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Estimation of sub-surface components in the water balance of lake Nainital (Kuamun Himalaya, India) using environmental isotopes

Rm. P. NACHIAPPAN, BHISHM KUMAR
Isotope Hydrology Divsion, National Institute of Hydrology, Roorkee - 247 667, India
U. SARAVANAKUMAR, NOBLE JACOB, SUMAN SHARMA, T. BABY JOSEPH, S. V. NAVADA
Isotope Applications Division, Bhabha Atomic Research Centre, Mumbai - 400 085, India
Rm. MANICKAVASAGAM
Department of Earth Sciences, University of Roorkee, Roorkee - 247 667, India

Abstract
Nainital Lake located in the Kumaun Himalayan region in northern India is a major drinking water source to the people living in and around the lake basin. Unfortunately, detailed computations of the lake water balance have not been carried out in the past. In this present investigation, the sub-surface outflow component has been computed by indirect means and used in the water balance equation to estimate the sub-surface inflow. The results have been verified by using the environmental isotope mass balance method. Further, chloride mass balance method has also been employed for comparison of results. The results indicate that the groundwater contributes about 50% of total annual inflow to Nainital lake. The sub-surface outflow is about 55% of the total annual outflow from the lake. It shows that the lake is a 'flow - through' type, with substantial groundwater inflow and lake seepage. The results of both chloride and isotope mass balance methods corroborate the results of water balance method. Water retention time - WRT (volume/outflow) as computed for Nainital lake by isotopic mass balance, chloride mass balance and conventional water balance methods is about 1.93y, 1.77y and 1.92 y respectively. The slope of the $\delta^{18}O$ - δD water line of the lake (7.1) is very close to that of the Local Meteoric Water Line (7.5) indicating that the effect of evaporation in the lake is not manifested in its isotope characteristics. This fact substantiates the shorter water residence time of Lake Nainital.

INTRODUCTION

The environmental isotope techniques have been applied to several lakes worldwide to understand the groundwater components of lake water balance (Dinçer, 1968; Fontes et al., 1970; Krabbenhoft et al., 1990; LaBaugh et al., 1997). However, it has been applied mostly to low or mid altitude lakes that are hydrologically and isotopically in a steady state condition. In India, the lake-groundwater interaction study has not been attempted so far to any of the lakes located either in the mountainous region or in the plains by using stable isotope techniques. In view of the above, an attempt has been made to estimate the groundwater components of Lake Nainital by using the stable isotopic technique. The lake has been selected for the present investigation as it forms the main fresh water resource for domestic use to a large population besides, Nainital is also an important tourist resort in northern India.

STUDY AREA

Lake Nainital (29°23'09" N and 79°27'35" E) is a high altitude (1937 m above m.s.l.) natural lake (Figure 1) located in Nainital district, Uttar Pradesh, India. It is a crescent-shaped lake with a maximum length of 1.4 km and width of 0.45 km. The maximum and mean depths of the lake are 27.3 m and 18.5 m respectively. The surface area of the lake is 0.46 km^2 with a maximum capacity of 8.57 Mm^3. The lake is bound, in the east by the Sher-ka-Danda hill, in the north by the landslide deposit called Flat, in the west by the Ayarpatta hill and in the south by Balia ravine. The western and northern banks of the lake are steep, while the eastern bank is slightly shallow due to deposition of sediments by drains. The largest deltaic type sedimentation is found near Nainadevi Temple. The total population in the basin is around 40,000. The lake is a major summer resort in north India, and attracts nearly 100,000 tourists annually. Tourism is the major industry of this region and there is no agricultural or industrial activity within the lake catchment area.

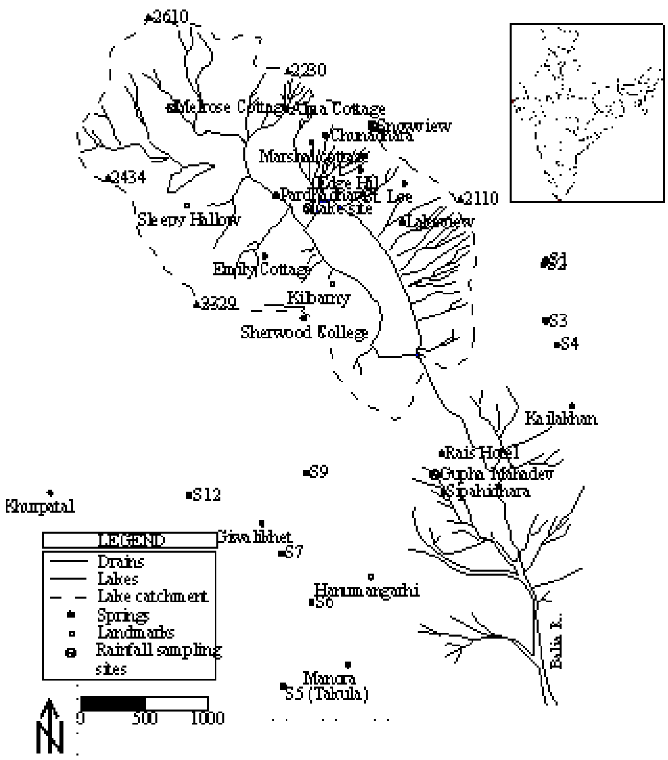

Figure 1. Location map of the study artea showing Nanital lake and sampling sites.

The study area is characterised by Krol and Tal formations of upper Mussoorie Group (Valdiya, 1980). The available literature suggest that the lake basin comprises of shales/slates, dolomites, dolomitic sandstones, purple sandstones, quartzite and dolerite. A regional fault, called Lake fault or Naini fault cuts the deformed synclinal massif into two parts. Parallel to the Naini fault, a sympathetic Ayarpatta fault (Middlemiss, 1890) has considerably deformed the overturned limb of the asymmetrical syncline lying south to it. The whole belt is cut by a large number of N-S and NE/ENE-SW/WSW trending tear faults (Valdiya, 1988). Two minor faults, the Sleepy Hallow fault and another fault (traceable from Narain Nagar through the Nainital Polytechnic), have affected the Middle Krol Unit leading to the formation of a lakelet behind Snowdon.

There are around 20 channels that drain the entire Nainital lake basin. Out of these only Nainadevi and Rickshaw stand drains are perennial due to spring discharge and sewage disposal. From the land use data, it is seen that the urbanisation and forestry are almost equal and account for about 80% of the total land area. The infiltration tests conducted by using standard ring infiltrometers at three different sites indicate that infiltration rate in the lake basin varies widely (from 1.1 cm/h to 78.0 cm/h). The higher infiltration rates along the valley bottom might be responsible for low surface runoff (25-30%) in the Nainital lake catchment (NIH, 1999).

The Nainital lake basin is structurally and stratigraphically a complex area, but essentially consists of carbonate and shale formations. Shales are the least productive rocks and carbonate rocks vary widely in their water yielding capacity. This is due to solvent action of circulating water, particularly in folded limestone, the water may move in the down dip direction from the recharge area to the discharge area. The joints and bedding planes have a pronounced effect on the solution patterns and movement of water in carbonate rocks. In carbonate terrain, faults affect the lateral movement of water especially if water bearing limestone beds are faulted against relatively impervious rocks (Stringfield and Le Grand, 1969). This condition leads to development of springs along the fault zone. The perennial Pardhadhara spring located in the Nainital basin, is probably a result of Naini fault that has brought the limestone of Middle Krol against the Manora shales of Lower Krol. Similar to this, there may be several sub-surface springs emerging in Nainital lake along Naini fault. Domestic water supply to the Nainital town is met through pumping of groundwater from deep tube-wells and an open-well located at northern banks of Nainital lake and from few natural springs. The pumping stations are operated and the records are maintained by different goverment agencies. The monthly draft of groundwater through pumping varied from 2,23,580 m^3/month to 4,99,100 m^3/month during 1994 and 1995.

CONCEPTUAL MODEL FOR THE LAKE WATER BALANCE

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

The water balance equation for a lake can be written as
ΔV = inflow B outflow

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

SSi B SSo = (Eo + So " ΔV) B (Pi + Si + Di) (1)

where, SSi	=	sub-surface inflow to the lake [L^3/T]
SSo	=	sub-surface outflow from the lake [L^3/T]
Eo	=	evaporation from the lake surface [L^3/T]
So	=	surface outflow from the lake [L^3/T]
ΔV	=	change in lake storage [L^3/T]
Pi	=	direct precipitation over the lake surface [L^3/T]
Si	=	surface water inflow to the lake [L^3/T]
Di	=	inflow to the lake through drains [L^3/T].

Water balance approach is used to determine the unmeasured components of a lake system for a particular condition. In the unsteady flow condition the changes in storage of the lake occur over a finite interval of time and therefore, the time interval used in the equation must be large. Further, all the known components should be estimated accurately for selected time interval. The magnitude of the computed component should be large relative to the sum of expected errors in measurement of other components; otherwise, the error may overshadow the computed components.

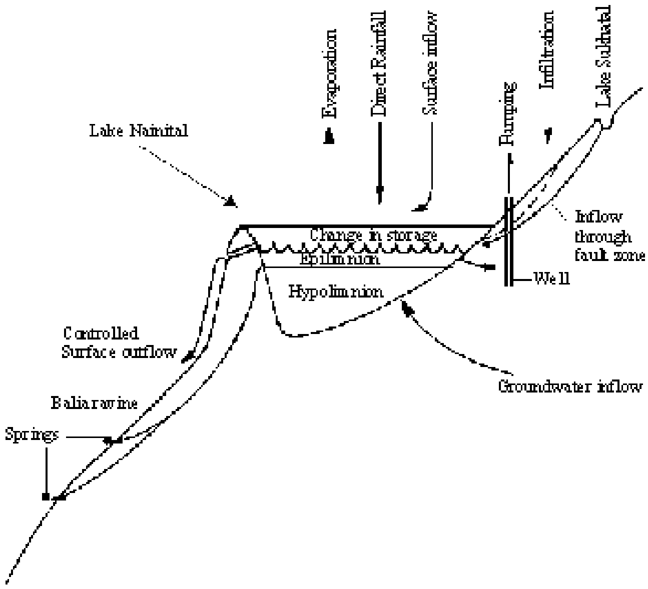

Figure 2. Conceptual model showing various water balance components of Nanital lake.

Sukhatal sub-catchment of Nainital does not have any surface outflow and appears to be a closed type. The rainfall received in this sub-catchment is lost through infiltration and evaporation in a short time. Because of the proximity of Lake fault to Sukhatal lake, it is possible that most of the water is lost through underground seepage that subsequently recharges Nainital lake. The change in lake storage responds quickly to direct precipitation and surface inflow as a consequence of steep hill slopes in the lake catchment. This is evident from daily lake level data. The other major component, that influences the lake storage, is the surface outflow. Evaporation from the lake surface during 24-hour time interval is negligible and is not readily discernible from daily lake level data. Apart from the above components that can be measured or estimated using standard methods, the lake level is also influenced by indirect withdrawals from the lake.

Withdrawals from lake Nainital do not take place directly from the lake, but through the wells installed at the periphery of the lake. The entire quantum of water, that is pumped out of these wells may not completely be from lake seepage. However, as the wells are located in unconsolidated landslide debris and occur very close to the lake, it is possible that a major portion of the pumped water is replenished by the sub-surface outflow from lake Nainital as seepage.

The sub-surface outflow towards the downstream side of the lake may be through the fractures and faults. Seepage from lake may not be occurring through lakebeds as they are characterised by thick layer of fine sediments. Therefore, sub-surface outflow may be occurring mainly in the epilimnion zone. Outflow from the lake recharges the unconfined aquifer, which in turn, discharges through numerous springs located in the downstream side of the lake. Therefore, in the absence of groundwater level data in the unconfined aquifers at downstream side, the seepage from the lake could be quantified only from discharge measurements of springs that are hydraulically connected to the lake and located in the downstream side.

Keeping the above in view, the sub-surface outflow from the lake may be divided into two parts viz., withdrawal from the lake through the wells installed in the northern bank (Wo) and outflow to the springs (SPo). Therefore, Equation (1) may be modified by incorporating Wo and SPo in place of SSo. The various flow components required for water balance study of the lake are shown in Figure 2.

Table 1. Estimates of different water balance components ($x10^3$ m^3) of Nainital lake for the years 1994 and 95 alongwith standard error in the estimates.

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

WATER BALANCE METHOD

Water balance of lake Nainital has been computed for the years 1994 and 1995. The different methods adopted for estimating/computing various parameters indicated in Equation (1), have been described in detail by Kumar et al. (1999a). The results are presented in Table 1. The methods adopted for estimating the sub-surface outflow component are as follows:

ESTIMATION OF PROPORTION OF LAKE WATER DURING PUMPING

The proportion of the lake water being pumped from the wells located near the lake was estimated by isotopic tracer technique. A two-component mixing model has been applied. The $\delta^{18}O$ data of admixture i.e., the well water, end-member indices alongwith the proportion of lake water being pumped are presented in Table 2. The results show that proportion of lake water component in the water pumped from the wells is lower in non-monsoon seasons, as compared to that in monsoon season.

Table 2. Proportion of lake water in the well water being pumped (Wo) along with $\delta^{18}O$ of end-members and admixture.

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

Estimation of Sub-surface Outflow Through Springs

As discussed earlier, it is likely that some of the downstream springs may be related to the lake. In order to understand the inter-relationship between the lake and the springs, hydrochemistry and isotopic characteristics have been studied (Nachiappan and Kumar, 1999). The results indicate that the lake is the main source for Balia ravine springs. Large variation in $\delta^{18}O$ values of Gupha Mahadev Temple Spring during different seasons indicate that the spring is replenished from the epilimnion zone of the lake. The stable isotope data confirms the inference (drawn from the comparison of ion concentrations of the Sipahidhara and Gupha Mahadev springs to the vertical concentration profile of the lake) that these springs receive water from the epilimnion zone of the lake.

Average monthly discharge of nine downstream springs located in Balia ravine were monitored by UPPWD for the period of 1948-52. The data suggest that out of the nine springs, only Rais Hotel and Sipahidhara springs account for about 92% of the aggregate discharge. Presently, many of these springs are dry, and the discharge of Sipahidhara is considerably reduced. The total monthly discharge of all the springs and that of Sipahidhara spring measured during the period 1948- 1952 alongwith discharge of Sipahidhara spring monitored during 1995 have been analysed. From the data, it is seen that there is a reduction of about 85% in the discharge of Sipahidhara spring in the past 50 years. The reduction is probably due to clogging of subterranean pathway as a consequence of lake sedimentation (Kumar et al., 1999b). Mean monthly ratio of discharge of Sipahidhara spring to the total discharge of all the springs have been calculated from the data for the period 1948-52. Total discharge of all the springs located in the Balia ravine, has been computed for the years 1994 and 95 by using the calculated ratio and the discharge of Sipahidhara spring observed in 1995.

Uncertainties in the Estimation of Water Balance Components

Overall accuracy of the water balance method depends on the accuracy of each flow component. Lake water balances, which are determined without error estimations could be misleading (Winter, 1981). In case of certain components of water balance, the amount of error could not be correctly evaluated due to the nature of the estimation methods. In the present study, errors in the estimation of different components of water balance are assumed to be independent and normally distributed. Estimated standard errors associated with different water balance components are ΔV - 10%, RFi - 10%, S_i - 20%, D_i - 15%, E_o - 15%, S_o - upto 5%, SPo - 15%, W_o - 10% and SSi - upto 10%.

ESTIMATION OF SUB-SURFACE INFLOW

Calculated values alongwith standard error for each component of monthly water balance for the years 1994 and 1995 are presented in Table 1. Groundwater inflow to the lake (SS_i) and the standard error in the estimation of groundwater inflow (σ_{SSi}) have been calculated by the following equations:

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

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

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

ISOTOPE MASS BALANCE METHOD

Isotope mass balance of a lake may be written as

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

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

$$\delta_g SS_I - \delta_L SS_O = (\delta_E E_O + \delta_{So} S_O \text{ " } \Delta\delta_L V) \text{ B } (\delta_P P_I + \delta_{Si} S_I + \delta_{Di} D_I) \qquad (5)$$

where, SS_I, SS_O, E_O, S_O, P_I, S_I, D_I and ΔV are as given in Equation (1) and $\delta_{g,}$ $\delta_{Go,}$ $\delta_{E,}$ δ_{So}, $\delta_{P,}$ δ_{Si}, δ_{Di} and δ_L are the corresponding isotopic values. Rearranging Equation (2) and solving simultaneously with Equation (5), we get:

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

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

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

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

Table 3. Isotopic composition of rainfall samples collected at different altitudes in the Nainital area.

Site	Elevation, m	Month	□18O, □	□D, □	'd', □
		July, 1995	-12.3	-87.0	11
		Aug, 1995	-12.4	-90.6	9
Snowview	2275	Sep, 1995	-12.2	-83.6	14
Mel		July, 1995	-11.9	-83.8	11
Rose		Aug, 1995	-11.8	-87.4	7
Cottage	2140	Sep, 1995	-11.3	-80.0	10
		July, 1995	-11.4	-79.2	12
		Aug, 1995	-11.3	-83.2	7
Lake site	1940	Sep, 1995	-10.5	-77.1	7
		Sep., 1994	-12.6	-88.1	13
		Apr., 1995	-1.6	-6.8	6
Lake Site*	1940	May, 1995	-10.5	-64.1	20
Gupha		July, 1995	-10.7	-76.6	9
Mahadev	1830	Aug, 1995	-11.0	-78.0	10
Temple		Sep, 1995	-9.5	-70.3	5

- This set of data has not been used to study the altitude effect, but used in defining LMWL.

Stable Isotope Ratios of Precipitation

In order to understand the stable isotope characteristics of precipitation in Nainital area, rainfall samples were collected from four stations set up at different altitudes. Among these three were within the basin and one on the downstream side (Figure 1). The statistical analysis of rainfall isotopic data (Table 3) for Nainital area yielded the following equation for the Local Meteoric Water Line (LMWL) valid for monsoon period:

$$\delta D \_ = 7.5 * \delta^{18} O + 4.82 \quad (n = 15; r = 0.97) \quad (8)$$

This equation compares well with that proposed by other workers (Bhattacharya et al., 1985; Seigel and Jenkins, 1987; Krishnamurthy and Bhattacharya, 1991; Bartarya et al., 1995).

Stable Isotope Ratios of Drain Water

A total of eleven samples were collected from the drains during the study period for stable isotope analysis. Out of these four represent the perennial Nainadevi drain and another four represent the Rickshaw Stand drain. The remaining three samples represent the seasonal drains viz., Boatclub drain and Library drain. The results are given in Table 4.

Table 4. Isotopic characteristics of drain water.

Drain ID	□18O (□)			□D (□)		
	#	Mean	□	#	Mean	□
Nainadevi/ R. Stand	4	-8.6	0.6	4	-52	7
Boat Club/ Library	3	-8	0.6	2	-57	-

It would be seen that the observed value of $\delta^{18}O$ ranges from -7.4λ to -9.6λ, while that of δD from -44λ to -64λ. If we consider all the drains, then the average values of $\delta^{18}O$ and δD are -8.4λ (σ=0.7) and -54λ (σ=7), respectively. The measured $\delta^{18}O$ and δD values of the drains are considerably higher than those of the local precipitation indicating that some amount of evaporative enrichment might have taken place. The slope of the $\delta^{18}O$ - δD line is -5.4, which is much less than that of LMWL (Equation 8). This also indicates that the drain water might have suffered evaporative enrichment.

Stable Isotope Ratios of Lake

Water samples for stable isotope analysis were collected from the lake during different months of the study period. The results are given in Table 5.

The equation for the best-fit line using the $\delta^{18}O$ and δD data pertaining to the lake is:

$$\delta D = (7.1 \pm 0.4) * \delta^{18} O + (2.3 \pm 2.6) \quad (n = 131; r = 0.74) \tag{9}$$

The above equation is very close to that of the LMWL (Figure 3) indicating that the lake has not been significantly affected by non-equilibrium evaporative enrichment processes. The effect of evaporative enrichment is confined mainly to the epilimnion zone. The annual mixing of hypolimnion water and also groundwater, both of which are less affected by evaporation, has probably contributed to the above relation between $\delta^{18}O$ and δD.

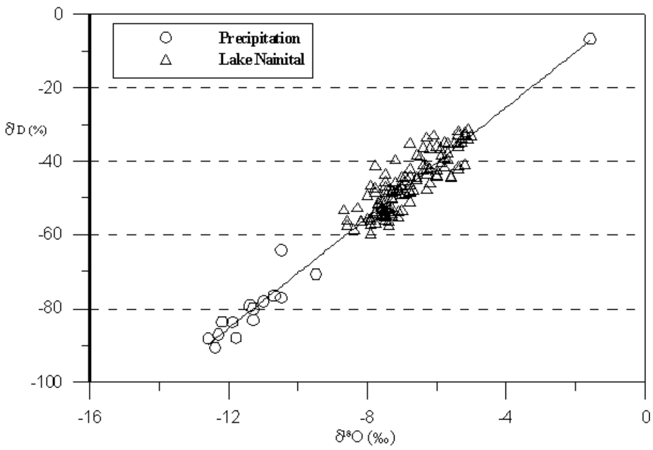

Figure 3. Stable isotope composition of Lake Nanital with LMWL.

Table 5. Mean δ^{18}O and δD data of epilimnion and hypolimnion zones of Nainital lake during different months.

Month of sampling	□18O		□D	
	Epilimnion x " □ (#)	Hypolimnion x " □ (#)	Epilimnion x " □ (#)	Hypolimnion x " □ (#)
February,94	-8.2 " 0.4 (2)	-8.1 " 0.1 (2)	-49 " 6 (2)	-55 " 2 (2)
May, 94	-6.2 " 0.4	-7.2 " 0.9	-	-
October, 94	-5.9	-7.3	-	-
December,94	-9.7 " 0.1 (7)	-9.8 " 0.1 (2)	-	-
February,95	-7.2 " 0.4 (3)	-7.4 " 0.3 (22)	-48 " 2 (3)	-52 " 3 (22)
March, 95	-6.0 " 0.4 (6)	-7.2 " 0.5 (20)	-42 " 1 (6)	-49 " 4 (20)
May, 95	-6.2 " 0.5 (15)	-7.3 " 0.9 (22)	-39 " 5(15)	-48 " 9 (22)
June, 95	-5.6 " 0.3 (6)	-7.1 " 0.7 (11)	-35 " 1 (6)	-46 " 6 (11)
August, 95	-5.5 " 0.3 (9)	-6.8 " 1.1 (16)	-38 " 4 (9)	-47 " 8 (16)
November,95	-8.4 (3)	-8.0 (1)	-	-
April, 96	-7.0 " 0.4 (2)	-7.7 " 0.5 (4)	-	-
September, 96	-8.1	-7.6 (2)	-53	-50 (2)

Stable Isotope Ratios of Lake Evaporates

The stable isotope composition of lake evaporate (δ_E) is not directly measurable, but can be calculated using the Craig and Gordon Linear Resistance (CGLR) Model. The simplified evaporation model (Craig and Gordon, 1965) can be written as:

$$\delta_E = \frac{(\alpha^* \delta_L - h\delta_a - \varepsilon)}{(1 - h + 10^{-3}\Delta\varepsilon)} \qquad (10)$$

where, δ_L is the isotopic composition of lake surface, δ_a is the isotopic composition of atmospheric water vapour, h is the relative humidity normalised to temperature at the lake water surface, α^* is the equilibrium fractionation factor, and ε & $\Delta\varepsilon$ are enrichment factors. In the present study, the fractionation and enrichment factors have been calculated by standard methods (Majoube, 1971; Gonfiantini, 1986) from the observed mean monthly temperature data. The isotope value observed in the epilimnion zone of the lake has been considered as δ_L, while δ_a has been estimated by the δ_a-δ_p Equilibrium Assumption method (Zimmermann et al., 1967; Zuber, 1983):

$$\delta_a = \alpha^* \delta_p - \varepsilon^* \tag{11}$$

where, δ_p is the isotopic composition of local precipitation. The calculated values of δ_E are presented in Table 6. δ_E values for the months of January and April, 1995 could not be calculated using the CGLR model as the limiting condition is not satisfied (Kumar and Nachiappan, 1999).

From the results presented in Table 6, it is seen that the δ_E values are controlled mainly by the relative humidity.

Table 6. Values of different input parameters used in the CGLR Model alongwith calculated values of δ_E for the lake Nainital.

Period	δ_L (λ)	δ_P (λ)	δ_a (λ)	h (%)	α	ε^*	Δε	δ_E (λ)
02/95	-8.4	-7.6	-18.4	58.6	0.9891	10.93	6.08	-
04/95	-6.6	-1.6	-11.7	32.6	0.9899	10.10	9.67	-
05/95	-6.2	-10.5	-20.1	40.9	0.9903	9.68	8.44	-26.8
07/95	-5.7	-11.4	-21.1	82.3	0.9902	9.80	2.78	-6.4
08/95	-7.5	-11.3	-21.0	85.5	0.9902	9.83	2.31	-11.9
09/95	-8.1	-10.5	-20.3	77.9	0.9901	9.94	3.42	-24.3

Stable Isotope Ratios of Groundwater

The δ^{18}O analysis was carried out on samples collected from upstream springs and also from the wells located on the lake bank. The results are given in Table 7. It is seen that the springs show considerable variation in δ^{18}O during different seasons. The variation in δ^{18}O is larger for the Pardhadhara spring (-7.3λ to -8.8λ). This is probably due to the presence of Sukhatal lake, the temporary lake in the recharge area of Pardhadhara spring. Sukhatal lake water, which is isotopically enriched due to evaporation during June to September, probably got mixed with the sub-surface reservoir. The δ^{18}O of the Pardhadhara spring shows a depleted value in winter 1994 than in post-monsoon 1995, probably due to the infiltration of the snowmelt water. However, this could not be verified due to non-availability of the isotopic composition of 1994 snowfall.

Table 7. δ^{18}O data of upstream springs during different seasons.

Season	Month	Spring ID	□^{18}O □
Winter	February, 94	Pardhadhara	-8.2
Pre-Monsoon	March, 95	Pardhadhara	-7.5
	May, 95	Pardhadhara	-7.7
	April, 96	Sariyatal	-7.4
	June, 95	Lakeview	-8

Monsoon	June, 95	Doctor House	-9.3
	August, 95	Lakeview	-9
	September, 95	Doctor House	-9.4
	September, 95	Lakeview	-8.3
	September, 96	Pardhadhara	-8.8
	September, 96	Alma Cottage	-9.1
	September, 96	Chunadhara	-9.1
Post-Monsoon	November, 95	Lakeview	-8.3
	November, 95	Alma Cottage	-8.2
	November, 95	Pardhadhara	-7.3

It is also seen that Chunadhara, Alma Cottage and Doctor House springs have δ^{18}O values of -9.1 to -9.4λ during monsoons. Compared to these, the δ^{18}O values of the Lakeview spring varies between -8.0λ and -9.0λ indicating that the spring has more than one source. The post-monsoon δ^{18}O values of Alma Cottage and Lakeview springs are comparable (-8.3λ) and are heavier than δ^{18}O value of Alma Cottage spring during monsoons. It indicates delayed recharge of groundwater, which has undergone enrichment due to partial evaporation. The frequency distribution analysis of δ^{18}O show that for monsoon and non-monsoon seasons, the peak values are -9.0λ and -8.2λ respectively indicating that the non-monsoon recharge results in isotopic enrichment of groundwater.

Since infiltration rates in the catchment area are quite variable, it is possible that the rain falling in zones of higher infiltration capacity percolates and reaches the groundwater regime more quickly than the rain falling in zones of lower infiltration capacity. Although the distribution of zones of different rate of infiltration is not well defined in the catchment area, the infiltration is higher in linear depressions coinciding with natural drains. The surfacial sheet flow over less permeable soil cover and the interflow may be heavier in δ^{18}O than the water that percolates into the groundwater regime. However, both these pathways lead to an overall δ^{18}O enrichment of the groundwater.

The isotopic enrichment in groundwater may also be due to the flushing of soil water, which has undergone evaporative enrichment by the infiltration of subsequent rainfall. This effect is more pronounced on barren top soil than the top soil covered with grass (Zimmermann et al., 1967). Since approximately 50% of the catchment area of Nainital lake is characterised by non-forestry land use, it is possible that the soil water suffers enrichment due to evaporation. Further, it is also not uncommon that a difference of about 2.0λ is observed between the δ^{18}O of rainfall and that of the local groundwater, as similar differences have been reported in other areas (Kumar et al., 1982; LaBaugh et al., 1997).

Isotope Mass Balance

Isotope mass balance has been attempted for the period between February, 1994 and February 1995. Since in the month of February, the lake reamins well mixed and homogeneous, it eliminates the stratification effects on the calculation. The mean δ^{18}O values of the lake considered for mass balance are B8.2λ (February, 1994) and B7.3λ (February, 1995) with a net change of 0.9λ. The δ^{18}O values for different components are precipitation -

11.3λ, evaporation -29.1λ, surface inflow -8.6λ and inflow through the drains -8.0λ. The $\delta^{18}O$ of surface outflow is taken as -8.0λ as surface outflow occurs mostly at higher lake water levels and with higher surface inflow, having less time for proper mixing. This is shown by the values observed during September 1996, when the surface layers were comparatively depleted than the bottom water. The $\delta^{18}O$ value of groundwater inflow is -9.0λ and that of the subsurface outflow from the lake is -8.0λ. Sub-surface outflow (SS_O) of the lake calculated by isotopic mass balance method is presented in Table 8. The results are used in Equation (7) to compute groundwater inflow (SS_I) to the lake. The results indicate that sub-surface components are dominant over other components. The SS_I and SS_O account for 51% and 56% of total inflow and total outflow respectively.

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

CHLORIDE MASS BALANCE METHOD

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

The concentration of chloride in lake water was 8 mg/L and 10 mg/L during February 94 and 95 respectively. The mean concentration in drain water (D_I) was 31 mg/L, and that in surface inflow (S_I) was 24 mg/L. The latter value has been used considering the fact that during monsoon period the flow in the drain water, particularly during the sampling period, was dominated by channelled surface runoff. The mean concentration of chloride in groundwater was 16 mg/L in the upstream springs viz., Pardhadhara, Alma cottage and Lakeview springs. The mean chloride concentration of the downstream springs, Sipahidhara and Gupha Mahadev Temple (17 mg/L), has been considered as representative of subsurface outflow from the lake. The input of chloride by precipitation has been considered as 1 mg/L, by interpolating the data pertaining to Lucknow (Handa et al., 1984) and Srinagar (Maske and Nand, 1982) stations.

Sub-surface outflow (SS_O) from the lake, computed using the chloride mass balance approach, has been presented in Table 8. The result has been used in Equation (7) to compute sub-surface inflow (SS_I) to the lake. The results corroborate the findings of conventional water balance method i.e., the sub-surface components are dominant over other components. The SS_I and SS_O computed using the chloride mass balance method account for about 55.0% of total inflow and about 59.0% of total outflow respectively. As compared with the estimates of conventional water balance, the SS_O computed by chloride mass balance method is higher by 5%.

COMPARISON OF RESULTS

The results presented in Table 8 show that the estimates of sub-surface inflow to the lake and outflow from the lake, obtained through isotopic and chemical balance, compare well with those obtained through conventional water balance method.

Table 8. SS_I and SS_O data estimated by isotopic, chemical and conventional mass balance methods.

	$\delta^{18}O$		Chloride		Conventional	
Method of estimation	SS_I	SS_O	SS_I	SS_O	SS_I	SS_O
Volume (x 10^3 m^3)	2269	2618	2777	3140	2234	2416
Depth (m)H	5.1	5.88	5.99	6.78	4.82	5.21
% to total inflow or outflow	51	56	55	59	50	54
Lake WRT -YearsI	1.93		1.77		1.92	

H Estimated volumes have been converted into units of depth by normalising to the maximum lake surface area, 463365 m^2.

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

The water retention time (WRT) of the lake, is a better parameter to compare the results as WRT is a function of the lake size. WRT computed using isotopic mass balance approach is 1.93 y, chloride mass balance is 1.77 y and conventional water balance is 1.92y. The results obtained by all the three methods do not vary significantly from each other and compare very well within the error limits. The WRT computed using the isotopic and chloride mass balance approach are more reliable, as they have been derived independently without considering outflow through umping and springs. The results of isotope and chloride mass balance methods support the conceptual model developed for the Nainital lake.

CONCLUSIONS

The following conclusions are drawn from the present investigations:

Water balance studies carried out for the total inflow show that the sub-surface contributes 50% of total annual inflow to Nainital lake. The sub-surface outflow is about 55% of the total annual outflow from the lake. It shows that the lake is a 'flow - through' type, with substantial groundwater inflow and lake seepage.

The results of both chloride and isotope mass balance methods corroborate the results of water balance method. Water retention time - WRT (volume/outflow) as computed for Nainital lake by isotopic mass balance, chloride mass balance and conventional water balance methods is about 1.93y, 1.77y and 1.92 y respectively. The WRT will be even lesser for years with higher annual rainfall.

Hydrogeological investigations indicate that the shale formation, which occupies about 50% of the lake catchment area, is not a suitable aquifer. However, the catchment area has well developed lineaments and faults. The hydrologic investigations conducted along these lineaments indicate higher infiltration capacity. Therefore, it is inferred that most of the groundwater inflow to the lake might be occurring along these zones. Seepage from Sukhatal lake appears to be a major recharge source for Nainital lake and any activity in Sukhatal lake may affect the Nainital lake.

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