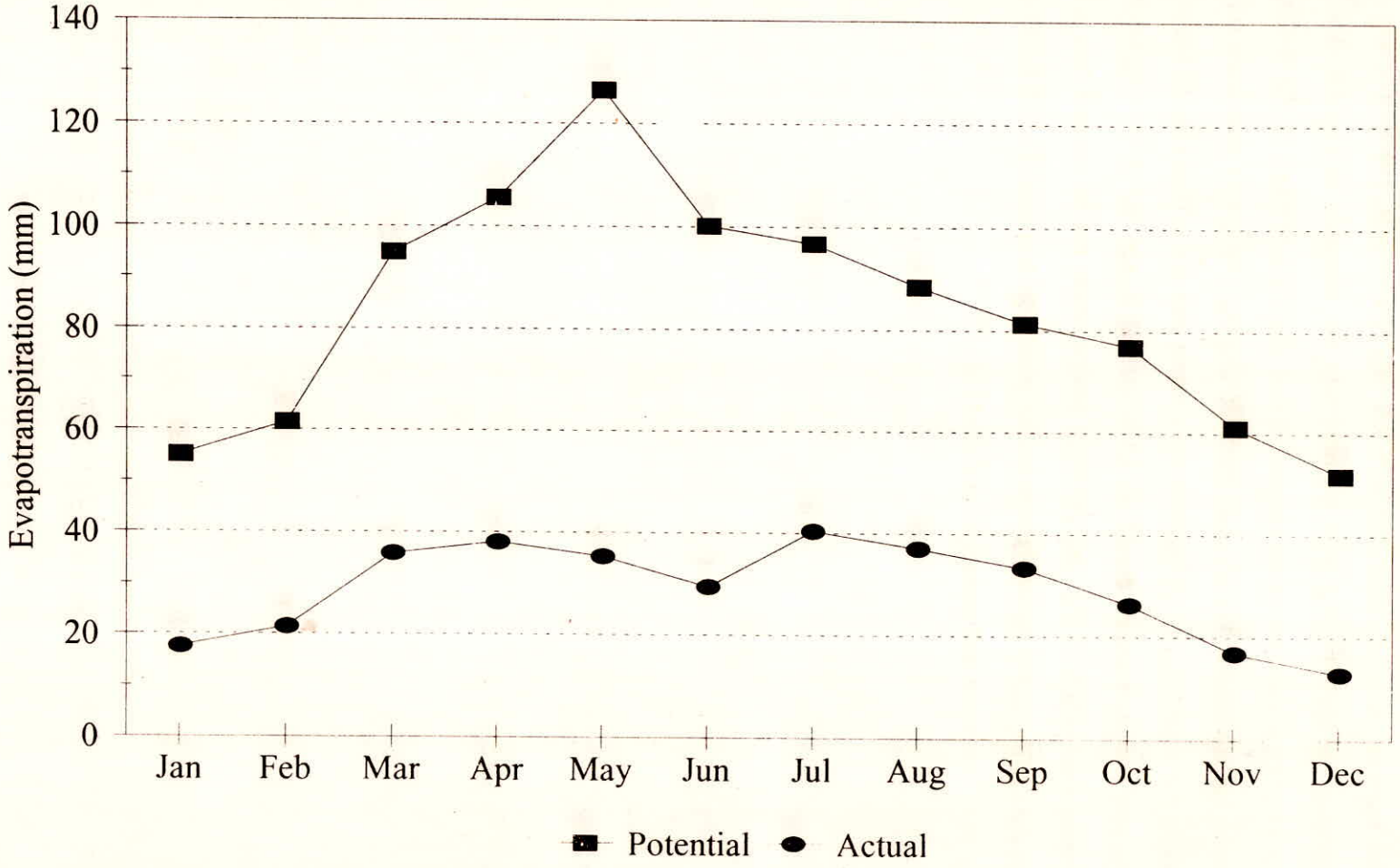
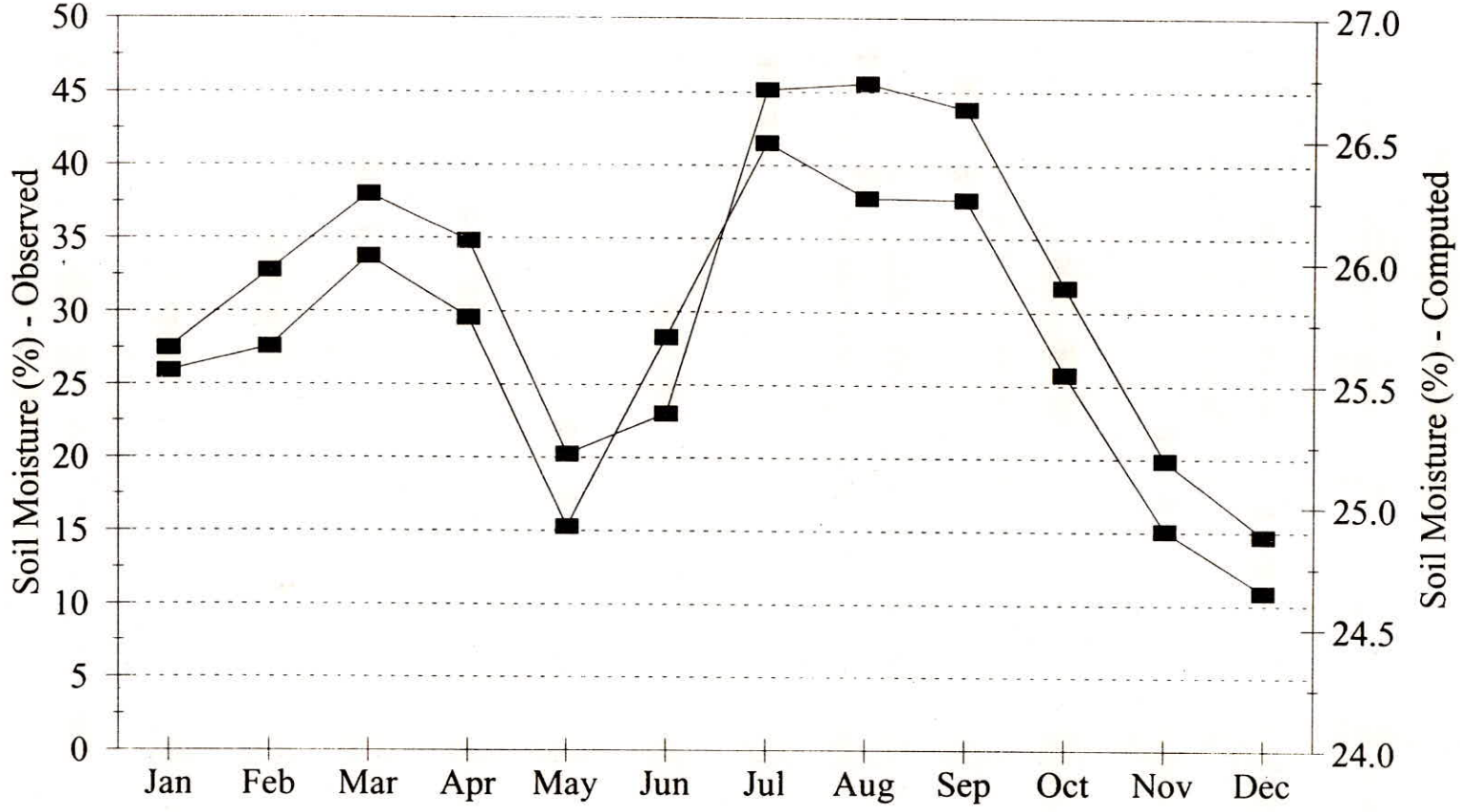


Fig. 18 Variation of observed and computed soil moisture in Lake Nainital catchment



REFERENCES

Dingman, S. I. (1993) Physical hydrology. Macmillan Publishing Co., New York.

Navada, S. V. and Kulkarni, U. P. (1989) Measurement of environmental deuterium and oxygen-18 in water samples. Technical report. Bhabha Atomic Research Centre, Mumbai.

Reckhow, K.H. and Chapra, S.C. (1983) Engineering approaches for lake management. Vol. I & Vol. II, Butterworth Publishers, London.

Soni, B. (1987) Estimation of runoff from agricultural watershed by SCS method. Technical Report, National Institute of Hydrology, Roorkee.

APPENDIX - F

RECHARGE SOURCES, DISCHARGE POINTS AND INTERCONNECTION OF SPRINGS WITH LAKE NAINITAL

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1.0 INTRODUCTION

The knowledge of recharge sources and discharge points of a lake is required for its better management. As the Nainital lake is located in the mountainous region therefore, it should have some invisible recharge sources as well as discharge points, i.e., many underground springs might be feeding to this lake and many springs might be also issuing from this lake.

A lake may have many recharge sources, i.e., direct precipitation (rainfall and snowfall), incoming river or channel, surface runoff due to precipitation in its catchment, aquifers or springs (subsurface inflow) etc.. Similarly, a lake may have many discharge points, i.e., outgoing river or channel, direct discharge of lake water from the controlled gates for maintaining the lake water level, direct or indirect pumping of lake water for various domestic /industrial or electric power generation purposes, underground outflow of lake water (leakage) in the form of springs in the downstream to the lake etc. In present case, the recharge sources and discharge points other than spring flows (inflow and outflow) are described in detail under Water Balance of Lake Nainital. Therefore, the information about springs flows and their interconnections with the lake have been discussed in this section. The interconnection between Lake Nainital and the adjoining aquifers including the springs issuing downstream to the lake catchment have been investigated using the isotopic and geochemical approaches.

2.0 RECHARGE SOURCES

Lake Nainital, located in Kumaun Lesser Himalayas, is surrounded by many freshwater springs. Lake Nainital is a precipitation fed lake. The annual average rainfall in the lake catchment is 24488 mm while snowfall ranging from 200 to 600 mm also occurs in a year. Owing to the geological formation in the lake catchment, the major part of precipitation infiltrates through fractures, faults and weathered zones which reappear in the form of springs. Therefore, the lake receives a major amount of its water input as subsurface inflow in the form of underground springs. The Dyke present in southern part

of the lake catchment also drives the flow of groundwater into the lake. The second major source to the lake is surface runoff from its catchment. The third source to the lake is direct precipitation on the lake surface. The lake also receives water from the snowmelt infiltration and runoff. It is also presumed that the precipitation falling outside the lake catchment also contributes to Lake Nainital through Nainital Fault. However, this fact is yet to be established, as it could not be clearly established by the investigations carried out under this study. In addition, the channel flow which mainly comprise of domestic liquid waste, except in rainy season, also contribute as input to the lake.

The lake is divided into two sub-basins, north basin and south basin, by a 100 m wide transverse underwater natural ridge, 7 m to 20 m below the water surface. This ridge is located north to south and extends from a place near the Library (north) to a place near the Pashan Devi Temple. It is presumed that this ridge has many openings of the underwater springs. The Nainital fault which is passing from the centre of the lake (west-east) also drain underground water from the lake catchment as well as form the outside. The individual contribution of the subsurface inflow being carried by the Nainital fault, Springs which have their openings at the underwater ridge or else where also and the Dyke located in the south to Lake Nainital could not be estimated. But, the total subsurface inflow computed using the isotopic approach is about 39 % of the total inflow to the lake. Sukhatal is located upstream in lake catchment. Its catchment area is 17.6 % of the total lake catchment area. Owing to its shape and geological formation (highly susceptible to infiltration of water). it contributes 45 to 50 % of the total subsurface inflow to the lake.

3.0 DISCHARGE POINTS

The discharge from the lake is taking place in four ways, i.e., i) in the form of direct outflow through the sluice gates which operates during the rainy season to control the water level in the lake; ii) pumping of lake water through infiltration well and deep tube-wells installed at the Mallital bank and Mall road side of the lake to meet out the

domestic and industrial demand of the city including Military Establishment located in the nearby area; iii) direct evaporation of lake water and iv) springs issuing from the lake downstream to the lake catchment.

In order to identify the source of the springs, the temporal and spatial variations in the geochemistry of the groundwaters have been studied through the springs issuing with in and outside the lake catchment. The study indicates that the groundwaters in the Manora Shales are different from the Pashandevi and Barapatthar Dolomites. Further, the rainfall run-off over the Manora Shales is high in sulphates. The lower sulphate content in the Lake Nainital is probably due to dilution by direct rainfall and considerable inflow from the dolomitic terrain, which may be low in sulphate content. The lake water and most of the upstream and downstream springs are of $MgHCO_3$ type. The downstream springs that issue on the Kailakhan area are of $MgSO_4$ type. The major cations in the lake viz., Ca^{2+}, Mg^{2+} and HCO_3^- are unsuitable for ion mass balance computations in the lake due to precipitation and dissolution processes. Na and K are present in low concentrations and the difference between the lake and the groundwaters is not significant above the analytical errors to be used as tracers. Sulphate may be considered as a useful tracer in the Lake Nainital environment. The open well located in the northern banks of the lake has lake as the main source. The tube-wells located adjacent to the open well however, has varying proportions of lake water and groundwater. The springs located in the Balia ravine viz., Sipahidhara, Gupha Mahadev springs have lake as the main source. Based on the vertical profiles of the lake water chemistry and isotopic signatures of lake and spring waters, it is found that the leakage from the lake takes place from the epilimnion zone. It also indicates that the underwater ridge may not only have only the openings of inflowing springs but it might also have inlets of the outflowing springs.

4.0 INTERCONNECTIONS BETWEEN THE LAKE AND SPRINGS

A few of the springs located south of the lake in the Balia ravine, have

considerably large discharges. This has created interest in the geologists who worked extensively in Nainital area during early part of this century (Holland, 1896; Coulson, 1939). The hypothesis that these springs discharge from Lake Nainital through interconnected fractures could not be established through the analyses of conventional hydrologic data, such as lake level, rainfall and spring discharge (Hukku, et al., 1968). The springs issuing in the southwestern and southeastern side of the lake catchment and at altitude below that of Lake Nainital may also have the lake as their source. Since these springs serve as a drinking water source to a few villages or dwellings around, it is imperative to establish the source of these springs to ensure long term dependability of the water supply. The upstream springs issuing within the catchment area of Lake Nainital have also been investigated for the water chemistry, as these are used for domestic water supply. Further, these upstream springs are indicative of the local groundwater chemistry and can be used to investigate the hydrological budget of the Lake Nainital through ion mass balance approach.

To address the above problems, a comprehensive geochemical and isotopic investigations were carried out during the period 1994-96. About 400 water samples were collected from Lake Nainital, springs located above and below the lake level, and wells located in the northern bank of Lake Nainital and on the banks of Lake Sukhatal. The samples were analysed for major ions and a few trace elements and $\delta^{18}O$. The details of the study are presented below.

4.1 Geochemical Approach

The water quality aspects of the Lake Nainital were monitored between 1994 and 1996. Sampling was carried out during February, May, October and December, 1994; February, March, May, June, August, September, November and December, 1995; January, April and July, 1996. The sampling locations are shown in Fig.1. The number of samples collected from the lake varied from a minimum of 6 (June, 1995) to a maximum of 37 (March, 1995). However, keeping in view the need for control points, the centre points of North and South basins (C2 and H2) were sampled regularly during



Water Sampling and measurement of Discharge of a Spring Located Downstream of Nainital Lake Catchment



Discharge Measurement of Gupha Mahadev Spring



Water Sampling of Lake View Spring Located Upstream to Lake Nainital



Water Sampling of Takula (S5) Spring

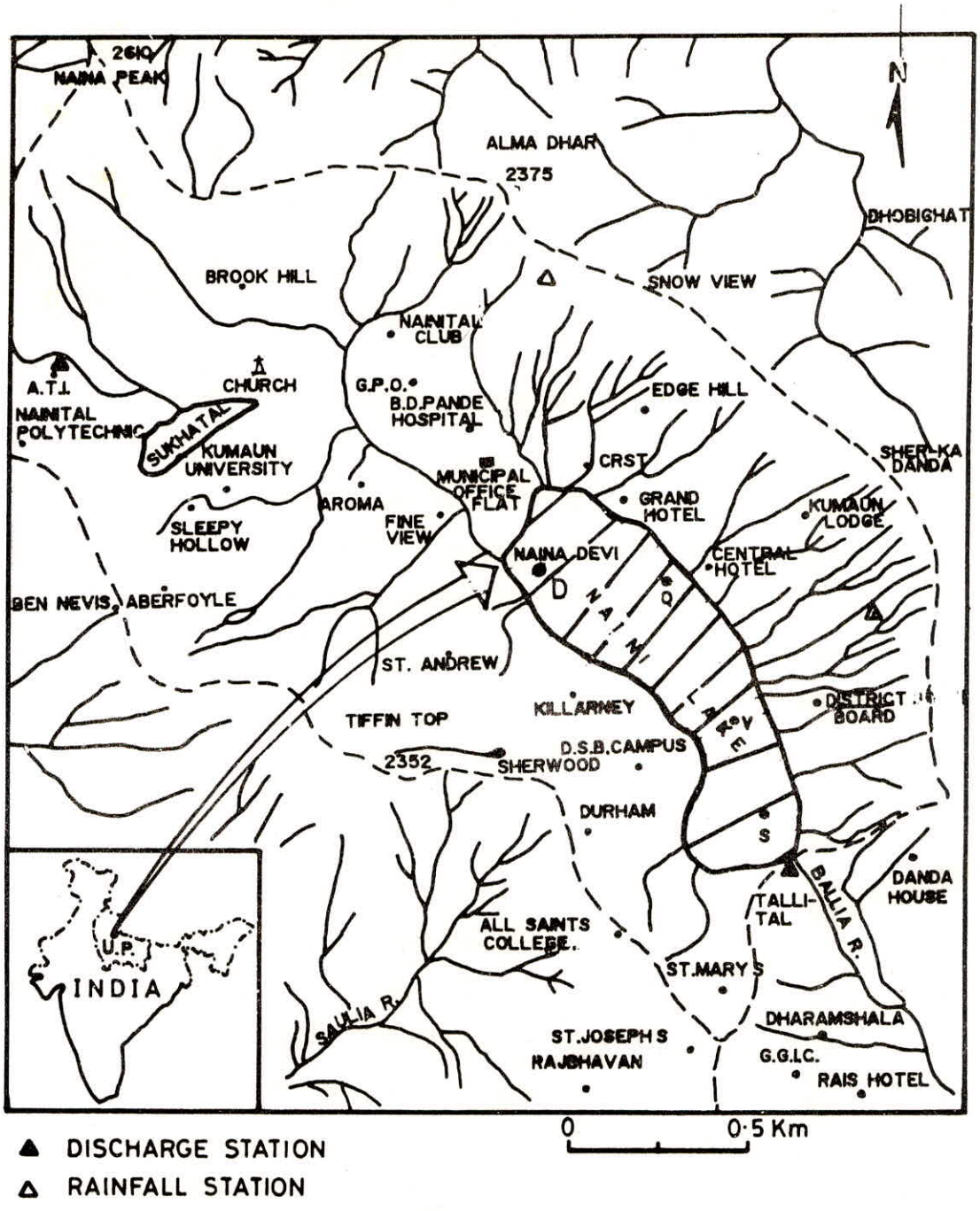


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

all the sampling periods. The lake was sampled, in general, from the top, middle and bottom layers. In order to understand the hydrodynamics of the lake, insitu measurements of pH, temperature and electrical conductivity was carried out at every three meter depth interval, starting from surface to the bottom. To establish the interconnection between the adjacent aquifers and springs issuing outside the catchment springs located in the upstream side of lake and within the catchment, springs located on the downstream side of lake and outside the catchment, nalahs draining into the lake and the tube wells and open well located around the lake were also studied for their water chemistry.

The samples from the lake were collected using a standard depth water sampler (Hydrobios make) of 2 L capacity with a built in thermometer of 0.2°C least count. The electrical conductivity (E.C.) and pH were measured in-situ using a 5-parameter field water testing kit. The collected samples were mainly utilised for three different aspects, viz. a) In-situ measurement of physico-chemical characteristics, b) Isotope composition and c) water quality aspects. The samples collected for the water quality aspects were first filtered using an 0.45 μm Whatman filter, preserved following standard procedures (Appello, 1988) and transported to Roorkee for analyses. The methods followed at the laboratory for analyses of different parameters discussed above are as follows:

Chloride was estimated by argentometric method in the form of silver chloride. Alkalinity was determined by titrimetric method using phenolphthalein and methyl orange indicators. Total hardness and calcium hardness were determined by EDTA titrimetric method while magnesium hardness was calculated by deducting calcium hardness from total hardness. Calcium and Magnesium concentration were determined by stoichiometric calculations using the values of total and calcium hardness values. Sodium and potassium were determined by flame-emission method using flame photometer. Nitrogen in the form of nitrate was determined by using spectrometric methods. Sulphate was estimated by turbidimetric method in the form of barium sulphate crystals.

In the present study, the ion-balance (electro-neutrality) is better than $\pm$ 10%. Duplicate analyses of samples used for ascertaining laboratory analytical efficiency

indicated that the results are within ± 1% accuracy. It is also observed that the anions are lower than the cations in the samples collected during certain sampling campaigns. The reason for this could be a) alkalinity was analysed using the unpreserved sample and b) the hardness and hence, calcium was determined using the preserved sample. Probably $CaCO_3$ has precipitated in the unpreserved sample and therefore, the total anions are lower than the total cations. The above fact, however, does not seriously hamper the present study as the information on most of the dissolved constituents are reliable. This is established by the better agreement found between the total cations and the electrical conductivity in the present case.

4.2 Isotopic Approach

The samples for stable isotope analyses were collected during the month of December, 1994 from the lake as well surrounding springs in 20 ml plastic vials and tightly sealed. The collected samples were analysed by Stable Isotope Ratio Mass Spectrometer at the Isotope Division, Bhabha Atomic Research Centre, Mumbai, India. The samples were analysed using the CO_2 equilibration method for $\delta^{18}O$. The procedure followed for the isotope analyses at the BARC laboratory has been presented in detail by Navada and Kulkarni (1989). The measurement precision for $\delta^{18}O$ was ± 0.1 ‰. All the isotope data reported in this article correspond to Vienna - Standard Mean Oceanic Water.

The environmental isotopes provide a clear picture of interconnection between the two water bodies as their composition does not affect in the process of flow etc. in most of the cases. However, if the sources are dynamic and distantly placed, the isotopic values are correlated with some time lag due to the time taken by the water to travel from the source to the outlet. The isotopic compositions of oxygen-18 and deuterium have been used to establish the interconnections between the lake and the downstream springs.

4.3 Interconnections

Although a few of the springs differed from the lake, in water types, it was considered that due to the presence of numerous fractures and faults, the springs that issue below the level of the lake may be connected to the lake. In order to complement the information obtained through the water chemistry, stable isotopic investigations were carried out. Samples collected from almost all the springs that issue in areas adjoining the lake catchment and at altitudes below the lake level were analysed for stable isotope $\delta^{18}O$ (Table 1). The Gupha Mahadev spring shows a $\delta^{18}O$ value close to that of the Lake.

Table 1: Stable isotope concentration and altitude of downstream springs issuing in the area surrounding the Lake Nainital catchment.

Location	Altitude (m a.m.s.l.)	$\delta^{18}O$ (‰)	Location	Altitude (m a. m.s.l.)	$\delta^{18}O$ (‰)
S1	1850	-10.6	S9	1760	-10.7
S2	1790	-7.5	S10	1760	-10.2
S3	1730	-7.4	S11	1650	-10.9
S4	1720	-7.0	S12	1700	-10.7
S5	1730	-7.7	G. Mahadev	1785	-9.5
S6	1750	-11.0	Lake Nainital	1940	-9.6
S7	1640	-11.8			

However, the springs S2, S3 and S4 in the Kailakhan area show enriched $\delta^{18}O$. Since, the lake has a $\delta^{18}O$ value of about -7‰ during July / August, the enriched values in the Kailakhan springs may be due to long travel time. If the waters that issue from springs S3 and S4 are considered as leakage from the Lake Nainital, the change in water type from Magnesium Bicarbonate to Magnesium sulphate could be ascribed to long travel time and contact with pyritiferous shales. The springs S1, S6, S7, S9, S10, S11 and S12 do not have connections with Lake waters as they show a more depleted $\delta^{18}O$ value during non-rainy season.

The inference that Gupha Mahadev spring and Sipahidhara spring are connected to the Lake through lineaments is substantiated by the chemical concentrations. Unlike the upstream springs Sipahidhara spring shows little variation in the total cations, TZ^+ with time (Fig. 2). Comparison of ion concentrations show that the series of springs viz., Sipahidhara and Gupha Mahadev receive water from the Lake's epilimnion zone.

5.0 RESULTS AND CONCLUSIONS

5.1 Characterisation of Waters

In general, all the springs that issue within the catchment, the water flowing in the nalahs and the Lake Nainital water are of Magnesium-Bicarbonate type. The springs Sipahidhara, Gupha Mahadev, Rais Hotel (Reserve police lines), Sariyatal, Takula spring are also of magnesium bicarbonate type, same as the lake water. But, the downstream springs S2, S3 and S4 located in the Kailakhan side are of Magnesium-Sulphate type (Table. 2a and 2b). Further, the springs that issue at Durgapur power house are also Magnesium-sulphate type. The water chemistry is shown in Fig. 3a and 3b.

In general calcium and magnesium are the major cations and bicarbonate is the major anion in all the springs and lake in the study area. However, in certain springs (S3, S4, Durgapur etc) sulphate is the major anion. Concentrations of sodium, potassium and chlorine are low in all the natural waters in the study area. Calcium and magnesium show considerable temporal variations in the Lake Nainital and in upstream springs like Lakeview, Chunadhara and Pardhadhara. These variations in the lake could be brought about either by precipitation and dissolution of calcite or by varying inflows from groundwaters at different seasons. The variations in the springs are probably brought about by the different pathways i.e., interflow or saturated flow (flow from the saturated zone) followed by the infiltrated water before reaching the discharge points. The high weathering in the calcareous shale has given rise to about 6 meters of weathered zone (Ashraf, 1978). The fragility gives rise to an conducive medium for dissolution of constituent elements which is carried by the infiltrating waters. Further, the channelised surface run-off (Boatclub Drain, Alka Drain, Church Drain), studied during the rainy

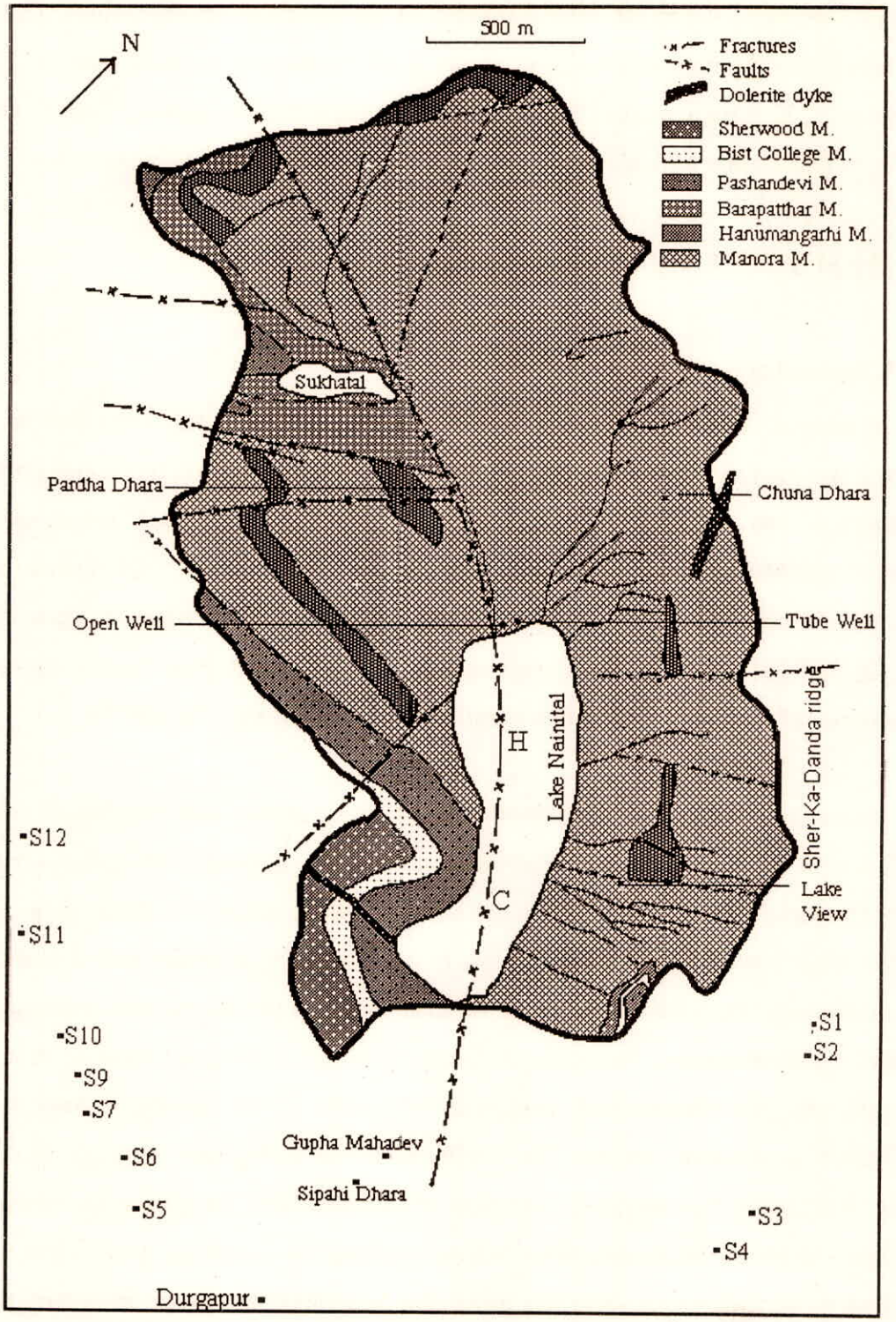


Fig.2 Geological map of Lake Nainital catchment showing locations of sampling points in lake and surrounding springs

Table 2a: Physical and chemical characteristics of Lake Nainital, groundwater discharge from with in and out side the lake catchment and the surface inflow to lake (May, 1995). Electrical conductivity (EC) in μmho/cm., Temperature in °C, and all concentrations are in mg/l.

Source	Location	Type	pH	EC	Temp.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	Saturation Index	
													Calcite	Dolomite
Lake	Epilimnion	$MgHCO_3$	7.9	571	20.8	36	49	11.3	4.6	210	97	14	0.148	0.741
Lake	Mesolimnion	$MgHCO_3$	7.5	642	9.1	41	57	10.8	4.7	253	94	11	-0.636	-1.149
Lake	Hypolimnion	$MgHCO_3$	7.4	645	8.6	42	58	10.0	4.6	249	92	13	-0.253	-0.382
U/s Spring	Pardhadhara	$MgHCO_3$	7.3	821	15.0	29	56	13.6	3.3	234	170	13	-0.530	-0.546
U/s Spring	Chuna Dhara	$MgHCO_3$	7.5	943	14.5	32	67	13.0	5.6	231	170	21	-0.296	-0.057
U/s Spring	Lake view	$MgHCO_3$	7.6	851	14.5	29	69	8.6	2.3	266	165	23	-0.192	0.208
Groundwater	Open Well	$MgHCO_3$	7.3	734	15.2	37	28	14.0	4.5	262	nd	15	-0.291	-0.174
Groundwater	Tube Well 3	$MgHCO_3$	7.5	745	nd	30	53	12.0	5.6	231	99	23	-0.179	0.211
Groundwater	Sukhatal Well	$MgHCO_3$	7.4	764	13.5	39	50	12.0	3.2	210	135	17	-0.378	-0.450
D/s Spring	Sipahidhara	$MgHCO_3$	7.7	632	nd	37	54	9.6	3.0	230	99	18	0.064	0.382
D/s Spring	G. Mahadev	$MgHCO_3$	8.0	602	nd	35	39	8.0	2.5	159	130	11	0.165	0.678
D/s Spring	S3	$MgSO_4$	7.6	885	nd	39	62	32.0	2.5	187	192	12	-1.050	-1.835
Drain	Naina Devi	$MgHCO_3$	7.1	1054	19.5	50	85	32.0	16.0	234	150	45	-0.415	-0.197
Drain	Rick. Stand	$MgHCO_3$	7.1	1549	14.5	39	99	72.0	35.0	360	126	82	-0.450	-0.278

nd: not determined

Table 2b: Physical and chemical characteristics of Lake Nainital, groundwater discharge from with in and out side the lake catchment (Dec., 1995). Electrical conductivity (EC) in μmho/cm., Temperature in °C, and all concentrations are in mg/l.

Source	Location	Type	pH	EC	Temp.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	Saturation Index	
													Calcite	Dolomite
Lake	Epilimnion	$MgHCO_3$	8.3	456	10.2	51	60	8.0	4.3	278	85	13	0.693	1.592
Lake	Mesolimnion	$MgHCO_3$	8.2	462	9.8	51	54	7.4	4.7	272	71	15	0.555	1.267
Lake	Hypolimnion	$MgHCO_3$	7.8	507	9.3	61	54	6.6	5.0	298	84	11	0.356	0.784
U/s Spring	Chuna Dhara	$MgHCO_3$	8.2	625	nd	100	60	8.0	7.0	360	162	22	0.798	1.304
U/s Spring	Lake view	$MgHCO_3$	8.4	629	nd	81	69	4.7	2.7	380	148	18	0.923	1.706
Groundwater	Open Well	$MgHCO_3$	8.0	548	nd	72	61	5.8	3.6	364	139	20	0.481	0.817
Groundwater	Sukhatal Well	$MgHCO_3$	8.8	530	nd	63	59	4.7	3.0	312	131	12	1.115	2.239
D/s Spring	Sipahidhara	$MgHCO_3$	8.3	434	nd	49	49	4.6	3.2	288	122	10	0.529	0.989
D/s Spring	G. Mahadev	$MgHCO_3$	8.3	468	nd	47	57	4.3	2.9	280	75	16	0.509	1.207

nd: not determined

Fig. 3a Fingerprint plot of Lake Nainital water chemistry

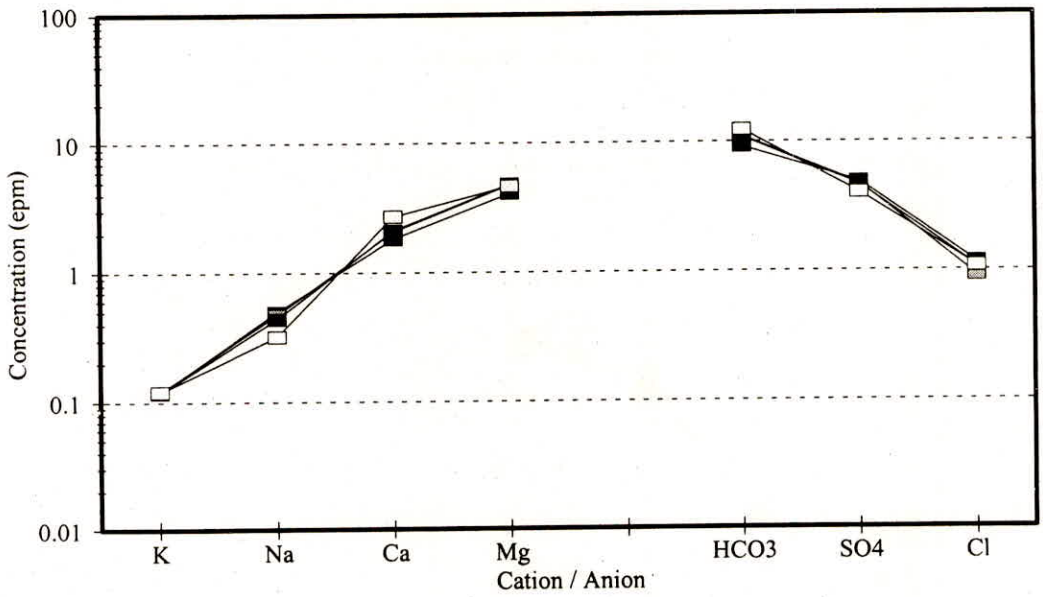
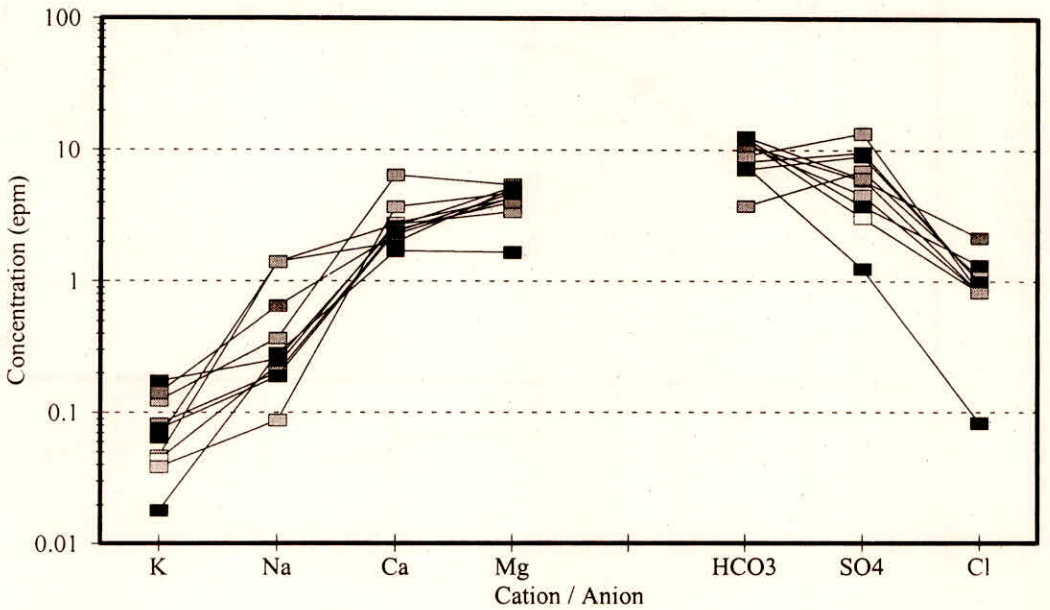


Fig. 3b Fingerprint plot of Nainital basin groundwater chemistry



season in the month of August and September, 1995 also show higher magnesium and sulphate concentrations. Sodium, potassium and chlorine concentrations are consistently higher in Naina Devi Drain and Rickshaw Stand Drain, compared to the springs and Sukhatal well.

5.2 Sources and Controlling Factors

The higher concentrations of Ca and Mg can be ascribed to the limestone and dolomite in the eastern part of the catchment and the calcareous slates that occupies most of the remaining catchment area (Fig. 4). The dolomite in the Ayarpatta region of Lake Nainital catchment comprises of about 50% of carbonates of lime and 41% carbonates of magnesia (Holland, 1896). Na and K are unimportant in the catchment as shown by low and uniform concentrations in all water sources in the catchment. The variation in the sulphate concentrations is of special interest in the study area as it may give some insights to the hydrogeology of the area. When sulphate concentrations are plotted against the more conservative chlorine (Fig. 5), the values plot in clusters. The upstream springs Lake View and Chunadhara fall in the higher side of the sulphate axis while the Lake Nainital falls in the lower side. The open well located on the northern bank of the Lake Nainital and the downstream spring Sipahidhara also plot within the Lake cluster. The tube well located on the banks of Sukhatal fall in between the two clusters.

The higher sulphate concentration in the upstream springs that issue from calcareous slates are probably because of the discharging waters are in contact with the gypsum pockets. The Lake Nainital waters have lower sulphate concentration probably because it receives a considerable quantity (about 10% of total volume) of direct rainfall which has negligible sulphate concentration (Table 3). However, the direct rainfall alone cannot account for lower sulphate concentrations in the lake, as the surface runoff from the shales which accounts for about 60% of the basin surface also has higher sulphate content (Table 3). Therefore, the higher sulphate load introduced into the lake by the channelised surface run-off from the shales and subsurface inflows from the shales is probably diluted by substantially large inflow from the dolomite and limestones in the

Fig. 4 Sulfate – Chloride cross plot for different water sources

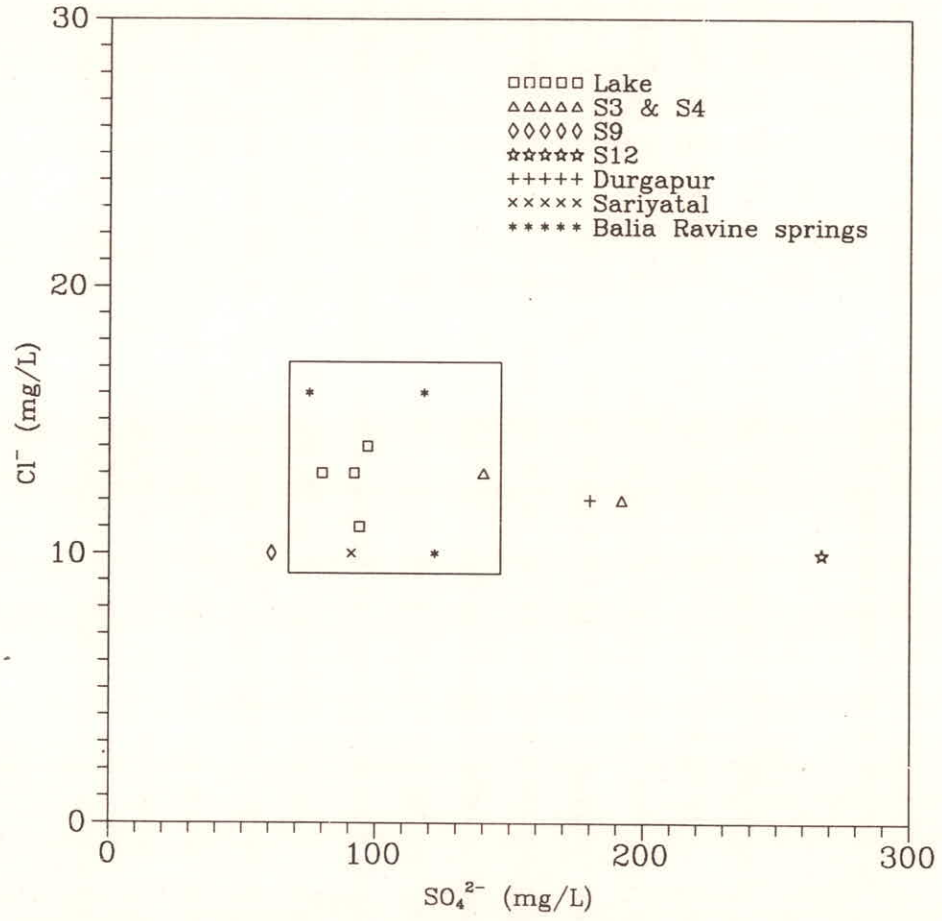


Fig. 5 Variation of total cations (TZ^+) of different water sources with time

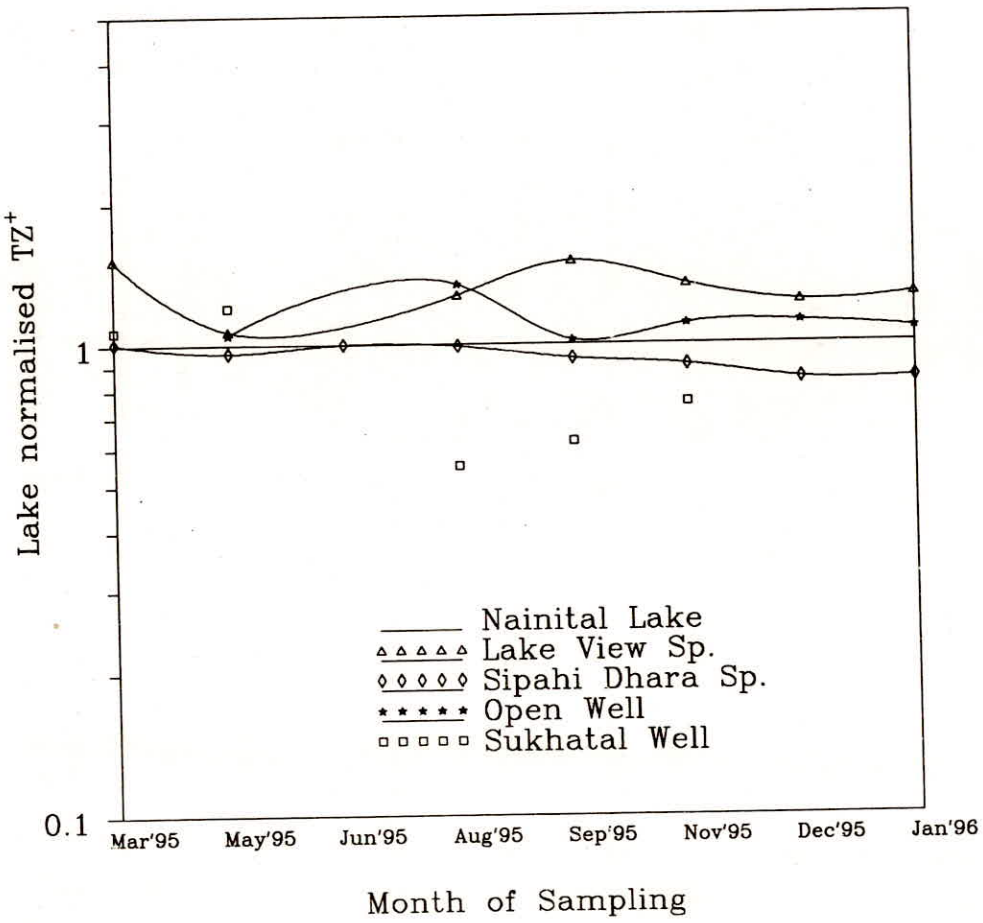


Table 3: Chemical characteristics of surface inflow to lake and Rainfall. All concentrations are in mg/l.

Month	Location	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-
Aug., 1995	R. Stand	37	72	27	12	278	144	42
	Drain-4	40	80	21	22	344	125	40
	Drain-6	15	110	20	6	346	199	18
	Drain-10	37	87	26	12	326	158	18
	Drain-20	40	77	31	11	288	134	46
Sep., 1995	R. Stand	33	81	37	13	306	125	32
	Boat club	31	94	35	10	306	171	24
	Alka	37	94	27	9	362	163	30
	Church	49	84	23	8	354	136	24
	Library	35	76	17	5	290	137	30
	Naina Devi	36	75	18	5	306	117	26
1982 †	Lucknow: RF	2.9	0.42	0.83	0.85	13.4	nd	2.1

nd: not determined
† Handa, et al. (1986)

south-eastern part of the catchment. In all probabilities, the water draining the dolomite and limestone as well as the groundwater in limestone and dolomite aquifers, are poor in sulphate concentrations. However, this assumption could not be verified as there are no springs or wells located in the limestone, within the catchment area. The Pardhadhara spring which issues near the Nainital fault zone, shows large variations in the sulphate concentrations, indicating that it may have more than one source. Its proximity to Hanumangarhi Member and Barapatthar Member of the Krol formation probably results in the temporal variation. Further, as the Pardhadhara spring is located very near to the Naini Fault, it may also receive a part of the water seeped from the Sukhatal lake.

5.3 Recharge Sources and Discharge Points

The lake receives 39 % of its input as subsurface flow through Nainital fault, Springs which have their openings at the underwater ridge or else where also, Dyke located in the south to Lake Nainital and Sukhatal. The contribution of surface flow is 30 %. Direct precipitation contributes to the lake 16 % of its total input and rest is contributed by channel flow. Sukhatal located upstream in lake catchment contributes 45 to 50 % of the total subsurface inflow to the lake. The discharge of lake water takes place in the form of direct outflow through the sluices gates (41 % of the total outflow) which operates during the rainy season to control the water level in the lake, pumping of lake water through infiltration well and deep tube-wells (32 %), direct evaporation of lake water (12 %) and springs issuing from the lake downstream to the lake catchment (16 %).

5.4 Interconnections

The Lake Nainital and several upstream and downstream springs in the surrounding area were investigated for their hydrogeochemical characteristics. The study reveals that the upstream springs reflect the basin geology. The subsurface contribution to the lake by limestone and dolomite aquifers could be substantial as the lake shows lower sulphate concentrations than the surface run-off through the drains (including rainy season) as well as the groundwaters from the calcareous shales. The interconnection between the Lake Nainital and downstream springs Sipahidhara, Gupha Mahadev and Rais Hotel spring are established through the similarity in the dissolved ion concentrations and stable isotopic composition. Further, through the water quality data on the stratified lake and that of these downstream springs it has been shown that the leakage from the lake take place in the epilimnion zone, i.e. between 0 to 6 m from the maximum lake level. The water pumped from the open well located in the northern bank of the lake is found to be as seepage from the lake. The tube wells TW1, TW2 and TW3 show a mixture of lake water and the groundwater. The springs S1, S6, S7, S9, S10, S11

and S12 do not have connections with Lake waters as they show a more depleted $\delta^{18}O$ value during non-rainy season.

The temporal variations in the calcium, magnesium and bicarbonate ions within the Lake Nainital are probably brought about by precipitation during summer season and dissolution during winter season. The saturation indices calculated for calcite and dolomite (Table 2a and 2b) indicate that while the lake water is super saturated with respect to calcite and dolomite during winter, is under saturated during summer. Therefore these ions are unsuitable for chemical mass balance estimates. On the other hand Cl^- may be conservative, but the difference between the end members i.e., the groundwater and the Lake is not significant to be used as a tracer. Sulphate may be used a as tracer in the case of Lake Nainital in addition to stable isotopes.

REFERENCES

Appello, C. A. G. (1988) Hydrochemistry for hydrogeologists - Application of chemical theory. Instt. for Earth Sciences, Free University, Amsterdam, The Netherlands.

Ashraf, Z. (1978) A geological report on the drilling explorations carried out for the study for the study of Nainital hill slope stability, Nainital District, Uttar Pradesh. Unpublished Report, Envi. Geol. Divn. (NR), Geol. Surv. India.

Coulson, A. L. (1939) Geological report on the alignment of the power pipe line of the Nainital Municipal Board's hydroelectric scheme. Geol. Surv. India.

Handa, B. K., A. Kumar and D. K. Goel (1986) Rainfall composition in Lucknow in 1982 and its significance to man. Mausam 37(2) : 245-250.

Holland, T.H. (1896) Report on the Geological Structure and Stability of the Hill Slopes Around Nainital, Geol. Surv. India, 132pp.

Hukku, B.M., Srivastava, A. K. and Jaitle, G.N. (1968) A geological Report on the Investigation of the Stability of the Hill-Slopes Around Nainital. Unpublished Progress Report, Envi. Geol. Divn. (NR), Geol. Surv. India.

Valdiya, K.S. (1988) Geology and Natural Environment of Nainital Hills, Kumaun Himalaya, Gyanodaya, Prakashan, Nainital, pp. 155.