Riverbank filtration in India – using ecosystem services to safeguard human health

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ABSTRACT

India has great potential to use riverbank filtration (RBF) for drinking water production as an ecosystem service for human health, principally through effective removal of common waterborne pathogens, even during monsoon. Water quality results from site investigations in North India have shown a removal of total and faecal coliform (indicator) bacteria in the range of 1.3 to >5.2 log for total coliforms and 2.3 to >4.2 log for faecal coliforms at the bank filtration schemes of Haridwar, Nainital, Patna, and Mathura. At rural RBF sites, where bank filtrate is collected and supplied by Koops (‘well’ in Hindi), a removal of 1.0–3.4 log and 0.3–2.8 log was observed for total and faecal coliforms respectively. At the RBF sites in Haridwar and Patna, there was only minimal breakthrough of coliforms during monsoon floods, for which disinfection using conventional chlorination was sufficient.

Key words | coliform removal, drinking water, ecosystem service, monsoon, riverbank filtration

INTRODUCTION

The resources and processes provided by natural ecosystems for the benefit of humans, including the provision of drinking water, are as a whole termed ecosystem services. High quality drinking water is paramount to human health. Aquifer recharge through induced infiltration of surface water from rivers and channels, termed riverbank filtration (RBF), is an important process which is used the world over to provide raw water for drinking water production and industrial water use. Large cities and industrial centres often developed at locations where surface water was available for water supply and transport, but the water quality has degraded as development progressed. Compared to direct abstraction of surface water for drinking water supply, RBF provides the following advantages:

- Protection against contamination by chemicals and pathogens.
- Sufficient water treatment to meet drinking water quality standards at some sites.
- Cost savings in water treatment if RBF is used as a pretreatment step.

These advantages are a direct result of the natural purification properties of the aquifer, an integral part of the ecosystem, and combine to yield (pre)treated water for drinking purposes.

RBF also provides sufficient water quality for irrigation even if the surface water is polluted by pathogens. Investigations at the Zarqa River, Jordan, demonstrated that faecal indicator bacteria and bacteriophages were removed from river water by RBF by 3.4–4.2 log and 2.7–3.3 log, respectively (Saadoun et al. 2008). In a well used for irrigation in Muzaffar Nagar, by the Kali River in the state of Uttar Pradesh in North India, total and faecal coliforms were removed by 1.7–1.9 log and >1.5 log respectively (Thakur et al. 2009). Furthermore, RBF is a type of naturally occurring and induced surface water–groundwater interaction and can be managed to enhance sanitation of surface water bodies due to very
efficient sorption and biodegradation processes in the hyporheic zone. Most RBF sites are robust against predicted climate change, especially to a higher temperature and a higher frequency of extreme events (Eckert et al. 2008; Schoenheinz & Grischek 2011; Sprenger et al. 2011).

In some towns and cities in India, existing bank filtration schemes (mainly on rivers, but also at some lakes) currently serve as both sustainable alternatives and supplements to existing surface water and groundwater sources for the public water supply. Water diversions for irrigation, hydropower generation and discharge of partially treated and untreated wastewater to surface water bodies with extremely low flows have aggravated the water supply situation and increased the vulnerability to pathogens of many Indian cities using surface water. Fortunately, most existing bank filtration systems achieve very effective pathogen and turbidity (often associated with the presence of pathogens) removal and do not require much additional treatment or disinfection of the filtrate for their water supply. Hence the further development of bank filtration in India represents a potential ecosystem service that can provide pathogen-free drinking water to many cities and towns located near perennial surface water bodies and having suitable hydrogeologic conditions.

The goal of this paper is to provide an overview of the system design, capacity, and pathogen removal efficiency of selected bank filtration sites in India, aiming to illustrate the ecosystem service they represent.

**BANK FILTRATION SCHEMES IN INDIA**

**Overview**

The benefit of obtaining very low-turbidity water via natural bank filtration as a result of the percolation of surface water during and after the monsoon has been recognised in India for a very long time. In Nainital, bank filtrate has been abstracted from Nainital Lake by production wells adjacent to the lake since 1956. The first large-diameter (∼10 m) caisson wells abstracting bank filtrate in Haridwar were constructed in the 1980s. In the cities of Ahmedabad on the Sabarmati River and Delhi and Mathura on the Yamuna, bank filtration supplements existing surface and groundwater abstraction for drinking water supply. In Haridwar and Patna on the Ganga River, and Medinipur and Kharagpur on the Kangsabati River, RBF is used as an alternative to surface water abstraction and to supplement groundwater abstraction.

**System capacity and design parameters of urban bank filtration schemes**

For an effective RBF scheme, the adjacent river should at a minimum be in hydraulic contact with the aquifer at the proposed site, but the location and design of a RBF scheme must also be based on the hydrology of the river basin, site hydrogeology and the specific water abstraction goals. A summary of system designs from selected RBF systems indicates that while in the United States a combination of vertical and horizontal or radial collector wells (RCW) is used, older RBF schemes in Germany mainly use a series of vertical wells (Grischek et al. 2002). Although a RCW is expensive to construct compared to a vertical well, the advantage of a RCW lies in its greater production capacity. This is beneficial for urban areas with a high water demand, where the production of a single RCW equals that of numerous vertical wells. This aspect is reflected in Table 1, where the RBF schemes of Ahmedabad and Mathura using RCWs have comparatively higher per-well production capacities. The RCWs in these cities are normally installed beneath the river bed in fine to medium alluvium. On the other hand, in Haridwar along the Ganga River, 22 large-diameter (∼10 m) vertical caisson wells without laterals are used to generate bank filtrate (Table 1). Due to their typical close proximity to rivers, the operation of RCWs should be accompanied by intensive water quality monitoring with respect to pathogen removal, especially during floods. Price et al. (1999) report coliform breakthrough in a RCW at the Russian River during high river stage, which resulted in temporary well closure. Also, Mutiyar et al. (2011) found lower removal of organochlorine pesticides in a RCW compared to vertical wells at the Palla well field in Delhi.

Up to the end of 2009, bank filtrate was pumped from 16 large-diameter caisson wells whose total production was 33,000 m³/day, comprising around 50% of the total...
supply, with the balance made up by groundwater from 50 tube wells (Sandhu et al. 2011a). The volume of bank filtrate abstracted as of January 2010 has increased following the construction of six new caisson bank filtration wells of a similar design to the existing wells (Figure 1). Since then more than 43,000 m$^3$ of water are abstracted every day in Haridwar by a total of 22 large-diameter caisson wells, which draw a high proportion of bank filtrate (>70%) and provide 68% of the total supply. These new wells were installed to meet the large increase in drinking water demand that was anticipated to (and did) occur during the huge religious gathering of the Kumbh Mela in January–April 2010.

**Development of Koop (wells) for small-scale bank filtration in rural Uttarakhand**

Many rural drinking water production schemes in the steeply sloped areas of the mountainous North Indian state of Uttarakhand are typically supplied by gravity tapping surface water from springs, rivers and streams with a highly variable seasonal discharge. The surface water is normally collected in boulder-filled galleries (BFGs), and does not undergo substantial pre- or post-treatment other than rapid sand filtration, and in some instances chlorination. However, the removal of turbidity and microbial pathogens by the BFGs is insufficient, especially during the monsoon (June–September) when the settling basins fill up with silt, and coagulation and filtration are inadequate to remove the turbidity. Especially large monsoon flows can also physically damage or completely wash away BFGs. Consequently, the interruption of water supply is a frequently recurring problem during the monsoon.

As a substitute to the BFG, the Uttarakhand State Water Supply organisation (UJS), developed a so-called Koop (in Hindi: well) in 1997, with more than 800 Koops installed since then, primarily for rural drinking

<p>| Table 1 | System capacity and design parameters of some bank filtration schemes in India |</p>
<table>
<thead>
<tr>
<th>Location</th>
<th>Source water body</th>
<th>Well type (number of wells)</th>
<th>Production capacity in m$^3$/day</th>
<th>Depth in m</th>
<th>Lateral distance from source water in m</th>
<th>Travel-time of bank filtrate</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haridwar</td>
<td>Ganga CW (22)</td>
<td>&gt;43,000</td>
<td>7–10</td>
<td>15–110</td>
<td>2– &gt; 100 days</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Srinagar*</td>
<td>Alaknanda VFW (6)</td>
<td>&gt;4,000</td>
<td>18–20</td>
<td>5–165</td>
<td>n. d.</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Patna</td>
<td>Ganga VFW (6)</td>
<td>&gt;3,500</td>
<td>150–300</td>
<td>9–236</td>
<td>n. d.</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Karnaprayag*</td>
<td>Alaknanda VFW (1)</td>
<td>&gt;700</td>
<td>20</td>
<td>53</td>
<td>n. d.</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Agastmuni*</td>
<td>Mandakini VFW (1)</td>
<td>&gt;280</td>
<td>30</td>
<td>53</td>
<td>n. d.</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Satpuli*</td>
<td>East Nayar VFW (1)</td>
<td>720</td>
<td>26</td>
<td>43–45</td>
<td>2 days (monsoon)– 2 weeks</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Kesarwala</td>
<td>Song River VFW (1)</td>
<td>900</td>
<td>48</td>
<td>40</td>
<td>n. d.</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Nainital</td>
<td>Lake Nainital VFW (9)</td>
<td>&gt;24,100</td>
<td>22–37</td>
<td>4–94</td>
<td>8– &gt; 30 days</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Bhimtal</td>
<td>Lake Bhimtal VFW (1)</td>
<td>&gt;320</td>
<td>48</td>
<td>16</td>
<td>n. d.</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Dehradun</td>
<td>Bandal RCW(s)</td>
<td>140–430</td>
<td>1.5–2</td>
<td>Beneath river bed</td>
<td>2–4 min</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>Sahaspur (Dehradun)</td>
<td>Swarna RCW(s)</td>
<td>210–570</td>
<td>3–4</td>
<td>Beneath river bed</td>
<td>&gt;150 min</td>
<td>Own data</td>
<td></td>
</tr>
<tr>
<td>Medinipur</td>
<td>Kangsabati RCW (1)</td>
<td>15,900</td>
<td>6–11</td>
<td>Beneath river bed</td>
<td>n. d.</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>Kharagpur</td>
<td>Kangsabati RCW (1)</td>
<td>22,700</td>
<td>6–8</td>
<td>Beneath river bed</td>
<td>n. d.</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>Muzaffar Nagar</td>
<td>Kali VFW</td>
<td>29–300</td>
<td>8–15</td>
<td>68</td>
<td>n. d.</td>
<td>c</td>
<td></td>
</tr>
<tr>
<td>Palla (Delhi)</td>
<td>Yamuna VFW (~90)</td>
<td>~100,000 (in 2007)</td>
<td>45–54</td>
<td>Few meters to 600 m</td>
<td>Few weeks</td>
<td>e, f</td>
<td></td>
</tr>
<tr>
<td>Mathura</td>
<td>Yamuna RCW (1)</td>
<td>2,400</td>
<td>15.5–18</td>
<td>Beneath river bed</td>
<td>1.5–3 days</td>
<td>d</td>
<td></td>
</tr>
<tr>
<td>Ahmedabad</td>
<td>Sabarmati RCW (7)</td>
<td>110,000</td>
<td>10–11</td>
<td>Beneath river bed</td>
<td>n. d.</td>
<td>a</td>
<td></td>
</tr>
</tbody>
</table>

CW: large-diameter (10 m) caisson well; VFW: vertical filter well (production well); RCW: radial collector well; RCW(s): small-scale radial collector well; n. d.: not determined; a: Sandhu et al. (2011a); b: Sandhu et al. (2011b); c: Thakur et al. (2009); d: Singh et al. (2010); e: Rao et al. (2007); f: Lorenzen et al. (2010); *RBF site under development since construction in 2010.
water production. However, due to the short retention time of the water from the surface to the Koop (usually a few minutes only), the attenuation of pathogens is limited. Thus, in order to obtain improved water quality by increasing the retention time of the filtrate in the subsurface, a Koop was constructed with a geotextile and improved filter-media layering (Figure 2) at a site in Sahaspur by the Swarna river (30 km west of Dehradun in Uttarakhand).

The Koop abstracts filtrate from beneath the stream bed and thus is protected from floods and has low operational costs. The Koop assembly typically consists of one vertical collector cylinder (1–2 m tall) and four perforated radial pipes. Each radial pipe is 0.5–1.0 m long and has a diameter of 0.05 m. The assembly is made from mild steel and is painted to prevent corrosion. The top of the Koop has a waterproof rubber seal and a fixed steel plate. A welded outlet socket for attaching the supply pipe is located in the
middle of the vertical cylinder. The assembled Koop is installed 3–4 m below (or beside) the bed (or bank) of the stream.

**REMOVAL OF PATHOGENS AND HARMFUL SUBSTANCES DURING RBF**

**Urban bank filtration schemes**

India is currently in a phase of rapid population growth and urbanisation that has resulted in sharply increasing quantities of domestic sewage being discharged (mostly untreated) into river systems. The efficiency of bank filtration in the pre-treatment of raw water for drinking and especially the removal of pathogens has been demonstrated for various schemes in India.

Studies on water quality changes during RBF in Haridwar commenced in 2005 on Pant Dweep Island (Figure 1). Sampling in December 2005, March 2006 and September 2006 revealed bank filtrate having very low (less than 1 mg/L) dissolved organic carbon content under aerobic conditions, an arsenic concentration of less than 0.01 mg/L and other trace metals below the Indian Standard IS 10500 (1999) limit. Dash et al. (2008) report that bank filtrate abstracted from production well 18 on Pant Dweep Island, when compared to raw Ganga River water, showed 2.5-log removal of total coliforms, 3.5-log removal of faecal coliforms, 0.7-log removal of turbidity in the non-monsoon period (November 2005–June 2006) for the shortest travel time of 84–126 days at a minimum distance of 115 m, and 4.7-log removal of total coliforms, 4.4-log removal of faecal coliforms (Table 2), 2.5-log removal of turbidity and 1.0-log removal for organics as measured by UV absorbance during the monsoon period (July–September 2006) for the shortest travel time of 77–126 days. All other water quality parameters were also within the limits prescribed by the Indian Standard IS 10500 (1999).

Lake Nainital is the primary source of drinking water for the town of Nainital. Nainital’s population before 2006 was estimated at around 42,500 people. The seasonal tourist influx temporarily adds an average of 100,000 people to this area each year. From 1990–2007 seven RBF production wells were installed adjacent to Lake Nainital. In 2008,
24,100 m³/day of water was abstracted from the production wells. The water from the production wells has been found to be of better bacteriological quality than that taken directly from the lake and treated with sand filter units. According to Dash et al. (2008), only 1.9-log (>98.6%) reduction of total and faecal coliform counts was achieved by the sand filter units whereas 5.2-log (>99.999%) and 4.2-log (>99.99%) reductions respectively were measured in the non-monsoon period while using bank filtration (Table 2). In monsoon, the removal of coliforms was greater. The observed log removal rates for faecal coliforms are in agreement with findings of Hijnen et al. (2005) and Weiss et al. (2005) in laboratory and field studies in the USA.

In Patna, the removal of total coliforms was observed to be in the range of 2.3 to 4.2 log, with a higher log removal during monsoons, on account of the higher pathogen loading and turbidity in the Ganga River (Table 2). In Mathura, the maximum breakthrough of coliforms in the RCW beneath the river bed is considerably high (Table 2) similar to the RCW at the Russian River (Price et al. 1999), not only due to the extremely high coliform counts in the Yamuna River water on account of the large quantities of untreated sewage discharged into the river, but also due to the relatively short travel time of 1.5–3 days and short flow paths to the radials positioned at depths of 15.5 and 18 m directly beneath the river bed (Table 1). Yet, RBF in Mathura serves as a significant pre-treatment step by reducing organics, contaminants, colour, UV-absorbance and coliform bacteria by around 50% from river to filtrate (Singh et al. 2010).

Up to now there are only a few data available on the occurrence of viruses and protozoa in surface water and bank filtrate in India. But viruses are regarded as the most critical microorganisms where the effectiveness of soil passage for removing pathogens from source water is concerned. However, faecal indicator bacteria also seem to be able to penetrate into an aquifer as far as viruses, and may therefore be useful indicators of faecal contamination (Schijven 2002). Foppen (2007) reports that due to the presence of dissolved organic carbon (DOC) (1–100 mg/L) attachment of E. coli to soil grains was 2 to 80 times less than in cases without DOC. Except for the bank filtration sites at the Yamuna River in Delhi and Mathura and the Kali River at Muzaffar Nagar, all investigated sites showed low DOC concentrations (0.5 to 3 mg/L) in river/lake water. As the DOC in River Ganga water and many of its tributaries and mountainous streams in Northern India is only around 1 mg/L, no negative effect on pathogen removal by attachment is expected. Another advantage of low DOC is a low risk of disinfection by-product formation if chlorination is used as the only further treatment step as often found in Northern India.

### Removal of coliforms by bank filtration through Koops in rural areas

Travel times for Koops were determined to be between 2 and 4 minutes only. For a new Koop installed using sorted filter media and a geotextile, the travel time was more than 150 minutes. An initial comparison of the removal efficiency of coliforms by conventionally built Koops for six different sites in Uttarakhand and the new Koop by the Swarna river in Sahaspur is shown in Table 3. Due to the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Koop</th>
<th>Coliform counts in MPN/100 ml without geotextile at 6 sites in Uttarakhand (n = 6)</th>
<th>Coliform colony forming units in CFU/100 ml with geotextile and improved filter-media at Sahaspur in Uttarakhand (own data; n = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCC in surface water</td>
<td>2,200–46,000</td>
<td>244</td>
<td></td>
</tr>
<tr>
<td>TCC in Koop</td>
<td>19–1,950</td>
<td>Not detectable</td>
<td></td>
</tr>
<tr>
<td>Log removal of TC</td>
<td>1.0–3.4</td>
<td>&gt;2.4</td>
<td></td>
</tr>
<tr>
<td>FCC in surface water</td>
<td>90–11,000</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>FCC in Koop</td>
<td>5–780</td>
<td>Not detectable</td>
<td></td>
</tr>
<tr>
<td>Log removal of FC</td>
<td>0.3–2.8</td>
<td>&gt;2.3</td>
<td></td>
</tr>
</tbody>
</table>

TCC (total coliform counts) and FCC (faecal coliform counts) data provided by UJS for six conventionally constructed Koops without geotextile.
very short travel times and non-standardised design geometry of Koops, the removal rates are highly variable. Surprisingly, even a very short travel time and flowpath length in the stream bed result in a considerable removal of coliforms. Although the first data from the new Koop indicate a higher removal of coliforms, prolonged monitoring is necessary to obtain comparable results with Koops installed without geotextiles, especially for monsoon conditions.

**CONCLUSIONS AND PROSPECTS OF RBF IN INDIA**

Most of the cited examples of bank filtration schemes in India illustrate the ecosystem service for providing drinking water for improved human health. Bank filtrate from a few sites monitored in recent years has shown a significantly higher quality when compared to directly abstracted surface water. However, log removal rates for faecal coliforms presented in the paper for selected sites cannot simply be transferred or assumed for other pathogens and other sites. For example, a recent study by Metge et al. (2011) suggests that in evaluating the efficacy of RBF operations to remove the protozoan pathogen Cryptosporidium parvum oocysts, it may be necessary to consider not only the geochemical nature and size distribution of the sediment grains, but also the degrees of sediment sorting and the concentration, reactivity, and aquifer penetration of the source water DOC as in the case of E. coli described above.

At most sites in India where directly abstracted surface water is used for drinking, the removal of pathogens has the highest priority. At some sites, the contamination by organic substances and heavy metals is also considerable. Bank filtration is known to provide good removal of such contaminants (Stuyfzand 1998, Ray et al. 2002). For lesser known pollutants such as persistent trace organics, detailed investigations are rare. Sprenger (2011) reports that a series of organic trace compounds including polar to nonpolar substances from household, industrial and agricultural sources were considerably attenuated following RBF by the Yamuna River.

The drinking water production of many cities and towns in India will be or is already in the process of being expanded and optimised to meet the growing water demand, such as through the City Development Plans or various schemes such as the ‘Jawaharlal Nehru National Urban Renewal Mission’, the Asian Development Bank’s current ‘North Eastern Region Capital Cities Development Investment Programme’ and the planned ‘Uttarakhand Urban Sector Development Investment Programme’ and the World Bank’s ‘National Ganga River Basin Project’. The technical and socio-economic feasibility of using RBF for urban and decentralised water supply schemes should be investigated for locations (covered by these programmes) having suitable hydrogeological conditions. This would also serve as a first step towards meeting the goals of the Government of India’s ‘National Action Plan on Climate Change’ (NAPCC 2008).

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