Lake bank filtration at Nainital, India: water-quality evaluation

R. R. Dash · I. Mehrotra · P. Kumar · T. Grischek

Abstract There are different water-supply schemes in Uttarakhand, India to tap the water from streams, rivers and lakes. At Nainital, seven tube-wells (depths 22.6–36.7 m), located at a distance of <100 m from the lake, are being used to abstract (1) lake water after passage through the soil and (2) subsurface water/groundwater flowing towards the lake. Water samples from the lake and tube-wells were analyzed in monsoon and non-monsoon periods from 1997 to 2006. Total dissolved solids, EC, alkalinity and hardness were found to be marginally greater in tube-well waters. The difference in hydrochemistry of tube-well water was mainly due to variation in flow regimes during monsoon and non-monsoon periods. Results clearly indicate that lake water as such is not potable as it contains unacceptable levels of organic matter in terms of COD (~44 mg/L), coliforms (~15.6×10^4 MPN/100 mL) and nutrients. Coliform bacteria and COD have not been detected in any of the tube-well water samples over the years. Lake water, treated by sand filters did not conform to drinking water standards. These investigations have led to the closure of the treatment facility and installation of two tube-wells in addition to the existing five tube-wells.

Résumé Il existe divers projets d'alimentation en eau dans l'état d'Uttarakhand, Inde, afin de capter l'eau de ruisseaux, de rivières et de lacs. A Nainital, sept puits tubés (profondeur de 22.6–36.7 m), situés à une distance < à 100 m du lac, sont utilisés pour prélever (1) de l'eau du lac après transit à travers le sol et (2) de l'eau de sub-surface/eau souterraine s'écoulant vers le lac. Des échantillons d'eau du lac et des puits tubés ont été analysés en périodes de mousson et de celles sans mousson 1997 à 2006. Résidu sec, C.E., alcalinité et dureté ont été trouvés marginalement supérieurs dans l'eau des puits tubés. La différence d'hydrochimie de l'eau des puits tubés était surtout due à la variation des régimes d'écoulement pendant les périodes de mousson et de celles sans mousson. Les résultats indiquent clairement que l'eau du lac en tant que telle n'est pas potable car elle contient des teneurs inacceptables de matière organique en termes de COD (~44 mg/L), de coliformes (~15.6×10^4 MPN/100 mL) et d'éléments nutritifs. Des bactéries coliformes et du COD n'ont été détectés dans aucun des échantillons d'eau de puits tubés au fil des années. L'eau du lac traitée par des filtres à sable ne se conformait pas aux normes de l'eau potable. Ces recherches ont conduit à la fermeture de l'installation de traitement et à l'implantation de deux puits tubés en plus des cinq puits existants.

Resumen En el estado de Uttarakhand, India, existen diferentes esquemas de abastecimiento de agua que explotan agua de arroyos, ríos y lagos. En Nainital, siete pozos (profundidades entre 22.6–36.7 m), ubicados a una distancia de <100 m del lago, se usan para extraer (1) agua del lago luego de su pasaje a través del suelo y (2) agua superficial y subterránea que fluye hacia el lago. En períodos de monzón y de no monzón de 1997 a 2006 se han analizado muestras de agua del lago y de las captaciones. Se halló que el agua de los pozos es ligeramente mayor en términos del total de sólidos disueltos, la conductividad eléctrica, la alcalinidad y la dureza. La diferencia en la hidroquímica del agua de las perforaciones se debe principalmente a la variación de los regímenes de flujo durante los períodos de monzón y de no monzón. Los resultados claramente indican que el agua del lago no es potable por su contenido inaceptable de materia orgánica medida como demanda de carbono orgánico/oxígeno –DCO- (~44 mg/L), coliformes (~15.6×10^4 NMP/100 mL) y nutrientes. En el período, no se han detectado bacterias coliformes ni DCO en las muestras de agua de las captaciones. El agua del lago, tratada con filtros de arena, no conformó los estándares de agua para bebida. Estas investigaciones han demostrado la

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necesidad de clausurar las instalaciones de tratamiento y la adición de dos captaciones a las cinco ya existentes.

Keywords Water supply · Lake bank filtration · Tube-wells · Laboratory experiments/measurements · India

Introduction

Lakes and rivers have been and continue to be major sources of water supply. The water quality is influenced by the strata through which incoming groundwater travels, as well as by the activities in the catchment affecting surface run-off to the lake. The surface water, which is vulnerable to pollution, can not be used without treatment. Groundwater often can be used without treatment. However, limited groundwater resources, decreasing level of groundwater due to over-abstraction and increasing cost of pumping, are not in tune with the environmental obligations for future generation. The preservation of the environment, without compromising the quality and quantity of water required to sustain the growing population, has become a challenge. It is time, perhaps, to revive traditional technologies of water supply.

In many countries of the world, alluvial aquifers hydraulically connected to a water course are preferred sites for drinking water production. Such aquifers are characterized by the relative ease of shallow groundwater exploitation. Also, these have generally high production capacity and proximity to demand areas (Doussan et al. 1997). Groundwater derived from infiltrating river water provides 50% of potable supplies in the Slovak Republic, 45% in Hungary, 16% in Germany and 5% in The Netherlands (Schubert 2002). Therefore, it is worth considering the role of bank filtration in the overall management of water from rivers and lakes.

Lake bank filtration has been used for drinking water supply in Berlin, Germany, for more than 100 years. The 3.4 million inhabitants of Berlin are supplied with drinking water with a contribution of approximately 70% from bank filtration and artificial groundwater recharge (Fritz et al. 2002). Large capacity waterworks are located at lakes Müggelsee, Tegel and Wannsee. To investigate the hydraulics and hydrochemistry of lake bank filtration, monitoring wells were installed between the lake banks and production wells. Sediment and groundwater samples in the vicinity of Lake Tegel were analysed. The catchment of the lake is strongly affected by treated sewage. Knappe et al. (2002) studied the behaviour of tracers of sewage components such as boron, ethylenediaminetetraacetate (EDTA), chloride and Gd-DTPA during bank filtration. The reduction in halogenated compounds and other trace organic compounds present in lake water depends on redox conditions in the aquifer and has been described in detail by Ziegler et al. (2001, 2002), Schittko et al. (2004) and Grünheid et al. (2005). Dissolved organic carbon (DOC) has been shown to decrease by 40 to 50% especially in the first few meters of aquifer passage. The attenuation of colloids and polycyclic aromatic hydrocarbon (PAH) has been studied intensively at the Hengsen test site located near Dortmund in the Ruhr River basin in Germany, where bank filtrate is abstracted near a small reservoir (Schulte-Ebbert and Hofmann 2000). Recently, Skark et al. (2006) classified lake and river bank filtration sites and compared removal efficiencies.

In Finland, lake bank filtration is used even where lake water has a high concentration of humic substances. Five production wells are located on the island of Hietasalo in Lake Kallavesi. The water is supplied to the city of Kuopio. The retention time of the infiltrating lake water correlates with the distance between the wells and the lake bank. It was determined using temperature measurements to be between 1 and 4 weeks (Miettinen et al. 1994). The mean total organic carbon (TOC) concentration of lake water was 12.1 mg/L. The mean reduction in TOC was about 20 and 64% for wells located at short and long distances respectively from the lake bank. Bacterial enzymatic activities decreased strongly after infiltration of lake water correlating with a decrease in bacterial counts and biomass production (Miettinen et al. 1996). For bank filtration sites at Lake Vihnusjärvi and Vesijärvi, with mean TOC concentrations of 10 and 4.8 mg/L respectively in lake water, the reduction of TOC content was 55 and 29% (Kivimäki et al. 1998). The decomposition of organic matter in sediment layers resulted in low concentrations of oxygen in bank-filtered water. Iron (median 4.9 mg/L) in the bank filtrate from the lake Vihnusjärvi is removed in post treatment in the Nokia waterworks.

North of the city of Dresden, Germany, a bank filtration site along the Radeburg reservoir has been in use since 1986. The fate of microcystins in bank filtration was investigated by Chorus et al. (2001). Water samples from 12 wells were analyzed for microcystins. Maximum dissolved microcystin concentration of 0.51 μg/L in reservoir water was reduced by 75–99%. The concentration in any of the wells did not exceed a value of 0.06 μg/L. Similar results were obtained from field studies at two bank filtration sites at eutrophic lakes in southern Finland (Lahti et al. 1998). Removal of microcystins was over 90%. The concentration of microcystin in the bank filtered water was less than 0.1 μg/L. In Lake Wannsee, Berlin, Germany, microcystin concentration up to 20 μg/L was observed in summer months by Grützmacher et al. (2002). Due to a strong reduction through bank filtration, only traces (less than 0.1 μg/L) were found in water from production wells. Results indicate that despite the eutrophic situation in lakes or reservoirs, breakthrough of microcystins at concentrations causing a health risk is unlikely in bank filtered water (WHO drinking water guideline value: 1.0 μg/L).

In the Netherlands, a deep gravel extraction lake, De Lange Vlieter, fed by water from the Maas River, is surrounded by well fields abstracting bank filtrate. Originally, the intention was to use the lake water directly, but aquifer passage has been selected, mainly because this removes microorganisms (Juhasz-Holterman et al. 1998). The effectiveness of bank filtration at rivers and basins to remove microorganisms including *E. coli*, clostridium

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spores and phage has also been proved through field site investigations by Medema and Stuyfzand (2002). According to them, critical situations may arise where infiltration intensities are high and travel times are short and where the recollection system may receive inputs through short circuits or imperfections in an air and water tight construction, allowing access of animal life or water from above.

Lake bank filtration has been in use at Nainital in northern India for more than 15 years. Nainital Lake has been extensively studied over several decades for structure and tectonic (Valdiya 1980, 1988), sediment accumulation (Das et al. 1994), water balance (Kumar et al. 1999), paleoclimatic conditions (Kotila et al. 2000), water sediment chemistry (Chakrapani 2002), eutrophication (Pant et al. 1980), phytoplankton community (Sharma et al. 1982), water pollution (Pant et al. 1981), benthic microinvertebrates (Gupta and Pant 1990), inshore macrozoobenthic community (Gupta and Pant 1986) and morphology and morphometry (Rawat 1987). However, a comprehensive study on the water quality after bank filtration has been lacking. Therefore, a study was undertaken with an objective of evaluating bank filtration as a treatment step for drinking water production. This report presents observations on water quality of natural lake bank filtrate, lake water and treated lake water.

Study site

Nainital Lake is located in the Kumaun region in the State of Uttarakhand, India (Fig. 1). The lake, a kidney shaped water body, is a big tourist attraction as well as a source of drinking water. It is fed by around twenty water channels. Only two of them are perennial open drains. Besides these surface drains, internal and underwater springs also feed into the lake at several locations.

To regulate the water level in the lake particularly during the rainy season, a dam has been constructed at the lower end of the lake. Excess water is discharged from the dam through five sluices, which then joins the Balia River. However, because of the intense activities in the catchment of the lake, resulting from the tourist influx and an increase in sedentary human population, there has been a rapid deterioration of the water quality through increased nutrient input. The present estimate of the population around the lake is 50,000. Additionally, the daily tourist influx in summer months averages around 5,000. Buildings around the lake have increased from 4,053 in 1971 to 7,836 in 1991. The capacity of the lake is progressively decreasing. The volume of the lake was estimated as $7{,}425\times10^3$ m^3 in 1899, $6{,}808\times10^3$ m^3 in 1969 and $5{,}907\times10^3$ m^3 in 1982 (Nachiappan et al. 2002). Scientists at the National Institute of Hydrology (NIH), Roorkee estimated the lake life based on the sedimentation rates by employing ^{210}Pb and ^{137}Cs dating techniques as $2{,}480\pm310$ and 2160 ± 80 years respectively (Kumar et al. 1999). The summary of location, morphological and meteorological data is given in Table 1.

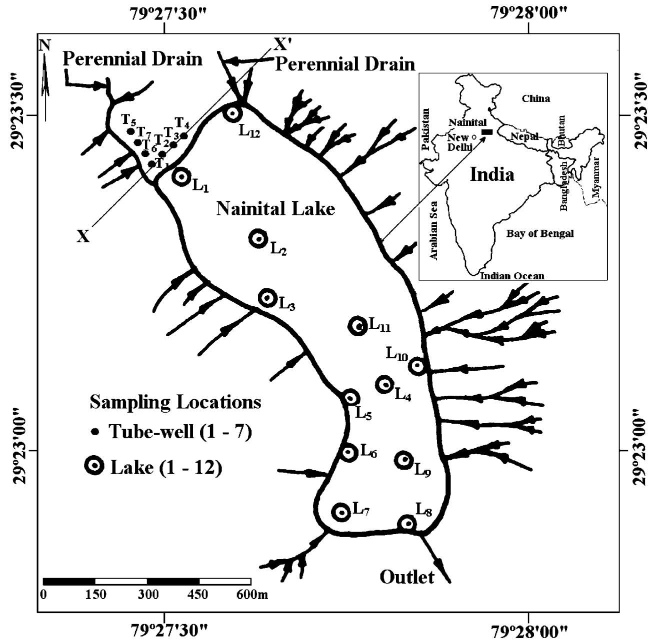

Fig. 1 Location of sampling sites at Nainital Lake in Uttarakhand, India

Nainital city has an over 50-year-old sewerage system which often bursts at bends and overflows into rainwater channels and ultimately into the lake. In addition, solid waste dumped into open drains is also sometime emptied into the lake by these drains. There are no major industrial activities in the catchment area. The land-use classification in the catchment area is: forests and shrubs (42%), buildings (41%), roads (2.1%), water bodies (10.3%), playground (1.1%), and barren lands (3.5%).

Nainital has a more than 100–year–old piped water supply, one of the oldest in the Kumaun region. It was conceived and designed at erstwhile Thomason College of Civil Engineering, Roorkee (now Indian Institute of Technology Roorkee) in 1895 and executed in 1898. The water used to be drawn from springs (main spring: Pardah Dhara) by steam engines. In 1914, diesel engines were installed and the system was augmented. In 1955, provision was made to pump and supply lake water in addition to spring water to meet the increasing water demand due to growing population. In 1985, a treatment plant having a roughening filter and two pressure sand filters (1 ML/day each) were installed at the north-west side of the lake to produce drinking water from lake water. Subsequently, between 1990 and 2005, five tube-wells (nos. 1–5) were installed adjacent to the Nainital Lake. The depths of these tube-wells ranged from 22.60 to 33.35 m. The sixth and seventh tube-wells of 36.7 and 35.9 m depths respectively were commissioned recently in 2006. At present, 24.1 ML/day of water is drawn from tube-wells and pumped to reservoirs at higher locations for supply by gravity.

Geology of the tube-well site

The geological exploration by means of drilling was undertaken during 1975–1976 (Ashraf 1978). The drill

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Table 1 Summary of location, morphological and meteorological data for Nainital Lake

Parameter	Values	Parameter	Values
Altitude (m asl)	1,937	Volume of water (m^3)	5,907,500
Longitude	79°28′ E	Annual rainfall (mm)	2,300
Latitude	29°23′ N	Maximum air temperature (°C)	24.6
Maximum length (m)	1,432	Minimum air temperature (°C)	0.5
Maximum breadth (m)	423	Maximum water temperature (°C)	25
Maximum depth (m)	27.3	Minimum water temperature (°C)	10
Mean depth (m)	16.2	Water retention time[a]:	
Surface area (km^2)	0.48	Isotopic mass balance	1.93 years
Catchment area (km^2)	3.96	Chloride mass balance	1.73 years
Shoreline (m)	3,630	Conventional mass balance	1.92 years

[a] Nachiappan et al. 2002

hole (DH) was put down near the tube-well site to a depth of 132.6 m. The abstract log of the DH is given in Fig. 2 along with the depth of tube-wells 1–7. The terrain around the tube-wells is flat/gently sloping and is occupied by a massive deposit of debris. The deposit is the result of recurrent landslides that occurred on the higher slopes especially during the years 1867, 1880, 1894, and 1924. The material has been reported to mainly comprise of rock fragments of shale/slate with subordinate and poorly sorted fine sand and clay. The depth wise profile of the overburden material indicates a varied assortment, i.e. debris deposits, materials carried by rainwater channels and lake sediments.

The geology of the tube-well site is quite complex as the area is dissected by a number of folds and faults. The trace of the lake fault or shear zone has been projected by Sharma (2001) close to the site at a depth of approximately 116 m (Fig. 3). The bedrock encountered below 116.4 m has been reported to be made up of red and green shales belonging to the Middle Krol Formation.

Water balance

Various flow components required for water balance studies of the lake are shown in Fig. 4. The water balance equation for the lake incorporating different inflow and outflow components can be written as:

$$\mathrm{SS}_i = (E_o + S_o + W_o + \mathrm{SP}_o + \Delta V) - (P_i + S_i + D_i) \quad (1)$$

Where,

$\mathrm{SS_i}$ Sub-surface inflow to the lake $[L^3/T]$
E_o Evaporation from the lake surface $[L^3/T]$
S_o Surface outflow from the lake $[L^3/T]$
W_o Withdrawal from the lake through wells installed at the northern bank $[L^3/T]$
$\mathrm{SP_o}$ Subsurface outflow in the form of springs $[L^3/T]$
ΔV Change in lake storage $[L^3/T]$

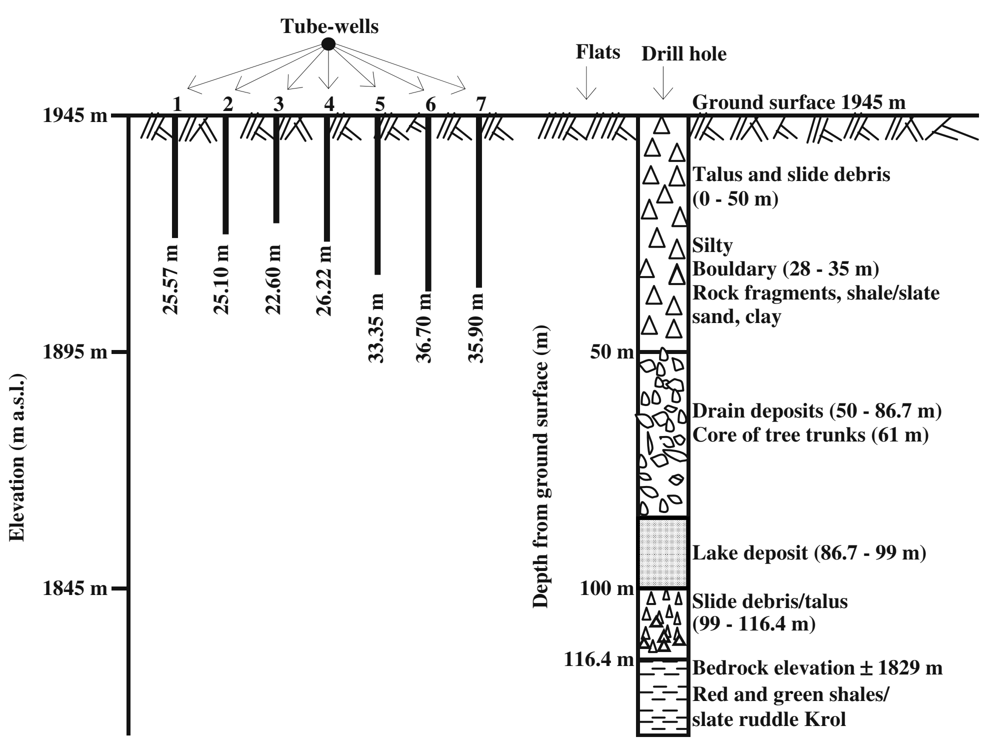

Fig. 2 Abstract log of drill hole near tube-well/waterworks site

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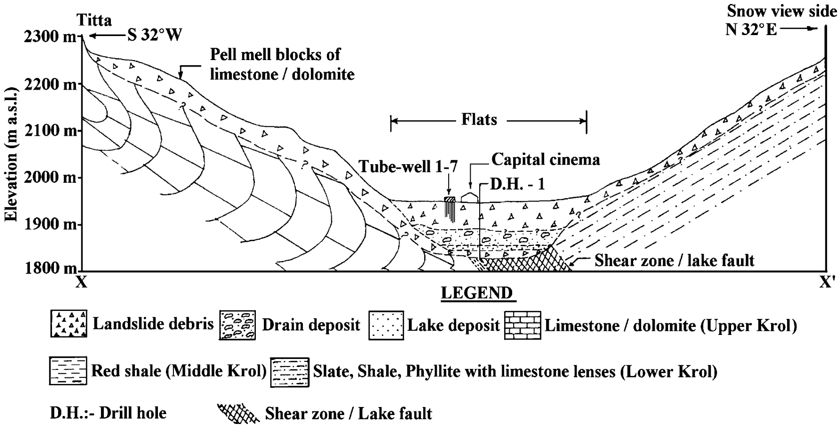

Fig. 3 Geological cross-section (*X-X'* in Fig. 1) across tube-well/waterworks site near northern edge of *Lake Nainital* (Sharma 2001)

P_i Direct precipitation over the lake surface [L^3 /T]
S_i Surface water inflow to the lake [L^3/T]
D_i Inflow to the lake through drains [L^3 /T]

The lake catchment is characterized by a multitude of faults and fractures coinciding with a surface drainage system. Groundwater movement preferentially takes place along these zones towards the lake. Another lake known as Sukhatal (a dry lake) is situated in the catchment of lake Nainital at a higher elevation. Sukhatal, as a sub-catchment of Nainital, does not have any surface out flow and appears to be of a closed type. Because of the proximity of the lake fault to Sukhatal, most of the water is lost through underground seepage that subsequently recharges Nainital Lake and feeds the aquifer tapped by the tube-wells 1–7 (Fig. 4).

The entire quantum of water that is pumped out of these tube-wells is not completely from lake bank filtration. However, as the wells are located in unconsolidated landslide debris very close to the lake, a substantial portion of the pumped water is replenished by the sub-surface out flow from Lake Nainital as seepage. The proportion of lake water being pumped from the wells located near the lake was estimated by isotopic tracer technique (Nachiappan et al. 2002). A two-component mixing model has been applied. The $\delta^{18}O$ data of admixture i.e., the well water, end-member indices along with the proportion of the lake water being pumped are given in Table 2. The results show that the proportion of the lake water component in the water pumped from the wells is lower in non-monsoon season (25–40%) as compared to that of monsoon season (80%).

Seepage from the lake, most likely, does not occur through the lake bed, as it is covered with fine sediments. Sub-surface outflow mainly takes place through an epilimnion zone. Different components of water balance for Lake Nainital have been computed using Eq. (1) and the 8-year hydro-meteorological data from 1994 to 2001 (AHEC 2002). The conceptual model (Eq. 1) has been

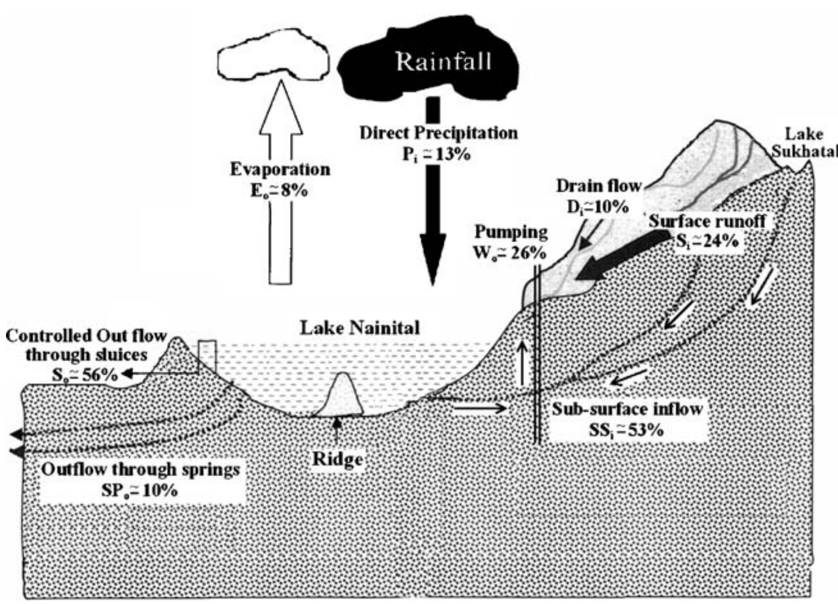

Fig. 4 Water balance components and their average annual percentages for Lake Nainital (based on data of 1994 to 2001 from Nachiappan et al. 2002 and AHEC 2002)

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Table 2 Proportion of lake water in tube-well water (Nachiappan et al. 2002)

Month	$\delta^{18}O$ (‰)			Proportion of lake water (%)
	Lake	Groundwater	Well	
February	–7.3	–8.2	–8	25
March	–7.1	–7.5	–7.4	25
May	–7.1	–7.5	–7.4	30
August	–6.3	–8.9	–6.8	80
November	–8.2	–7.9	–8	40

validated using techniques such as isotope mass balance and chloride mass balance (Nachiappan et al. 2002). Average quantities of annual water loss or gain by the lake Nainital through different processes have been found to be 7.7×10^6 m^3. Average percentages of different components on an annual basis are shown in Fig. 4, which clearly highlights the qualitative information that the subsurface inflow and outflow (the combined pumping from tube-wells and outflow through interconnected springs) are the prominent processes. The evaporation loss, direct rainfall over the lake surface area and inflow through the drains are minor components. The current indirect withdrawals from the lake through the pumping operations (lake bank filtration) are sustainable as the excess water released through the sluice gates far exceeds the pumping. The annual rainfall during the years 1994–1997 was recorded as less than the normal rainfall. However, the quantity of excess water drained through the sluice gates was substantial. Therefore, the present water-withdrawal rate from the adjacent aquifer does not affect the water availability for the maintenance of aesthetic value of the lake.

Methodology

Water samples from tube-wells (1–5) and Nainital Lake (12 locations) were collected six times during non-monsoon and monsoon periods from 1997 to 2006 (Nov. 1997, Feb. 2002, March 2002, Aug. 2005, Nov. 2005 and March 2006). Sampling locations of lake water are shown in Fig. 1. Samples from the lake were collected at depths varying from 1.5 to 15 m. Water samples were analyzed at the Environmental Engineering Laboratory of the Department of Civil Engineering, IIT Roorkee, Roorkee. The collection, preservation, transportation, and analysis of samples were done in accordance with the procedures laid down in the standard methods (APHA, AWWA, WPCF 1995, 1998, 2005).

Temperature, pH, electrical conductivity (EC), oxidation reduction potential (ORP) and dissolved oxygen (DO) were measured on site. Other parameters such as turbidity, total dissolved solids (TDS), major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-,SO_4^{2-} and HCO_3^-), UV absorbance and fecal coliforms were estimated in the laboratory. Turbidity was determined using a nephelometer (AN 2100, Hach, USA). Electrical conductivity and pH were measured using meters supplied by WTW, Germany. Samples for TOC were analyzed with a TOC analyzer (VCSN 5000, Shimadzu, Japan). All spectrophotometric measurements were made by DR-4000 UV-VIS spectrophotometer (Hach, USA). DO was measured by Senso Direct OX-24 DO meter (Aqualytic, Germany). Sodium and potassium were analyzed using a microprocessor based flame photometer (Toshniwal, India).

In addition, filtered water samples (prior to disinfection) were also collected from the water treatment plant during one of the sampling program (August 2005). Lake water (5.5 ML/day) (not the bank filtrate) was being fed to the filtration plant consisting of two pressure filters and two rapid sand filters.

Aquifer soil samples from different depths (3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36 and 37 m) were collected in November 2005, when drilling of tube-well no. 6 was in process. Samples were transported and analyzed in the laboratory for particle size distribution using dry sieving and the method specified in IS 2720 Part 4 (1985).

Results and discussion

Sieve analysis for aquifer soil

Grain size analysis carried out as per Indian Soil Classification (IS 1498 1970) indicates that the surface soil up to the depth of 36 m has higher percentage of gravel, coarse sand, and medium sand. Gravel, however, is not found beyond a depth of 36 m. The soil after 36 m has mainly medium sand, fine sand and clay fractions. Therefore, the water-bearing strata can be assumed up to 36 m. The required soil parameters for estimating hydraulic conductivity were determined from the sieve analysis (Table 3). Values of hydraulic conductivity (*K*), a necessary parameter to estimate travel time at different depths was estimated using different methods (Table 4). The travel time between the screens of the tube-wells and the lake bank is an important parameter for bacteria and turbidity removal. A 60-day travel time was assumed to be adequate to inactivate pathogenic bacteria to the degree that no health risk exists (Knorr 1937; CBW 1980). In Germany, a travel time of 50 days is commonly recommended for the elimination of bacteria and to design a water protection zone where no microbial pollution should occur. In the present case, the travel time was calculated (using Darcy's law) on the basis of water level

Table 3 Parameters determined from grain size distribution of aquifer soil at different depths

Depth (m)	d_{10} (mm)[a]	d_{50} (mm)[b]	d_{60} (mm)[a]
6	0.73	4.8	8.1
18	0.60	8.2	12.0
27	0.63	9.0	12.5
30	0.73	6.0	10.0
36	0.37	4.6	8.1
37	0.17	0.3	0.4

[a] d_{10} and d_{60}=grain sizes for which 10 and 60% of the grains are finer respectively

[b] d_{50}–median grain diameter

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Table 4 Calculated hydraulic conductivities of aquifer soil

Depth (m)	Hazen (1893) K (m/day)[a]	Beyer (1964) K (m/day)[b]	Alyamani and Sen (1993) K (m/day)[c]
6	460.4	392.8	455.4
18	311.0	224.3	389.1
27	342.9	247.9	592.3
30	460.4	370.8	306.0
36	118.3	82.9	139.9
Average	327.5	250.3	394.5

[a] Hazen: K (mm/s)=C d_{10}^2

Where, C = constant

[b] Beyer: K(m/s)=(g/υ) C_b d_{10}^2

Where C_b=0.0006 $\log_{10}$ (500/U), U = uniformity coefficient = d_{60}/d_{10}, ν = kinematic viscosity of water

[c] Alyamani and Sen: K (m/s)=0.015[I_o + 0.025 (d_{50}–d_{10})]^2

Where, I_o–intercept of the line formed by d_{50} and d_{10} with the grain size axis

measurements in the lake and in the pumping wells assuming that the lake water infiltrates at the bank. Travel time computed from the average value of the coefficient of hydraulic conductivity (Table 4) during monsoon, for tube-wells 1 to 4, which are very close to the lake bank, was found to be 1–2 days and for tube-well 5, which is around 84 m away from the lake, the travel time was estimated to be 11–19 days. The travel time thus calculated is shorter for the treatment achieved than reported by other researchers (Medema et al. 2000; Schijven et al. 1998; Matthess and Pekdeger 1985). To reach 4–5 log removal of coliform during bank filtration, travel time between 10–20 days is needed. Such travel time may be achieved by continuous well operation due to clogging of the lake bed extending from the tube-well site border to the lake. Benthos organisms churn and graze the clogged layer for nourishment. In lake bank filtration, a clogged layer is produced, which is likely to be sustained

Table 5 Water quality comparison: Lake water vs. tube-well water

Physical, chemical and bacteriological parameters	Monsoon		Non-monsoon		Conventional treatment	
	Lake water	Tube-well water (Nos. 1–5)	Lake water	Tube-well water (Nos. 1–4)	Lake water	Water from conventional treatment plant
Temperature (°C)	18–24 (21)	16.5–17 (17)	NA	NA	22	20
Turbidity (NTU)	6.7–7.3 (7.1)	0.1–0.4 (0.25)	3.7–6.1 (4.9)	0.1–0.3 (0.2)	6.7	0.2
Electrical conductivity (μS/cm)	544–605 (577)	821–954 (869)	631–653 (640)	573–708 (655)	582	710
Total dissolved solids (mg/L)	361–398 (376)	542–639 (580)	324–472 (407)	471–528 (501)	380	467
Suspended solids (mg/L)	24–31 (28)	ND	18–31 (25)	ND	30	ND
pH	8.4–8.8 (8.64)	8.1–8.24 (8.16)	7.6–8.1 (7.9)	7.6–7.7 (7.68)	8.5	8.2
DO (mg/L)	ND–8.4 (5.5)	2.6–4.9 (3.9)	NA	NA	5.5	0.0
ORP (mV)	(−6)–372 (225)	291–348 (308)	NA	NA	280	285
Total hardness (mg/L as $CaCO_3$)	260–286 (277)	370–434 (405)	320–338 (328)	370–420 (387)	280	328
Ca^{2+} (mg/L)	20.0–26.4 (23.5)	44.0–51.2 (49.0)	48.9–52.6 (51.6)	58.8–65.3 (61.5)	24	46
Mg^{2+}(mg/L)	48.0–56.6 (52.5)	58.6–73.4 (68.3)	45.7–50.7 (48.2)	53.7–61.4 (56.1)	53	51
Na^+ (mg/L)	11.0–11.8 (11.3)	11.4–19.1 (16.0)	7.18–13.3 (9.5)	18.2–25.7 (22)	11.5	12.3
K^+ (mg/L)	4.3–7.1 (5.4)	2.8–6.1 (4.7)	2.9–5.9 (4.9)	5.2–6.1 (5.7)	5.4	4.6
HCO_3^- (mg/L)	207–242 (225)	254–322 (284)	224–234 (229)	364–390 (377)	226	264
SO_4^{2-} (mg/L)	87–104 (94)	124–195 (148)	57–69 (64)	132–163 (147)	95	108
Cl^- (mg/L)	11.0–16.0 (14.3)	19.0–27.0 (23.0)	6.73–8.65 (7.37)	12–15.5 (13.5)	14	20
PO_4^{3-} (mg/L)	0.027–0.078 (0.044)	ND–0.006 (0.001)	0.16–0.22 (0.19)	0.01–0.03 (0.02)	0.04	0.16
NO_3^- (mg/L)	0.23–0.41 (0.3)	2.2–5.67 (3.5)	0.05–0.70 (0.2)	2.6–4.4 (3.5)	0.3	1.8
F^- (mg/L)	0.15–0.22 (0.19)	0.15–0.2 (0.18)	0.16–0.23 (0.21)	0.14–0.16 (0.15)	0.19	0.16
NH_4^+ (mg/L)	0.1–0.24 (0.17)	0.02–0.22 (0.08)	4.85–7.84 (6.3)	0.46–0.83 (0.64)	0.18	0.03
Chlorophyll – a (μg/L)	NA	NA	11.4–102 (35)	ND	NA	NA
COD (mg/L)	19–42 (31)	ND	20–80 (57)	ND	30	ND
UV absorbance at 254 nm (cm^{-1})	0.056–0.061 (0.059)	0.002–0.009 (0.007)	NA	NA	0.06	0.007
Total coliform (MPN/100 mL)	0.5×10^2–50×10^4 (17×10^4)	<2	4.6×10^4–24×10^4 (14.3×10^4)	<2	17×10^4	2,300
Fecal coliform (MPN/100 mL)	0.5×10^2–50×10^3 (19×10^3)	<2	5×10^3–24×10^3 (14.5×10^3)	<2	20×10^3	230

NA not available; *ND* not detectable (values in parenthesis are average values); *MPN* most probable number

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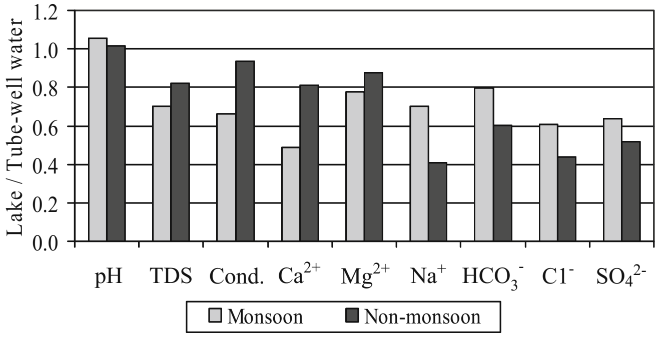

Fig. 5 Quality of tube-well water relative to lake water

during well operation and its extension is balanced out by self-cleaning mechanisms of benthos. Therefore, the effective travel time can be speculated to be more than the calculated travel time from Darcy's law. Work on groundwater flow modeling to determine travel time between the screens of the tube-wells and lake is in progress.

Quality of lake water and tube-well water (natural treatment)

Water samples from the tube-wells (1–5) and from the lake at different depths were analyzed separately during monsoon and non-monsoon periods. The detailed observations regarding water quality parameters are compiled in Table 5. The percentage error in ionic balance varied from 0 to 8%. Water quality analysis of lake water and tube-well water during monsoon and post-monsoon periods demonstrates the dominance of calcium, mangnesiumand bicarbonate. Tests for total coliform in all the tube-well samples yielded negative results indicating that water is free from any fecal contamination and is fit for drinking purpose as per Indian Standard (IS 10500 1991).

The hardness of the tube-well water ranged from 370 to 434 mg/L as $CaCO_3$ and was more than the desirable value of 300 mg/L. Indian Standard of drinking water also specifies a permissible limit of 600 mg/L as $CaCO_3$, in the absence of an alternate source. Nainital tube-well as well as lake waters have an excess of magnesium hardness particularly associated with bicarbonate and sulphate ions. Magnesium hardness in association with sulphate is reported to have a laxative effect on persons unaccustomed to it. Magnesium hardness on an average is more than the calcium hardness. Temporary hardness (i.e. carbonate) is 3–5 times the permanent (i.e. non-carbonate) hardness in bank-filtered waters collected from different tube-wells. At present, hardness of water from tube-wells is in conformity with the Indian Standard for drinking water (IS 10500 1991).

The lake is fed by surface, sub-surface and groundwater. The water from tube-wells is the groundwater under the direct influence of (1) surface water from Lake Nainital and (2) seepage water flowing through faults and fractures from Sukhatal sub-catchment. The water drawn from the tube-wells is expected to be different from the lake water depending upon the mixing of the bank filtrate and groundwater during different months in a calendar year (Table 2). The concentration of major ions is likely to be more in the tube-well water than the lake water. A comparison between tube-well water and lake water is presented in Fig. 5. Following are the main points of difference:

- TDS, electrical conductivity, calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulphate: tube-well water > lake water
- Ammonia, phosphorus: lake water > tube-well water
- Organic matter: lake water > tube-well water
- Total coliform: lake water > tube-well water

Lake water of widely varying characteristics e.g. temperature, TDS, ORP etc. (due to seasonal variations, depth stratification, seasonal overturn, and yearly changes) enters into slotted pipes of tube-wells at different levels after traveling through the aquifer formed by natural deposits around the lake bank (Fig. 3). During bank filtration, the water from the lake presumably causes weathering and/or leaching of materials from the deposits. Perusal of observations recorded in Table 5 and Fig. 5 reveals higher increase in calcium, chloride and sulphate of tube-well water than magnesium, sodium and bicarbonate in monsoon period. However, during the non-monsoon period, sodium, bicarbonate, chloride, and sulphate increase more than calcium and magnesium. Average electrical conductivity of lake water increases from 577 μS/cm in the monsoon period to 640 μS/cm in the non-monsoon period. It seems, therefore, that processes operating in monsoon and non-monsoon seasons are somewhat different. It has been shown that during the monsoon period, more water flows (80% lake water 20% groundwater probably from fault and fractures) through the deposited aquifer material, causing weathering and/or leaching of material. During the non-monsoon period, however, the flow of lake water through deposits is reduced considerably resulting in reduced level of leaching. The proportion of mixing of groundwater predom-

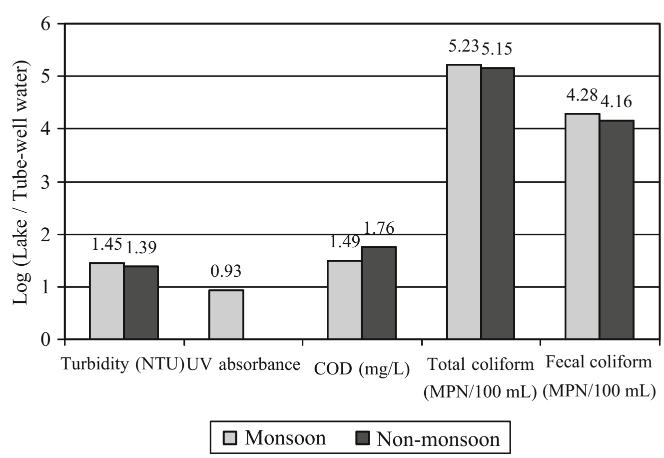

Fig. 6 Turbidity, UV-absorbance, COD and coliform counts of tube-well water relative to lake water

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inates and most probably leads to significant increase in bicarbonate, sulphate, chloride, and sodium.

The impact of catchment activities on the quality viz. chemical oxygen demand (COD), coliform, nutrients of lake-water is quite evident. Nevertheless, during lake bank filtration all the suspended solids, COD, chlorophyll-a and bacteria are reduced to less than the detection limit of the method(s). The tube-well water when compared with lake water showed 5.2 log removal of total coliform, 4.2 log removal of fecal coliform, 1.4 log removal of turbidity and 1.6 log removal of organics (in terms of COD; Fig. 6). The removal can be attributed to physical filtration and straining of particles.

Comparison of bank filtration to rapid sand filtration

Water samples from the filter units were analyzed to compare the engineered filtration with natural lake bank filtration. Water from tube-wells was found to be better in terms of bacteriological quality than that from the treatment unit having sand filters. Only 1.9 log reduction of total and fecal coliform was achieved in filter units, whereas 5.2 log and 4.2 log removals respectively were noticed during natural filtration at the same sampling period (Fig. 7). Also the water from sand filters had a total coliform count (MPN/100 mL) of 2,300. Such water is not considered fit for chlorination. Water to be chlorinated should not have MPN >50 per 100 mL (CPCB 1974). The tube-well water is free from any coliforms and not even chlorination is required. This may be due to the fact that in rapid sand filters, mechanical filtration dominates, whereas in lake bank filtration, various mechanisms like filtration, sorption, chemical precipitation, redox reaction and biodegradation etc. take place simultaneously. However, the main reason for the difference in removal may be due to the difference in flow velocity (or loading rate), grain size characteristics and travel time (Table 6).

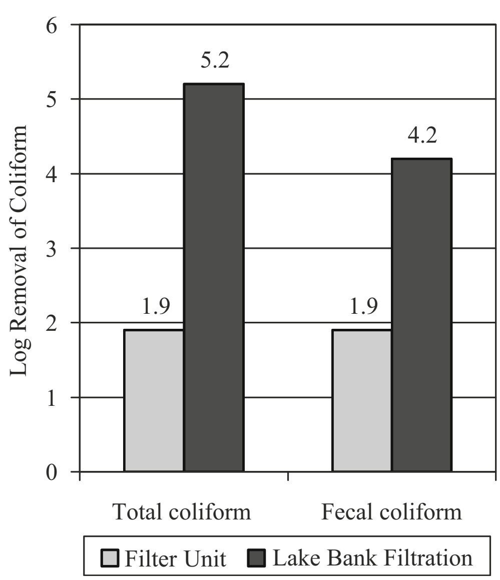

Fig. 7 Comparison of bacteriological quality of water from tube-wells and sand filters

Table 6 Comparison of flow and media characteristics of lake bank filtration with engineered filtration at Nainital

Parameters	Lake bank filtration[a]	Water treatment plant
Seepage/flow velocity (m/day)	13.4–21.5[b]	100
Grain size characteristics:		
Effective size, $E=d_{10}$ (mm)	0.37–0.73[c]	0.35–0.55
Uniformity coefficient, $U=d_{60}/d_{10}$	11.1–21.9[c]	1.3–1.7
Travel time (days)	1–2[d]	0.008

[a] Values for tube-wells 1–4, which are nearer to the lake bank

[b] V_n, seepage velocity (m/day)=[K (H-h)]/Ln

Where K = hydraulic conductivity (from Table 4), (H-h) = hydraulic head difference between the water level in the lake and tube-wells (1–4)*, L = average distance between tube-well screen and lake bank[†], n = porosity[ψ]

[c] From Table 3

[d] Travel time = L/V_n

*(H-h)=0.4 m

[†] L=25 m

[ψ] n=0.3

Conclusions

This study clearly illustrates the benefits of lake bank filtration as an alternative to direct surface-water abstraction followed by rapid sand filtration. Rapid sand and pressure filters do not yield water safe for drinking. Also, an additional treatment is required prior to chlorination. The present study was carried out with five tube-wells. Based on the results from the present investigation, the treatment of lake water by rapid sand and pressure filters has been discontinued and, subsequently, additional two tube-wells have been installed.

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