Saph Pani

Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India

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Database of relevant pollutants in urban areas and their attenuation at RBF sites

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Authors in alphabetic order	Adlakha LK, Ghosh NC, Grischek T, Gröschke M, Grützmacher G, Gulati A, Jain CK, Kimothi PC, Kumar P, Mehrotra I, Mittal S, Patwal PS, Rohilla RK, Ronghang M, Sandhu C, Singh H, Sprenger C, Voltz TJ
Review	Chittaranjan Ray
Compilation of deliverable and contact for queries	Cornelius Sandhu Dresden University of Applied Sciences Faculty of Civil Engineering & Architecture Division of Water Sciences Friedrich-List-Platz 1 D-01069 Dresden, Germany Email: sandhu@htw-dresden.de
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1 Introduction

1.1 Overview of the development of bank filtration in India

Until around 2004, the term riverbank filtration (RBF) or simply bank filtration (BF, a unified term for river and lake bank / bed filtration) was not commonly used in context to drinking water supply in India. The abundant recharge of traditional dug wells (used for drinking and irrigation) located near surface water bodies (mainly rivers but also some lakes) by very low-turbidity water via natural bank filtration during and after the monsoon has been recognised in India for a very long time. Induced bank filtration has been suggested in the 1970s to address the growing agricultural irrigation demand in the alluvial plains along the Ganga River by inducing recharge from surface water bodies during and after the monsoon (Chaturvedi and Srivastava 1979).

Documented evidence till date suggests that induced bank filtration has been used in India for at least 56 years, although even older BF systems may exist. In Nainital, bank filtrate has been abstracted from Nainital Lake since 1956 (Kimothi et al. 2012). BF supplements existing surface and groundwater abstraction for drinking water supply in the cities of Ahmedabad (by the Sabarmati River), Delhi and Mathura (Yamuna) and Nainital (Nainital Lake); on the other hand in Haridwar and Patna (Ganga), and Medinipur and Kharagpur (Kangsabati), BF is used as an alternative to surface water abstraction and to supplement groundwater abstraction (Sandhu et al. 2012).

Considering the continuously growing demand for drinking water in sufficient quantities, the emphasis at many BF sites has traditionally been on maximising the volumes of raw water abstracted. Furthermore, the results of a fact-finding study (Ray and Ojha 2005) on the use of BF for drinking water production in India on one hand confirmed that a number of river-side communities have been already using BF for a long time, but that on the other hand only scarce information on the hydrogeological conditions and water quality of these BF sites existed. Holistic investigations on water quality aspects and sustainability (qualitative and quantitative) of these existing BF sites began only after 2004.

1.2 Water quality aspects and relevant pollutants

Water quality investigations conducted at the BF sites of Srinagar by the Alaknanda river (Ronghang et al. 2011), Haridwar and Nainital (Dash et al. 2008, 2010; Sandhu et al. 2011a), Delhi (Sprenger et al. 2008; Lorenzen et al. 2010) and Mathura (Singh et al. 2010; Kumar et al. 2012) and Patna (Sandhu et al. 2011b) showed that the main advantage of using BF in comparison to direct surface water abstraction lies in the removal of pathogens and turbidity. The surface water concentration of trace organic contaminants and their removal at the investigated sites has not been widely investigated, but has shown to be high at sites in Delhi and Mathura (Sprenger et al. 2008; Singh et al. 2010).

For conventional treatment, high concentrations of organic contaminants requires high (40–60 mg/L) doses of chlorine prior to flocculation thus creating a greater risk for formation of carcinogenic disinfection by-products, as reported in Mathura (Singh et al. 2010; Kumar et al. 2012). In such situations BF is advantageous as a pre-treatment in order to reduce the necessary doses of chlorine prior to flocculation. Additional advantages of BF may also be seen during the monsoon season principally in the removal of turbidity and pathogens, as well as in the removal of color and dissolved organic carbon (DOC), UV absorbance, turbidity, total and thermotolerant coliform counts, endocrine disruptor compounds and organochlorine pesticides (Dash et al. 2008, 2010; Sandhu et al. 2011a; Thakur et al. 2009a, 2009b; Sprenger et al. 2011; Mutiyar et al. 2011).

BF, however, does not present an absolute barrier to other substances of concern (e.g. ammonium) and some inorganic trace elements may even be mobilized. This has been observed in Delhi which has poor surface water quality (Sprenger et al. 2008), at which extensive post-treatment is applied to remove high levels of ammonium.

1.3 Objectives

The objective of this deliverable is to provide an overview of known BF schemes in urban areas of India where the abstraction of bank filtrate is intentional by means of production wells by means of production wells. The main water quality issues of concern are highlighted. Related published and unpublished data, as well as new data collected since the commencement of the Saph Pani project in October 2011, are presented for the BF schemes in Haridwar, Nainital, Srinagar (by the Alaknanda river in Uttarakhand), Delhi, Mathura and Satpuli (by the Eastern Nayar river in Uttarakhand).

2 Haridwar

2.1 Drinking water production by riverbank filtration

The permanent population of the entire urban agglomeration of Haridwar that includes the outgrowths (suburban areas) was 310,582 persons according to the 2011 census, out of which 225,235 persons permanently reside in the main or core city area (Census of India, 2011). The bank filtrate abstracted from 22 large-diameter (10 m) caisson wells is supplied solely within the limits of the main city (Figure 2-1, Figure 2-2). Being one of the most important Hindu pilgrimage sites in the world, Haridwar has a “floating” population of around 200,000 persons who reside temporarily within the main city in religious retreat locations (“Ashrams”) and hotels, and an additional 400,000 – 500,000 persons (mainly pilgrims) visit the main city every day (Uttarakhand Jal Sansthan, 2012). Accordingly, the production from the 22 RBF wells accounts for nearly 50 % (> 43,000 m^3/day) of the total drinking water demand of the entire population within the main city. Groundwater abstraction through vertical production wells (“tube” wells) covers the remainder of the drinking water demand in the main city.

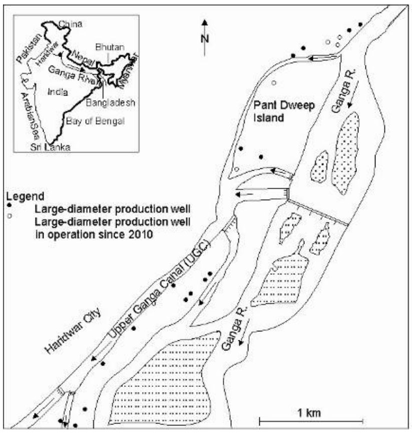

Figure 2-1 Location of large-diameter RBF wells in Haridwar (after Sandhu et al. 2011a)

Figure 2-2 Example of large-diameter RBF well adjacent to Ganga River, Haridwar (Photo: L. Rossoff, HTWD, 2011)

The bottom-entry caisson wells (RBF) are 7 – 10 m deep and are located 15 – 110 m from the Ganga river or the Upper Ganga Canal. As of April 2011, at least 12 wells operated continuously (24 hours), with the remaining wells operating for 9 – 19 hours per day. Each well usually has 2 – 3 fixed-speed vertical line shaft pumps, with each pump having a rated discharge of 600 – 2820 litres per minute (LPM), with a mean rated discharge of 1620 LPM for all pumps. However, the pumps operate on a rotational basis for a fixed number of hours each day, which is necessary for the other pump(s) to cool and avoid malfunctions. Usually during the summer (pre-monsoon) and during religious festivals, the wells operate continuously as the demand for drinking water peaks. At other times only some wells operate continuously. The abstracted water is chlorinated at the wells and then supplied directly into the distribution network. The shortest travel time of bank filtrate to the RBF wells located on Pant Dweep island < 15 m from the bank of the surface water body is 2 days to > 100 days for wells located further away.

2.2 Water quality

Due to the relatively low impact of population and absence of industries along the Ganga river upstream of Haridwar (compared to downstream), and the sufficient discharge and gradient of the river, the main water quality parameters of concern for RBF in Haridwar are pathogens and turbidity (Table 2-1). During monsoon, the total and fecal coliform counts and turbidity of the Ganga by the RBF wells in Haridwar are significantly higher than during non-monsoon periods. Dash et al. (2010) report that bank filtrate abstracted from production well 18 on Pant Dweep Island (Figure 2-3), when compared to raw Ganga River water, showed 2.5-log removal of total coliforms, 3.5-log removal of fecal 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 fecal coliforms, 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. The higher removal during monsoon is due to the significantly higher turbidity and coliform counts in surface water compared to non-monsoon. Other studies on RBF in Haridwar (Sandhu et al. 2011) have revealed bank filtrate having very low dissolved organic carbon content of < 1 mg/L under aerobic conditions, an arsenic concentration of less than 0.01 mg/L and other trace metals and major ions below the Indian Standard IS 10500 (1991) limit.

Table 2-1 Removal of coliforms and turbidity during RBF on Pant Dweep Island, Haridwar

Parameter	Range of concentration [Min. – Max. (mean ^{n})]			Proportion of bank filtrate [%]	Removal [% or Log_{10} for pathogens & turbidity]
	Surface water	Observation wells MW1 & MW2	Production wells 18 & 40		
Total coliform [MPN/100 mL]	4,300 – 230,000	<2 – 23	<2 – 93	> 70 %	2.5 (non-monsoon) – 4.7 (monsoon)
Fecal coliform [MPN/100 mL]	1,500 – 93,000	0 – 23	0 – <2		3.5 (non-monsoon) – 4.4 (monsoon)
Turbidity [NTU]	1 – 200	0.1 – 13.1	0.2 – 0.6		0.7 (non-monsoon) – 2.5 (monsoon)
n = number of samples	22	22	11	-	-

From January to April 2011, a range of physical, chemical and bacteriological water quality parameters were analysed monthly for 19 large-diameter caisson RBF wells, two vertical filter wells and the Ganga river and Upper Ganga Canal (Saini 2011). Accordingly a significant removal in the total and fecal coliform counts was observed during RBF (

Table 2-2). The total and fecal coliform counts of most of the water samples from production wells and tube wells were < 2 MPN/100 mL. Total and fecal coliform counts in the UGC were observed to be very high in the month of April because of very low flow in at the time of sampling.

Table 2-2 Total and fecal coliform counts in surface water compared to bank filtrate and groundwater from January to April 2011 (Saini 2011)

Parameter	Month	Surface water (Ganga river and UGC)	Bank filtrate (large diameter caisson well)	Groundwater (vertical filter production wells)
Total coliform count [MPN/100 mL]	January	950-1700	< 2-170	< 2
	February	160-900	< 2-13	< 2
	March	2200-9000	< 2-4	< 2
	April	3000-16000	< 2-9	< 2
Fecal coliform count [MPN/100 mL]	January	950-1700	< 2-170	< 2
	February	160-500	< 2-9	< 2
	March	2200-5000	< 2	< 2
	April	2300-14000	< 2-2	< 2

According to Saini (2011) a comparative analysis of water quality from the RBF wells shows two distinct patterns, because of which the Haridwar RBF system can be divided into the North and South parts (Figure 2-3) separated by the New Supply Channel (NSC).

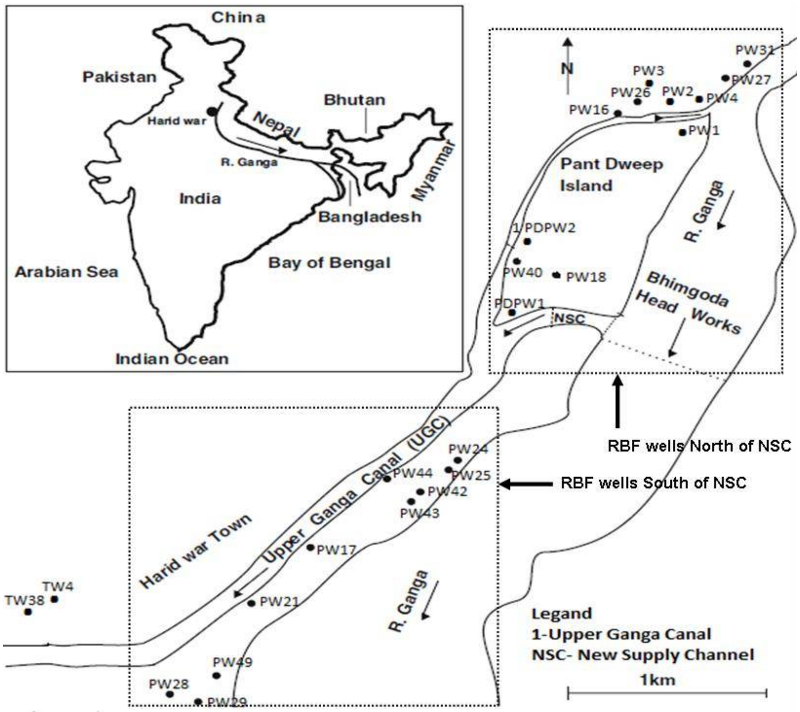

Figure 2-3 Location of RBF wells (PW) to North and South of New Supply Channel (adapted from Saini 2011)

Saini (2011) observed a different water quality pattern by analyzing the electrical conductivity, alkalinity, total organic carbon (TOC) and major ions (Annex 1). The water abstracted from the RBF wells to the North of the NSC exhibited higher mean values of electrical conductivity and concentrations of TOC, Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-} compared to the wells from the south. Furthermore the abstracted water from the RBF wells to the South of the NSC had a comparable electrical conductivity to the surface water (UGC and Ganga river). This indicates that the production wells to the north of the NSC abstract a lower proportion of bank filtrate compared to the south. A large variation of coliform counts between winter (January – February 2011) and spring months (March – April 2011) was observed for the surface water. But this did not affect the efficiency of the RBF system because the removal of turbidity and total and fecal coliforms was found to be constant.

3 Nainital

3.1 Drinking water production by bank filtration

Nainital is a popular hill station situated around Nainital Lake and located in the Kumaon region of the state of Uttarakhand, North India. The Nainital Lake provides a major source of drinking water for the towns inhabitants. The maximum depth of the lake is around 27 m and the mean depth is around 19 m. In recent decades the water quality of the lake is deteriorating due to increased human activity in the catchment area. The population around the lake was estimated to be around 50,000 persons in 2008 with a daily influx of about 5,000 persons in summer season (Dash et al. 2008). From 1990 to 2007 seven vertical production wells were installed adjacent to Lake Nainital (Figure 3-1). The depths of these wells ranged from 22.6 to 36.7 m. In 2010 around 24.1 million liters per day (MLD) of water was drawn by UJS from tube wells and pumped to reservoirs at higher elevations to allow the water distribution system to be pressurised by gravity.

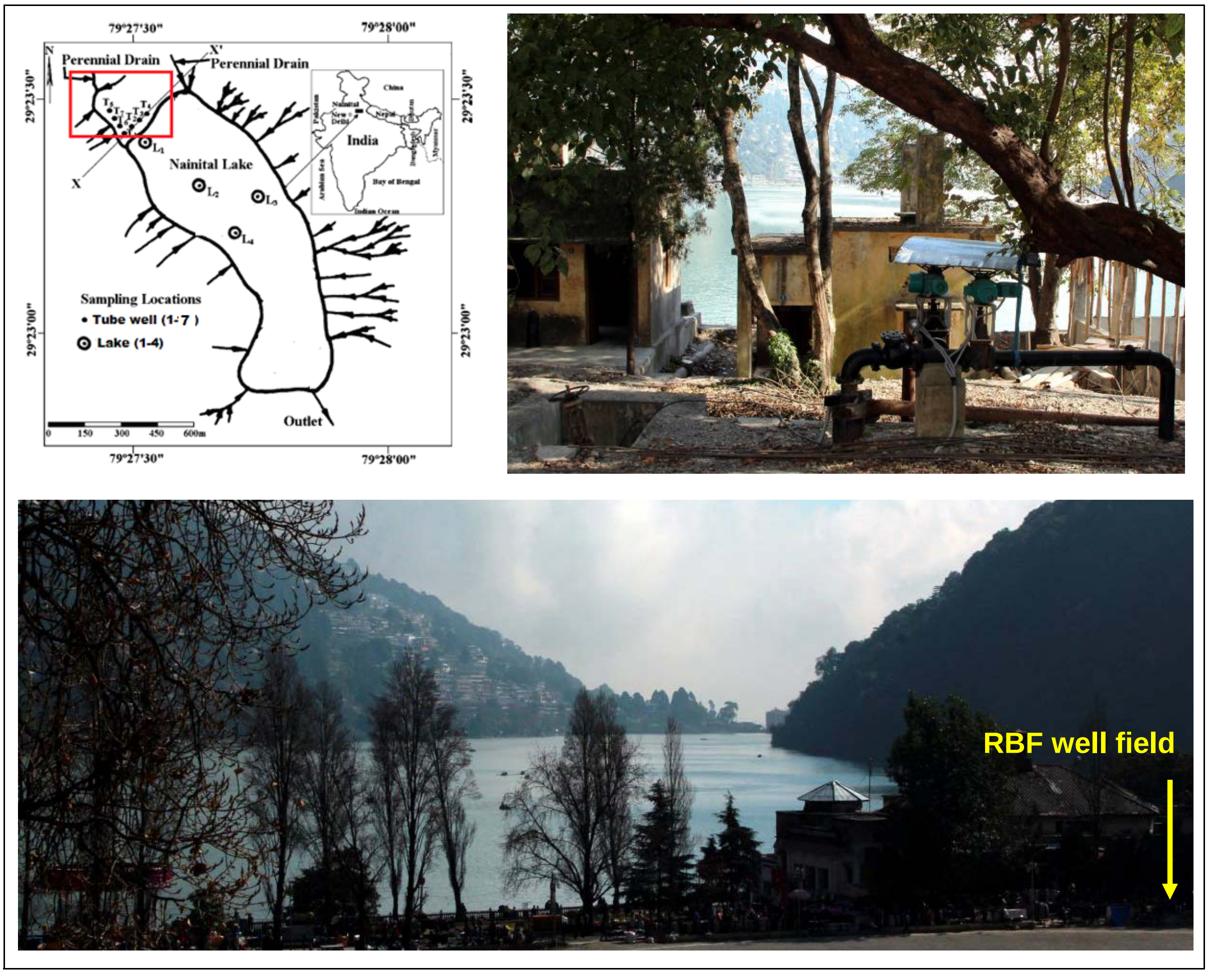

Figure 3-1 BF well field in Nainital by Nainital Lake (map: Dash et al. 2008; Photos: L. Rossoff and T.J. Voltz, HTWD, 2011)

3.2 Water quality

As there is no major industrial activity in the catchment, the main water quality parameter of concern in the abstracted water from tube well are pathogens for which disinfection is done prior to distribution (Annex 3). In some of the production wells the occasional presence of total coliforms was in the range of < 2 – 7 MPN/100 mL, but no fecal coliforms were observed and hence the water can be considered suitable for drinking purposes after disinfection. Comparison of bank filtrate to the raw lake water showed removal of total coliform in the range of 2.1 to > 2.9-log. For the removal of fecal coliform this range varies from 1.7- to 2.1-log.

Turbidity levels in all the production well is less than 1 NTU which is well within the range of the Indian Standard IS 10500 (1991). Removal of turbidity is in the range of 0.2-log to 1.6-log for the period June – September 2012 (monsoon). The abstracted water from some of the wells shows a low level of dissolved oxygen, which may indicate prevalence of anaerobic conditions in certain parts of the aquifer. Analysis of lake water and bank filtrate showed concentration of major ions like Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} to be more in the well than in the lake. But even the maximum reported concentration of the ions is within the permissible range given in the Indian Standard IS 10500 (1991).

Average total dissolved solids and electrical conductivity for lake water are 354 mg/L and 590 µS/cm, respectively while the same ranges from 388 – 523 mg/L and 646 – 867 µS/cm for well water, which is quite evident given the higher concentration of various ions in well water than the lake water.

The hardness as $CaCO_3$ of the abstracted water from different wells ranges from 303 – 455 mg/L and in the absence of an alternative source, it lies within the permissible range of the Indian Standard IS 10500 (1991). A lower UV absorbance of bank filtrate than the lake water signifies reduction in TOC.

4 Srinagar

4.1 Drinking water production by bank filtration

The town of Srinagar is located on the south bank of the meandering Alaknanda River along the main road to the Hindu shrine of Badrinath in the Lesser Himalayas of Garhwal in the state of Uttarakhand. Srinagar had a population of around 19,658 persons up to 2001 (Census of India 2001), which was expected to increase up to 31,500 persons by 2010 (Kimothi et al. 2012). Similar to Haridwar, the seasonal population of pilgrims can account for a significant (8 % – 17 %) portion of the total population of Srinagar, and thus the town's total population is projected to further increase (compared to 2001) by 52 – 60 % for the period of 2013 – 2018 (Sandhu et al. 2011a).

The combined drinking water production for Srinagar and the town of Pauri (the water for which is abstracted and treated in Srinagar before being pumped 29 km to Pauri at an altitude of around 1660 m above MSL) in 2010 was around 3,750 m^3/day in contrast to a total demand of approximately 4,880 m^3/day (Kimothi et al. 2012). Currently around 80 – 82 % of the total raw water for the drinking water supply of Srinagar and Pauri is abstracted upstream of the town directly from the Alaknanda River. The abstracted surface water is passed through rapid sand filters and chlorinated before being supplied to the distribution network. But with the completion of the dam and a tunnel (>3 km; Kaur and Kendall 2008) in the near future to divert a major portion of the flow for a river-run hydropower generation plant on the Alaknanda at Koteshwar, approximately 4 km upstream of Srinagar, will soon make the current surface water abstraction system inoperable resulting in the Alaknanda having severely reduced flow along the 4 km stretch where the current surface water abstraction system is located (Sandhu et al. 2011a).

In May 2010, one production and one monitoring well (PW-DST & MW1) were constructed in the south-west part of the town (Figure 4-1) as part of a separate project (Ronghang et al. 2011; Kimothi et al. 2012). The wells were drilled up to a depth of 20 m BGL and at a distance of 170 m from the flood-protected riverbank. The interpretation of the borehole material showed that the aquifer comprises medium to coarse sand. Interpretation of pumping test data from PW-DST showed the hydraulic conductivity to be in the range of 7.7×10^{-5} – 4.0×10^{-3} m/s. The PW-DST currently operates for 20 – 22 hours/day with a production of 852 – 937 m^3/day. After abstraction and on-site disinfection by chlorination, the water is pumped into a storage reservoir and then supplied into the distribution network by gravity. The production from the PW-DST accounts for 18 – 22 % of the combined drinking water production of Srinagar and Pauri (Kimothi et al. 2012).

However, the predominantly ambient groundwater initially abstracted contained high nitrate concentrations in the range of 53 – 123 mg/L (Table 4-1). High nitrate concentrations in groundwater is a common occurrence in areas where agricultural activities lead to widespread fertiliser application or wastewater from leaky open urban drains and sewers (such as in Srinagar) comes in contact with groundwater. With the objective to lower the high nitrate concentrations by increasing the proportion of bank filtrate in the abstracted water, and to cater to future increases in demand, four additional wells were drilled (currently only PW4 has a temporary submersible pump for testing purposes) in between the existing PW-DST and the river from July – September 2011 (Figure 4-2).

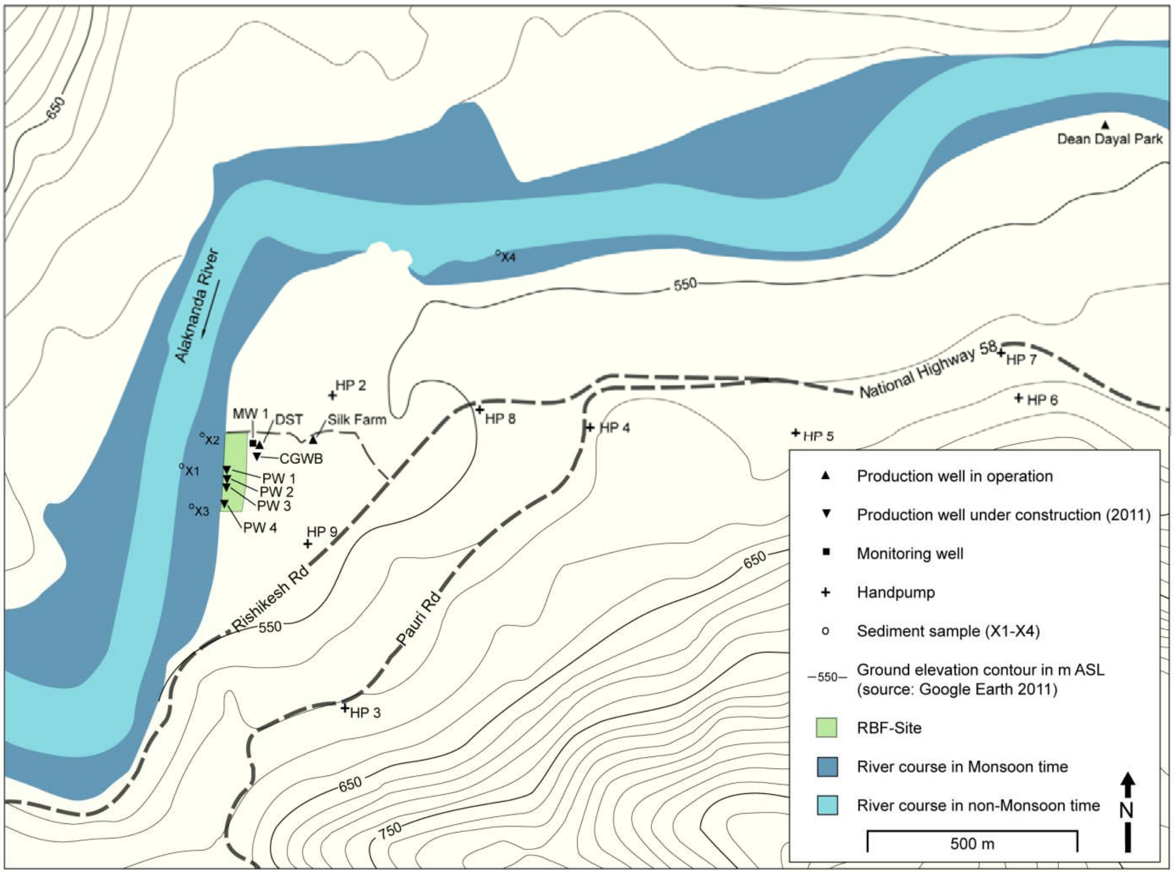

Figure 4-1 RBF well field in Srinagar under development since May 2010

Figure 4-2 View of four additional production wells installed in August 2011

4.2 Water quality

Within the framework of the Saph Pani project, a monitoring well (MW4) was constructed in May 2012 by the project partners Akshay Jaldhara and Uttarakhand Jal Sansthan in between PW4 and the river (Figure 4-3 and Figure 4-4). MW4 is 15.1 m deep and is situated at a distance of 4 m from the flood-protected river bank and 0.75 m from PW4. The close proximity to the high-flow mark of the river is intentional in order to investigate the removal efficiency of pathogens during monsoons and floods. The determination of the removal efficiency of pathogens, by comparing the total and fecal coliform counts of the abstracted water from PW4 and the Alaknanda, commenced in end September 2012.

Figure 4-3 Monitoring well MW4 (left) constructed in between PW4 (right) and Alaknanda, Srinagar (Photo: HTWD, 2012)

Figure 4-4 Pumping test and sampling being conducted on MW4 and PW4, Srinagar (Photo: V.D.A. Nguyen, HTWD, 2012)

The water quality from the DST production well (PW-DST) and surface water are shown in Table 4-1. All the parameters in the PW-DST were within the stipulated Indian Drinking Water Standards (IS 10500, 1991), except nitrate and total hardness concentrations. However, in the absence of an alternative drinking water source, the limit for the concentration of the total hardness is extended to 600 mg/L. Thus the average total hardness concentration of 439 mg/L can be accepted to be within the limits. On the other hand the hardness of the river water is in the range of 59 – 141 mg/L as $CaCO_3$. An occasional presence of total coliforms in the raw water abstracted by the PW-DST was also encountered. This is not uncommon, especially downstream of human habitation (Ferguson et al. 2011). The abstracted water quality has shown an improvement in terms of turbidity and coliform removal. All other essential parameters are within the permissible limits. The removal of coliforms and turbidity is observed to be up to 5 log orders. The turbidity from the water of PW-DST is observed to be in the range 0.5 – 2 NTU, which is significantly lower than the mean turbidity of 417 NTU (max. 1771 NTU during monsoon) observed in the Alaknanda river.

Table 4-1 Water quality of production well PW-DST compared to Alaknanda river

Parameter	Range of concentration [Min. – Max. (mean ^{n})]	
	Surface water	Production well
pH	7.6-8.5 (8.1)	6.5-7.8 (7.2)
T, ^{0}C	14-18 (17)	23-24 (24)
Electrical conductivity, µS/cm	104-185 (138)	724-1158 (1027)
Total Dissolved Solids, mg/L	81-131 (96)	514-793 (715)
Turbidity, NTU	12-1771 (417)	0.5-2 (1.1)
Dissolved Oxygen, mg/L	9.4-12 (10.5)	1.1-3 (1.7)
Alkalinity (as $CaCO_3$), mg/L	51-112 (63)	310-375 (342)
Hardness (as $CaCO_3$), mg/L	59-141 (83)	376-629 (439)
UV-A, cm^{-1}	0.01-0.05 (0.03)	0.01-0.05 (0.03)
DOC, mg/L	0.6-1.1 (0.9)	0.7-1.9 (1.5)
Sodium (as Na^{+}), mg/L]	0.9-7.7 (3)	34-78 (60.7)
Potassium (as K+), mg/L	0-3.8 (1.3)	5-39 (15.5)
Calcium (as Ca^{2+}), mg/L	21-56 (30)	39-171 (99)
Magnesium (as Mg^{2+}), mg/L	2.4-20 (6.7)	32-71 (43.2)
Fluoride (as F^{-}), mg/L	0-0.2 (0.1)	0-0.2 (0.1)
Chloride (as Cl^{-}), mg/L	0.4-10 (2.3)	39.6-72 (59.1)
Nitrate (as NO_3^{-}), mg/L	0.7-2.2 (1.4)	53-123 (86)
Sulphate (as SO_4^{2-}), mg/L	2.3-27 (13)	49-253 (107.7)
[a]Total coliform, MPN/100 mL	1.3×10^4-9.2×10^5 (2.2×10^5)	<2-300 (53)
[a]Fecal coliform, MPN/100 mL	5×10^3-9×10^4 (1.7×10^4)	<2
n =7 (number of samples) a= mean based on 6 samples (collected in May 2010, and in 2012 in February, May, June, July and August		

5 Delhi

5.1 Drinking water production by riverbank filtration

According to the 2011 census, 16,753,235 persons are permanently residing in the area of the National Capital Territory (NCT) Delhi, with a decadal population growth of 24.56 % in the past decade (Census of India 2011). In the past years, the annual water requirement of the city was estimated to be 1,435×10^6 m^3, of which the Delhi Jal Board (DJB) supplied 1,044×10^6 m^3 (Chatterjee et al. 2009 after CGWB 2006). This volume was provided by the diversion of surface water from the neighbouring states Haryana and Uttar Pradesh and by the extraction of groundwater (Shekhar and Prasad 2009). The proportion of groundwater in the DJBs water supply was about 15 %; figures here vary between 140×10^6 m^3 per year (Sejwar 2005) and 166×10^6 m^3 per year (Chatterjee et al. 2009 after CGWB 2006). However, the actual groundwater extraction probably is higher, as many households have private bore wells in order to close the gap between public supply and actual demand. In their current annual report, the CGWB estimates the groundwater extraction in Delhi to be 400×10^6 m^3 (CGWB 2012).

The River Yamuna, with the NCT Delhi mainly located on its right (East) bank, originates from the Yamnotri Glacier in the Himalayas and after covering a distance of 1376 km it joins the River Ganga at Allahabad. The Newer Alluvium (also called Younger Alluvium) in the flood plain of the Yamuna constitutes Delhi's aquifer with the highest fresh water potential. It consists of Quaternary sands with partings of silt and clay. It has an average depth between 30 and 40 m and is underlain by the Older Alluvium, which has less favourable hydraulic properties (Kumar et al. 2006). The transmissivity of the Newer Alluvium aquifer ranges from 730 to 2100 m^2/day and the recorded discharge of wells in that formation is about 150 – 300 m^3/h (Chatterjee et al. 2009). Numerous tube wells and about 20 horizontal collector wells that tap the Newer Alluvium were constructed in the flood plain, although no well fields have been specifically designed for RBF. However, it can be assumed that the wells situated very close to the river draw a high share of bank filtrate. In the frame of the TECHNEAU project, two locations in Delhi, Palla and Nizamuddin, were investigated to determine their potential as RBF sites (Lorenzen et al. 2007; Sprenger et al. 2008; Lorenzen et al. 2010a, 2010b).

5.2 Palla well field

The Palla well field is located in North Delhi before the urbanised areas of the NCT begin, and where the water quality of the Yamuna is comparatively good. On a stretch of 10 km on the west bank of the Yamuna approximately 90 wells are operated by the municipal water supplier Delhi Jal Board (Lorenzen et al. 2010a). The well field was designed for the abstraction of monsoon flood recharge and not for bank filtration. Wells are often situated not parallel to the river bank, as suggested for bank filtration well fields, but are situated perpendicular to the shore line (Fehler! Verweisquelle konnte nicht gefunden werden.).

The first well at the shore line abstracts a comparatively high share of bank filtrate and the following wells receive only minor amounts of bank filtrate. The wells were constructed on pillars; this allows operation during floods. However, local residents report that there has been no flood event since at least 2006.

The well investigated in the frame of the TECHNEAU project (Sprenger et al. 2008, Pekdeger et al. 2008) is situated in the northern part of the well field (Figure 5-1). Depending on the river stage and the course of the Yamuna River, the RBF well is at a distance between 40 – 60 m from the river bank. The partially penetrating well has a total depth of 54 m below ground level. According to the CGWB, the diameter of the casing is 12" and the well diameter is around 15". A gravel pack fills the entire depth of the well and no clay grout was built. The filter screen was constructed with a total length of 29 m (CGWB, 2005). The well field was reported to abstract around 100,000 L/day (24 MGD) (Rao et al. 2007) for the municipal water supply of Delhi. The well has a capacity of 3,800 m^3/day and is running approximately 18 hours a day (Lorenzen et al. 2010a). It was found that travel times during monsoon (2 months) are substantially shorter compared to pre-/post monsoon period (2.5 months).

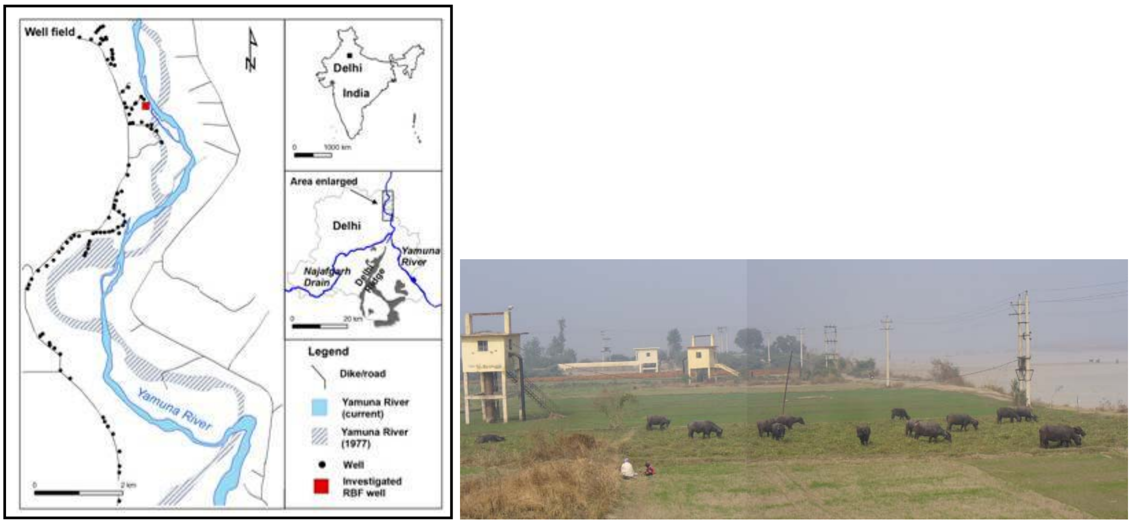

Figure 5-1 Location and example of production wells in Palla well field, Delhi (Photo: G. Lorenzen, FUB, 2009)

5.3 Water Quality of Palla well field

Due to the situation of the well field upstream of Delhi, the water quality of the Yamuna is comparatively good. Even in the surface water, main ions and heavy metals are all below Indian drinking water standard threshold values, this is also the case for the observation and the production well. The main water quality parameters of concern are pathogens because travel times and hence purification capacity vary largely. In non-monsoon times pathogens are successfully attenuated during the aquifer passage (Table 5-1). However, during monsoon floods, the shortened travel times might lead to pathogen breakthrough.

The following analyses are of samples taken from one observation well and the RBF well. Data were taken from the report TECHNEAU D 5.2.6 (Sprenger et al. 2008), whereby only samples analyzed by the SGS laboratory were considered. In the report, units for coliforms, E. coli and Enterococci were accidentally given as cfu/100 mL; the correct units, however, are MPN/100 mL for coliforms and E. coli and cfu/mL for Enterococci.

Table 5-1 Values of relevant parameters and their removal during RBF in Palla

Parameter	Concentration			Proportion of bank filtrate [%]	Reference
	Surface water	Observation well PZ2	Production well		
Coliforms [MPN/100 mL]	1.2×10^3	< 1	---	Approx. 60 %	Sprenger et al. (2008)
E. coli [MPN/100 mL]	4×10^2	<1	---		Sprenger et al. (2008)
Enterococci (Fecal Streptococci) [cfu/ mL]	20	<1	---		Sprenger et al. (2008)
n = number of samples	1	1	1	-	-

5.4 Nizamuddin well field

The production wells of the Nizamuddin site are situated in East Delhi, on the east bank of the Yamuna River near the Akshardham Temple. Here the flood plain can be divided into the active flood plain, which is about 200 m wide and the upper flood plain with a width of 2 km. All wells are located on the upper flood plain, which is protected by an embankment. The wells are not arranged parallel to the river bank but were constructed across the complete width of the upper flood plain (Fehler! Verweisquelle konnte nicht gefunden werden.). The well field consists of Ranney wells (radial collector wells), which are between 15 and 20 m deep, (personal communication DJB 2012) and tube wells. However, it is not known how many wells make up the well field, how many hours per day they are operated, and if the water is transferred into the drinking water supply network.

The production well in the frame of the TECHNEAU project is a Ranney well at a distance of 500 m from the shore. It was not in regular use until 2011 but was only operated during times of water shortage. Currently the well is operated on a daily basis; however, the water is not transferred into the water supply network (personal communication DJB 2012).

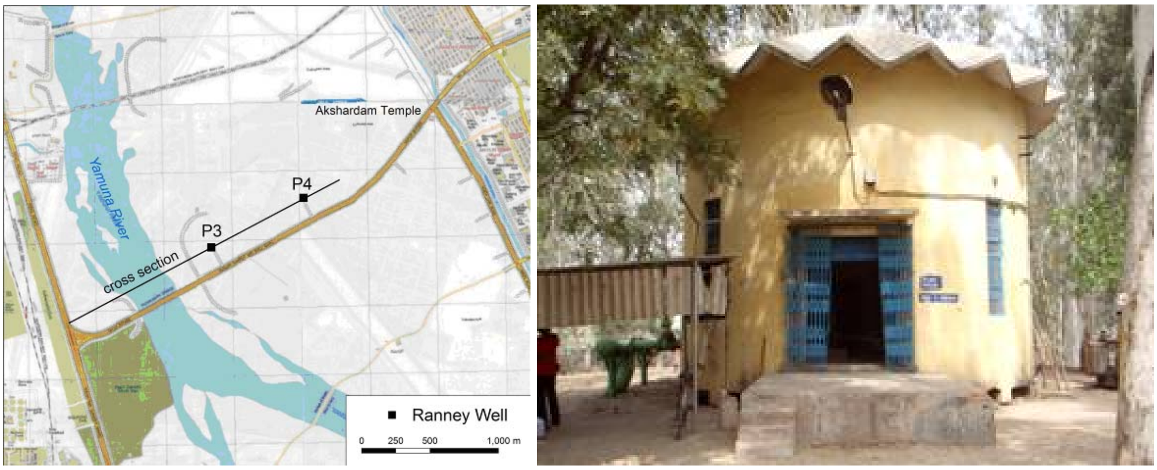

Figure 5-2 Location and example of the investigated Ranney well P3 in the flood plain in East Delhi (Photo: M. Groeschke, 2012). Geological cross section is shown in Figure 5-3.

5.5 Water quality of Nizamuddin well field

Due to the discharge of domestic and industrial sewage water into the Yamuna River through several drains in Delhi, the river is highly polluted at the Nizamuddin field site (Lorenzen et al. 2010a). Thus pathogens are a water quality parameter of concern. Microbiological analysis at this site includes fecal bacteria and indicator bacteria, bacteriophages and enteric viruses in the river and proximal observation wells. Because the investigated production well (Figure 5-3) is at a distance of 500 m from the river bank, no microbiological analyses have been made of samples from the well.

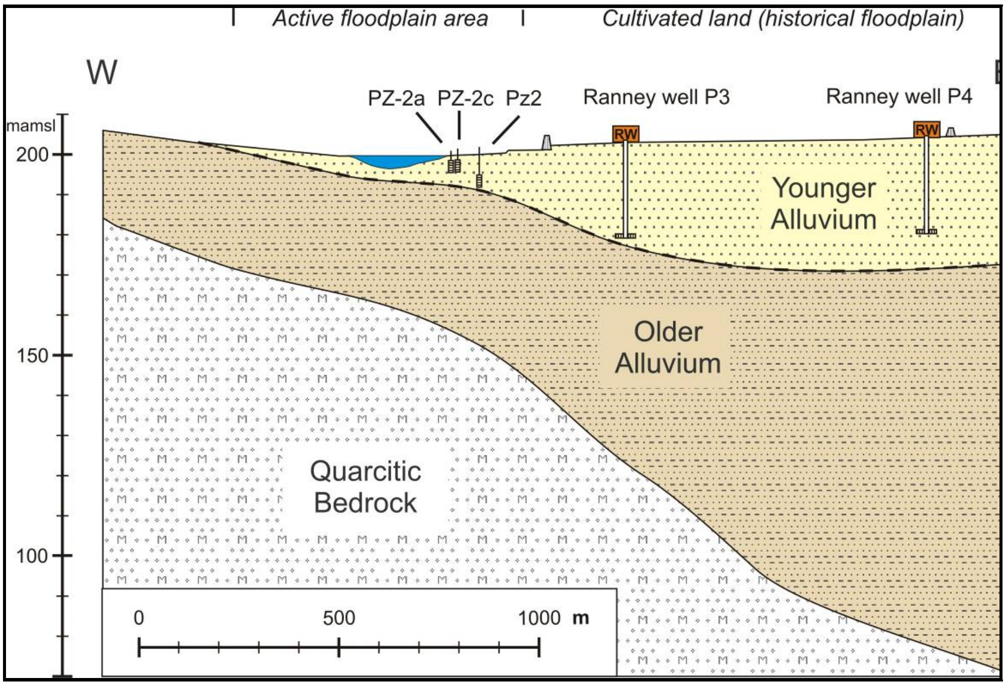

Figure 5-3 Cross sectional view of local geology, location of the observation wells (PZ2a, PZ2c, PZ2) and production well (P3)

In addition to the microbiological contamination, Fe, Mn, As, F, NH_4 are critical water quality parameters at this field site. In the surface water, only Mn and F sometimes exceed the threshold values of the Indian standard IS 10500 of 0.3 mg/L (Mn) and 1.5 mg/L (F) (Indian Standard IS 10500, 1991). However, both parameters, as well as Fe and As, increase during underground passage, so that all four parameters can be found in elevated concentrations in the production well and make a post treatment necessary (Pekdeger et al. 2008). Furthermore, NH_4 can be found in concentrations up to 40 mg/L in the surface water and up to 32 mg/L in the groundwater (Table 5-2).

Table 5-2 Values of relevant parameters and their removal or increase during RBF in Nizamuddin

Parameter	Range of concentration [Min. – Max.]					Reference
	Yamuna River	Observation wells			Production well P3	
		NI-PZ-2a	NI-PZ-2c	NI-PZ-2		
Distance from River (m)		1.5	3.8	50	n. d.	
Well depth (m)		3.4	3.9	13	~ 15	Sprenger et al. (2008)
Proportion of bank filtrate (%)		100	100	80-90	n. d.	Sprenger (2011)
Total Coliforms (MPN/100 mL)	1.5×10^5	8×10^4	4×10^2	1.8×10^3	n. d.	Sprenger et al. (2008)
E. coli (MPN/100 mL)	1.2×10^5	6.8×10^4	5×10^2	2×10^2	n. d.	Sprenger et al. (2008)
Enterococci (fecal streptococci) (cfu/mL)	5000	3600	<100	<100	n. d.	Sprenger et al. (2008)
n = number of samples	1	1	1	1		
Somatic bacteriophages (pfu/100 mL)	1.2×10^5	47	2	n. d.	n. d.	Sprenger et al. (2008)
n = number of samples	3	3	3	n. d.	n. d.	
Fe (ppm)	0 – 1	0 – 2.6	2.5 – 2.9	0 – 4.85	0.6 – 6.9	Mostly unpublished data till April 2012
Mn (ppm)	0.22 – 0.73	0.73 – 0.9	1 – 1.2	0.4 – 1.82	0.8 – 1.05	
As (ppm)	0 – 0.006	0.005 – 0.009	0.006	0 – 0.056	0.033 – 0.11	
F (ppm)	0 – 3.5	0.6 – 0.8	0.6 – 0.8	0 – 4	0 – 0.3	
NH_4 (mg/L)	4 – 40	5	5	10 – 32	8 – 9	
n = number of samples	13	2	2	14	3	

6 Mathura

6.1 Drinking water production by RBF at Mathura

The River Yamuna has been acclaimed as a holy river in the Indian mythology. Around 155 km downstream of Delhi, the city of Mathura (27° 28' N, 77° 41' E; State-Uttar Pradesh: Northern part of India) is located on the Yamuna's bank. According to Central Pollution Control Board (CPCB 2006) about 85 % of the total pollution in the river is caused by domestic sewage. Water supply schemes at Mathura-Vrindavan and Agra utilize the polluted river water as raw water for the production of potable water. Mathura has two water supply schemes at two sites which are approximately 4 km apart.

At one of the sites, sub-surface water is collected from a 25-year-old radial well, centered in the riverbed and having thirteen radials (total length of 522 m) laid at 15.5 to 18 m below and located entirely beneath the bed of the river. A sketch of this 44-m tall radial well at Mathura is given by Singh et al. (2010). Bank-filtrate is aerated, filtered, chlorinated and distributed. Water is neither pre-chlorinated nor coagulated. Only post-chlorination (with a chlorine dose of around 1 mg/L) is practiced.

The water-bearing stratum at the RBF site at Mathura was estimated to be as much as 26 m below the bed of the river. The Indian practice of using the horizontal collector wells is in general different than the practice in Europe and USA. In India, it is a common practice to place the caisson in the river bed so that all the laterals remain completely below the river bed, as at Mathura. The water supply scheme of Ahmedabad, India where seven radial wells are placed in the centre of the River Sabarmati is another example. Although exact comparison has not been attempted, Indian practice is quite successful where groundwater is saline. The aquifers in and around Mathura are characterized by varying hydrogeological conditions, even within short lateral distances. Placement of the well in the centre of the river in such a situation yields filtered river water with little or no mixing with groundwater. One of the major disadvantages is that the travel time is relatively short and correspondingly limited purification in terms of organics and microorganisms is achieved. Travel time from the bed to the laterals computed from the values of the coefficient of hydraulic conductivity ($K = 1\times10^{-2}$ to 2×10^{-2} m/s) was estimated to be 1.5 to 3 days. In Germany, a travel time of 50 days is commonly recommended for the elimination of the microorganisms and to create a sanitation zone around the well. However, in the USA RBF systems are operated at a much shorter detention time.

6.2 Water quality

Perusal of the data in Table 6-1 indicates a variation in turbidity of the river water only up to around 14 NTU. This was due to samples having been collected in pre- and post-monsoon periods only. Turbidity of the Yamuna water during monsoon ranged from 70 to 180 NTU (CPCB 2006). The pH of the river water varied from 7.4 to 8.2. River water on an average contained dissolved salts of around 825 mg/L which is more than the desirable limit of 500 mg/L. Average conductivity (~1370 µS/cm at 25 °C) and alkalinity (~320 mg/L as $CaCO_3$) were also high due to the presence of substantial amounts of dissolved salts. Average values of dissolved organic carbon (DOC) (~7 mg/L), UV-absorbance (~21 m^{-1} at 254 nm) and colour (~55 colour units, CU) indicated the presence of organic compounds in the Yamuna water. The colour due to inorganic metal ions at pH 7.4 to 8.2 is unlikely. River water was found to be contaminated with coliform bacteria having a most probable number (MPN) in the range of 23 x 10^2 to 15 x 10^5 per 100 mL.

Table 6-1 Water Quality Parameters: RBF site at Mathura (Kumar et al. 2012)

Water quality parameters	River water (n[a]=17)	Riverbed filtrate (n=13)	Filtrate after post-treatment (n=31)
Temperature (ºC)	19.8 - 21.6	21.4 - 24.7	21.6 - 24.4
Conductivity (µS/cm at 25ºC)	1170 - 1527	1292 - 1483	1391 - 1515
Total dissolved solids (mg/L)	690 - 902	622 - 934	683 - 954
Turbidity (NTU)	3.83 - 13.60	0.67 - 4.29	0.15 - 3.48
pH	7.43 - 8.20	7.18 - 8.23	7.69 - 8.20
Colour (CU)	40 - 166	18 - 29	15 - 20
		[55 - 82.5 %]	[62.5 - 88 %]
UV absorbance (m^{-1} at 254 nm)	11.0 - 28.0	7.00 - 13.0	7.0 - 11.0
		[36 - 54%]	[36 - 61%]
DOC (mg/L)	4.04 - 29.1	1.65 - 6.30	2.32 - 5.77
		[59.2 - 78.4%]	[43 - 80.2%]
DO (mg/L)	5.14 - 7.17	0.22 - 0.97	5.36 - 6.68
Ammonia (mg/L)[c]	10.2	15.4	-
Bromide (µg/L)[e]	263	371	372
TC (MPN/100 mL)	23×10^2 - 15×10^5	43 - 75×10^3	< 3
FC (MPN/100 mL)	150 - 23×10^4	43 - 93×10^2	-

[a] n indicates the number of samples analyzed.
[b] Values in brackets [ ] in the 3rd , and 4th columns indicate percent decrease.
[c] Limited data: analysis carried out only during seventh and sixth sampling respectively.

Additional information on the water quality of the Yamuna River (just down-stream of Mathura) was obtained from the report on Water Quality Status of Yamuna River published by the Central Pollution Control Board (CPCB 2006), based on data collected during a period of six years from 1999 to 2005. Based on the data of CPCB, the Yamuna at Mathura appears to be substantially polluted in terms of organics (COD: 13-94 mg/L and BOD: 3-21 mg/L), nitrogen (ammonia: up to 36.6 mg/L and total Kjeldahl nitrogen: 1.12-41.3 mg/L) and bacterial contamination (total coliforms: 13.2 x 10^3 - 26.1 x 10^6 and fecal coliforms: 90 x 10^1 - 28.2 x 10^5 MPN per 100 mL). DOC, UV-absorbance and colour reported in Table 6-1 are also indicative of organic pollutants in the river. The BOD to COD ratio works out roughly 0.25, indicating that organic matter is largely refractory in nature. Very high values of total and fecal coliforms are indicative of substantial bacterial contamination. Values clearly prove that Yamuna water at Mathura is grossly polluted. It is a difficult raw water source to be treated to the level of human consumption using only conventional treatment, making use of Yamuna water for water supply at Mathura questionable.

At RBF site, bed filtration effectively reduced colour, UV-absorbance and DOC by 55 to 82 %, 36 to 54 %, and 59 to 78 % respectively. Accordingly, radial well water was found to have an average UV-absorbance of 9.6 m^{-1} at 254 nm, DOC of 4 mg/L and colour of 23 CU. Total coliforms in the river water (23 x 10^2 to 15 x 10^5 MPN/100 mL) were reduced to between 43 and 75 x 10^3 MPN/100 mL, a reduction of around two logs. The high removal rates are indicative of a longer travel time of the bank filtrate than calculated based on the simple grain-size analysis. This could be a result of the river bed clogging in the vicinity of the well as the quantity of the water withdrawn has reduced over the years. Bed filtered river water is post-chlorinated to maintain a residual chlorine concentration of 0.2 mg/L.

UV-absorbance of a water sample at 254 nm is a measure of the prevalence of organic compounds. During RBF organics are sorbed and/or degraded. The Specific UV Absorption Coefficient (SUVA) is the UV-absorbance at 254 nm per mg/L of DOC. It is a measure of the aromaticity of the organic compounds. It reveals the shift in the ratio of organics which absorb at 254 nm to DOC. On average, SUVA of river water of around 1.18 L/ (m) (mg) was found to increase by more than two times to around 2.52 L/ (m) (mg) in bank filtrate. If data of only the seventh sampling investigation is considered, SUVA was estimated to increase from 0.68 L/ (m) (mg) (river water) to 2.33 L/ (m) (mg) (bank filtrate). There is a major shift in the character of the organic matter reflecting preferential removal of organics of a particular character during RBF and unequal removal of materials of different characters. The removal mechanisms in the subsurface (e.g. biodegradation, sorption, filtration) appear to respond differently to various molecular-weight fractions of DOC during ground passage. The increase in SUVA value in the river bed indicates a stronger attenuation of non-UV-active compounds compared to UV-active compounds. Although RBF produced water of low DOC, however, the water collected through RBF did not met the guideline of 2 mg/L.

The distribution of THMs (chloroform, bromodichloromethane, dibromochloromethane, bromoform) in different water samples collected in Dec. 2007 (sixth sampling) was found. River water, bank filtrate, and RBF treated water were found to have very low values of total THMs (Kumar et al. 2012). Bank filtrate and RBF treated waters (with post-chlorination, using a dose of 1 mg/L chlorine) had total THMs < 1 µg/L.

To investigate this aspect further, chlorination of the radial well water samples was carried out using the separate Cl_2 doses of 1 and 10 mg/L for 0.5 hour. Concentrations of THM species were found to be either low or less than detectable. Total THMs and the distribution determined for the samples collected from Mathura and samples generated in the laboratory by adding Cl_2 matched quite well. It confirmed that, in case of Mathura water, THMs were not being produced. Free Cl_2 concentrations were found to be very low while concentrations of bound Cl_2 were high. It was thought that Cl_2 could bind to ammonia nitrogen and/or to organic compounds resulting in production of chloramines, chloroorganics and N-nitrosamine compounds.

Accordingly, water samples collected during the seventh sampling campaign in May 2008 were also analyzed for ammonia, inorganic ions, AOX, THMs, and selected trace organics in addition to parameters analyzed earlier. DOC and colour of river water were found to be higher than in earlier campaigns. Their reductions during RBF were also higher. DOC was reduced substantially from 29.1 mg/L to 4.0 mg/L (~ 86 % reduction) while colour was reduced from 166 CU to 29 CU, a reduction of ~ 82 %. AOX concentration was low in the river water (23.5 µg/L) and bank filtrate (17.5 µg/L).

Water samples were screened for trace organics. 4-fluorohistamine and 9-octa-decenamide were detected in the river water while 2-aminodiphenyl ether was detected in the bank filtrate.

Both river water and bank filtrate contained ammonia concentrations in excess of 10 mg/L. Hypochlorous acid is known to react with ammonia to form chloramines like mono-, di-, and tri-chloramines, supposed to be about 100 times less efficient than chlorine as disinfectants. Chloramines are known to produce considerably lower levels of THMs (<3 %) and total organic halogens (TOX, 9-48 %) than chlorine alone (Zwiener 2006). Ammonia concentrations together with chlorination result in the formation of N-nitroso-dimethylamine (NDMA), a potential human carcinogen (Giger et al. 2003; Zwiener 2006; Charrois et al. 2007). NDMA is a non-halogenated DBP, and has a drinking water unit risk two to three orders of magnitude greater than currently regulated halogenated DBPs. Other N-nitrosamine compounds N-Nitrosopyrrolidine and N-nitrosomorpholine have also been identified in drinking water. Growing evidence suggests NDMA occurs more frequently and at higher concentrations in drinking water systems having chloramines compared to chlorination-only systems. N-Nitrosamine monitoring efforts in drinking water continue to increase. With the inclusion of NDMA and five other N-nitrosamines in the Unregulated Contaminant Monitoring Regulation 2 (UCMR 2) (USEPA 2005), it is reasonable to anticipate that additional utilities will be identified as having elevated N-nitrosamine concentrations, when more systems start analyzing for them. However, no investigations on NDMA in waters in India are known so far.

7 Satpuli

7.1 Drinking water production by bank filtration

The town of Satpuli is located between the towns of Kotdwar and Pauri on the Eastern Nayar River (in the Garhwal region of the state of Uttarakhand), a tributary of the Ganga River (confluence with the Ganga downstream of Devprayag), in the Sub-Himalayan range (Lesser Himalayas) at an altitude of 657 m above mean sea level (Ronghang et al. 2012). The population of the town as per the 2001 Census was around 5,200 persons, and was projected to be around 7,900 persons in 2010.

In May 2010, one production and one monitoring well (Table 7-1) were constructed by the Eastern Nayar River as part of a separate project (Ronghang et al. 2011, 2012; Kimothi et al. 2012). The interpretation of the borehole material showed that the aquifer comprises coarse sand and gravel. Pumping test data showed the hydraulic conductivity to be in the range of 1.1×10^{-4} to 4.5×10^{-4} m/s (Kimothi et al. 2012; Ronghang et al. 2012). The production well has a capacity of 756 m^3/day, of which around 80 % is bank filtrate and 20 % is groundwater (Ronghang et al. 2012). The production from this single well covers around 71 % of the total drinking water production of Satpuli with the remaining 29 % based on direct surface water abstraction from the Redul stream 9 km away from Satpuli (Kimothi et al. 2012).

Table 7-1 Site and design parameters of RBF system by the Eastern Nayar river in Satpuli (Kimothi et al. 2012; Ronghang et al. 2012)

Parameter	Value
Distance from production well to river [m]	45
Distance from monitoring well to river [m]	33
Depth of production well [m below ground level]	26.3
Depth of monitoring well [m below ground level]	35.9
Production well filter-section [m below ground level]	8.6 – 24.5
Aquifer material	coarse sand & gravel
Hydraulic conductivity of aquifer [m/s]	1.1×10^{-4} – 4.5×10^{-4}
Estimated travel time of bank filtrate [days] (Ronghang et al. 2012)	~ 2 (monsoon) to ~ 14 (non monsoon)
Average daily production capacity [m^3/d]	756

7.2 Water quality

The RBF system in Satpuli is found to be capable of almost complete removal of turbidity in non-monsoon as well as monsoon (Table 7-2). According to Ronghang et al. (2012) comparison of production well water and river water qualities indicated a 2.5 log removal of turbidity in both seasons, complete removal of fecal coliform and about 2 log removal of total coliform during monsoon. Despite a shorter travel time during monsoon (~ 2 days), fecal coliform in pumped water was below detection limit (<2 MPN/100 mL). The estimated travel time is very short from the shortest distance, which means the travel time may be not sufficient for removal or inactivation of other pathogens. The electrical conductivity (EC) of the abstracted water from the production well is, in agreement with the EC of the surface water, also very low. This is a further indication for a high portion of bank filtrate in the abstracted raw water. Consequently, the concentrations of major ions in the abstracted water were found to be very low. The low mineralization is also an indication for a relatively short residence time of the water in the aquifer and the low content of minerals in the aquifer.

Table 7-2 Water quality parameters for the RBF system in Satpuli (Ronghang et al. 2012)

Parameters	Non-monsoon		Monsoon		Hand pump (groundwater)
	River	Production well (bank filtrate)	River	Production well (bank filtrate)	
pH	8.6	7.6	7.9	7.7	7.2
Electrical conductivity [µS/cm]	137	173	118	165	1286
Turbidity [NTU]	1.7	1.5	19.9	0.8	ND
Total suspended solids [g/L]	0.017	0.018	1.32	0.015	ND
Alkalinity [mg/L as $CaCO_3$]	82	97	37	76	169
Hardness [mg/L as $CaCO_3$]	90	100	53	80	271
Dissolved oxygen [mg/L]	ND	ND	7	6.7	2.5
UV-254 [m^{-1}]	4.0	3.0	3.0	1.0	99
DOC [mg/L]	1.3	1.0	1.06	0.4	45
SUVA [L/(mg m)]	3.1	3.0	2.8	2.5	2.2
Na^+ [mg/L]	7.5	12.9	5	11.9	90
NH_4^+ [mg/L]	0.59	0.03	BDL	BDL	BDL
K^+ [mg/L]	<1	<1	<1	<1	<1
Ca^{2+} [mg/L]	25	28.5	21.4	29.9	60.4
Mg^{2+} [mg/L]	6.6	7.7	<1	1.4	29.2
Cl^- [mg/L]	2.9	7.8	1.6	6.3	27.6
NO_3^- [mg/L]	0.5	1.7	1.7	4.5	3
SO_4^{2-} [mg/L]	10.6	16.9	23.3	11.7	49
Total Coliform count [MPN/100 mL]	ND	ND	920	49	ND
Fecal Coliform count [MPN/100 mL]	ND	ND	8	<2	ND
BDL: below detectable limit; ND: not determined; all values are from single sampling events					

According to Ronghang et al. (2012), the DOC concentration of the river water was found in the range of 1.1 – 1.4 mg/L. The values in the abstracted water were < 1 mg/L in both occasions. Due to the low DOC concentration (< 1 mg/L), the risk for the formation of disinfection by-products (DBPs) during chlorination is very low. The abstracted water could be disinfected by chlorination, which would be sufficient for supply into the drinking water network, no other treatment is required. All other parameters determined are below the limits for drinking water of the Bureau of Indian Standards (BIS 10500, 1991).

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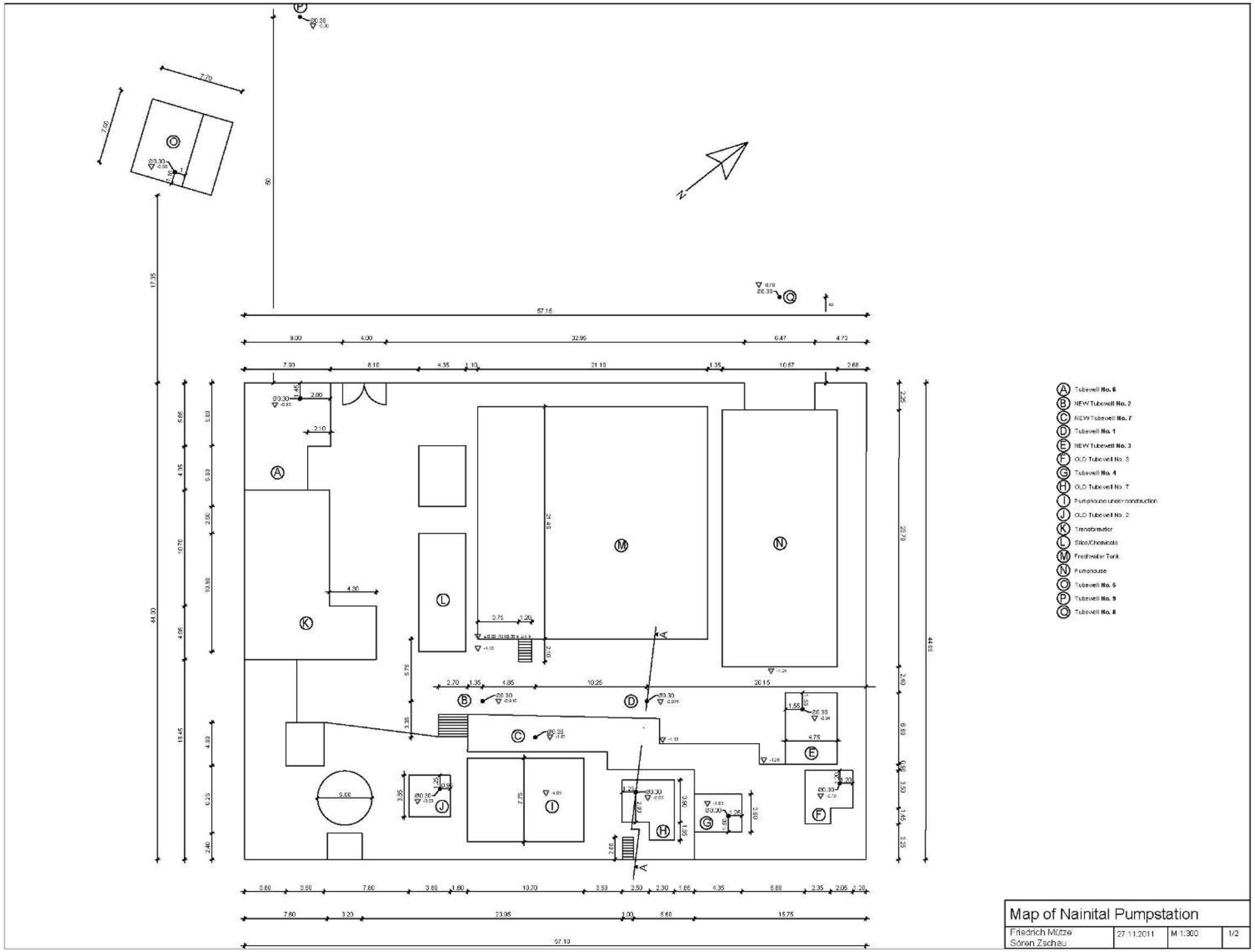
Annexes

Annex 1 Compilation of water quality of surface water and production well water to the north and south of the New Supply Channel (NSC) in Haridwar for the periods November 2005 – September 2006 (HTWD 2006), January – April 2011 (Saini 2011) and April – May 2012 (NIH 2012)

Parameter	River and UGC	RBF wells to the north of NSC	RBF wells to the south of NSC
pH	7.4-8.8 (8.1)	6.1-8.0 (7.2)	7.3-8.4 (7.8)
Turbidity (NTU)	6.8-38.5 (22.7)	0.18-10.2 (1.67)	0.36-9.33 (1.5)
Electrical Conductivity (µS/cm)	136-287 (196)	384-912 (649)	193.5-347 (259)
TDS (mg/L)	82-173 (119)	230-547 (389)	116-208 (155)
Total hardness (mg/L as $CaCO_3$)	71-141 (98)	147-450 (284)	82-190 (119)
Total alkalinity (mg/L as $CaCO_3$)	42-80 (60)	152-310 (210)	70-106 (88)
Ca^{2+} (mg/L)	19.5-33 (25)	32-127.7 (76.1)	24-49 (33)
Mg^{2+} (mg/L)	4.0-11 (7)	8.9-32.9 (22.2)	5-27 (9.0)
Na^{+} (mg/L)	3.2-6.0 (4.5)	12.7-40 (23.6)	4-10 (6.0)
K^{+} (mg/L)	3.2-5.8 (4.7)	0.1-25.1 (6.6)	0.1-11.0 (3.2)
HCO_3^- (mg/L)	50-83 (69)	155-420 (293)	80-150 (109)
SO_4^{2-} (mg/L)	12.4-31.9 (20)	15.4-75.1 (31.4)	14-30.2 (22.1)
Cl^- (mg/L)	1.2-2.6 (1.6)	5.1-45 (18.7)	1.6-5.4 (3.4)
NO_3^- (mg/L)	8.1-12 (9.8)	0.7-18 (11.4)	10-14 (11.2)
Fe (mg/L)	0.4-3.0 (1.8)	0.1-4.2 (0.8)	0.3-3.3 (1.0)
Mn (mg/L)	0.1-0.5 (0.1)	0.1-0.4 (0.1)	0.1-0.4 (0.08)
UV absorbance at 254 nm (cm^{-1})	0.06-0.1 (0.08)	0.014-0.08 (0.05)	-0.018-0.05 (0.03)
Total organic carbon (mg/L)	0.1-1.9 (0.4)	0.1-1.7 (0.9)	0.1-0.5 (0.2)
C_T (M/L) or (TIC)	0.0005-0.0008 (0.0007)	0.0016-0.0049 (0.0033)	0.0008-0.0016 (0.0011)
Total coliform (MPN/100 mL)	160-16000 (4305)	< 2-240 (53)	< 2-240 (53)
Fecal coliform (MPN/100 mL)	160-14000 (3434)	< 2-240 (36)	< 2-90 (34)

Annex 2 Survey map of well field at Nainital bank filtration site (HTWD, 2011)



Annex 3 Water quality data for BF site in Nainital (Singh, 2012)

Parameter	**Range of concentration [Min. – Max. (mean ^{n})]**														
	Nainital Lake				**NTW 1**	**NTW 1(O)**	**NTW 2**	**NTW 3**	**NTW 3(O)**	**NTW 4**	**NTW 5**	**NTW 6**	**NTW 7**	**NTW 8**	**NTW 9**
	NL 1	**NL 2**	**NL 3**	**NL 4**											
Temperature (^{o}C)	19.7-21.6 (20.6)	20.8-21.7 (21.1)	20.4-20.9 (20.8)	20.4-20.9 (20.6)	18.3	16-18.5 (17.4)	17.9-19.2 (18.6)	17-18.9 (18.3)	17-19.9 (18.5)	16.6-20.1 (18.9)	15.3	14.5-19.6 (16.6)	17.3-19.6 (18.4)	17.1	16.1-18.1 (17.4)
pH	7.5-8.7 (8.2)	7.8-8.7 (8.1)	7.8-8.6 (8.1)	7.8-8.1 (7.9)	7.5	5.3-7.7 (7.1)	7.7-8.2 (7.8)	7.6-7.9 (7.75)	7.5-7.9 (7.7)	7.7-7.9 (7.8)	7.8	7.5-7.9 (7.7)	7.6-7.7 (7.65)	7.7	6.1-7.7 (7.2)
Dissolved oxygen (mg/L)	4.3-6.2 (5)	3.6-5.5 (4.5)	3.7-5.6 (4.6)	3.8-5.8 (4.8)	1.7	0.4	0.7-3.6 (1.9)	.8-2.8 (2.025)	1-2 (1.8)	4.4-5.4 (4.83)	4.9	0.8-2.3 (2.4)	1.1-3.5 (2.3)	4.8	4.3-6.1 (5.7)
Turbidity (NTU)	1.9-4 (2.85)	1.4-3.8 (2.28)	1.6-5.6 (2.97)	1.1-1.6 (1.3)	0.2	0.3-1.4 (0.9)	0.5-0.7 (0.5)	0.2-0.5 (0.3)	0.1-0.4 (0.2)	0.3-0.5 (0.4)	0.3	0.2-0.4 (0.3)	0.4 (0.4)	1	0.1-0.2 (0.4)
Total dissolved solids (mg/L)	347-362 (357)	348-360 (354)	348-361 (355)	347-354 (351)	490	374-417 (398)	374-423 (400)	386-499 (421)	371-481 (421)	376-393 (388)	458	434-520 (480)	385-517 (472)	449	521-527 (523)
Electrical conductivity (µS/cm)	578-601 (594)	580-602 (590)	580-601 (590)	578-591 (584)	816	624-658 (662)	624-705 (665)	643-813 (700)	618-801 (710)	627-655 (646)	763	724-862 (798)	641-862 (751)	749	855-878 (867)
UV-absorbance (cm^{-1})	0.036 -.049 (0.041)	0.033 - 0.038 (0.030)	0.033 - 0.042 (0.036)	0.029 - 0.034 (0.0315)	0.01	0.01-0.019 (0.012)	0.0130-.02 (0.016)	0.005-0.02 (0.008)	0.003-0.029 (0.009)	0.008-0.013 (0.009)	0.019	0.004-0.016 (0.008)	0.006-0.012 (0.009)	0.007	0.002-0.024 (0.008)

Annex 3 Water quality data for BF site in Nainital (continued) (Singh, 2012)

Parameter	**NL 1**	**NL 2**	**NL 3**	**NL 4**	**NTW 1**	**NTW 1(O)**	**NTW 2**	**NTW 3**	**NTW 3(O)**	**NTW 4**	**NTW 5**	**NTW 6**	**NTW 7**	**NTW 8**	**NTW 9**
Total organic carbon (mg/L)	3.96	_	_	_	-	3.39	3.66	2.19	3.28	3.64	3.52	3.28	3.05	3.15	3.12
Dissolved organic carbon (mg/L)	3.33	-	-	-	-	2.06	2.66	1.57	1.69	1.45	2.36	1.66	1.31	1.13	3.05
Total Hardness (mg/L as $CaCO_3$)	265-279 (275)	285-298 (291)	251-287 (274)	266-291 (275)	360	289-411 (389)	330-427 (305)	273-337 (381)	278-398 (332)	273-337 (303)	411	316-478 (409)	408	398	444-465 (455)
Alkalinity (mg/L as $CaCO_3$)	194-204 (199.5)	194-200 (198)	200-201 (200)	201-202 (201)	241	230-250 (237)	186-240 (222)	231-286 (258)	202-276 (230)	226-234 (227)	272	234-324 (275)	250-318 (284)	266	275-290 (285)
Ca^{2+} (mg/L)	42.7-46.7 (44.4)	42.1-46.4 (44.2)	44.7-46 (45.3)	44.8-45.1 (44.95)	55-61 (58)	48-51.6 (49.8)	51.8-53.7 (52)	42.8-62.8 (55.4)	48.-88.7 (63)	41-55 (48.5)	76	43-71 (61)	12.2	73.5	44-69.3 (56.7)
Mg^{2+} (mg/L)	35.6-42.2 (39.4)	43.1-43.7 (43.4)	32.5-42 (37.2)	37.2-37 (37.1)	40-53.2 (46.7)	40.7-52.8 (50.4)	36-40.7 (38.2)	42-60 (48.2)	37.5-46.3 (44.3)	40.3-41.8 (41)	52.8	50-67 (56)	1.2	51.4	64-70 (67)
Na^{+} (mg/L)	9.4-10.9 (10.3)	9.-9.6 (9.3)	9.9-12.6 (11.2)	9.4-10.2 (9.8)	11.9-17.3 (14.6)	11.7-22.2 (16.9)	9.6-12.4 (10.6)	11.7-21.6 (15)	11.4-23.7 (16.9)	11.1-22.3 (15)	22.2	11.2-20.4 (16.5)	22.4	28.6	15.1-17 (16.05)

Annex 3 Water quality data for BF site in Nainital (continued) (Singh, 2012)

Parameter	NL 1	NL 2	NL 3	NL 4	NTW 1	NTW 1(O)	NTW 2	NTW 3	NTW 3(O)	NTW 4	NTW 5	NTW 6	NTW 7	NTW 8	NTW 9
Cl^- (mg/L)	6.7-10.2 (8.7)	7.4-8.1 (7.75)	7-7.6 (7.3)	7.5-9.8 (8.65)	10.4-14 (12.2)	7-11.4 (9.2)	4-8.3 (6.8)	8.5-12.7 (10.8)	7.6-13.6 (10.7)	8-10.8 (8.9)	8.8	7.5-14.4 (10.4)	11.1	14.2	11.6-13.5 (12.5)
SO_4^{2-} (mg/L)	89-102 (93.1)	93-120 (106.5)	89-97 (93)	94.2-95 (94.6)	116-134 (125)	85-138 (111.5)	16-95 (67)	90.1-116 (102)	84.3-173 (120.7)	92.3-98.7 (94.6)	122	121.7-149.7 (133)	99	117	156-172 (164)
NO_3^- (mg/L)	1.7-5.7 (3.1)	3.9-4.1 (4)	3.3-4.9 (4.1)	4.7-8.2 (6.45)	2.4-15.7 (9.04)	1.4-1.9 (1.65)	0.9-4 (2.9)	.8-15.6 (8.8)	.8-12.1 (7.9)	1.1-2.1(1.46)	1.5	1-17.6 (6.9)	1.3	1.3	1.3-12.7 (7)
Total coliform (MPN/100 mL)	>1600	1600 - >1600	900->1600	500-1600	<2	<2- 2	<2-2	<2-4	<2	<2-7	4	<2-2	<2-7	<2	<2
Fecal coliform (MPN/100 mL)	170-220	110-280	170-280	110-300	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2