

# Lake bank filtration in landslide debris: irregular hydrology with effective filtration

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**Abstract** A lake bank filtration (LBF) scheme comprising of nine tubewells on the bank of the lake Naini in Nainital, India exists in landslide debris while most bank filtration sites globally are in alluvial aquifers. The water quality and stable isotopes ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) have been studied to assess the proportions of bank filtrate drawn by the wells. Results show that of the nine wells, two wells perennially abstract mainly bank filtrate, three abstract predominantly bank filtrate during non-monsoon but groundwater during monsoon, and four wells largely abstract groundwater perennially. Bank filtrate proportion in a well is not dependent on its distance from the lake. Also, more than one groundwater stream appears to be contributing to the well field. Such anomalous hydrology is likely due to hydrogeological heterogeneity in the landslide debris or drainage from fractures and faults in the underlying geology. The study shows that an LBF well in a landslide deposit can sustainably deliver water of drinking

quality at a short distance of  $\sim 5$  m and travel time of  $\sim 2$  to 3 days from the lake.

**Keywords** Lake bank filtration · Landslide deposit · Water quality · Stable isotope · Water supply · Drinking water

## Introduction

Bank filtration, a natural filtration process, leads to attenuation of pathogens, organics, turbidity, as well as many inorganic contaminants in the surface water as it passes through the bank aquifer (Ray et al. 2003). Bank filtration is applicable to both river banks and lake banks. However, there are a few differences between lake bank filtration (LBF) and river bank filtration (RBF). Due to low water movement in lakes, colmation layer at lake banks grows steadily. It is not disrupted by the seasonal changes in water flows, as in the case of river banks. Studies on the littoral zones of the Lake Tegel, Berlin (Germany) have shown that the colmation layer, extending to a thickness of  $\sim 10$  cm, is biologically active (Hoffmann and Gunkel 2011). Complete clogging of the layer does not take place due to aquatic organisms feeding on it.

Compared to RBF, very few water supply schemes based on LBF exist in the world in Germany, Finland, The Netherlands, Lithuania, Brazil, and India. In Berlin, Germany, LBF wells at Lake Tegel along with other aquifer filtration schemes furnish 70 % of the city's water supply (Fritz et al. 2002). At the LBF schemes at Lake Tegel and Lake Wannsee in Berlin, bank filtrate takes a time of  $\sim 4$  months to travel to shallow wells located  $\sim 100$  m from the lake bank as estimated using stable isotopes ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ), chloride, and boron as tracers (Massmann et al.

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2008). In Dresden, Germany, an LBF scheme at Radeburg reservoir is used since 1986 for the city's water supply which abstracts 90 % bank filtrate and 10 % groundwater (Chorus et al. 2001). Chorus et al. (2001) also showed that the bank filtration scheme filters 60–99 % of the microcystins concentration in the reservoir water. An LBF scheme installed at the bank of Lake Lagoa do Peri in Santa Catarina Island in Brazil is effective in removing 100 % of the phytoplankton and the cyanobacteria from the lake water (Romero et al. 2014). Miettinen et al. (1994) studied the LBF scheme on the bank of the Lake Kallavesi in Hietasalo Island, Finland. They observed removal of total organic carbon (TOC) from 12.1 mg/L in the lake water to 9.7 and 4.4 mg/L in wells located within 100 m and between 100 and 300 m, respectively, from the lake bank. Additionally, Finland also has LBF schemes at lakes Vihnusjärvi and Vesijärvi having TOC removal of >55 and >29 %, respectively (Kivimäki et al. 1998). In the Netherlands, water from the river Maas is pumped to a deep gravel extraction reservoir De Lange Vlieter, from where the water is abstracted through LBF wells (Juhász-Holterman et al. 1998). This process has the capacity to reduce pathogens by at least 3.5 logs in the water. In Lithuania, bank infiltrate from the Kaunas reservoir in the Kaunas City recharges the LBF well field (G. Jonkutė, personal communications, 2010). These schemes, however, are located in alluvial aquifers consisting of sands and gravels of varying geological ages.

An LBF scheme developed in 1990 on the bank of the lake Naini in Nainital town in the state of Uttarakhand, India exists in a landslide debris deposit rather than an alluvial aquifer. Landslide deposit as an aquifer has fundamental differences from alluvial aquifers. Alluvial aquifers have vertical stratification and horizontal long-range homogeneity. Landslide deposits, on the other hand, lack horizontal or vertical homogeneity. There is no geomechanical stratification, and the deposit consists of randomly distributed impermeable zones and permeable channels, whose location and connectivity may change with time (Matti 2008). Permeable zones are preferentially found closer to the sliding surface of the landslide. In addition, particles in the landslide deposits have higher heterogeneity in shapes and sizes than in alluvial aquifers. As a result, movement of water through the deposit is highly unpredictable.

An investigation by Dash et al. (2008) showed that the Nainital LBF scheme rendered water free from coliform. Total Coliform counts up to  $5 \times 10^5$  MPN/100 mL in the lake water were completely eliminated during bank filtration. Nachiappan et al. (2002) analyzed stable isotopes of water in the various water sources in the region in 2000 and assessed average proportion of lake water in the LBF wells. Subsequently, additional tubewells have been

commissioned, and the number of wells has increased from 5 to 7 and then to 12. However, one of the old wells was dismantled, and two wells have not been in regular operation due to functional difficulties. Thus, the scheme presently consists of nine functional tubewells.

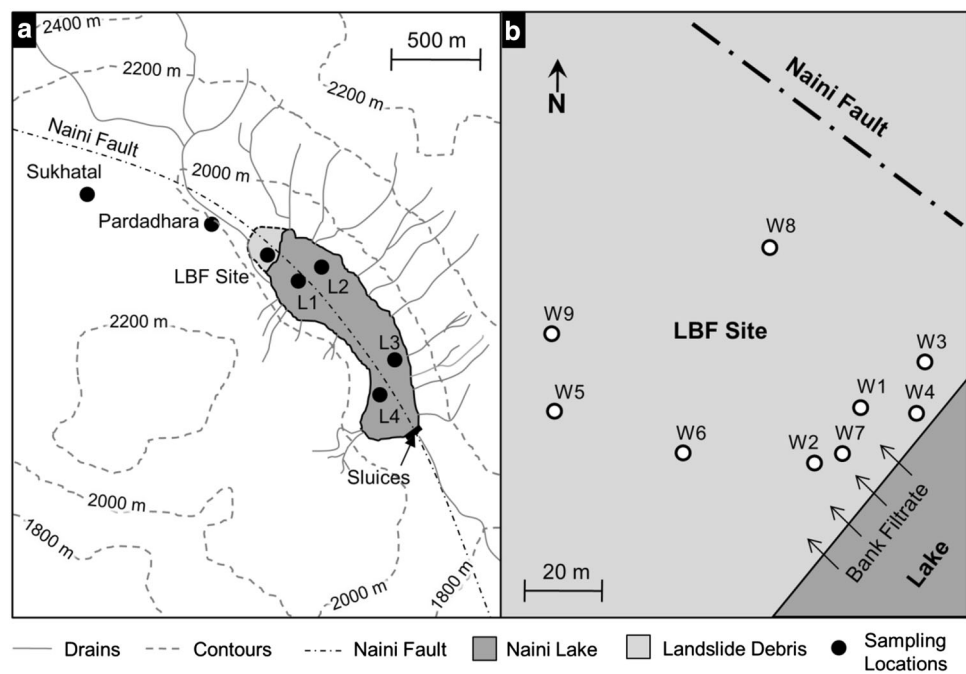
With the extension of the LBF scheme, a necessity of investigating the entire well field was felt. A study was undertaken in 2012–2013 to assess the performance of LBF scheme in terms of the (1) spatio-temporal variations in the quality of the lake water and the well water and (2) the proportions of bank filtrate in the well waters. The evaluation is based on the analysis of the data on water quality and stable isotope ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) values of the waters.

### Site description

Lake Naini (29°23'N, 79°28'E) is located 1936 m above sea level in a geologically unstable region of the Kumaun Himalayas, India. It is surrounded by steep mountain ranges as shown in Fig. 1a. The Naini Fault that runs midway across the lake separates the two ranges. On the southeast end of the lake, the terrain slopes downhill and sluices are installed to control the water level in the lake. Mean retention time of water in the lake is  $\sim 1.16$  years (AHEC 2002). Rainfall in the region mostly occurs during the monsoon season lasting from June to September. In the present study, however, the monsoon period has been defined from June to November to include the effects of post-rainfall sub-surface flows generated by the rains.

The geology of this tectonically active and landslide prone region has been extensively studied by many researchers (Valdiya 1988). The region has a hard rock geology consisting of folded bedrocks. The mountains consist of slates, marls, carbonates, limestones, dolomites, sandstone, and conglomerates (Valdiya 1980). The northwest bank of the lake (Fig. 1a) comprises of substantial debris deposit from several landslides that occurred between 1867 and 1924, before which this area was a part of the lake. An exploratory drilling done near the LBF wells revealed that the deposit consists of irregular collapsed boulders and rock fragments, shale/slate, and sand approximately to a depth of about 36 m followed by a clay layer (Ashraf 1978). Rest of the lake periphery largely consists of bedrocks. There are no alluvial deposits in the region. Groundwater moves largely along numerous faults, fractures and pore spaces in the rocks, often emerging as perennial or seasonal springs. The LBF scheme at Nainital is a unique example of bank filtration in non-alluvial aquifers with fault- and fracture-ridden bedrock geology beneath. Dash et al. (2008) have described the bank filtration site and the local geology in detail.

**Fig. 1** **a** Sampling locations in and around Naini Lake (Based on GoogleMaps 2014 and AHEC 2002). **b** Sketch of the LBF site showing locations of the wells W1–W9. The well numbers are assigned by the water supply organization Uttarakhand Jal Sansthan



Nainital was one of the first towns in India to have a piped water supply system developed in 1898 with water drawn from local springs. In 1955, the use of lake water was started to augment the existing water supply. Over the years, anthropogenic activities in the lake catchment resulted in severe eutrophication of the lake (Pant et al. 1981). Therefore, a treatment plant was established in 1985 for purification of the lake water for water supply. Subsequent to installation of the LBF scheme, direct pumping of the lake water and its purification were discontinued.

With the addition of new wells and decommissioning of the old wells since then, the current LBF well field consists of nine wells, shown in Fig. 1b. Of the nine wells, W1, W2, W3, W4, and W7 are within 15 m of the lake bank, and W5, W6, W8, and W9 are between 40 and 95 m from the lake bank. The wells are located close to the Naini fault. The ground level of the well field is gently sloping with an altitude difference of 1.5 m between the wells W4 and W9. Wells W4 and W5 are the oldest existing wells drilled in years 1999 and 2000, respectively. Wells W6 and W7 were drilled in 2006, and the remaining wells W8, W9, W1, W2, and W3 were drilled during 2008–2009. The wells have a diameter of 30 cm with depths of 26.7 m for W4 and between 33 and 38 m for the other wells. Filter screens are located between 10 and 26 m below ground level in W4 and between 13 and 37 m below ground levels in other wells. Wells abstract water at a rate ranging from 23 to 40 L/s. The abstracted water is stored and chlorinated before supply.

Grain size distribution of the aquifer material obtained during drilling of the well W6 yielded hydraulic conductivities at different depths ranging from 200 to 400 m/day (Dash et al. 2008). Based on hydraulic conductivities, travel time of the bank filtrate to the wells W4 and W5 was estimated to be 1–2 days and 11–19 days, respectively. Similar values of hydraulic conductivities of  $\sim 275$  m/day were obtained for the wells W1 and W3 and  $\sim 430$  m/day for the well W5 using pumping tests with Boulton's analysis (Sandeep 2011).

Among the other water sources, many of the springs in the region have dried over the years. Pardadhara (PD) is one of the perennial springs running for more than 100 years and is located close to the LBF wells. In recent years, it has a very low discharge particularly during the non-monsoon period. Water from this spring is also used for municipal supply when needed and if the discharge is sufficient. Sukhatal, a rainy season lake, is located uphill along the Naini fault, which soon dries after the monsoon season is over. A tubewell has been drilled near Sukhatal to abstract groundwater for local supply, henceforth called Sukhatal Tubewell (ST).

Lake Naini and its catchment have been the focus of environmental studies and conservation efforts. There have been studies on the lake water and sediment geochemistry by Das et al. (1995), Chakrapani et al. (2002), and Purushothaman et al. (2012), and its water balance by AHEC (2002). Since 2007, there have been improvements in sewage and solid waste management in the lake catchment and hypolimnetic aeration has been implemented in the

lake. The aeration system includes 30 aeration disk modules installed at the lake bottom (Kumar 2008). The modules release compressed air mixed with small amounts of ozone at a pressure of  $\sim 310$  kPa. Dissolved oxygen (DO) levels of  $>3\text{--}4$  mg/L are maintained up to the lake bottom by controlling the aeration rate. Gupta and Gupta (2012a, b) have studied the water quality and ecosystem changes in the lake during introduction of the aeration system.

## Materials and methods

### Sample collection

Sampling campaigns to collect both lake and well water samples were organized almost monthly from April, 2012 to November, 2013. Lake water samples from four locations, L1–L4, as shown in Fig. 1a were collected from  $\sim 0.5$  m below the lake surface. Water samples were also collected from the nine tubewells W1–W9, as shown in Fig. 1b, while the pumps were in operation. PD and ST water samples were collected from Jan 2013 to Nov 2013 and from Feb 2013 to Nov 2013, respectively. A portable multi-parameter probe (HQ40d, Hach, Loveland, USA) was used for on-site measurements of electrical conductivity (EC), pH, temperature and dissolved oxygen (DO). Samples for off-site analysis at IIT Roorkee for the other parameters were collected, preserved, and transported as per the Standard Methods (APHA et al. 2005). Polypropylene bottles of 15 mL capacity were used to collect and transport the analysis of stable isotopes. It was ensured that no air was entrapped in the head space of the bottles.

### Sample analysis

Water quality analysis at IIT Roorkee was carried out as per the methods prescribed in Standard Methods (APHA et al. 2005). The water samples were first filtered through  $0.22\ \mu\text{m}$  size filter (Millipore, GVWP) for the estimation of dissolved ions and organics. Cations and anions were analyzed using an ion chromatograph (Metrohm, AG-861) while titrimetric method was used for the determination of alkalinity. TOC- $V_{\text{CSN}}$  Total Organic Carbon Analyzer (Shimadzu) and DR5000 spectrophotometer (HACH) were used for the determination of DOC (dissolved organic carbon) and UV-A (UV absorbance at 254 nm), respectively. Total and fecal coliform counts were analyzed using the multiple-tube fermentation technique.

Stable isotope analysis was carried out using GV Iso-prime Dual Inlet Isotope Ratio Mass Spectrometer at National Institute of Hydrology, Roorkee (India). Samples ( $400\ \mu\text{L}$ ) were equilibrated for 7 h with  $\text{CO}_2$  for  $\delta^{18}\text{O}$

analysis and with  $\text{H}_2$  reference gas and Pt catalyst for  $\delta^2\text{H}$  analysis. The precisions were  $\pm 0.1\ \text{‰}$  and  $\pm 1\ \text{‰}$  for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ , respectively. The delta ( $\delta$ ) values reported are with respect to Vienna Standard Mean Ocean Water (VSMOW).

## Results and discussion

Water withdrawn from a well at a lake bank is either filtered lake water or groundwater or mixture of lake water and groundwater. The first task was to ensure the connectivity of the wells with the lake through sub-surface flow and to know the proportions of bank filtrate in the water samples of different wells in different seasons. An assessment of the proportions of bank filtrate in the well waters has been done by analyzing (1) EC, (2) stable isotopes, and (3) ionic compositions of the lake water, well waters, and the ground water sources. The attenuation of the contaminants has been assessed in terms of changes in total and fecal coliform counts, DOC, turbidity, and UV absorbance of the water samples.

### EC and stable isotopes data

An insignificant variation in the water quality and stable isotope characteristics of the lake water samples collected from four locations (L1–L4 as marked in Fig. 1a), was observed. The lake water is vertically mixed due to hypolimnetic aeration. Keeping these observations in view, subsequent sampling of the lake water was done at location L1 only. The  $\delta^{18}\text{O}$  values for the lake water were higher than the water samples from PD and ST by  $\sim 1\ \text{‰}$  (Table 1). The EC values of the lake water were lower than those of the other water samples.

Drying of springs over years, and lack of hand pumps or wells in the area limited the possible groundwater sampling locations. The ground water generally does not exhibit much temporal variation whereas surface and sub-surface water quality reveals the seasonal changes. Therefore, groundwater has been fixed on the basis of the seasonal variability in EC, isotopic signatures and ionic concentrations.

The  $\delta^{18}\text{O}$  of water from all the wells is in between the  $\delta^{18}\text{O}$  values of the lake water and the PD and ST samples (Table 1). These values suggest the mixing of the bank filtrate with the PD and/or ST water in the RBF wells. The average EC values of the waters from the nine wells ranging from 622 to 847  $\mu\text{S}/\text{cm}$  (Table 1) are higher than that of the lake water. However, the EC of the water from the wells W5, W6, W8, and W9 is consistently 100–150  $\mu\text{S}/\text{cm}$  higher than the PD and ST samples. Therefore, on the basis of the EC values, mixing of lake

**Table 1** EC and  $\delta^{18}\text{O}$  values of the water samples

	Lake	W4	W2	W1	W7	W3	W5	W6	W8	W9	PD	ST
Monsoon												
<i>N</i>	18	7	8	6	5	8	4	8	3	8	3	3
$\delta^{18}\text{O}$ (‰)												
Average	−8.6	−8.8	−8.9	−9.2	−9.4	−9.3	−9.5	−9.3	−9.4	−9.5	−9.6	−9.6
SD	0.3	0.3	0.3	0.3	0.1	0.3	0.3	0.2	0.5	0.1	0.1	0.8
EC ( $\mu\text{S}/\text{cm}$ )												
Average	591	644	664	712	734	732	800	814	870	847	717	693
SD	29	17	21	56	72	75	29	66	31	31	15	16
Non-monsoon												
<i>N</i>	13	7	6	6	7	5	6	6	4	6	3	–
$\delta^{18}\text{O}$ (‰)												
Average	−8.5	−8.9	−8.7	−8.7	−8.7	−9.1	−8.9	−8.8	−9.2	−9.3	−9.5	–
SD	0.4	0.6	0.4	0.6	0.4	0.4	0.4	0.8	0.6	0.4	0.3	–
EC ( $\mu\text{S}/\text{cm}$ )												
Average	599	622	625	682	650	670	790	767	789	840	732	–
SD	43	21	42	48	36	24	88	64	53	40	43	–

*N* number of samples, *SD* standard deviation

water with PD or ST water in W5, W6, W8, and W9 is ruled out. Among these, the EC of water from the W9 remained nearly unchanged from monsoon to non-monsoon periods, thus displaying characteristics of groundwater.

The plot of  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  values further showed the seasonal and spatial differences in the various well waters (Fig. 2). The isotopic values of the waters were close to the local meteoric water line, determined based on the rainfall isotopic data from Kumar et al. (2010), and the global meteoric water line (Rozanski et al. 1993). During non-monsoon months, the lake and well waters showed a characteristic enrichment of  $^{18}\text{O}$  without a significant change in  $^2\text{H}$  concentration. Evaporation enrichment of surface water leads to variation of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values along local evaporation lines with slopes typically between 4.0 and 6.0 (Gibson et al. 2008). Isotopic enrichment of  $^{18}\text{O}$  without change in  $\delta^2\text{H}$  can occur due to oxygen exchange with carbonate or silicate minerals, particularly in deep groundwater and at higher temperatures (Gat 2010). The observed variation in  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  values for non-monsoon samples (along lines with slopes <4.0) indicates a combined effect of evaporative enrichment of lake water and deeper sub-surface  $^{18}\text{O}$  isotopic enrichment in groundwater, likely from carbonate minerals present in the Nainital geology.

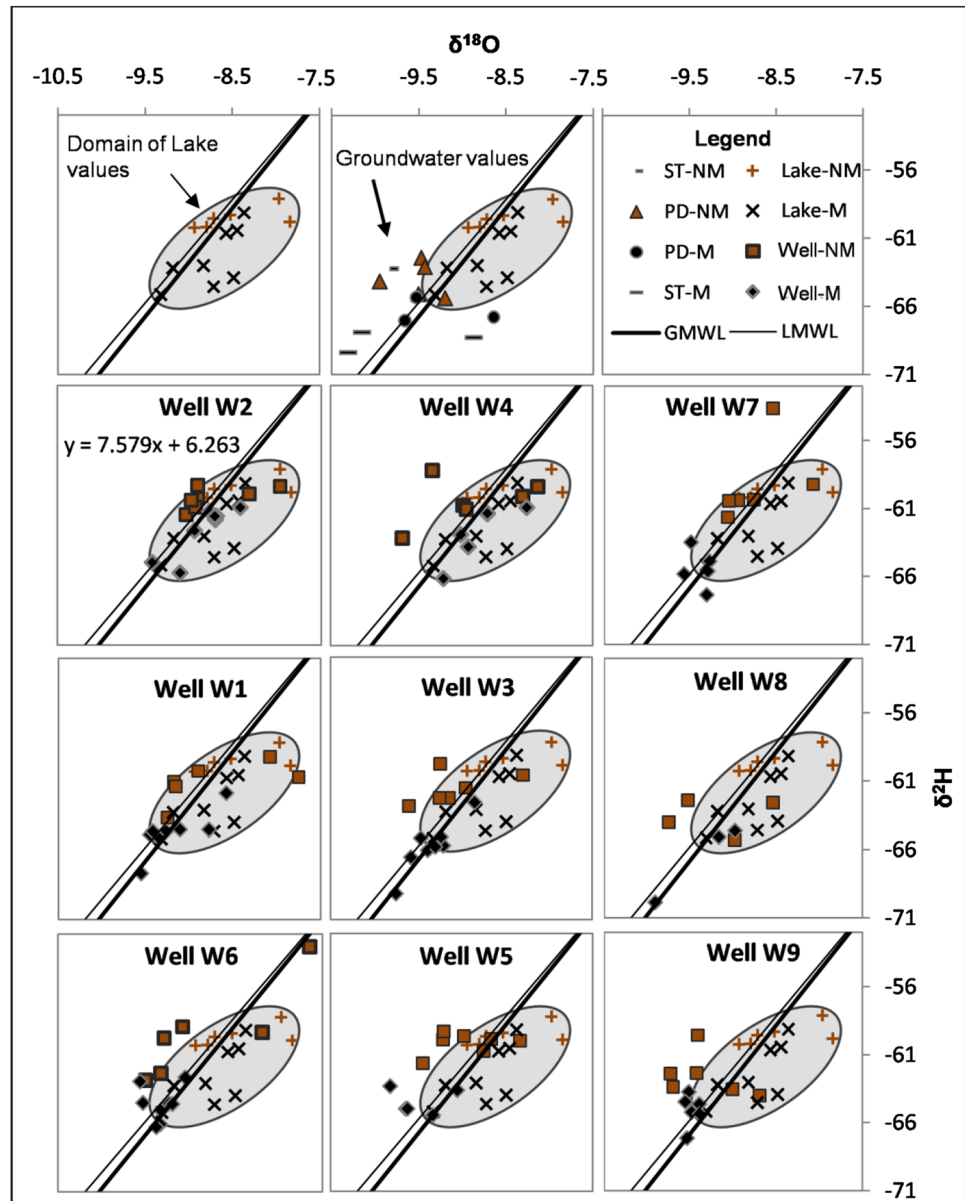
The monsoon and non-monsoon values of W9 water are different from the corresponding values of lake water. The isotopic pattern of the waters from W5 and W6 is similar to W9. However, W1, W3, W7, W8 and ST waters have analogous isotopic signatures but are lighter than the lake

water in terms of both  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ . Their isotopic values are scattered equally on the two sides of the meteoric line. On the other hand, water samples of W6, W5, and W9 were isotopically lighter than the lake mostly in terms of  $\delta^{18}\text{O}$  only and their data points are mostly left of the meteoric line. This dissimilarity in patterns suggests that more than one stream of groundwater contribute to the well field and their contributions are different in each well. These streams might have a common origin—most likely recharge from the precipitation—but have undergone different hydro-geological trajectories before reaching the bank aquifer. The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of W2 and W4 are similar to the lake water in both monsoon and non-monsoon periods, suggesting these two wells to be predominantly drawing the bank filtrate.

### Inorganic ions in the waters

EC of water samples is presented in Table 1. Concentrations of major ions  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$ , and  $\text{HCO}_3^-$  contributing to EC are shown in Fig. 3. The amounts of ions  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Cl}^-$ , and  $\text{NO}_3^-$  are low, adding little to EC. The  $\text{K}^+$  concentrations ranged from 3 to 9 mg/L in the water from the lake and wells. Concentrations of  $\text{Na}^+$  were in the range 7–14 and 9–29 mg/L in the lake and well waters, respectively. The  $\text{Cl}^-$  concentration of the lake and well waters, however, fluctuated in the range 6–9 and 7–21 mg/L, respectively. The  $\text{NO}_3^-$  concentration in the lake and the wells ranged from 2 to 16 mg/L and <1 to 35 mg/L, respectively. In the PD and ST samples,  $\text{NO}_3^-$  concentrations ranged from 9 to 14 mg/L.

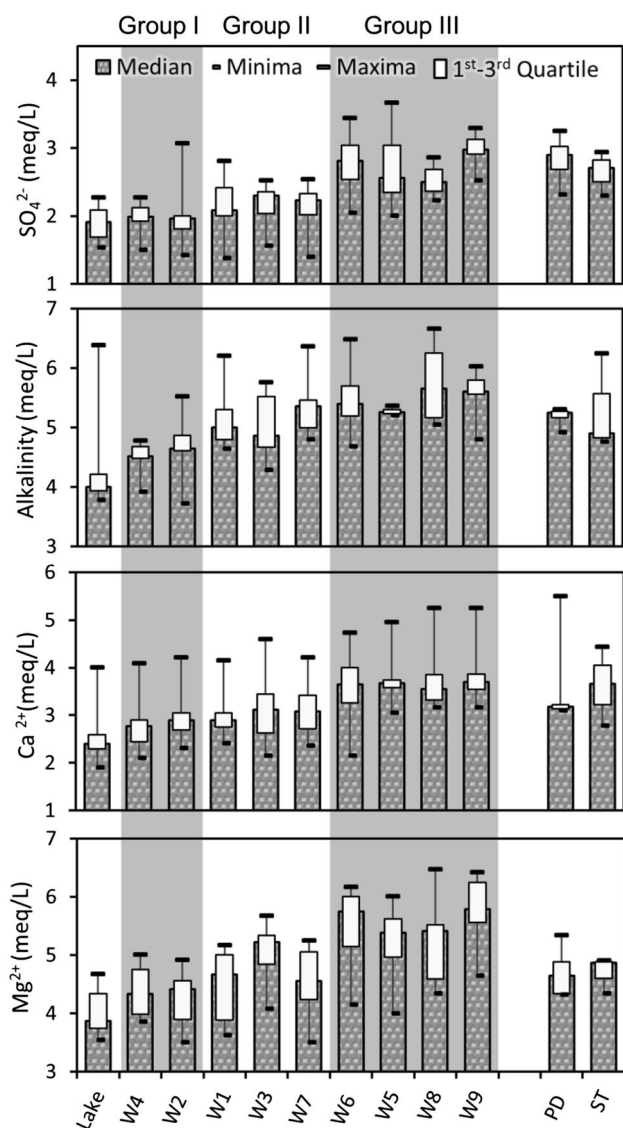
**Fig. 2**  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  plots of water sources in Nainital. The first plot shows the domain of values in monsoon (M) and non-monsoon (NM) seasons. Other plots show values of other sources with respect to the lake water. The equation of LMWL is shown with the well W2 data



Perusal of data in Fig. 3 indicates that ionic concentrations of the well waters are more than in the lake water. The average ionic concentrations of the water from the wells W5, W6, W8, and W9 are also more than in the waters from PD and ST. This observation could be due to the mineralization of water during sub-surface flow of the water or mixing of groundwater other than the water from PD and ST. Moreover, based on ionic concentrations as seen in Fig. 3, the well waters could be categorized into three groups. Waters from Group I wells W2 and W4 have  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  concentrations almost similar, and  $\text{Mg}^{2+}$  and alkalinity ( $\text{HCO}_3^-$ ) slightly higher, than the lake water values. Waters from Group II wells W1, W3, and W7 have  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and alkalinity more than the lake water during

the summer and monsoon months but comparable to that of lake water during other times. Water from Group III wells W5, W6, W8, and W9 has much higher ionic concentrations than the lake water, as well as PD and ST—similar to the trends in the EC values (Table 1).

The average Langelier Saturation Index (LSI) of lake water was estimated to be 0.65 with range  $-0.2$  to  $1.6$ , and that of the wells was  $0.35$  with range  $-0.1$  to  $0.8$ . The average LSI values of PD and ST were  $0.14$ , and  $0.49$ , respectively. These values indicate that the lake, the wells, as well as the ground waters are largely saturated or supersaturated, and there is no significant  $\text{CaCO}_3$  mineralization in the well field aquifer. These data also supported that the groundwater reaching wells W5, W6, W8 and W9



**Fig. 3** Concentration of major ions in various water samples

has a component different from the ground waters at PD and ST, because PD and ST waters mixing with the lake water alone could not yield the increased ionic concentrations in the waters from these wells.

It was observed that, in general,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations in the lake and the bank filtrate decreased during summer and monsoon but remained nearly constant in the groundwater. Such temporal variation was not noticed in the concentrations of the other ions. Indian drinking water standard IS:10500 (2012) has specified desirable limits of 75 mg/L for  $\text{Ca}^{2+}$  and 30 mg/L for  $\text{Mg}^{2+}$ . In addition, the standard has also specified the maximum permissible limits of 200 mg/L and 100 mg/L for  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , respectively, in the absence of an alternate source. The concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions

often exceeded the prescribed desirable values. However, the concentrations were less than the permissible limits.

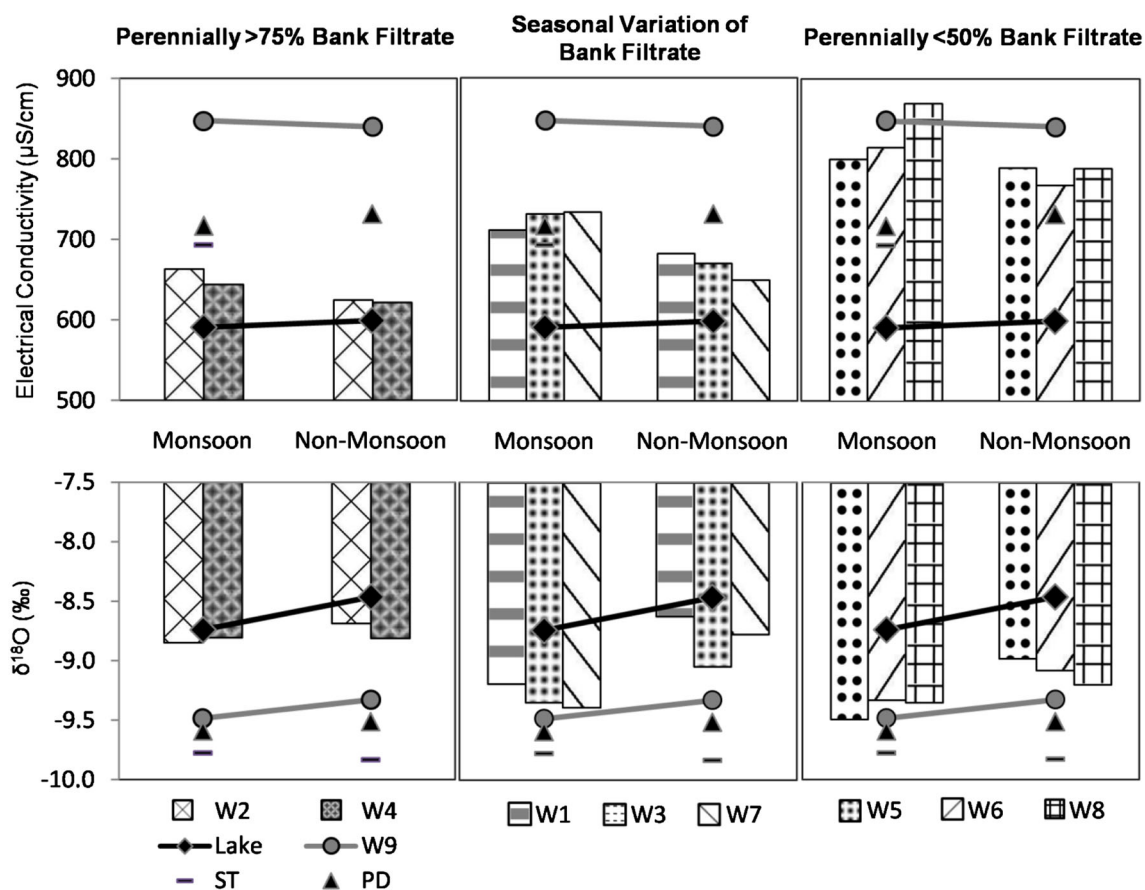
The observed ionic composition of the waters is consistent with the findings of Nachiappan and Kumar (1999) and Chakrapani et al. (2002), who ascribe the presence of limestone, dolomite, and other carbonates as source for  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{HCO}_3^-$  ions; silicate minerals as source for  $\text{Na}^+$  and  $\text{K}^+$  ions; and oxidation of sulfides in pyritiferous shale and dissolution of gypsum deposits as source for  $\text{SO}_4^{2-}$  ions. Lack of any spatial pattern in the  $\text{NO}_3^-$  concentrations suggested that these were caused by localized contamination from anthropogenic activities. The molar ratio of  $\text{Ca}^{2+}$  to  $\text{Mg}^{2+}$  in the water samples from all the sources was found to be around 0.75. This ratio is indicative of leaching from predominantly  $\text{Mg}^{2+}$ -containing minerals such as dolomite. During May 2013, most water quality parameters showed an abrupt change in values. The  $\text{Ca}^{2+}/\text{Mg}^{2+}$  molar ratio in all water sources suddenly increased to about 1.3. The parameters reached their steady-state values within next 2 months. It is not possible to ascribe the cause of this abrupt change based on the present data.

#### Proportion of bank filtrate in the wells

Perusal of data presented in Table 1, Figs. 2 and 3, and subsequent discussion indicate the following:

1. The EC of the lake water is less than that of the well waters.
2. The EC of the well waters varies from well to well. Also, the EC of the waters from the wells during monsoon has been found to be more than that in the non-monsoon.
3. Waters from W5, W6, and W8 exhibit seasonal variation and are chemically similar.
4. The EC of the water from the well W9 does not vary from monsoon to non-monsoon. Isotopic signature of W9 water is consistently different than the lake water.
5. Waters from W2 and W4 are isotopically and chemically similar to the lake water.
6. The  $\delta^{18}\text{O}$  values of waters from W1, W3, W5, W6, and W7 in monsoon is less than in non-monsoon.

Based on these observations, isotopic characteristics of W9, PD, and ST water samples have been considered as representative of the ground water streams contributing to the well field. Although, possibility of other groundwater streams contributing to the wells cannot be ruled out. Based on these assumptions, a comparison of the monsoon to non-monsoon variation in average isotopic and EC values of the three groups of wells (categorized on the basis of the ionic concentrations) with respect to lake and groundwater samples is presented in Fig. 4.



**Fig. 4** Average EC and  $\delta^{18}\text{O}$  values for the monsoon and non-monsoon months of the water from the lake, wells, PD and ST

The first group of wells, W2 and W4 with water isotopically and chemically similar to the lake almost throughout the year continuously draw bank filtrate. The second group of wells, W1, W3, and W7 draw large proportions of bank filtrate during the non-monsoon period and largely groundwater during the monsoon period. These results are unusual particularly because the wells W1, W2, and W3 are located at similar distances from the lake bank, have similar depths and filter screen locations (variation  $\sim 1$  m), and yet abstract such different proportions of bank filtrate. The third group of wells W5, W6, and W8 (along with W9) with isotopic and chemical characteristics largely similar to the groundwater abstracts predominantly groundwater throughout the year. These results suggest the presence of a highly localized and channeled groundwater flow close to these wells as postulated in Fig. 5.

Based on the average  $\delta^{18}\text{O}$  values, annual average bank filtrate proportions were estimated for the wells. The wells W2 and W4 abstracted  $\sim 80$  % lake water, W1 and W7 abstracted 40–75 % bank filtrate annually. Interestingly, while variation of bank filtrate proportions in W3 was similar to W1 and W7, annual average proportion of bank filtrate in this well was  $\sim 30$  % only. The wells W5, W6,

and W8 abstracted  $<35$  % bank filtrate. These proportions are shown with pie diagrams in Fig. 5.

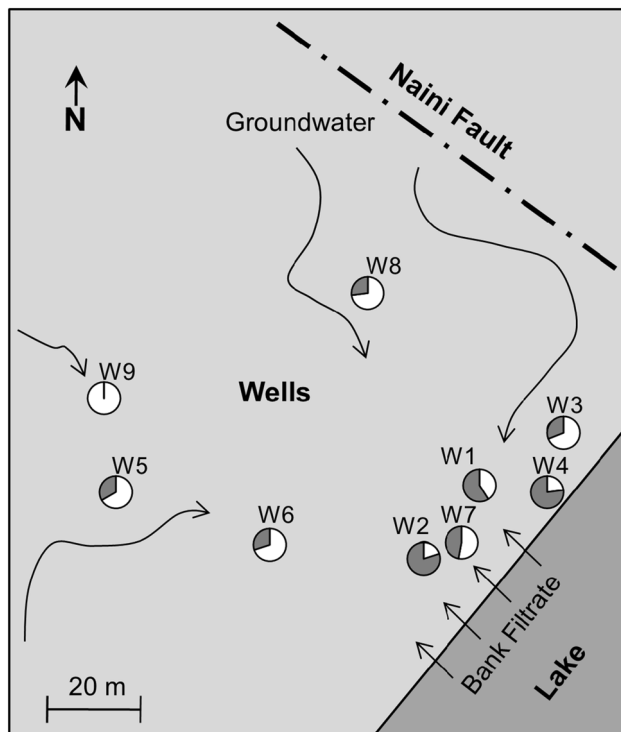
Nachiappan et al. (2002), however, estimated higher proportion of bank filtrate (80 %) in the wells during monsoon and a lower percentage (20 %) during non-monsoon. This difference in results could be pointing to actual changes in the local hydrology in the lake bank aquifers over the years, as reflected in the differences in the isotopic values of the waters in the two studies. Their groundwater sample was average from the springs in the whole region. Most of these springs have dried by now, and the present analysis includes only three representative groundwater streams contributing to the well field.

Wells W2 and W4 should be pumped more to obtain water with lower  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations. Wells W5, W6, W8, and W9 should be pumped only in cases of higher demand of water.

#### Attenuation of coliforms, turbidity, and dissolved organics

Since the introduction of hypolimnetic aeration, coliforms, turbidity, and organics have significantly decreased in the



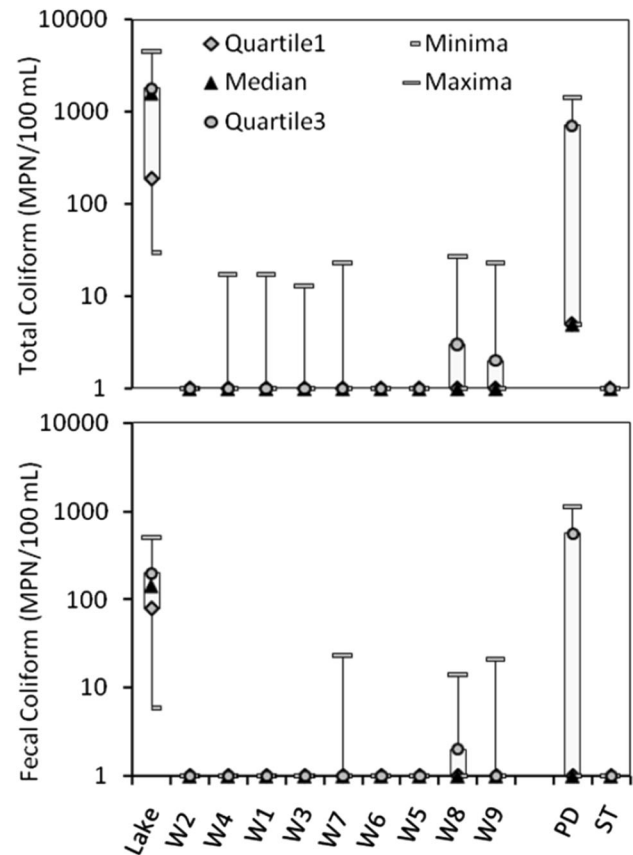


**Fig. 5** Relative proportions of bank filtrate and groundwater in the wells with gray sectors in the pie diagrams representing the bank filtrate. Curved lines depict postulated groundwater flow

lake water. The coliform counts in the lake have decreased by two orders of magnitude to low levels of  $\sim 2000$  MPN/100 mL. A decrease in the coliform counts of the lake is also likely to be due to disinfection by ozone used in the aerators. During the study period, DO of the lake surface water ranged from 4.5 mg/L in July to 9.0 mg/L in January. The turbidity of the lake ranged between 1.7 and 5.5 NTU. The mean UV-A of the lake was  $0.035 \text{ cm}^{-1}$  with a mean DOC of 3.1 mg/L—much lower than the DOC of most lakes in the world (Sobek et al. 2007).

Total coliform counts of  $<2$  MPN/100 mL were observed in most of the well waters except for contamination of  $\sim 10$ – $30$  MPN/100 mL in a few wells in the summer months (Fig. 6). The PD samples invariably responded positively to the total coliform test possibly due to local contamination from anthropogenic activities. The wells did not have any significant fecal contamination, except once or twice in W7, W8, and W9. Such occasional contamination is addressed by chlorination of the abstracted water before supply.

Turbidity and organics were consistently lower in the wells than the lake throughout the year. As shown in Fig. 7a, turbidity in well waters never exceeded 5 NTU and mostly remained around 0.2 NTU. The average DOC and UV-A values of the well waters were  $\sim 1$  mg/L and less than  $0.03 \text{ cm}^{-1}$ , respectively (Fig. 7b, c). The organics



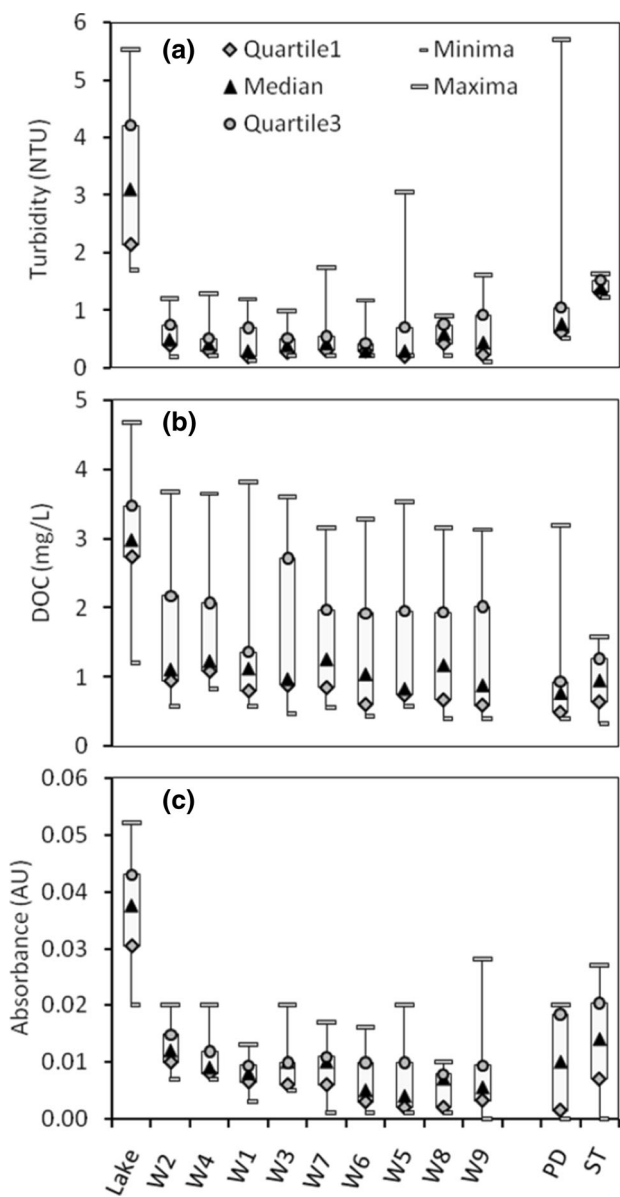
**Fig. 6** Variation of total and fecal coliforms in various sources

present in the lake water are reduced by 19–76 % during filtration through the aquifer material. This percentage is comparable to organics removal in other LBF systems in the world (Miettinen et al. 1994; Kivimäki et al. 1998). The SUVA values of the well waters ranged from 0.1 to  $2.3 \text{ L mg}^{-1} \text{ m}^{-1}$ , while that of the lake water ranging from 0.7 to  $2.3 \text{ L mg}^{-1} \text{ m}^{-1}$ , suggesting a slight decrease in aromatic compounds in the wells compared to the lake (Weishaar et al. 2003).

The study demonstrates that it is possible to obtain high-quality bank filtrate at very short distances and short travel times from a lake bank throughout the year.

### Sustainability of pumping at the Nainital LBF site

The water balance study was undertaken by the AHCC (2002) in 2001. It was reported that of the lake outflow, 26 % was pumped by the LBF wells (at that time), 56 % was flow through sluices, 8 % was lost through evaporation, and 10 % was through downhill springs. Pumping by LBF wells can be increased to a maximum of 82 % of the lake outflow, when the outflow through sluices would decrease substantially. Beyond this limit, water abstraction would reduce the water quantity in the lake and the



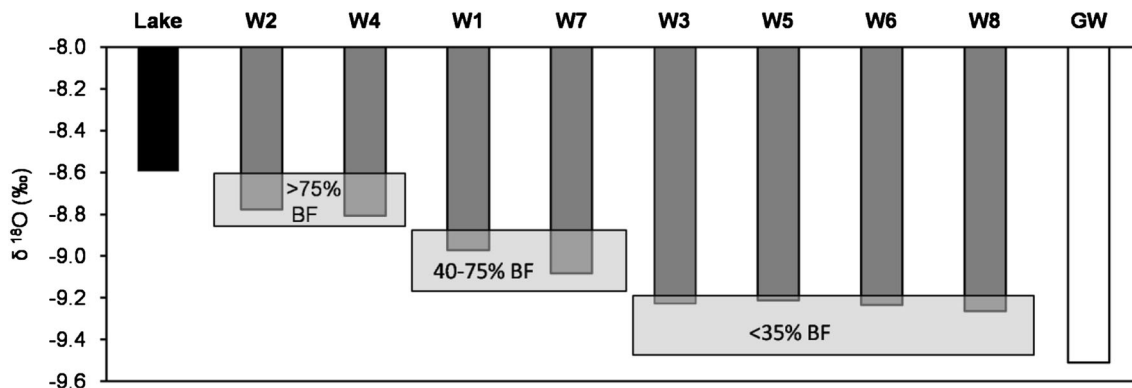
**Fig. 7** a Turbidity, b DOC, and c UV absorbance at 254 nm of the lake, well, and groundwater samples

groundwater level in the region. Therefore, based on volumetric balance calculations, with a lake volume of  $5.91 \times 10^6 \text{ m}^3$  and a mean retention time of 1.16 years, pumping through LBF wells can remain sustainable up to an abstraction rate of  $\sim 13.9 \times 10^3 \text{ m}^3/\text{day}$ . Current water abstraction by the wells varies between  $12 \times 10^3$  and  $16 \times 10^3 \text{ m}^3/\text{day}$  (depending on seasons) of which  $\sim 40$  to  $50 \%$  is bank filtrate on an average. Therefore, current operation of the LBF wells is sustainable, but in future, the quantity of bank filtrate abstraction can only be increased by up to a factor of 2.

**Conclusions**

Present study shows that the proportions of bank filtrate in the LBF wells at Naini lake bank **do not strictly decrease with the distance from the lake**. In addition, there are different seasonal variations in different wells. Two wells located within 15 m of the lake bank abstract  $\sim 80 \%$  bank filtrate almost throughout the year. However, three other wells located between 10 and 15 m of the lake bank and close to the first two wells abstract 50–80 % bank filtrate during the non-monsoon period but mostly groundwater during monsoon. Four wells located between 40 and 100 m of the lake bank abstract  $<35 \%$  bank filtrate almost throughout the year. Average proportions of the bank filtrate in the wells are shown in Fig. 8. Possible reasons for such unusual hydrology are the heterogeneity in the landslide debris aquifer and the presence of Naini fault and other fractures very close to the well field. This study has shown that combined use of stable isotope and water quality data can help in understanding of complex hydrological systems.

This study also shows that a landslide deposit is effective at removing coliforms, turbidity, and organics from surface water. The LBF scheme in Nainital abstracts mostly drinking quality water at short infiltration distances



**Fig. 8** Average  $\delta^{18}\text{O}$  values of the lake, the wells, and the groundwater samples (including PD, ST, and W9) and annual average proportions of bank filtrate in the wells

of <5 m and travel times of ~2 to 3 days. A few events of coliform contamination in some of the wells are observed for brief periods, possibly caused by local contamination from infiltrating surface water, which are addressed by chlorination. The LBF pumping in Nainital is sustainable with respect to water balance of the lake.

The waters in the region have  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ , and  $\text{SO}_4^{2-}$  as the predominant ions.  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations are slightly higher than the desirable limits but lower than the maximum permissible limits for drinking water. Wells W2 and W4 drawing the maximum bank filtrate should be pumped more to obtain water with lower  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  than the groundwater. Abstraction from other wells can be regulated according to the seasonal changes to get a maximum amount of bank filtrate with a lower amount of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ .

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