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Riverbank filtration: a case study of four sites in the hilly regions of Uttarakhand, India

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Abstract

Riverbank filtration (RBF) schemes based on the filtration of the river water through adjacent aquifers have been successfully implemented in the plains globally. In the mountainous regions, alluvial aquifers are generally narrow and restricted to the riverbanks. The present study assesses the possibility and potential of RBF in the lower Himalayan region for drinking water supply. Production wells (18–30 m deep) were commissioned on the banks of the rivers (1) Alaknanda in Srinagar (546 m a.m.s.l.) and Kaleshwar (Karnaprayag; 778 m a.m.s.l.); (2) East Nayar in Satpuli (576 m a.m.s.l.) and (3) Mandakini in Agastyamuni (783 m a.m.s.l.) in Uttarakhand, India. Waters from the rivers, production wells, and hand pumps were analyzed for major ions, coliforms and stable isotopes ($\delta^{18}O$ and δ^2H). The wells delivered coliform- and turbidity-free water even during monsoon. The proportion of the bank filtrate was site specific and also varied from monsoon to non-monsoon periods. The Satpuli scheme draws almost completely bank filtrate round the year. The other three schemes substantially draw groundwater and its proportion increases in monsoon. In Srinagar, the well water was chemically similar to the ground water but isotopically similar to the river water. The region also has a complex hydrology with paths that deliver river water containing coliforms and even suspended silt up to ~0.5 km inland. A severe flooding event during the study period affected the RBF sites in Srinagar and Kaleshwar, thereby indicating the need to make RBF wells flood proof. In general, the study shows RBF to be an effective and sustainable option to supply drinking water in a few regions of lower Himalayas.

Keywords Riverbank filtration · Himalayas · Stable isotopes · Water quality · Groundwater

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Introduction

Lakes and rivers are common sources of water for municipal supply. The surface water from these sources is abstracted, treated and supplied. Another approach is to abstract it after it has infiltrated through the riverbank aquifer. The process, known as riverbank filtration (RBF), attenuates coliform, turbidity, viruses, and trace contaminants present in the surface water (Ray et al. 2003; Sprenger et al. 2014). In many cases, RBF delivers filtrate that is used for drinking purpose even without further treatment and disinfection. As a result, the degree and cost of further treatment of water is reduced.

RBF wells have been used successfully for the municipal water supply in many parts of the world such as Austria, India, Germany, The Netherlands, Hungary, Slovak Republic, The United States, Serbia, etc. Ray et al. (2002, 2008, 2011) have given a worldwide perspective of the riverbank filtration and Sprenger et al. (2017) a European perspective of managed aquifer recharge including RBF. RBF accounts

for 45–50% of potable supplies in the Slovak Republic and Hungary, 16% in Germany and 5% in The Netherlands (Kuehn and Mueller 2002; Grischek et al. 2002). Eckert and Irmscher (2006) gave an overview of 130 years of experience with riverbank filtration in Dusseldorf, Germany. Lee and Lee (2009) analyzed the suitability of a site for RBF in the Han River in Korea. Potential of the riverbank filtration in India has been reviewed by Sandhu et al. (2011). Lorenzen et al. (2010) investigated the RBF potential on the bank of the river Yamuna in the water-stressed megacity Delhi, India. The occurrence of organic micropollutants in the river Yamuna and the Ranney wells at its banks in Delhi in the monsoon and non-monsoon seasons has been reported by Kumari (2015). RBF is in use in other Indian cities like Haridwar (Dash et al. 2010; Saini et al. 2013) and Mathura (Kumar et al. 2012; Singh et al. 2010) for more than 30 years.

Long-term sustainability of RBF systems depend on the hydraulic connections between the surface water and the bank aquifers, especially river and lake bed clogging. This conductance varies as a function of time and topography (Caldwell 2006; Hubbs 2006). In the course of time, clogging is one of the factors that can alter the well specific capacity. The formation of gas bubbles, microbial growth, and exo-polymer production are amongst the mechanisms that can change the hydraulic conductivity of the active layer at the river/bank interface (Heeger 1987; Grischek et al. 1994; Grischek and Bartak 2016; Ray et al. 2002; Schubert 2002).

The success stories of RBF are mostly confined to the middle and lower courses of the rivers in the plains (Ray et al. 2002; Grischek and Ray 2009; Cady et al. 2013). The upper reaches of rivers are normally not considered feasible locations for RBF wells because the aquifers at these locations tend to be too small to support the systems (Caldwell 2006). Nainital in Uttarakhand, India, at an altitude of around 2000 m has water supply scheme based on lake bank filtration (Dash et al. 2008; Gupta et al. 2015b). There are several vertical wells in the land slide debris on the bank of the Nainital Lake.

The Himalayas in Uttarakhand, India, are endowed with several perennial rivers fed by precipitation and melting glaciers. A study on the neighboring and geologically similar central Himalayan zone of Nepal has shown that groundwater contributes up to two-third to the discharge of the rivers in the region, particularly during the post-monsoon period (Andermann et al. 2012). The Himalayan rivers are characterized by relatively good water quality as compared to the rivers in the plains. However, the river water is not potable due to its bacterial content and turbidity, particularly during the monsoon season (Semwal and Akolkar 2006). In uphill areas of these regions, it is often difficult to tap groundwater due to scarcity of suitable aquifers or tapping zones (Gupta 2014).

Some of the groundwater-based sources dry-up during the summer months. The surface water-based conventional treatment plants using flocculation, sand filtration and disinfection are faced with practical difficulties in the hilly region (Kimothi et al. 2012). Frequent landslides and floods in the region often disrupt water abstraction and supply systems. The RBF schemes—known to be highly effective in removing turbidity and pathogens in the plains—have the potential to give drinking quality water in these regions.

The hydrogeology of the riverbanks in the Himalayan region is not the most suitable for RBF schemes. Lithology often changes over short distances (~ 10–50 m) with outcrops of bedrocks even in the middle of riverbeds. The geology of the region is marked with faults, fractures and folds, leading to complex groundwater flow patterns. River discharges increase by 10–20 times in monsoon than in the non-monsoon period, often leading to flooding and damage to bank structures. The rivers have high flow velocities and there is large-scale erosion and deposition of alluvium with seasonal cycles (Chakrapani and Saini 2009). The riverbanks consist of medium sand to large boulders (0.4 mm–10 m diameter) as opposed to fine sand to coarse gravel (0.05 mm–0.1 m diameter) in the plains. The coarser material may not support the formation of a continuous clogging layer at the river/aquifer interface and high seasonal erosion of riverbed disrupts the clogging layers, which serve as the first prime barrier for contaminants (Hubbs 2006). With high seasonal erosion in monsoon periods, coliform breakthroughs have been reported in other RBF schemes in plains (Saini et al. 2013). In spite of challenges, there is a need to explore the potential of RBF in the Himalayan region.

To assess the potential of RBF in Himalayan region, production wells were installed in 2010–2011 in alluvial aquifers available at four sites in Uttarakhand: Satpuli, Srinagar, Agastyamuni, and Kaleshwar. The performance of these schemes was evaluated in terms of two criteria: the proportions of bank filtrate in the water drawn by the wells and the quality of the abstracted water. This study covered the installation of the wells and monitoring period of about one year for the four sites after their commissioning to understand the seasonal changes in the performance of the schemes. In June 2013, a severe flood in the Alaknanda River deposited about 1.5–3 m sediment layer at the RBF site in Srinagar and disrupted the functioning of the scheme for a few months (Sandhu et al. 2017). This study also presents the effect of flooding on the water quality of the scheme after it was restored.

Site descriptions

Figure 1a shows the location of the four sites in India with reference to the related river systems. The terrain of the four sites, shown in Fig. 1b–e, represent a wide range

of altitude gradients, curvatures of river bends and areal extent of alluvial terraces at the river banks. Details of the location and geology of the sites are specified in Table 1. Each RBF scheme comprised one production well (PW) with a borehole diameter of 200 mm. Figure 2 shows the general schematic of the PWs at these sites and the parameters for each well. In addition, a monitoring well was constructed within 6–10 m of each production well. The distances of the production wells from the rivers at these sites were 50–165 m in non-monsoon which reduced up to 7 m in the monsoon. There are no large-scale industries or large agricultural fields in these regions. The areas are thinly populated. Therefore, anthropogenic influences are negligible and the performance of the RBF site is largely determined by the local hydrogeology.

Satpuli

Satpuli is a small town located at the left bank of the River East Nayar just before it joins the River West Nayar to form the River Nayar, which is a tributary of the River Ganga. The rivers are surrounded by high steep terrain on both sides. The RBF scheme is located where the river takes a sharp U-turn, as seen in Fig. 1b. The alluvial aquifer is a narrow stretch (~ 500 m) but sufficiently deep (> 36 m). The right bank opposite to the town has a hard rock lithology, as is the case with most sharp turns of rivers in the Himalayas. Before the installation of the RBF scheme, the water supply of the town was based on direct surface water abstraction in addition to the ground water abstraction through hand pumps and springs. Now, the RBF scheme has become the predominant source for the town's water supply.

Fig. 1 **a** Location of the four sites in Uttarakhand, India, and terrain maps of **b** Satpuli, **c** Srinagar, **d** Agastyamuni, and **e** Kaleshwar sites (based on GoogleMaps 2014)
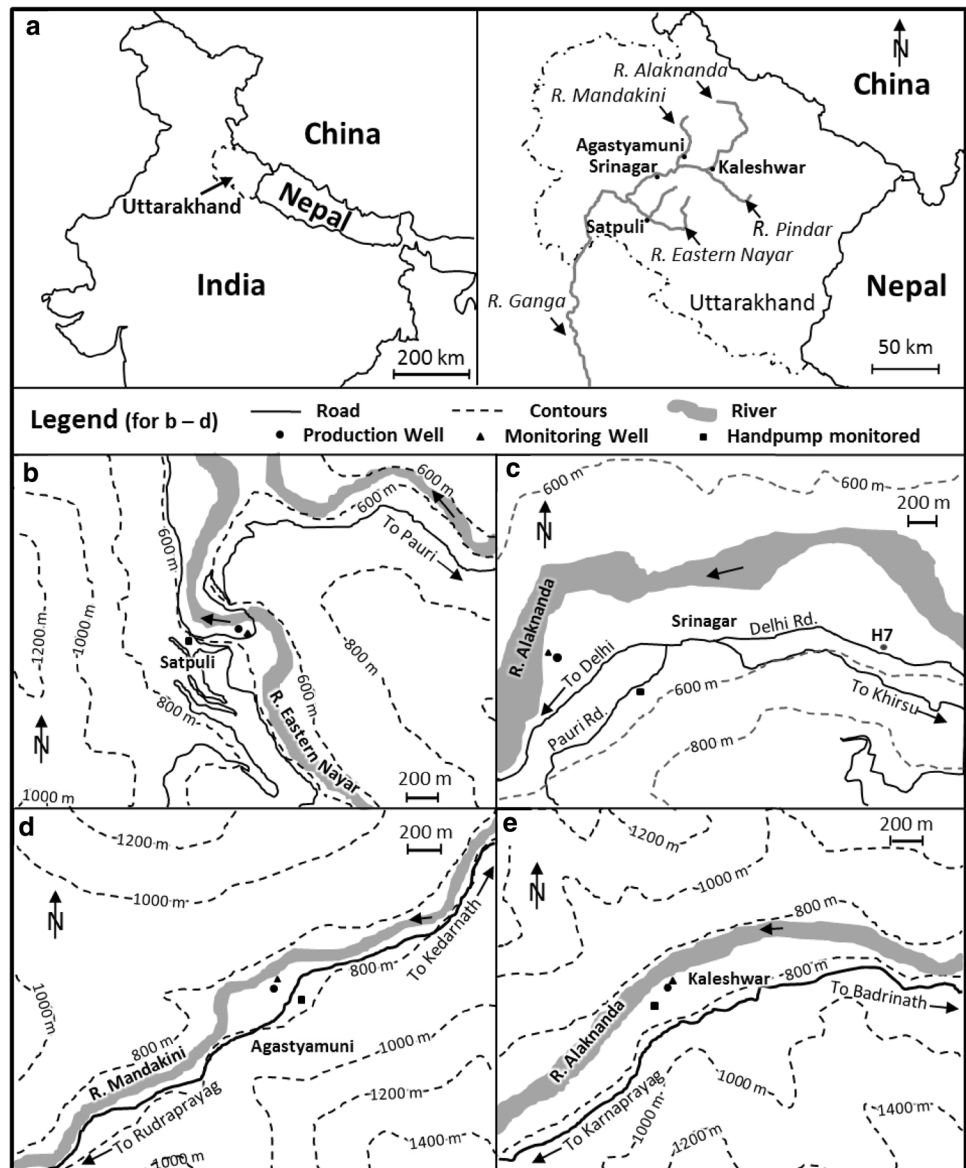
Table 1 Location and geological details of the four sites

	Satpuli (Fig. 1b)	Srinagar (Fig. 1c)	Agastyamuni (Fig. 1d)	Kaleshwar (Fig. 1e)
Latitude	29°55′05″N	30°13′12″N	30°23′28″N	30°17′18″N
Longitude	78°42′40″E	78°46′48″E	79° 01′16″E	79°15′05″E
Altitude (m above mean sea level)	576	546	783	778
Location of RBF well	Left bank, R. East Nayar	Left bank, R. Alaknanda	Left bank, R. Mandakini	Left bank, R. Alaknanda
Population (Census of India, 2011)	8934	20,115	7336 + ~700 (seasonal tourists)	569 + 8297 (Karnaprayag)[a]
Geology/bedrocks	Predominantly phyllite, quartzite and slate (Maithani 1972)	Phyllite and quartzite bedrocks	Schists and schistose quartzite bedrocks with thin bands of dolomite (CGWB 2011b)	Fanglomerates and bedrocks of quartzites, slates, phyllites and low-grade schists (CGWB 2011a)

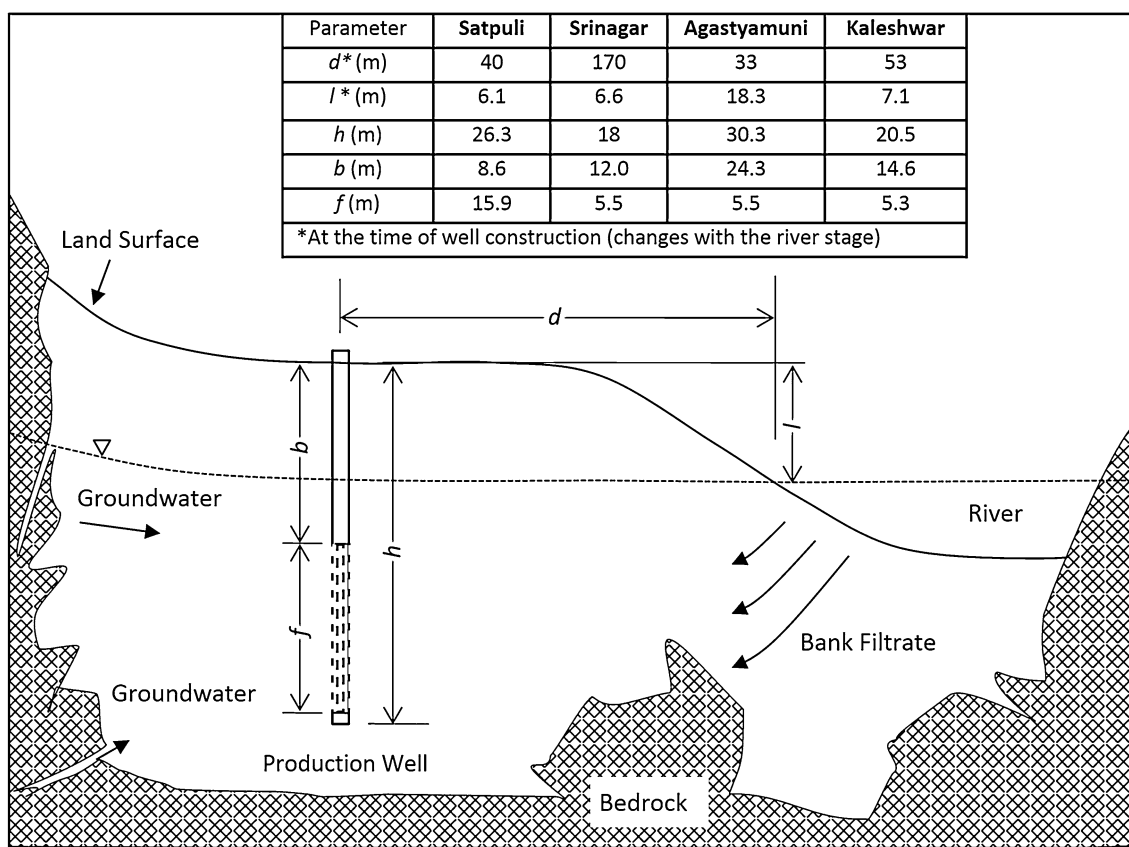[a]The population of Karnaprayag, to where water from the scheme is also to be supplied

Parameter	Satpuli	Srinagar	Agastyamuni	Kaleshwar
$d*$ (m)	40	170	33	53
$l*$ (m)	6.1	6.6	18.3	7.1
h (m)	26.3	18	30.3	20.5
b (m)	8.6	12.0	24.3	14.6
f (m)	15.9	5.5	5.5	5.3

*At the time of well construction (changes with the river stage)

Fig. 2 Schematics of the sites in the Himalayan region along with the production well parameters: d distance from the riverbank; l height of ground level at the well above the river water level; h depth of production well below the surface level; b depth of the filter screen; f length of the filter screen

Srinagar

Srinagar is one of the larger towns in the Himalayan region with a relatively lower gradient and a larger alluvial flood plain compared to the other sites. River Alaknanda meanders around the town over a stretch of about 3 km. The RBF scheme is located towards the downstream part of the meander (Fig. 1c). The right bank of the river is flanked by a relatively narrow alluvial deposit soon followed by steep bedrock. Srinagar also has a water supply system based on direct river water abstraction, as well as groundwater abstraction through hand pumps and springs.

Agastyamuni

Agastyamuni is a town located on the bank of the River Mandakini on route to the famous pilgrimage site of Kedarnath. The alluvial terraces here are extended along the river with short lateral extent of < 500 m, and a high surface gradient. The river has a very low curvature near the site (Fig. 1d). The local water demand is also met by hand pumps, natural springs and *gadheras* (streams flowing down the hills).

Kaleshwar

Kaleshwar (also known as Kaldu) is a small village located along River Alaknanda, around 6 km upstream of the town Karnaprayag (Fig. 1e). The site is characterized by a gentle curvature of the river, large alluvium deposits extended over a stretch of about 2 km with highly steep mountains on both sides. The ground water is abstracted through hand pumps. Water levels in these hand pumps located at various elevations range from 1 to 60 m with a seasonal fluctuation of 10–11 m below ground level (CGWB 2011a). The scheme is designed to supply water to the local population in Kaleshwar as well as the town of Karnaprayag, but was not started for regular water supply during the period of study.

Materials and methods

Initial RBF site-assessment was conducted through (1) a visual reconnaissance, (2) analyses of borehole profiles and (3) pumping tests at the four sites during pre-monsoonal low-flow conditions in May 2010 (Kimothi et al. 2012). The surveys indicated favorable hydro-geological conditions for RBF such as presence of alluvial deposits, perennial rivers, and low pollution of the river water (Sandhu et al. 2011).

Grain size analysis

Samples of the aquifer materials at various depths were obtained during the drilling of the wells. The material from the aquifers was washed and filtered through 75 microns sieve to remove the bentonite clay. The washed samples were oven dried at 105 °C for 24 h. The grain size distribution was determined by sieve analysis.

Pumping test

A long-duration pumping test (~ 47–70 h) followed by a recovery test was conducted at each site in November 2011 after ~ 1 year of commissioning. During the tests, drawdown and recovery were measured in both the production and monitoring wells using a pressure and temperature transducer (Schlumberger Mini-Diver Model DL505). The data were used to estimate hydraulic conductivity by the Dupuit (1863) and Thiem (1906) methods.

Sample collection

Water samples were collected from the PWs, the rivers and hand pumps (HPs) near the production well site during the well drilling in May 2010, and post-drilling in August 2010. The hand pump for the later sampling for each site was selected after analyzing waters from 10 hand pumps at Srinagar, 8 hand pumps at Satpuli, 14 hand pumps at Agastyamuni and 4 hand pumps at Kaleshwar in May and August of 2010. The samples were then collected almost monthly from January 2012 to March 2013. Samples for isotope analyses were collected from May 2012 to March 2013. At the Srinagar site, samples were collected till September 2014. The water samples from the PWs were collected while the pumps were in operation or after half an hour of starting the pump. The HPs were initially pumped to flush about 40 L of water before collecting the samples. For ionic analysis, water samples were collected in 1000 mL polythene and polypropylene bottles. Samples for isotopic analyses were collected in 15 mL polypropylene bottles ensuring no trapped air bubbles in the bottle at the time of collection. A portable multiparameter probe (HQ40d, Hach, Loveland, USA) was used to measure electrical conductivity (EC), pH, temperature, and dissolved oxygen (DO) on site. Samples for bacteriological analysis were collected in sterilized glass bottles. Samples were stored at 4 °C in the dark and transported within 24 h to the laboratory for further analysis.

Sample analysis

Total and fecal coliform counts in the water samples were determined by multiple tube fermentation technique. For other analyses, the samples were first filtered through 0.22 μm filter (Millipore, GVWP). The major ions (Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}) were determined by ion chromatography (Metrohm, AG-861). Alkalinity was determined by titration with N/50 H_2SO_4 (aq.). Concentration of HCO_3^- was then estimated from alkalinity, based on the assumption that at the given pH, the alkalinity is completely due to bicarbonate. All procedures for sample storage and analyses were in accordance with the procedures given in Standard Methods (APHA, AWWA and WEF 2005).

Stable isotope analysis of the water samples was conducted to assess the proportions of bank filtrate and groundwater in the RBF wells. Stable isotope concentrations, $\delta^{18}O$ and δ^2H of water samples were estimated using GV Isoprime Dual Inlet Isotope Ratio Mass Spectrometer. For $\delta^{18}O$ analysis, water samples (400 μL) were equilibrated with CO_2

reference gas for 23 h. For δ^2H analysis, equilibration was done for 7 h with H_2 reference gas and Pt catalyst. The delta (δ) values are reported with respect to Vienna Standard Mean Ocean Water (VSMOW) with a precision of $\pm 0.1‰$ for $\delta^{18}O$ and $\pm 1‰$ for δ^2H.

Results and discussion

Grain size distribution

The grain size analyses showed that the riverbank aquifers at the well sites had mostly sand and gravel of various sizes along with large boulders at some locations. The lithologs of the four sites are shown in Fig. 3a–d. Satpuli had the coarsest grains while Agastyamuni had the finest grains among the four sites. At Kaleshwar and Agastyamuni, drilling was done by the ODEX technique, therefore well-defined boundaries of various layers were not observed. Absence of a well-defined clay layer or bedrock in these lithologs showed that all the four production wells were located in unconfined aquifers. The grain size distributions are consistent with the

findings for Alaknanda River Basin sediments by Panwar and Chakrapani (2016).

Discharge and hydraulic conductivity

Table 2 lists the discharges of the production wells and hydraulic conductivities of the surrounding aquifers at the four sites as determined from the pumping tests. The hydraulic conductivity of the Satpuli riverbank aquifer was the highest among the four sites. This is consistent with the riverbank deposit at this site consisting of coarser grains as compared to the other three sites.

Isotopic analyses and water quality

As mentioned in the introduction, the two most important water quality parameters of concern in the Himalayan Rivers are turbidity and coliform. The river waters studied here had EC and DOC values consistently in the low ranges of 50–200 $\mu S/cm$ and 0.2–2.0 mg/L, respectively. Due to very low values of DOC, its attenuation during bank filtration has not been discussed here. However, since waters with

Fig. 3 **a–d** Lithologs of the bank aquifers at the four sites obtained during drilling of the RBF wells represented with respect to depth below ground level (BGL)
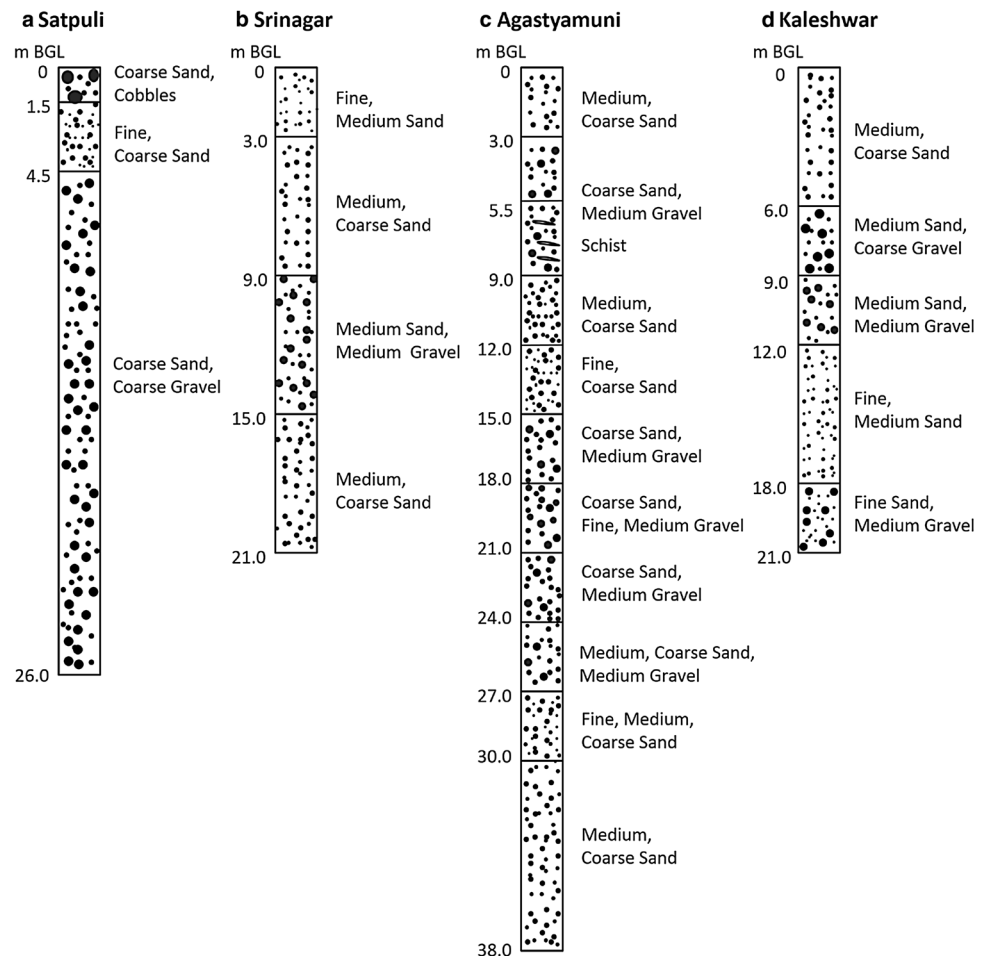
Table 2 Discharges and hydraulic conductivities of the production wells

Parameter	Satpuli	Srinagar	Agastyamuni	Kaleshwar
Duration of pumping (h)	67.3	47.2	70.5	49.1
Discharge (L/min)	630	710	230	690
Hydraulic conductivity (m/s)	6.5×10^{-4}	4.0×10^{-4}	2.2×10^{-4}	2.8×10^{-4}
Water table BGL (m)	5.8	6.6	18.3	7.2

low EC value can undergo significant mineralization in an aquifer (Dash et al. 2010), water quality changes in the RBF schemes have been discussed in terms of major mineral ion concentrations in addition to turbidity and coliforms. The stable isotope data have been discussed in terms of its temporal variation. This data has also been compared with the local meteoric water lines (LMWL) for Devprayag (465 m a.m.s.l., 30°08′26″N, 78°35′48″E) and Gomukh (3800 m a.m.s.l., 30°55′34″N, 79°04′15″E) in the Himalayas to assess possible source of river and groundwater at these sites.

Satpuli

The $\delta^{18}O$ and δ^2H values for the water from the river, PW, and HP at Satpuli are presented in Fig. 4a, b. The $\delta^{18}O$ values of the PW water on four out of seven occasions coincide well with the river water (Fig. 4a). The river samples had an annual variation of 4.6‰ in the $\delta^{18}O$ values with the lowest value in the monsoon and the maximum in the summer. The $\delta^{18}O$ and δ^2H values of the HP water had a much lower seasonal variation. The similarity of the PW water samples with the river water and dissimilarity from the groundwater samples from HP shows that the PW has been drawing predominantly river water as bank filtrate. The differences observed in monsoon could be either due to higher proportion of groundwater during that period or due to water already stored in the bank aquifer mixing with the infiltrating river water.

The data presented in Fig. 4b indicate the river water to be similar to LMWL (Devprayag) in the monsoon months of July and August. It points out the high fraction of local rainwater in the river. The isotopic signature of river water in winters is different from the LMWL (Devprayag), possibly suggesting increased fraction of drainage from higher altitudes. Nevertheless, isotopic composition of the PW water remains similar to the river.

A perusal of the water quality data indicates that the three water sources mainly contained Na^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, and SO_4^{2-} (Table 3). The PW water had EC values similar to the river water and much lower than the hand pump water throughout the year (Fig. 5a). The Na^+ concentration of the HP water was ~ 132 mg/L in the pre-monsoon period which increased to 191 mg/L during the monsoon period. However, such an increase in the Na^+ concentration was not observed in the PW water (Fig. 5b). Therefore,
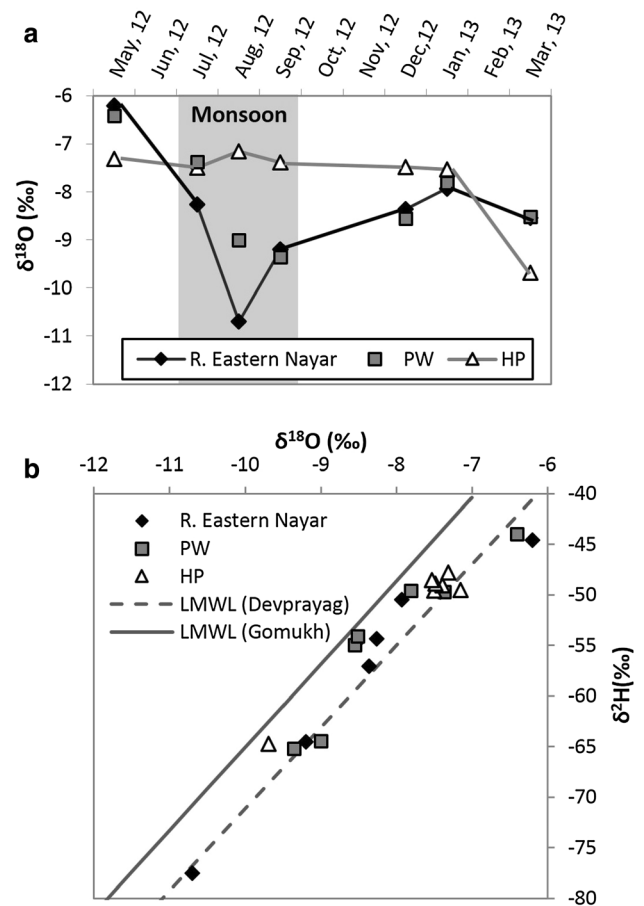

Fig. 4 Satpuli: **a** Temporal variation in $\delta^{18}O$ of water samples; **b** $\delta^{18}O$ vs. δ^2H along with LMWLs (Kumar et al. 2010)

the isotope data combined with the water quality data show that the production well has been drawing > 95% river water throughout the year.

The PW water was of potable quality as per the Indian Drinking Water Standards (IS10500: 2012) except for a total coliform count of < 100 MPN/100 mL in May and July 2012. Fecal contamination was not detected in the PW water samples analyzed throughout the study period. The contamination is addressed by chlorination before supply. Turbidity was below 2 NTU throughout the year. Interestingly, both the river and groundwater had high average pH values of 8.4, occasionally rising to above 9.0. However, the PW water had a lower pH consistently < 8.5—the prescribed limit for

Table 3 Satpuli: physico-chemical and bacteriological characteristics of the water samples

Parameter	R. East Nayar	PW	HP
N	15	15	15
pH	8.4 (7.7–9.0)	7.9 (7.4–8.3)	8.4 (7.8–9.4)
Temperature (°C)	22.4 (13.2–31.0)	22.4 (14.0–26.9)	23.7 (19.7–27.1)
Turbidity (NTU)	18.1 (1.2–135)	0.8 (0.2–1.6)	3.8 (1.5–5.9)
EC (µS/cm) at 25 °C	140 (112–211)	193 (151–247)	611 (532–681)
Alkalinity (as mg/L $CaCO_3$)	65 (49–89)	88 (63–112)	292 (234–357)
Na^+ (mg/L)	7.9 (3.0–12.9)	12.9 (6.7–17.1)	153 (129–191)
K^+ (mg/L)	1.3 (0.6–2.5)	2.2 (1–4.9)	4 (1.1–7.1)
Ca^{2+} (mg/L)	19.2 (12.2–38.5)	22.6 (16.1–30.1)	25.1 (11.9–95.9)
Mg^{2+} (mg/L)	5.6 (2.8–18.3)	6.8 (4.1–17.9)	13.7 (4.8–38.9)
Cl^- (mg/L)	3.2 (1.6–8.0)	5.4 (2.8–12.0)	24.3 (11.9–59.8)
NO_3^- (mg/L)	1.5 (<1–5.0)	2.8 (<1–8.3)	1.0 (<1–2.1)
SO_4^{2-} (mg/L)	9.8 (3.8–18.1)	11.9 (5.0–17.2)	39.9 (15.7–107.9)
Total coliform (MPN/100 mL)[a]	69,233 ($500–3.5 \times 10^5$)	8 (<2–70)	2 (<2–23)
Fecal coliform (MPN/100 mL)[a]	29,771 ($50–9 \times 10^4$)	<2	<2

Concentrations are the average of the *N* number of samples;

[a]*N* = 12 for the coliform samples; numbers in the parentheses are the range of values
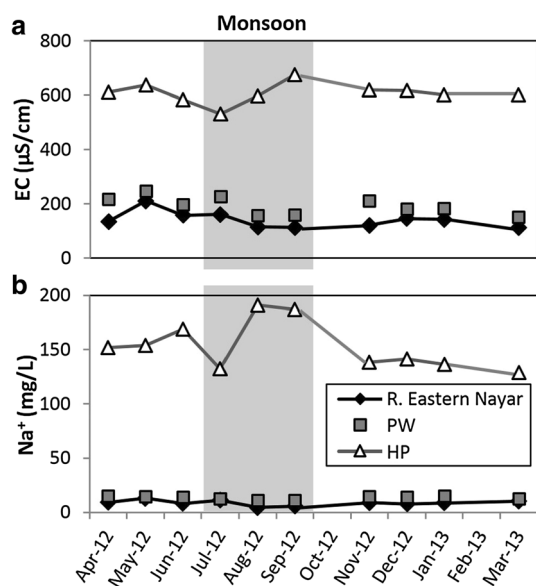
Fig. 5 Satpuli: temporal variation in **a** EC and **b** Na^+ concentration

drinking water (IS10500: 2012), even though its alkalinity was always slightly higher than the river water and lower than the groundwater.

Srinagar

The stable isotope data of Srinagar waters, shown in Fig. 6a, b, suggest that the PW in Srinagar draws predominantly river water during non-monsoon, and largely groundwater during the monsoon period. The $\delta^{18}O$ and δ^2H values of the PW water match with the river water values during December to May and with the groundwater values during August to September. The mineral content, however, of the PW water was higher than the river water and comparable to the ground water. The EC value of the PW water (Table 4) was consistently higher than the river water throughout the year and was comparable to the groundwater irrespective of the proportion of the bank filtrate. The evidence suggests mineralization of the bank filtrate during its passage through the bank aquifer.

To investigate the origin of mineralization of bank filtrate, water samples from several hand pumps in the nearby region were analyzed. An interesting feature of the local geology was discovered from analysis of the waters from the hand pumps. Hand pump H7 (Fig. 1c), which is about 0.5 km away from the river bank, was found to deliver water similar to the river water in terms of EC, temperature, isotopic characteristics, ionic composition as well as coliform counts (Fig. 6; Table 4). The water from the H7 was distinctly different from the water drawn from the other hand pumps and the wells in the vicinity (Gupta et al. 2015a). These unusual characteristics indicate the presence of a subsurface channel of high hydraulic conductivity through which the river water flows into the land without filtration. The channel may also be providing an alternative flow path for the river water to the PW well that is not through any of the (visible) alluvium.

The PW water was of potable quality as per the Indian Drinking Water Standards (IS10500: 2012) except for nitrate concentration and a single observation of total coliform contamination (with no fecal contamination). Such occasional bacterial contaminations are addressed by chlorination before supply.

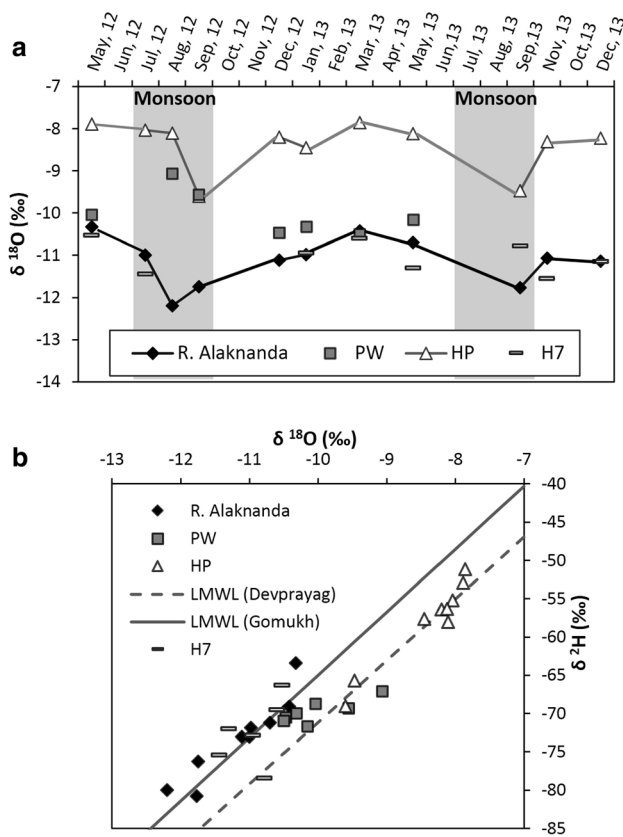The quality of the water from the PW after the June 2013 flood was similar to that during the pre-flood period.

Fig. 6 Srinagar: **a** temporal variation in $\delta^{18}O$, **b** $\delta^{18}O$ *vs.* δ^2H along with the LMWLs (Kumar et al. 2010)

This showed that a massive flood with additional sediment deposit did not change the water quality at the PW site. However, water samples collected from a hand pump near the RBF well in July, 2013 immediately after the floods showed the presence of fecal coliforms that are attributed to the direct entry of floodwater due to inappropriate well-head sealing (Sandhu et al. 2017). These results show the resilience of RBF scheme for Himalayan conditions, provided they are built in a manner to withstand the risks from floods. The flood also did not lead to a decrease in the (highly soluble) nitrate and other ionic concentrations of the PW water. This evidence shows that the nitrate contamination is not due to any anthropogenic or localized nitrate source in the riverbank aquifer. Instead, it reflects a large-scale source of nitrate in the underlying geology of the site (Gupta et al. 2015a).

Agastyamuni

Stable isotope data of the Agastyamuni site (Fig. 7a, b) reflect perennial dissimilarity in the river, the PW, and the HP waters. The PW water was isotopically lighter than HP but heavier than the river water. The δ^2H and $\delta^{18}O$ values

for the PW water and groundwater fall on the LMWL of Devprayag. The values of the river water, however, are not matching with the meteoric water line of Devprayag. Kumar et al. (2010) have reported such an observation for the rivers at higher altitudes in the Himalayas.

The temporal variations in $\delta^{18}O$ of the groundwater and the PW water were nearly parallel. The PW water could either be a mixture of the groundwater being sourced from HP and the river water or a groundwater other than the HP water that has been monitored. This data shows that the PW at Agastyamuni abstracts a large fraction of groundwater. During monsoon, the $\delta^{18}O$ values of the PW were closer to the groundwater values than the river water and became closest to the river water during peak summer months. This suggests that the proportion of groundwater in the PW increases during monsoon and decreases during the non-monsoon months.

The quality of the PW water was also similar to the groundwater from HP. The three water sources had Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-} as the major ionic constituents (Table 5). However, the PW water had NO_3^- and Cl^- concentrations higher than the river and the hand pump water samples. It indicates that either there is high mineralization of river water as it moves through the riverbank aquifer or the groundwater reaching the PW well is different than the HP groundwater that has been monitored. Also, the observation that the temperature of the PW was also higher than the river and the HP water further substantiate that PW may be abstracting a shallower groundwater of different origin than the groundwater in HP. The concentrations of NO_3^- observed in the RBF well water was also high for natural water bodies. The source of this NO_3^- in the riverbank aquifer is unclear—however, the possibility of a geogenic origin as in the case of Srinagar cannot be ruled out. As the well was newly constructed and was operated at a low abstraction rate, the processes in the aquifer stretch between the river and the well, especially dissolution of minerals, may be still affected by former groundwater flow towards the river. Also, nitrate input from land use between the river and the well would be possible. Thus, from first year´s monitoring of hydrochemical parameters alone, the proportion of bank filtrate cannot be accurately determined.

All the ionic concentrations (including of nitrate), however, were within the Indian Drinking Water standards (IS10500: 2012). In 3–4 samples from the PW, total coliform counts of ≤ 50 MPN/100 mL were observed, but no fecal coliforms were observed at any times. Thus, the Agastyamuni RBF well delivered potable water with chlorination.

Kaleshwar

Stable isotope data for the Kaleshwar site (Fig. 8a, b) show that the PW water is similar to the groundwater samples and

Table 4 Srinagar: physico-chemical and bacteriological characteristics of the water samples

Parameter	R. Alaknanda	PW (pre-flood)	PW (post-flood)	HP	H7
N	20	16	2	18	7
Turbidity (NTU)	173 (2.5–1771)	0.9 (0.5–1.9)	0.8	14 (2.0–67)	5.5 (1.4–11)
DO (mg/L)	10.4 (9.1–12.8)	1.6 (0.7–3.2)	0.7	1.5 (0.9–2.1)	6.2 (3.5–9.6)
pH	8.2 (7.5–9.0)	7.2 (6.4–7.9)	7.3	7.5 (7.0–7.9)	7.5 (7.0–7.8)
Temperature (°C)	18 (13–21)	24 (21–26)	23.6	23(18–26)	17 (16–20)
EC (µS/cm)	160 (104–204)	1073 (986–1158)	951, 1076	1287 (951–1991)	209 (171–295)
NO_3^- (mg/L)	1.6 (0.3–4.2)	99 (53–138)	67, 91	122 (23–378)	4.1 (1.8–8.8)
SO_4^{2-} (mg/L)	15.3 (6.2–36.7)	92 (31–254)	54, 91	104 (45–154)	18.9 (7.6–27.8)
F^- (mg/L)	0.2 (0.1–0.5)	0.6 (0.2–2.6)	0.3, 0.3	0.2 (<0.05–0.4)	0.2 (0.1–0.4)
Cl^- (mg/L)	1.1 (0.4–4.6)	56 (34–75)	26, 38	110 (62–172)	3.0 (0.7–10.3)
HCO_3^- (mg/L)	86 (62–137)	409 (378–458)	-	408 (364–486)	89 (71–116)
K^+ (mg/L)	1.9 (<1.0–7.2)	12 (<1–22)	16, 21	50 (<1–128)	2.5 (1.4–3.8)
Na^+ (mg/L)	3.1 (0.6–7.7)	59 (16–78)	51, 70	96 (45–181)	6.1 (2.5–17.8)
Ca^{2+} (mg/L)	26 (19–56)	121 (79–171)	103, 170	121 (31–192)	28 (14–45)
Mg^{2+} (mg/L)	5.9 (2.4–19.8)	41 (33–65)	43, 49	46 (33–64)	5.7 (2.2–7.2)
Total coliform (MPN/100 mL)	73.1×10^3 $(3 \times 10^3 – 9 \times 10^5)$	251 (<2–3000)[a]	<2	3 (<2–23)	1971 (48–5000)[b]
Fecal *E. Coli* (MPN/100 mL)	30.2×10^3 $(800–3 \times 10^5)$	<2(<2–2)[a]	<2	<2 (<2–3)	1822 (7–5000)[b]

Concentrations are the average of the N number of samples; numbers in parentheses are the range of values. Concentration of NH_4^+ was <0.5 mg/L for all the samples

[a]Single case of contaminated sample in July 2012

[b]3 samples

different from the Alaknanda River water throughout the year. The bank filtrate always had $\delta^{18}O$ values 1–4‰ higher and δ^2H values 5–30‰ higher than the river water values. The three water sources had predominantly Ca^{2+}, Mg^{2+}, and HCO_3^-. The ionic concentrations in the PW water were slightly higher than the HP and the river waters (Table 6). The concentrations, however, conform to the Indian Drinking Water Standards (IS10500: 2012). Turbidity in the PW water was consistently ~1 NTU. In July and September 2012, non-zero total coliform counts were observed in the PW water, but even then the fecal coliform count was only 2 MPN/ 100 mL. As in Agastyamuni and due to the discontinuous operation with a low abstraction rate, the new PW delivered predominantly groundwater, which was of potable quality after chlorination.

Comparison of the RBF sites

The study presents four entirely different hydrological situations ranging from almost completely river water being abstracted at Satpuli PW to almost complete groundwater abstraction at Kaleshwar PW. The subsurface hydrology in the Himalayan riverbank aquifer, as judged from the water quality data is highly variable. Part of the problem is also due to site-specific operational issues such as the discontinuous well operation, which also contributes to the uncertainty in analyzing the results. For quantitative estimates of the

bank filtrate proportions in the PWs, annual average $\delta^{18}O$ values (calculated as average of all values available in present study) were taken for the river and the groundwater samples. For the PW samples, monsoon and non-monsoon $\delta^{18}O$ averages were taken separately to assess the changes in the proportions of river water during the two periods (Table 7). For Kaleshwar, Agastyamuni, and Srinagar, the percent river water in the two periods was determined by binary mixing model. Accordingly, the concentration of an isotope in PW water was assumed to be weighted average of the isotopic concentrations in the river water and groundwater, weighted with percentages of the two waters. For Satpuli, combined isotopic and water quality study showed the abstraction of almost completely river water in the monsoon as well as non-monsoon seasons (refer "Satpuli" section above). Due to small range of $\delta^{18}O$ values and thus higher relative fluctuations for the Satpuli site, the binary mixing model cannot be rigorously applied. Therefore, estimate of percentage river water in Satpuli PW given in Table 7 is based on qualitative assessment of the water quality and isotope data.

All these RBF sites were on the concave side of a river meander, but the differences in the river water infiltrate in these aquifers were significant. The site at Satpuli drawing the maximum proportion of the river water is located inside the sharpest curvature of a river. The PWs at Kaleshwar and Agastyamuni were drawing large proportions of
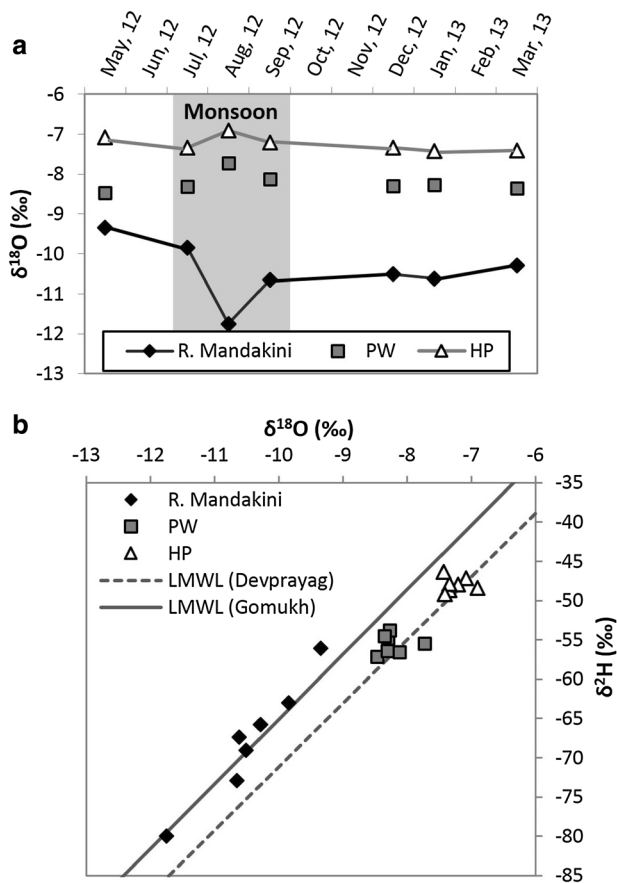
a

b

Fig. 7 Agastyamuni: **a** temporal variation in $\delta^{18}O$ of the water samples; **b** $\delta^{18}O$ vs. δ^2H along with the LMWLs (Kumar et al. 2010)

groundwater. Both these sites are located near rivers having very low curvatures and have extended riverbanks along the river length. Both these PWs also have short and discontinuous well operating hours, which may also explain the observed results. The well at Srinagar is located inside an extended meander with sharp turns. The abstracted water changes from predominantly groundwater in the monsoon to largely river water in non-monsoon. The site has a complex riverbank hydrogeology.

The observed pattern of increased groundwater abstraction by the RBF wells during monsoon and increased river water contribution during non-monsoon was contrary to conventional expectations of higher bank infiltration during the high discharge period of river. This is indicative of higher groundwater flow towards the river as a result of the monsoon rains, which is consistent with the findings of Andermann et al. (2012).

The three rivers had comparable water quality, but very distinct isotopic signatures from each other. The groundwaters at the sites except at Satpuli also had very different isotopic characteristics from the river waters. Even though these sites are located within 100 km of each other, the differences in the isotopic characteristics are likely because of their origins being precipitations at widely varying altitudes (Kumar et al. 2010). Rivers Alaknanda and Mandakini have the lightest water because of their origins at glaciers at ~3500–4000 m above mean sea level (a.m.s.l.). Therefore, their isotopic values are around the local meteoric water line (LMWL) $\delta^2H = 8.22 \times \delta^{18}O + 17.12$ at Gomukh (30°55′34″N, 79°04′15″E) located in the higher Himalayas at ~3800 m a.m.s.l. River East Nayar originates in the Dudhatoli range of the middle Himalayas at altitude of ~3000 m a.m.s.l. Its isotopic values lie close to the LMWL $\delta^2H =$

Table 5 Agastyamuni: physico-chemical and bacteriological characteristics of the water samples

Parameter	R. Mandakini	PW	HP
N	15	15	15
pH	8.1 (7.5–9.1)	6.8 (6.5–7.9)	7.4 (6.4–8.5)
Temperature (°C)	14.5 (8.8–20.5)	24.2 (17.8–28.6)	20.6 (15.5–23.6)
Turbidity (NTU)	27.8 (2.1–116)	0.6 (0.2–1.9)	10.4 (2.0–25)
EC (μS/cm) at 25 °C	100 (59–149)	312 (253–381)	426 (387–478)
Alkalinity (as mg/L $CaCO_3$)	44 (22–65)	124 (105–221)	209 (105–245)
Na^+ (mg/L)	3.7 (1.5–7.5)	18.4 (12.5–22.8)	56.5 (43.7–64.1)
K^+ (mg/L)	2.3 (1.4–5.0)	3.9 (0.9–6.8)	4.2 (1.0–6.5)
Ca^{2+} (mg/L)	16 (8–24)	42 (29–56)	39.5 (33.1–48.3)
Mg^{2+} (mg/L)	1.7 (0.4–5.1)	8.4 (4.6–14.6)	11.9 (7.6–21.1)
Cl^- (mg/L)	1.3 (0.3–3.1)	10.7 (6.2–16.8)	6.3 (4.4–8.6)
NO_3^- (mg/L)	1.4 (0.3–2.1)	21.7 (10.8–31.0)	1.1 (0.4–3.1)
SO_4^{2-} (mg/L)	9.1 (4.5–12.5)	12.3 (5.9–19.1)	10.8 (7.5–15.0)
Total coliform (MPN/100 mL)	65,850 (1600–3×10^5)	6 (<2–50)	5 (<2–50)
Fecal coliform (MPN/100 mL)	18,817 (900–5×10^4)	<2	<2

Concentrations are the average of the N number of samples; numbers in parentheses are the range of values; $N = 12$ for the coliforms
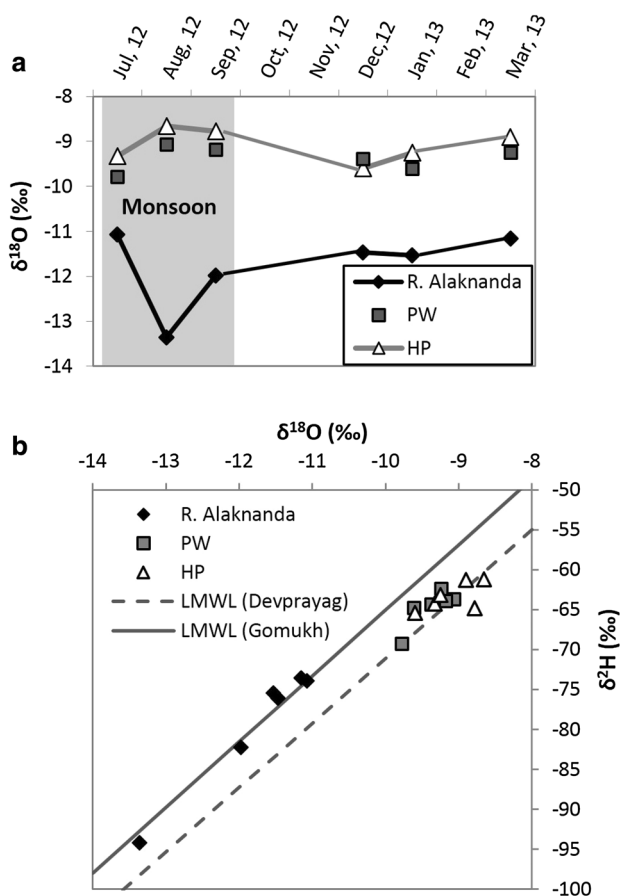
Fig. 8 Kaleshwar: **a** temporal variation in $\delta^{18}O$ of water samples; **b** $\delta^{18}O$ vs. δ^2H along with the LMWLs (Kumar et al. 2010)

$8.07 \times \delta^{18}O + 9.54$ at Devprayag (30°08′26″N, 78°35′48″E) located in the middle Himalayas at an elevation of ~ 500 m a.m.s.l. The various groundwaters are likely to be recharged from local precipitations in the middle Himalayas and therefore have stable isotopic values closed to the LMWL at Devprayag. The stable isotope data were not sufficient to highlight the seasonal variation in the proportion of the river water in the production well waterand to determine the travel time, and hence the temporal correlation of the river water sample to the well water samples could not be established.

The discharges from the wells as well as hydraulic conductivity of the aquifers are comparable to that of other RBF sites in Europe (Grischek et al. 2002) and the USA (Caldwell 2006). In general, the improvement in water quality is very good, comparable to other RBF sites globally. The quality of the production well water at all sites is in conformity with the Indian and WHO standards for drinking water supply except for nitrate concentration in Srinagar and occasional bacterial contamination observed during the late summer/monsoon periods. The electrical conductivity of water from almost all wells is also higher than the prescribed limit of 250 µS/cm as per the WHO standards. The bacterial contamination was at low levels that could be easily addressed by chlorination. The nitrate problem in Srinagar is being addressed by mixing the RBF water with a conventional water treatment plant output based on river water pumping. Therefore, the four RBF sites in the Himalayan region have been able to support drinking water supply needs without significant needs for post-treatment.

Altitude appears to be one of the factors influencing the RBF capacity to deliver river water as bank filtrate. The observation is in agreement with the statement made by

Table 6 Kaleshwar: physico-chemical and bacteriological characteristics of the water samples

Parameter	R. Alaknanda	PW	HP
N	14	14	14
pH	8.3 (7.9-9.0)	7.8 (7.4–8.4)	7.5 (7.1–8.1)
Temperature (°C)	13.2 (9.0 -16.9)	21.0 (17.4–24.3)	22.7 (16.6–35.2)
Turbidity (NTU)	241 (3.8–1338)	1.1 (0.6–2.2)	4.6 (1.1–10.3)
EC (µS/cm) at 25 °C	151 (111–200)	287 (235–345)	237 (198–297)
Alkalinity (as mg/L $CaCO_3$)	66 (48–78)	158 (134–170)	135 (121–157)
Na^+ (mg/L)	3.0 (1.8–8.8)	3.6 (1.6–5.7)	2.2 (1.3–3.8)
K^+ (mg/L)	1.0 (<0.5–2.7)	2.4 (<0.5–4.1)	0.5 (<0.5–2.1)
Ca^{2+} (mg/L)	26 (19–34)	44 (37–56)	41 (29–55)
Mg^{2+} (mg/L)	3.7 (1.2–8.0)	12.3 (9.2–16.0)	10.3 (8.1–13.8)
Cl^- (mg/L)	1.2 (0.1–6.0)	2.3 (0.4–12.0)	1.1 (0.3–2.1)
NO_3^- (mg/L)	1.6 (0.3–5.0)	3.5 (0.4–8.3)	1.2 (<0.2–2.1)
SO_4^{2-} (mg/L)	12.6 (2.1–26.2)	8.9 (2.0-21.1)	6.3 (1.4–13.2)
Total coliform (MPN/ 100 mL)[a]	11,419 (130–6×10^4)	83 (<2 -900)	<2 (<2–4)
Fecal coliform (MPN/ 100 mL)[a]	4473 (80–13×10^3)	<2 (<2–2)	<2

Concentrations are the average of the N number of samples; numbers in the parentheses are the range of values

[a]$N = 12$ for the coliform samples

Table 7 Average δ^{18}O values of the various waters and the river water proportion in the RBF wells at each site in monsoon (M) and non-monsoon (NM)

Site	δ^{18}O (‰)				% river water	
	River	HP	PW		M	NM
			M	NM		
Satpuli	− 8.5	− 7.7	− 8.6	− 7.8	> 95	100
Srinagar	− 11.1	− 8.3	− 9.3	− 10.3	36	72
Agastyamuni	− 10.4	− 7.2	− 8.1	− 8.3	25	35
Kaleshwar	− 11.8	− 9.1	− 9.3	− 9.4	10	12

Grischek and Ray (2009). Also, at higher altitude due to moderate to steep gradient, the recharge water disperses down gradient and results in lower recovery efficiency of the aquifer recharge (Dillon and Jiménez 2008). However, local hydrogeology seems to be playing a more important role in determining bank infiltration as compared to the altitude.

These case studies further support the potential of RBF as a reliable scheme for drinking water supply in mountainous regions, which by combining the inputs from both the surface water and the groundwater ensures year round supply. In addition, it improves the water quality over both the groundwater-based and the surface water-based abstraction systems.

More work is required to understand the hydro-geochemistry of the location at Srinagar especially in reference to nitrate in water. Longer period studies of the water can help in better understanding the travel time and seasonal variation in the proportion of the river water in the bank filtrate. Development of the groundwater flow and transport model for the RBF site in the hilly region can strengthen the speculation. Increasing the pumping rate and the duration of operation (wherever possible) may also be explored to increase proportions of river water in the wells.

Conclusions

Potential for RBF was investigated at four sites located at an altitude of 551–769 m above msl in Uttarakhand, India. The aquifer characteristics at four sites are nearly the same with slight effect of the altitude on the value of hydraulic conductivities. The wells have discharges comparable to the other RBF sites in the world. The proportions of the river water and groundwater drawn by the production wells were highly variable across the four sites with different locations of the wells with respect to the river trajectories. The proportion of the river water in the bank filtrate was the highest in the Satpuli production well (576 m above msl), located inside a small and sharp U-turn of a meander. The production wells at Srinagar (546 m above msl) yielded about 70% river water in the bank filtrate. The production well at Kaleshwar (778 m above

msl) mostly abstracted ground water. The production well water at Agastyamuni (783 m above msl) was more than 65% groundwater. In general, the bank filtrate proportion in the production wells in the sites decreased during the monsoon season and increased during the summer season.

In Srinagar, unusually high mineralization of the river water was observed as it passes through the aquifer. At this site, an unusual hydrology was also observed involving inland flow of river water through a high hydraulic conductivity channel, which leads to river water flow up to a few hundred meters inland as observed in a hand pump. The quality of the water from the hand pumps varies widely in the vicinity of the production wells, indicating sharp change in geology at the riverbanks.

Production well waters at all sites had all water quality parameters within the requirements of Indian standards IS:10500 (2012) except for nitrate in Srinagar and occasional bacterial contamination. The production well waters in Satpuli, Agastyamuni, and Kaleshwar are suitable for drinking water supply with chlorination. The study shows that RBF can be a successful technology for water supply in the mountainous regions.

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