A sustainable solution for safe drinking water through bank filtration technology in Uttarakhand, India

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Bank filtration (BF) has emerged as an economical and sustainable water pre-treatment technology for drinking water supply. In this method, subsurface water of a water body moves into the well by seepage. BF wells adjacent to a river or lake pump the stored groundwater abstracted from the surface through aquifers. Chemical and biological contaminants such as turbidity, microbes, dissolved chemicals and natural organics are removed by the channel of aquifers present in the area. The whole process follows a series of physical, chemical and biological processes with some redox reactions. This study highlights the role of BF method in regulating water quality and quantity improvement. Besides, attempts have been made to discuss the mechanism, significance and the development of BF technology in the hilly state of Uttarakhand. Water quality status of Srinagar and Satpuli river BF sites of Uttarakhand are also described and compared with the Bureau of Indian Standards guidelines.

Keywords: Bank filtration, drinking water, rural community, sustainable solution, Uttarakhand.

RIVERS and lakes are a major source of drinking water supply, but surface water (SW) can be contaminated due to its susceptibility to pollution. Conservation of the environment maintaining the quality and quantity of water has become a big challenge. Alluvial aquifers which are hydraulically associated with a water system have come into consideration for production of drinking water. Bank filtration (BF), a water treatment method, is a natural approach to extract water from rivers through wells installed in neighbouring alluvial aquifers. Usually alluvial aquifers are a potential source of groundwater (GW) due to their properties such as high production potential and economy of extraction[1]. The SW flows through the river bed and banks by hydraulic gradient to the pumping well adjacent to the river as shown in Figure 1 (ref. 2). Moreover, some other important factors such as the quality of river water and GW, residence time of water in an aquifer, porosity, pH and temperature, etc. also dominate their role in-bank filtration[3]. A decrease in the concentration of pollutants can be achieved by various processes such as filtration, biodegradation, adsorption, precipitation and redox reactions between GW and SW[2,4].

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BF technology has become popular in Europe, the United States and some Asian countries[4–8]. European countries have adopted the BF method as a common practice for more than 130 years. Moreover, BF has been successfully carried out in some countries such as Austria, Netherlands, Germany, United Kingdom, United States, etc. and in India also[7,9–12]. Now 50% of drinking water demand in the Slovak Republic, 16% in Germany, 45% in Hungary and 5% in Netherlands is satisfied by GW obtained through river water infiltration[5].

Bank filtration method

The construction of a BF well requires survey of the field for a suitable site, laboratory analysis for major cations and anions and bacteriological studies along with GW flow modelling. However, the lithology, i.e. study of coarse sand and gravel is an important segment which decides the favourable or unfavourable conditions to establish a river bank filtration (RBF) system at any place. The comparison of water quality data of SW, bank filtrate and ambient GW is very much useful in the determination of suitability of any installed BF well. The pumping test is also an important and necessary feature of a BF well. BF is an established technique used to improve aquifer recharge from the SW by constructing abstraction wells in the vicinity of natural SW bodies, i.e. rivers and sometimes lakes. Before the execution of BF technology, it is

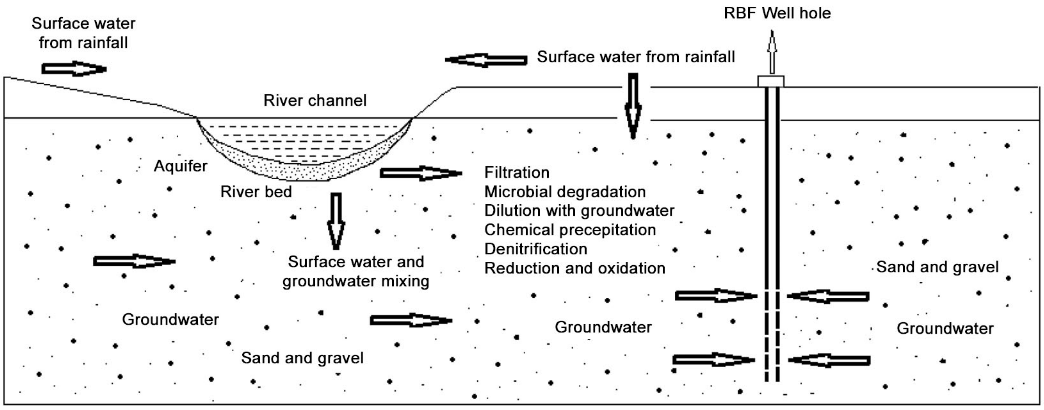

Figure 1. Modified general scheme of RBF[2].

essential to accomplish an exhaustive hydrogeological pre-investigation. BF is a hydraulic gradient induced influx of river water to the aquifer. A BF well generates a pressure head difference between the aquifer and the river. Ultimately, water percolates from the river towards the production well and GW from adjacent aquifers.

Production well is a simple hydraulic and a large diameter structure which receives naturally filtered water from the adjacent river or lake. A filtration well primarily derives water from the river or lake seepage. The process of BF is initiated by lowering of the GW table below that of an adjoining SW table, which causes SW to flow through the permeable river bed and bank or lake bed into the aquifer as a result of the difference in water levels, provided that no artificial or natural barriers to this subterranean flow exist, viz. brick or concrete lined river, canal or lake bed, or a low hydraulic conductivity layer such as clay. This flow may be the direct result of river influent under natural circumstances or can be induced by GW abstraction wells. Discharge of a filtration well mainly depends on the hydraulic conductivity and thickness of the tapped aquifer. The distance of a well from water body should be such that the aquifer is able to filter the stream water[12,13]. During the BF process, ground and SW levels, geological data pertaining to the aquifer and river bed, and hydrogeological modelling help in describing the flow conditions as given in Figure 1 (ref. 2).

Effect of BF on water quality and quantity

Any layer within the riverbed can reduce hydraulic conductivity due to blockage by the input of fine sediment particles, microorganisms and colloids, precipitation of iron and manganese oxy-hydroxides and calcium carbonates along with the formation of gas bubbles. This is an important factor which affects the volume of the derived bank filtrate[2]. Heavy biodegradation and sorption of pollutants also occur in this type of layer. The permeability of such clogged segments of the river bed varies with fluctuating surface flows. This affects the bank filtrate volume and cannot be considered constant. Therefore, the quantitative management of any BF unit needs significant information such as SW quality, SW hydrology, river bed stability, GW catchment, SW infiltration zones, mixing proportions of SW and GW in the abstracted raw water, flow paths with flow velocities of the bank filtrate.

Low electrical conductivity (EC) from a production well indicates that a large portion of bank filtrate is present in abstracted water and ultimately the concentration of major ions will be very low in abstracted water. Further, it is an indication of low mineralization with less residence time of water or low mineral content in that aquifer. The proportion of bank filtrate in a production well (PW) can be studied by the equation[14]

$$C_{\mathrm{BF}} = \left[\frac{C_{\mathrm{PW}} - C_{\mathrm{GW}}}{C_{\mathrm{SW}} - C_{\mathrm{GW}}}\right] \times 100,$$

where C_{BF}, percentage of bank filtrate in PW; C_{PW}, Tracer concentration in PW; C_{SW}, Tracer concentration in SW; C_{GW}, Tracer concentration in GW.

However, the quality of water is affected dominantly by the strata through which water travels. Purification during BF mainly depends on environmental conditions, location at bank, well design, well operation, travel time, runoff regime, and SW and GW qualities[2,3]. The porous media behaves as a natural filter and also biochemically attenuates potential contaminants present in the SW.

Nitrate (NO_3^-) in SW or GW may be present due to natural or anthropogenic activities. Nitrate may occur due to seepage from domestic sewage or landfill sites besides fertilizers. A reduction of nitrate concentration in BF well water in comparison to SW, i.e. river water takes place due to an effective denitrification process and can be expressed as

$$5CH_2O + 4NO_3^- \rightarrow 4HCO_3^- + H_2CO_3 + 2H_2O + 2N_2\uparrow \quad \text{(denitrification)}.$$

Decrease in pH of RBF well water from surface river water during underground passage occurs due to the degradation of organic matter as given below

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \text{ (aerobic respiration).}$$

A fraction of CO_2 reacts with water forming carbonic acid which lowers the pH value of water. The decrease in nitrate content and dissolved organic carbon (DOC) through RBF method makes this technique a method of choice to supply pure drinking water.

In hydrodynamic process, the aquifer behaves as a filter for the temporal variation of contaminants and dilution of bank filtrate occurs due to the mixing of GW. Some important mechanical processes, take place during BF, such as natural filtration of fine sediments, organic matter and microbes. The type of pathogens which inhabits a particular aquifer also affects the quality of filtered water. Moreover, physicochemical processes such as sorption, precipitation, coagulation, flocculation and oxidation–reduction reactions play an important role in water quality of BF well[15,16].

Removal of microorganisms during soil passage mainly occurs through the inactivation, adsorption, staining and sedimentation processes and is controlled by the temperature, rainfall, nature of the soil and the type of microbe present[17–20]. Some studies have revealed that BF method is a very effective treatment technology for water which is contaminated by several organic pollutants such as pesticides, herbicides and pharmaceuticals[21,22].

Therefore, the yield of a BF unit depends on several factors such as the transmissivity, porosity, hydraulic conductivity, storage coefficient of the aquifer, site geometry, river hydrology, river-bed quality, water temperature in river and aquifer, and water quality[23].

Advantages of BF

The efficiency of a BF well, travel time of bank filtrate and the distance between a river and a PW mainly depend on the river hydrology, aquifer thickness and hydraulic conductivity[24]. The benefit of BF technique is to improve the quality of water by natural filtration through river bed and aquifer[23]. Moreover, the success of a BF unit depends specially on the thickness of the aquifer, infiltration area in the surroundings of a river, flow path length as well as technical, economical and land-use factors[24].

RBF method not only improves the physicochemical quality of water but also its biological quality during underground passage from the SW body to the abstraction well. Some of the important advantages of BF technology are given herein[13,17,24].

(i) Removal of particles and turbidity, bacteria and other protozoa.
(ii) Reduction of biodegradable organic compounds.
(iii) Reduction in carbon footprint if a renewable energy system is incorporated with RBF system.
(iv) Ensured riverbank storage for water which is less vulnerable to drought or flood events.
(v) BF serves as a pre-treatment step in the drinking water treatment system. It therefore lowers the maintenance compared to the conventional treatment methods. It is helpful in reducing the use of chemicals and accumulation of disinfection by-products in drinking water.

Finally, it can be concluded that BF technique is very useful due to the following reasons[12,25,26]:

1. Natural, sustainable and low-cost method.
2. Effective elimination of pathogens and other organics.
3. Disinfection is sufficient in most cases.

BF in India

Several Indian cities such as Rishikesh, Haridwar, Kanpur, Allahabad and Varanasi along the river Ganga and New Delhi, Mathura and Agra along the Yamuna river receive SW by direct abstraction for drinking and other domestic purposes; but the direct use of such type of water is not safe especially during low water flow condition due to high concentration of untreated waste. At these places, RBF technology has been considered as a suitable method to supply water of good quality[9,27–31]. Besides, BF has also become popular in Nainital adjacent to Naini lake[32] and Muzaffarnagar by the river Kali[33]; Ahmedabad and Vadodara in Gujarat state are also implementing this method. Several production wells have been installed on the bank of the Ganga river in Patna for the supply of drinking water[12].

Efforts of establishing BF in Uttarakhand

Uttarakhand has a total geographical area of 53,566 km^2, of which 93% is mountainous and 64% is covered by forest. The state comprises two regions, i.e. Garhwal and Kumaun. Out of 13 districts, 7 districts namely, Chamoli, Pauri, Tehri, Uttarkashi, Dehradun, Haridwar and Rudraprayag lie in Garhwal region; and 6 districts, i.e. Nainital, Almora, Pithoragarh, Udham Singh Nagar, Champawat and Bageshwar lie in the Kumaun region. However, four districts namely Haridwar, Dehradun, Nainital and Udham Singh Nagar occur mainly in plain areas, whereas the other nine districts comprise the hilly region of the state. The hilly parts of the districts are less developed in terms of infrastructure, especially pertaining to availability of water, either for drinking or irrigation purposes. Due to physical, geographical and environmental reasons, a major part of the rural population in the hills either survives on subsistence resources or migrates to other parts of the state or country for better resources. More than three-fourths of the state population depends on agriculture for their livelihood. Water occurs abundantly in the hilly districts of Uttarakhand and this region has great potential to supply this natural resource[13].

The proximity of rivers such as Ganga and Yamuna with various tributaries like Pinder, Mandakini, Alaknanda and Bhagirathi enable the state to select suitable target locations for RBF. Due to seasonal variations, river discharges are minimum in winters and maximum in rainy season. However, as a result of seasonal variation, i.e. either less or no rain in rainy or winter season, water scarcity results which leads to depletion in water level in main river and its tributaries. Moreover, the current water supply systems meet the local demand to some extent require renovation as well as face functional problems. Therefore, it can be said that there is lack of any permanent and long-term solution to grant adequate quantity of good quality water round the year to the population of the state.

Subsequently, BF technique has been proposed to tackle the problem of sustainable quantity and quality of domestic water supply in the state. The crucial topography of the state makes this technique a feasible option. Besides, BF is a low-cost and efficient alternative water treatment for drinking water and provides a natural means of water purification. RBF holds great potential, being a reliable and low-tech method, benefiting from the storage and contaminant attenuation capacity of the aquifer. In view of the current domestic water supply scenario, the use of BF is very important due to favourable hydrogeological conditions in Uttarakhand and is a good solution to avoid huge investments. The BF production wells have been installed successfully at the foothills in Haridwar and Rishikesh near the Ganga River and also in Nainital near the Naini lake[12,13,25,34,35].

BF has been developed in the hilly areas of the state to provide a low-cost domestic water treatment technology to remove turbidity and microbial pathogens in drinking water. In Uttarakhand, a large difference in SW quality has occurred mostly during monsoon when the turbidity is of the order of 10,000 NTU, whereas the discharge in rivers, springs or gadheras has decreased significantly in non-monsoon period. Several studies have highlighted the significance of BF as a part of an integrated water resources management to secure the quality and quantity of drinking water supply[6,11]. Drinking water production in Haridwar is approximately 60,000 m^3 per day and 38% of this water is being produced by 16 large diameter vertical caisson wells with 6.5–10.7 m depth below the ground level. Similarly, 62% of total water supply in Muni Ki Reti of Rishikesh is abstracted through two production wells installed on the banks of river Ganga[12,13,25,35].

Recently, in a project sponsored by the Department of Science & Technology (DST), New Delhi, four new RBF wells have been installed successfully by Uttarakhand Jal Sansthan at Srinagar, Karanprayag, Agastmuni and Satpuli on the banks of Alaknanda, Mandakini and East Nayar rivers respectively, with the support of Uttarakhand State Council for Science and Technology (UCOST) and University of Applied Sciences, Dresden, Germany. The success of these RBF wells can be guaged by an average daily production capacity of 852–937, 432–706, 220 and 756 (m^3) of all these four RBF units, respectively. Therefore, BF has become an alternative not only in urban areas but also for rural communities, for the production of safe drinking water in a sustainable manner in Uttarakhand[36].

RBF units at Srinagar and Satpuli towns of Garhwal: case studies

Srinagar RBF site is situated in the southwest area of Uttarakhand on the bank of river Alaknanda in Pauri district. The river has a boundary of Rudraprayag district in the east and Tehri district in the north. Geological study of the area clearly shows that the flood plain area is dominated mainly by gravel, sand and boulders. The local aquifer of the site is mainly composed of medium to coarse sand and gravel.

Satpuli RBF site is located on Kotdwar–Pauri National Highway of Pauri district on the bank of river East Nayar which is a tributary of the River Ganga. The soil of this site is the product of fluvial processes of the river Nayar and its tributaries. It is dry, porous and sandy, consisting of cobbles and gravels. The results of water quality analysis of Srinagar and Satpuli RBF sites are compared with IS 10500 drinking water quality parameters in Table 1 (refs 37–39).

A schematic cross-section diagram of RBF location at Satpuli near East Nayar river in Pauri district of Uttarakhand is given in Figure 2 (refs 39, 40).

All the selected physicochemical and bacteriological water quality parameters for water samples of both the RBF sites were found within the prescribed limit of BIS. The results of pH, turbidity, iron, fluoride and bacteriological analysis clearly indicate the effectiveness of RBF unit which is also evident in other studies[41]. After the comparison of river water with river bank filtrate, it was found that the values of total dissolved solids (TDS), total hardness, magnesium, nitrate, sulphate and chloride were higher in RBF samples than river water samples except sulphate values at Satpuli site.

In RBF sample, the pH is low due to the degradation of organic matter and formation of carbonic acid by the reaction of carbon-dioxide with water[42]. The concentration of iron in bank filtrate is less due to some oxidation–reduction reactions. In such redox reactions, iron oxides are mobilized under reduced conditions whereas these oxides are adsorbed and precipitated under oxidized conditions. No coliform colony was observed in RBF samples of both the sites which reflects the high efficiency of the

Table 1. Results of water quality analysis of Srinagar and Satpuli RBF sites in Uttarakhand[37–39]

Water quality parameter	IS 10500		Srinagar Garhwal		Satpuli Garhwal	
	Desirable limit	Permissible limit	Alaknanda river water	River bank filtrate	East Nayar river	River bank filtrate
pH	6.5	8.5	8.2	7.2	8.4	7.8
Turbidity (NTU)	5	10	3	2	1	1
TDS (mg/l)	500	2000	109	679	95	105
Total hardness (mg/l)	300	600	84	425	66	72
Magnesium (mg/l)	30	100	11	39.1	6	6.2
Nitrate (mg/l)	45	No relaxation	<1	2	<1	<1
Sulphate (mg/l)	200	400	20	152	13	13
Iron (mg/l)	0.3	1.0	0.08	0.03	0.04	0.06
Fluoride (mg/l)	1.0	1.5	0.22	0.20	0.3	0.1
Chloride (mg/l)	250	1000	8	51	7	9
Manganese (mg/l)	0.1	0.3	<0.01	<0.01	<0.01	<0.01
Arsenic (mg/l)	0.01	No relaxation	<0.005	<0.005	<0.005	<0.005
Zinc (mg/l)	5	15	0.01	0.01	0.02	0.3
Lead (mg/l)	0.05	No relaxation	<0.01	<0.01	<0.01	<0.01
Phenolic compounds (mg/l)	0.001	0.002	<0.001	<0.001	<0.001	<0.001
Coliform colonies (MPN/100 ml)	Absent	Absent	240	Absent	900	Absent

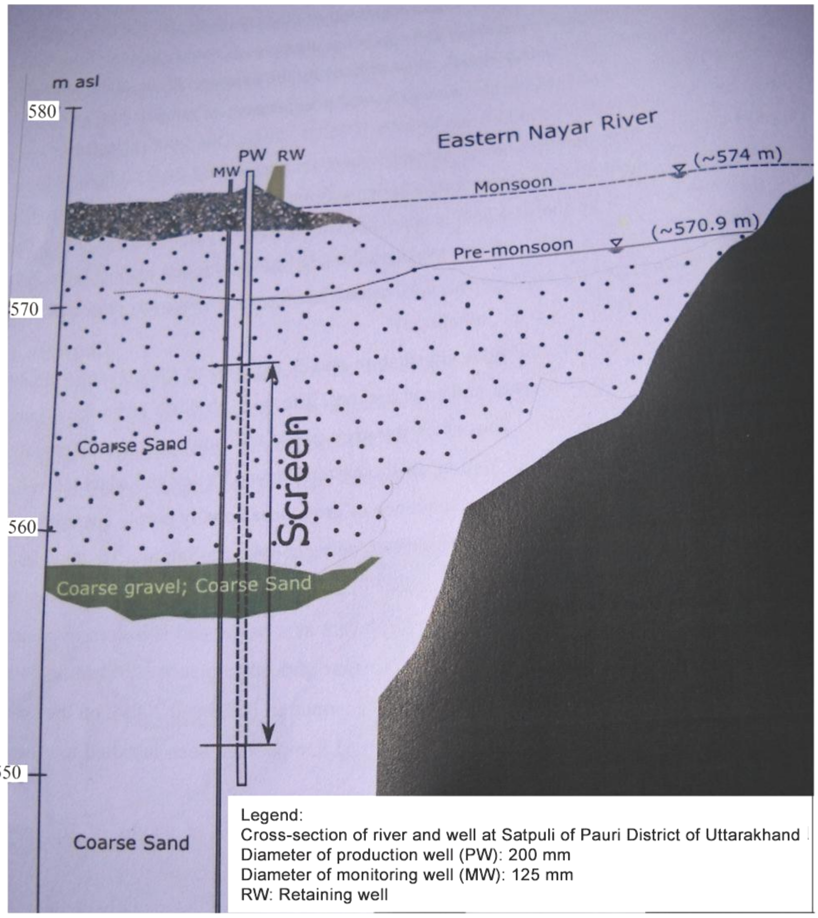

Figure 2. A schematic cross-sectional diagram of RBF location at Satpuli near East Nayar river in Pauri district of Uttarakhand[39,40].

RBF technique over any bacterial reduction method. Elimination of microbial organisms and turbidity in RBF occurs through biodegradation, natural filtration, sorption and dilution of ground water[43]. Besides, some other factors such as pH, ionic strength, redox conditions in GW, travel time in the bank, temperature, pore water velocity and soil properties, are also involved in coliform removal[44].

Higher values of other inorganic water quality parameters in river bank filtrate samples such as TDS, hardness, magnesium, sulphate, chloride may occur due to the mixing of GW and local underground lithology of the area. Nitrate value is also slightly higher in Srinagar RBF sample than the river water which may be due to the seepage of nitrogenous fertilizer or mixing with underground water; but it is below the prescribed limit of BIS. Therefore, analytical results of all the collected water samples clearly indicate the usefulness and effectiveness of RBF technique at both the places, i.e. Srinagar and Satpuli sites of Uttarakhand, thus, fulfilling the drinking water needs of the local population.

Conclusion

The RBF is a cost-effective technology for providing safe drinking water. The only difficulty of clogging of the porous media during physical filtration can be resolved by other physical processes. Moreover, the BF method has become a natural method of choice due to the enhancement of most of the water quality parameters; and it serves as an inexpensive tool to purify water from river, lake or any other water body. Besides, it has been able to replace other costly methods of water treatment and can work even in flood conditions. The results of Srinagar and Satpuli RBF sites also indicate its suitability for drinking purposes. Therefore, a small-scale community-operated RBF unit can be more beneficial to the rural areas of the state. In Uttarakhand, RBF technology has been adopted very well. Moreover, 100 more sites have been identified by UJS to establish RBF wells in the state and it is expected that the current drinking water crisis can be resolved.

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