Estimation of subsurface components in the water balance of Lake Nainital (Kumaun Himalaya, India) using environmental isotopes

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Abstract Lake Nainital, 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. The water balance of the lake has been computed for the first time. The subsurface outflow components are estimated by indirect methods and then the subsurface inflow calculated by means of the water balance equation. The results are verified using the environmental isotope mass balance method. Further, the chloride mass balance method is also employed for comparison of the results with two other methods. 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 the isotope characteristics of the lake. The mass balance results indicate that the groundwater contribution is about 50% of the total annual inflow to the lake. The subsurface outflow is about 55% of the total annual outflow from the lake. This 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 the water balance method. The water retention time for Lake Nainital, estimated by isotopic mass balance, chloride mass balance and conventional water balance methods, is about 1.93, 1.77 and 1.92 years, respectively.

Key words lake hydrology; water balance; groundwater–surface water interactions; mass balance; environmental isotopes; Himalaya, India

Estimation des composantes de sub-surface du bilan hydrologique du Lac Nainital (Himalaya Kumaun, Inde) grâce à des isotopes environnementaux

Résumé Le Lac Nainital, situé dans la région de l'Himalaya Kumaun dans le nord de l'Inde, est une source d'eau importante pour la consommation des populations vivant au sein et autour du bassin du lac. Le bilan hydrologique du lac a été établi pour la première fois. Les écoulements de sub-surface sortant sont estimés par des méthodes indirectes puis les écoulements de sub-surface entrant sont calculés à partir de l'équation de bilan. Les résultats sont vérifiés grâce à la méthode du bilan massique d'isotopes environnementaux. La méthode du bilan massique des chlorures est également employée et ses résultats sont comparés à ceux des deux autres méthodes. La pente de la ligne $\delta^{18}O$–δD de l'eau du lac (7.1) est très proche de celle de l'eau météorique locale (7.5), ce qui indique que l'évaporation dans le lac n'a pas d'effet sur les caractéristiques isotopiques du lac. Les résultats du bilan massique indiquent que la contribution souterraine à l'écoulement entrant annuel total est d'environ 50%. L'écoulement de sub-surface sortant correspond quant à lui à environ 55% de l'écoulement sortant annuel total. Cela montre que l'eau du lac est très renouvelée avec un afflux et une fuite souterrains substantiels. Les résultats des deux méthodes de bilan massique pour les chlorures et pour les isotopes corroborent les résultats de la méthode du bilan hydrologique. Le temps de séjour de l'eau dans le Lac Nainital, estimé par les méthodes de bilan massique isotopique, de bilan massique des chlorures et de bilan hydrologique conventionnel, est respectivement d'environ 1.93, 1.77 et 1.92 ans.

Open for discussion until 1 February 2003

Mots clefs hydrologie lacustre; bilan hydrologique; interactions eaux de surface-eaux souterraines; bilan massique; isotopes environnementaux; Himalaya, Inde

INTRODUCTION

Freshwater available from surface water bodies such as lakes and rivers is a precious resource that is becoming increasingly scarce in recent times. Inappropriate management of freshwater has resulted in extensive environmental degradation of many lakes and rivers worldwide. Environmental damage caused to surface water bodies may further be propagated into the hydraulically connected groundwater system and would drastically reduce the availability of this alternative source of potable water.

Surface water and groundwater systems have been fairly well understood independently, but the interaction between them continues to be an active area of research. Improvements in understanding the interaction between surface water and groundwater may facilitate the better management of available freshwater resources (Wright, 1980; Winter, 1995). Although analytical and numerical models of surface water and groundwater interaction are being used increasingly, they need continuous improvements for the management of water resources in different environmental situations to be effective. Future studies will also benefit from the increased use of interdisciplinary approaches including isotope techniques.

The isotope technique for lake studies is theoretically sound, but very few successful applications are reported. This is mainly due to the lack of a co-ordinated approach towards the clear understanding of the hydrological regime by applying both conventional and isotope techniques. A few lake studies in Europe and North America have been carried out using the isotope technique with the focus on lake–groundwater interaction. Dinçer (1968) demonstrated the applicability of isotope techniques to lake water balance studies, by using an index-lake approach to circumvent the problem of measuring/estimating the isotopic composition of the lake evaporates. Fontes *et al.* (1970) and Krabbenhoft *et al.* (1990) successfully used the isotope method in a lake water balance study of Tchad and Sparkling lakes. More recently, LaBaugh *et al.* (1997) used both isotopes and hydrochemical tracers to study the water balance of a closed lake. However, all these studies are carried out on low- to mid-altitude lakes assuming the hydrological and isotopic characteristics are in steady-state conditions. Such lake–groundwater studies have not been done by using conventional methods, nor isotopic methods, for any of the Himalayan lakes. Therefore, one of the relatively bigger lakes in the Kumaun Himalaya, Lake Nainital, has been chosen for the lake water–groundwater study presented here, and has been comprehensively investigated for hydrological, hydrochemical and isotopic characteristics from which data the water balance has been worked out.

STUDY AREA

Lake Nainital (29°23′09″N and 79°27′35″E) is a high altitude (1937 m a.m.s.l.) natural lake (Fig. 1) located in Nainital district, Uttaranchal, India. It is a crescent-shaped lake with a maximum length of 1.4 km and a width of 0.45 km. The maximum and mean depths of the lake are 27.3 and 18.5 m, respectively. The surface area of the lake is

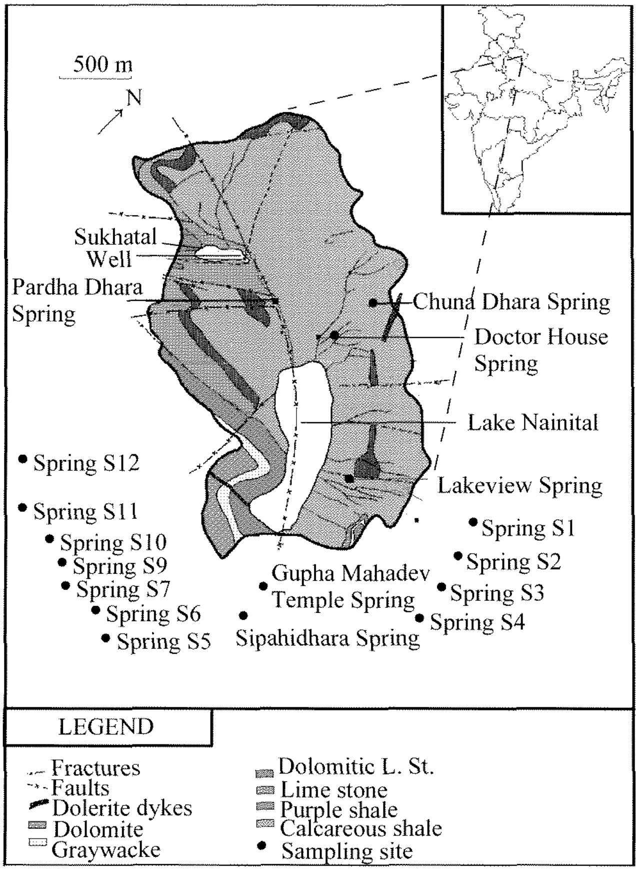

Fig. 1 Index map of the study area showing Lake Nainital, locations of springs and geological features.

0.46 km^2 with a maximum capacity of 8.57 Mm^3. Lake Nainital is one of the largest of a cluster of seven lakes in the Kumaun region. The lake is of monomictic type that remains stratified from March to November and well mixed during the winter season (December–February). The hill slope of the basin varies between 5° and 49° (mean 19°) (Rawat, 1987). The lake basin is marked by several fractures and faults and is dissected by a fault (known as the Lake Fault).

The monsoon period in the study area is observed from mid-June to mid-September and precipitation is moderate to heavy. During winter, precipitation is generally light to moderate with occasional snowfall. The mean annual rainfall of the basin is 2488 mm and the monsoon rainfall accounts for about 86% of the annual total. Monthly rainfall data from three stations in and around the basin indicated the lack of significant spatial variation in the precipitation. Time series analysis by autocorrelation method of 101 years of annual rainfall data (1895–1995) collected from local government agencies showed no trend in the annual rainfall series.

Lake Nainital basin is drained by about 20 channels of which only two (Nainadevi and Rickshaw stand drains) are perennial due to spring discharge and sewage disposal. The land-use pattern, as deduced from satellite imageries and thematic maps of the study area, reveal that reserved forests occupy about 21%, other types of forests and shrubs 21%, built-up area 41%, water bodies 10%, barren land 4%, roads 2% and playgrounds 1%. The limited number of infiltration tests conducted in the basin indicates that the infiltration rate varies widely from 1.1 to 78.0 cm h^{-1}, and the higher infiltration rate is observed along the valley bottom.

CONCEPTUAL MODEL FOR THE LAKE WATER BALANCE

The general water balance equation for a lake is written as:

$$\Delta V = \text{inflow} - \text{outflow}$$

where ΔV is the change in lake storage for a selected period of time [L^3 T^{-1}]. Incorporating different inflow and outflow components, the equation becomes:

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

where P_I is direct precipitation over the lake surface; S_I is surface water inflow to the lake; SS_I is subsurface inflow to the lake; E_O is evaporation from the lake surface; S_O is surface outflow from the lake; and SS_O is subsurface outflow from the lake, all variables in [L^3 T^{-1}].

In the case of Lake Nainital, the increase in lake storage is due to direct precipitation, surface inflow from the steep hill slopes of the basin and subsurface inflow. The surface inflow may further be divided into two parts: (a) runoff that is generated due to rainfall and (b) inflow through the drains that are sustained by sewage and baseflow. The latter may be separately accounted for by incorporating an additional component in the water balance equation. The rainfall received in the Sukhatal sub-catchment of Nainital basin, which is a closed catchment (Fig. 1), is possibly lost through infiltration and evaporation. As the Lake Fault runs in the proximity of Sukhatal Lake, it is possible that most of the water is lost through underground seepage and recharging of Lake Nainital. This subsurface inflow to the lake is in addition to the contribution from the adjacent hillslopes in the form of interflow or groundwater seepage.

The decrease in lake storage is due to surface outflow, subsurface outflow and evaporation from the lake surface. However, as evaporation is negligible it is not readily discernible from the daily lake level data. The lake level is also influenced by pumping for domestic use from nearby wells. As the wells are located very close to the lake in unconsolidated landslide debris, it is possible that a major portion of the pumped water is replenished through subsurface seepage from the lake. The subsurface outflow on the downstream side of the lake may be through the fractures and faults. Seepage from the lake is unlikely to be through the lake bed as this is characterized by a thick layer of fine sediments. Thus, the subsurface outflow may be occurring only from the upper part of epilimnion zone. Outflow from the lake may recharge the unconfined aquifer, which in turn might be discharging through a number of downstream springs. Therefore, in the absence of groundwater level data of the unconfined aquifers on the downstream side, the seepage from the lake may be estimated from the discharge of downstream springs that are hydraulically connected to the lake. Hence, the subsurface outflow from the lake may be divided into withdrawal from the wells located on the bank of the lake (W_O) and outflow from the downstream springs (SP_O). Then equation (1) may be modified by replacing SS_O with W_O and SP_O.

METHODOLOGY

In addition to the conventional water balance approach, isotope and ion mass balance methods are used to determine the subsurface components. Uncertainties in the measured/estimated values of a few water balance components were evaluated after Winter (1981). The error propagation for the estimated subsurface components was evaluated by standard methods (Bevington, 1969).In the present study, the input to the lake through direct precipitation over the lake was estimated by Theissen polygon method from the rainfall data at four stations in the lake basin. The surface inflow to the lake through rainfall in the catchment was determined by using the US Soil Conservation Service curve number method and the lake level trend analysis method.

The change in lake storage was estimated from daily records of lake level. Surface outflow from the lake was computed by an empirical method using submerged rectangular sluice operational data. Evaporation from the lake was computed by the modified Penman method (Jensen, 1974) from the meteorological data collected near the lake. The groundwater withdrawal from the wells, located in the periphery of the lake, was calculated from the pumping data recorded by the local agencies concerned. However, the contribution from the lake to these wells was estimated using environmental tracers. Monthly discharges of some of the downstream springs, such as Sipahidhara, Gupha Mahadev Temple, S3, S4, and S5 springs, were monitored during 1994 and 1995 and data were also collected from local agencies for the period from 1948 to 1952, in order to work with all available data.

The groundwater inflow to the lake (SS_I) is estimated by conventional water balance method as follows:

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

The isotope mass balance for the lake may be written as:

$$\Delta\delta_L V = (\delta_{P_I} P_I + \delta_{S_I} S_I + \delta_{D_I} D_I + \delta_G SS_I) - (\delta_{E_O} E_O + \delta_{S_O} S_O + \delta_L SS_O) \qquad (3)$$

and the subsurface terms may be obtained by rearranging equation (3):

$$\delta_G SS_I - \delta_L SS_O = (\delta_{E_O} E_O + \delta_{S_O} S_O \pm \Delta\delta_L V) - (\delta_{P_I} P_I + \delta_{S_I} S_I + \delta_{D_I} D_I) \qquad (4)$$

where SS_I, SS_O, E_O, S_O, P_I, S_I, and ΔV are as given in (modified) equation (1), D_I is inflow from drains and δ_G, δ_L, δ_{E_O}, δ_{S_O}, δ_{P_I}, δ_{S_I}, and δ_{D_I} are the corresponding isotopic values.

Rearranging equation (2) and solving simultaneously with equation (4), one obtains:

$$SS_O = \frac{\left|\delta_G (S_O + E_O \pm \Delta V - S_I - D_I - P_I) - (\delta L S_O + \delta_E E_O \pm \Delta\delta_L V - \delta_{P_I} P_I - \delta_D D_I - \delta_S S_I)\right|}{(\delta_L - \delta_G)} \qquad (5)$$

Equation (5) was used to determine the subsurface outflow component of the lake, which in turn was used to estimate groundwater inflow to the lake by the following relationship:

$$SS_I = [(E_O + S_O \pm \Delta V) - (P_I + D_I + S_I)] + SS_O \qquad (6)$$

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

Sampling procedures and analyses

Water samples from different locations in the lake, springs, pumping wells and drains were collected on a monthly basis and precipitation samples were also collected from different altitudes for chemical and isotopic analysis. The chemical analyses were carried out using standard procedures (APHA, 1992). The overall accuracy of the chemical analyses as determined by replicate measurements was found to be better than ±10%. Measurements of $\delta^{18}O$ and δD for all the water samples were done at the Isotope Hydrology Laboratory, Bhabha Atomic Research Centre, Mumbai, India and at the Environmental Isotope Laboratory, University of Waterloo, Ontario, Canada. The overall analytical accuracy for $\delta^{18}O$ and δD was found to be within ±0.2‰ and ±2.0‰ respectively.

RESULTS AND DISCUSSION

Water balance method

Monthly values of different water balance components for Lake Nainital, except for the subsurface ones, were computed for 1994 and 1995 by conventional techniques. Tracer techniques were used for estimating (a) the outflow from the lake through pumping wells and (b) the subsurface outflow through springs. The results are discussed below.

Estimation of proportion of lake water in pumping wells The $\delta^{18}O$ data of the wells (admixture), lake and groundwater are presented in Table 1. By considering the lake and groundwater as endmembers, the proportion of lake water contribution to the wells was calculated by a two-component mixing model and the results (Table 1) show that the contribution from the lake to the wells is lower in the non-monsoon season than in the monsoon season.

Interconnection between Lake Nainital and downstream springs To know the hydraulic interconnection between the lake and the downstream springs, their hydro-

Table 1 Level of $\delta^{18}O$ (‰) of end-members and admixture and the proportion of lake water contribution to the wells.

Month	$\delta^{18}O$ (‰): Lake	Groundwater	Well	Contribution of lake water (%)
February 1995	−7.35	−8.25	−8.00	25
March 1995	−7.10	−7.50	−7.40	25
May 1995	−7.17	−7.50	−7.40	30
August 1995	−6.30	−8.90	−6.80	80
November 1995	−8.20	−7.90	−8.02	40

Table 2 Values of $\delta^{18}O$ for downstream springs during December 1994.

Spring	Altitude (m a.m.s.l.)	$\delta^{18}O$ (‰)	Spring	Altitude (m a.m.s.l.)	$\delta^{18}O$ (‰)
S1	1850	−10.6	S7	1640	−11.8
S2	1790	−7.5	S9	1760	−10.7
S3	1730	−7.4	S10	1760	−10.2
S4	1720	−7.0	S11	1650	−10.9
S5	1730	−7.7	S12	1700	−10.7
S6	1750	−11.0	Gupha MT	1785	−9.5

chemical and isotopic characteristics were analysed. Relevant isotopic data are presented in Table 2 and their temporal variations are plotted in Fig. 2.

The hydrochemical data show that the SO_4^{2-} and Cl^- concentrations of Lake Nainital and of the downstream springs Sariyatal, Sipahidhara, Rais Hotel and Gupha Mahadev Temple are comparable, while the other downstream springs, such as S3, S9 and S12, show greater sulphate concentrations than the lake. Further, the values of total cations in Sipahidhara Spring are comparable to those of the lake in all the seasons, while Lakeview Spring, spring S3 and the open well do not compare well. This suggests that the lake may be the main source for Sipahidhara Spring.

Likewise, from Table 2 it may be seen that the isotopic values of some of the springs are very similar to that of the lake (see also Table 5). Springs S2, S3 and S4, located in the Kailakhan area, show higher $\delta^{18}O$ values (−7.0 to −7.5‰), which is comparable to $\delta^{18}O$ values of the lake in summer (cf. Table 5). However, some of the springs, such as S1, S6, S7, S9, S10, S11 and S12, show lower $\delta^{18}O$ values of −10.2 to −11.8‰ as compared to those of the lake in the same period (cf. Table 5). If the springs are isotopically similar to the lake or heavier than the lake, i.e. showing more positive values, then there is a possibility of lake seepage contributing to the spring discharge. On the other hand, if they are lighter than the lake, i.e. showing more

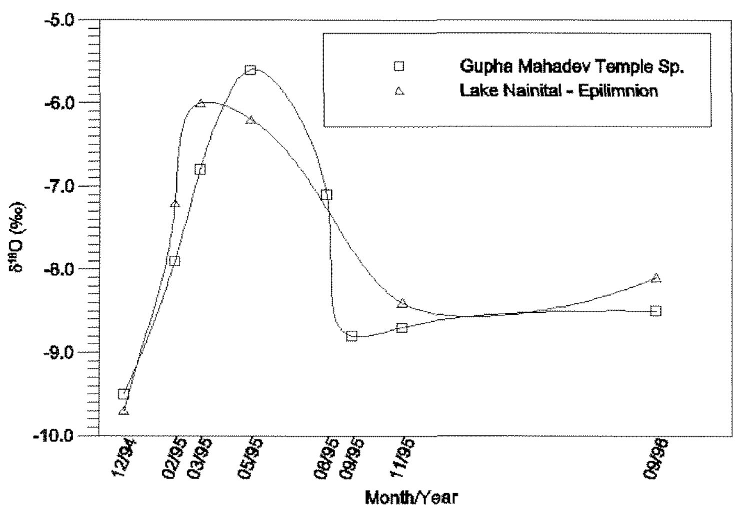

Fig. 2 Temporal variation in $\delta^{18}O$ of Gupha Mahadev Temple Spring and the lake epilimnion zone.

negative values, then one may rule out the possibility of lake seepage contributing to the spring discharge. In this case, lower values indicate different sources for the springs suggesting the absence of hydraulic connection with Lake Nainital. The similarities in the isotopic characteristics of Gupha Mahadev Spring and the lake are shown in Fig. 2. Temporal variations in $\delta^{18}O$ values of Gupha Mahadev Temple Spring in different seasons indicate that the spring is replenished mainly from the epilimnion zone of Lake Nainital.

Estimation of subsurface outflow through springs Following the investigation of hydraulic interconnection, average monthly discharge values for the Balia ravine springs, including Sipahidhara Spring, were compared for the period 1948–1952 and for 1995. It was observed that of all the springs, Sipahidhara Spring alone contributed more than 50% of the aggregate discharge. Presently, many of the springs that were active during 1948–1952 are dry and the discharge of Sipahidhara Spring has also declined considerably to about 85% in approximately 50 years. This may be due to clogging of the subterranean pathway as a consequence of lake sedimentation. The ratio of historic mean monthly discharge of Sipahidhara Spring to the total discharge of all the springs was used in estimating the total discharge of the Balia ravine springs for the years 1994 and 1995.

Estimation of subsurface inflow The results of the water balance method for the years 1994 and 1995 are given in Table 3. The absolute error for the groundwater inflow varies for the monthly estimates, but annual estimation results in an error of about 10% for all the flow components.

Table 3 Estimated data ($\times 10^3$ m^3) of water balance components for Lake Nainital.

Year	Parameter	ΔV	P_I	D_I	S_I	S_O	E_O	W_O	SP_O	SS_I
1994	EV	–29	631	772	827	1570	564	1582	783	2240
	σ	37	32	36	110	57	26	52	37	154
1995	EV	49	805	772	1491	2025	575	1798	783	2162
	σ	58	40	36	174	63	26	58	37	214

EV: estimated values; σ: standard error.

Isotope mass balance method

Isotopic composition of rainfall Rainfall samples were collected at different altitudes from four stations, three within the basin and one on the downstream side of the lake (Fig. 1). All the samples were analysed for $\delta^{18}O$ and δD and the results are presented in Table 4. The statistical analysis of rainfall isotopic data gives the following equation for the local meteoric water line (LMWL) valid for the monsoon period:

$$\delta D = 7.5 \cdot \delta^{18}O + 4.82 \qquad (n = 15;\ r = 0.97) \qquad (7)$$

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

Table 4 Isotopic composition of rainfall samples collected at different altitudes in the Nainital area.

Site	Elevation (m a.m.s.l.)	Month	$\delta^{18}O$ (‰)	δD (‰)
Snowview	2275	July 1995	–12.3	–87.0
		August 1995	–12.4	–90.6
		September 1995	–12.2	–83.6
Melrose Cottage	2140	July 1995	–11.9	–83.8
		August 1995	–11.8	–87.4
		September 1995	–11.3	–80.0
Lake site	1940	September 1994	–12.6	–88.1
		February 1995*	–7.6	-
		April 1995	–1.6	–6.8
		May 1995	–10.5	–64.1
		July 1995	–11.4	–79.2
		August 1995	–11.3	–83.2
		September 1995	–10.5	–77.1
Gupha Mahadev Temple	1830	July 1995	–10.7	–76.6
		August 1995	–11.0	–78.0
		September 1995	–9.5	–70.3

* Predominantly snowfall.

Isotopic composition of drain water The $\delta^{18}O$ composition of water samples collected from the drains flowing into the lake varies from –7.4 to –9.6‰, while that of δD varies from –44 to –64‰. If one considers both perennial and seasonal drains, then the average values of $\delta^{18}O$ and δD are –8.4‰ (σ = 60.7) and –54‰ (σ = 67), respectively. The $\delta^{18}O$ and δD values of the drains are considerably higher than those of the local precipitation, which indicates some effect of evaporative enrichment. The slope of the $\delta^{18}O$–δD best-fit line was found to be 5.4, which is much less than the LMWL (equation (7)), which also confirms evaporative enrichment.

Isotopic composition of the lake Stable isotope data of lake water samples 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:

$$\delta D = 7.1 \cdot \delta^{18}O + 2.3 \qquad (n = 131; r = 0.74) \qquad (8)$$

The above equation is very close to that of the LMWL (Fig. 3; equation (7)) indicating that the lake does not undergo any significant non-equilibrium evaporative enrichment. The temporal variation in the isotopic composition of the epilimnion zone is significantly larger than that of the hypolimnion zone during summer months, due to evaporative enrichment. The annual winter mixing cycle and significant contribution from the groundwater to the lake prevent the permanent manifestation of the effect of evaporative enrichment in the lake.

Isotopic composition of lake evaporates (δ_E) It is not possible to estimate δ_E directly and hence it has been estimated by using the Craig & Gordon linear resistance model (Craig & Gordon, 1965). Monthly δ_E values could not be calculated for all the months using this model due to its inherent limitations (Kumar & Nachiappan, 1999). As the isotopic mass balance values are computed on an annual scale, the isotopic composition of the lake evaporates was estimated using the annual mean values of the

Table 5 Mean $\delta^{18}O$ and δD data of epilimnion and hypolimnion zones of Nainital Lake during different months.

Month of sampling	$\delta^{18}O$ (‰): Epilimnion $x \pm \sigma$	Hypolimnion $x \pm \sigma$	δD (‰): Epilimnion $x \pm \sigma$	Hypolimnion $x \pm \sigma$
February 1994	–8.2 ± 0.4 (2)	–8.1 ± 0.1 (2)	–49 ± 6 (2)	–55 ± 2 (2)
May 1994	–6.2 ± 0.4	–7.2 ± 0.9	-	-
October 1994	–5.9	–7.3	-	-
December 1994	–9.7 ± 0.1 (7)	–9.8 ± 0.1 (2)	-	-
February 1995	–7.2 ± 0.4 (3)	–7.4 ± 0.3 (22)	–48 ± 2 (3)	–52 ± 3 (22)
March 1995	–6.0 ± 0.4 (6)	–7.2 ± 0.5 (20)	–42 ± 1 (6)	–49 ± 4 (20)
May 1995	–6.2 ± 0.5 (15)	–7.3 ± 0.9 (22)	–39 ± 5(15)	–48 ± 9 (22)
June 1995	–5.6 ± 0.3 (6)	–7.1 ± 0.7 (11)	–35 ± 1 (6)	–46 ± 6 (11)
August 1995	–5.5 ± 0.3 (9)	–6.8 ± 1.1 (16)	–38 ± 4 (9)	–47 ± 8 (16)
November 1995	–8.4 (3)	–8.0 (1)	-	-
April 1996	–7.0 ± 0.4 (2)	–7.7 ± 0.5 (4)	-	-
September 1996	–8.1	–7.6 (2)	–53	–50 (2)

Number of samples considered is given in parentheses.

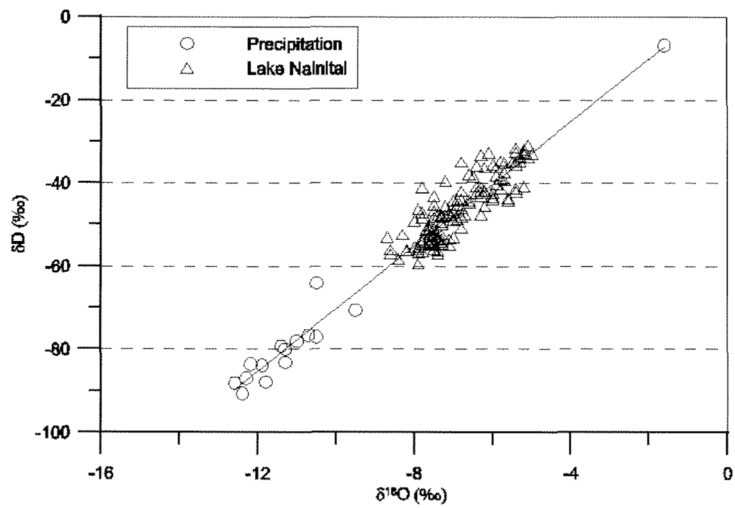

Fig. 3 Plot of $\delta^{18}O$ and δD data of Lake Nainital showing local meteoric water line.

hydrometeorological data and the mean annual isotopic composition of rainfall. Using the Craig & Gordon model, the mean annual $\delta^{18}O$ value of the lake evaporates was estimated as –29.1‰.

Isotopic composition of groundwater The upstream springs issuing at higher altitudes than Lake Nainital were considered representative of local groundwater and the $\delta^{18}O$ data pertaining to these springs are given in Table 6. It may be observed from the table that the springs show considerable variation in $\delta^{18}O$ during different seasons. The variation in $\delta^{18}O$ is greater for the Pardhadhara Spring (–7.3 to –8.8‰). and this may be a result of mixing of seepage from Sukhatal Lake that is enriched isotopically due to evaporation. The $\delta^{18}O$ of the Pardhadhara Spring shows a depleted value in

Table 6 Values of $\delta^{18}O$ for upstream springs in different seasons.

Season	Month	Spring ID	$\delta^{18}O$ (‰)
Winter	February 1994	Pardhadhara	–8.2
Pre-monsoon	March 1995	Pardhadhara	–7.5
	May 1995	Pardhadhara	–7.7
	April 1996	Sariyatal	–7.4
Monsoon	June 1995	Lakeview	–8
	June 1995	Doctor House	–9.3
	August 1995	Lakeview	–9
	September 1995	Doctor House	–9.4
	September 1995	Lakeview	–8.3
	September 1996	Pardhadhara	–8.8
	September 1996	Alma Cottage	–9.1
	September 1996	Chunadhara	–9.1
Post-monsoon	November 1995	Lakeview	–8.3
	November 1995	Alma Cottage	–8.2
	November 1995	Pardhadhara	–7.3

winter 1994 compared to the post-monsoon period (1995) and this could be due to the infiltration of snowmelt water. However, this could not be verified due to non-availability of the isotopic data of 1994 snowfall.

It was also observed that Chunadhara, Alma Cottage and Doctor House springs have $\delta^{18}O$ values of –9.1 to –9.4‰ during the monsoon season. However, the $\delta^{18}O$ values of the Lakeview Spring vary between –8.0 and –9.0‰ indicating that the spring has more than one source. The $\delta^{18}O$ value of Alma Cottage Spring during the post-monsoon period is heavier than that during the monsoon. This may be due to the delayed recharge of groundwater, which might have undergone enrichment at the same time due to partial evaporation.

The isotopic enrichment of groundwater may also be due to the flushing of soil water that might have undergone evaporative enrichment during the summer. The infiltration of subsequent rainfall water through the soil zone may lead to isotope enrichment in the groundwater. This effect is more pronounced on barren topsoil than on that covered with grass (Zimmermann *et al.*, 1967). As approximately 50% of the Lake Nainital catchment area is characterized by non-forestry land use, it is possible that the soil water enrichment in isotopes is due to evaporation. Further, there is a difference of about 2.0‰ in $\delta^{18}O$ values between the rainfall and the local groundwater, which is similar to the observation made in other areas (Kumar *et al.*, 1982; LaBaugh *et al.*, 1997).

The frequency distribution analysis for $\delta^{18}O$ for monsoon and non-monsoon seasons show that the peak values are –9.0 and –8.2‰ respectively. Since the monsoon rainfall dominates and accounts for 85% of annual rainfall, the groundwater isotopic index may be considered as –9.0‰.

Isotope mass balance Isotope mass balance was worked out for the period between February 1994 and February 1995. In the month of February, the lake remains well mixed and homogeneous, which therefore eliminates the stratification effects on the calculation. The mean $\delta^{18}O$ values considered for the lake are –8.2‰ (February 1994) and –7.3‰ (February 1995). The $\delta^{18}O$ values for the various components are:

Table 7 Comparison of subsurface inflow (SS_I) and subsurface outflow (SS_O) data estimated by isotopic and chemical mass balance methods with those by water balance method.

Method of estimation	$\delta^{18}O$: SS_I	SS_O	Chloride: SS_I	SS_O	Conventional: SS_I	SS_O
Volume ($\times 10^3$ m^3)	2042–2496	2356–2880	2499–3055	2826–3454	2011–2457	2174–2658
% of total inflow or outflow	46–56	50–62	49–61	53–65	45–55	49–59
Lake mean WRT (years)	1.93		1.77		1.92	

–11.3‰ (precipitation), –29.1‰ (evaporation), –8.6‰ (surface inflow), –8.0‰ (inflow through the drains and outflow). The surface outflow occurs exclusively from the epilimnion zone which is replenished by isotopically lighter surface inflow. Therefore less time is available for proper mixing. This is evident from the data of September 1996, where the surface layers were relatively depleted compared to the bottom water. The $\delta^{18}O$ of the groundwater inflow was taken as –9.0‰ and that of the subsurface outflow from the lake as –8.0‰.

Using the above isotope data for all the components and the isotope mass balance equation, the subsurface outflow (SS_O) of the lake was calculated as presented in Table 7. The results thus obtained were used in equation (6) to compute the groundwater inflow (SS_I) to the lake. The results show that SS_I and SS_O account for 51 and 56% of the total inflow and outflow respectively, indicating that subsurface components dominate over other components.

The isotope mass balance method is sensitive to the differences in $\delta^{18}O$ values of the groundwater inflow and of the lake seepage. The relative error decreases with the increase in the difference between these two isotopic values. In a similar kind of study, LaBaugh *et al.* (1997) calculated the uncertainty in the subsurface components of the lake by conventional flow-net method B rather than by the classical propagated error estimation approach. In the present investigation, a similar approach has been adopted and the uncertainty in the estimated subsurface components in the isotope mass balance method is considered to be same as that in the water balance method.

CHLORIDE MASS BALANCE METHOD

Lake mass balance is also determined using chloride species (as it is a conservative species and unlike the isotopes has zero loss from the lake due to evaporation). There is a possibility of chloride entering the lake and groundwater systems through anthropogenic activities and this may affect the mass balance calculations. Therefore, chloride mass balance was calculated mainly for the purpose of comparison.

The concentration of chloride in the lake water was 8 and 10 mg l^{-1} during February 1994 and February 1995, respectively. The mean concentration of drain water (D_I) was 31 mg l^{-1}, and that of surface inflow (S_I) was 24 mg l^{-1}. The latter value was used considering the fact that, during the monsoon period, the flow in the drain water was dominated by channelled surface runoff. The concentration of chloride in groundwater was 16 mg l^{-1} in the upstream springs and 7 mg l^{-1} in the downstream springs hydraulically connected with the lake. The chloride from precipitation was considered as

1 mg l^{-1}, by interpolating the data of Lucknow (Handa *et al.*, 1984) and Srinagar (Maske & Nand, 1982) stations.

Subsurface outflow (SS_O) from the lake was calculated by the mass balance method and the results are presented in Table 7. The data thus obtained were used in equation (6) to estimate the subsurface inflow (SS_I) to the lake. The results corroborate those obtained using the conventional water balance method. The SS_I and SS_O values estimated by this method account for about 55.0% of total inflow and about 59.0% of total outflow. However, the SS_O computed by the chloride mass balance method is higher by 5%.

COMPARISON OF RESULTS

For better comparison of the results obtained by various mass balance approaches, the water retention time (*WRT* = volume/outflow) of the lake was calculated. The values of *WRT* calculated by the different methods are comparable: 1.93 years (isotope mass balance approach), 1.77 years (chloride mass balance method) and 1.92 years (conventional water balance method). From the water balance studies, it may be observed that the subsurface contribution through annual inflow to Lake Nainital is within the range 46–61% and the annual outflow from the lake is within the range 49–65%, suggesting that the lake is of a "flow-through" type with substantial inflow from groundwater and outflow through lake seepage.

SUMMARY AND CONCLUSIONS

The water balance of Lake Nainital located in the Kumaun Himalayan region was studied and a conceptual model was developed. Initially, environmental tracer techniques were employed to identify the springs that are hydraulically connected to the lake. Following this, the subsurface outflow from the interconnected springs was estimated by a relationship that was developed using the historical spring discharge data. Further, the component of lake seepage towards the northern bank of the lake was estimated using a two-component mixing model. The indirectly estimated net subsurface outflow data were then used to calculate the subsurface inflow by means of the water balance equation.

Independent of the water balance method, isotope and chloride mass balance approaches were also applied to estimate the subsurface inflow component, as these two approaches do not require data on the subsurface outflow from the lake. The results of both chloride and isotope mass balance methods corroborate the results of the water balance method, confirming the validity of the conceptual model.

The isotopic studies of the lake system reveal that the slope of the $\delta^{18}O$–δD water line of the lake (7.1) is very close to that of the LMWL (7.5). This indicates that (a) the evaporation loss from the lake is a minor component in the lake water balance and (b) the lake has low water residence time.

The isotope and chloride mass balance approaches yielded comparable results for the Lake Nainital area due to their closed system behaviour and also because there is less anthropogenic activity than in many other lake environments. The chloride mass balance method is advantageous compared to the isotope mass balance method, in that it is cost effective and does not require estimation of ionic concentration in the lake evaporates, thus reducing the overall uncertainty in the final results. On the other hand, the isotope approach with better understanding of the isotope systematics allows one to have better insight into different hydrological processes within the system.

The results of this study suggest it may be useful to apply this approach to examine the water balance of other natural lakes of the Kumaun Himalayan region for better management and conservation.

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