Saph Pani

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

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Deliverable D 1.2

Guidelines for flood-risk management of bank filtration schemes during monsoon in India

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1 Introduction

1.1 Objectives and structure

The content of this deliverable (Deliverable D1.2) reflects the sequence of tasks conducted to address the following objectives, at the RBF sites of Haridwar by the Ganga River and in Srinagar by the Alaknanda River (state of Uttarakhand in Northern India):

- to conduct a risk evaluation of riverbank filtration (RBF) wells for drinking water supply in the Saph Pani project case study sites of Haridwar and in Srinagar (both in Uttarakhand, North India), with focus on sustainable operation during monsoon floods and addressing the removal / breakthrough of hygienically relevant bacteriological indicators during floods,
- and to develop cost efficient technical elements for the improvement of flood-protection of RBF sites.

Deliverable 1.2 contains guidelines based on the results of the tasks conducted to fulfil the mentioned objectives. A brief description of the RBF case study sites in Haridwar and Srinagar are presented in chapter 2, and the extreme monsoon flood events of 2010 and 2011 that affected these sites are described. Thereafter the risks to these sites are identified in chapter 3. Chapters 4 and 5 describe the field investigations conducted in Haridwar and Srinagar respectively to assess the risks from floods. The laboratory and field experiments conducted using columns to assess the removal of bacteriological indicators in context to floods are presented in chapter 6 and 7. The measures to mitigate the risks from floods at RBF sites in general, based on the examples of the Haridwar and Srinagar case study sites, are presented in chapter 8.

1.2 The effect of the monsoon on drinking water production

The monsoon and consequent dynamic river flows, including floods that cause widespread inundation of adjacent low-lying areas, are an annual event of the Indian Subcontinent that occur typically during a three-month period between June and September. The disruption of drinking water production during monsoon is also common, especially for those river-side towns and cities where raw water is directly abstracted from rivers. On one hand the quality can be impaired due to the insufficient removal of typically high turbidity and microbial pathogens by the coagulation and rapid-sand filter units used in the conventional drinking water treatment plants. As a result, the elimination of pathogens by the common disinfection method of chlorination cannot be guaranteed. On the other hand the drinking water production and supply during the monsoon is interrupted due to excessive silting of settling basins, water storage reservoirs and blocking of pipes by fine suspended solids (e.g. silt and clay).

While the above qualitative impact on drinking water production is common for normal high-flow situations in rivers, extreme flows (even in non-perennial surface water bodies) accompanied with simultaneous inundation of the floodplain cause structural damage to the drinking water production units and water-pipe distribution networks potentially result in faecal contamination of drinking water. Faecal contamination is one of the commonest causes of Viral Hepatitis (type E caused by the Hepatitis E Virus) and other waterborne disease outbreaks in Delhi and many parts of India (Hazam et al., 2010; Annex 1). The incidences of waterborne disease outbreaks presented in Annex 1 reveal that Viral Hepatitis, Gastroenteritis, Typhoid and Diarrhoea rank amongst the waterborne diseases most frequently reported in literature, thereby underlining the fact that concentrations of viruses even in small doses can be highly infectious. Viral Hepatitis outbreaks in Kanpur in 1990 – 1991 (Naik et al., 1992) and Baripada in 2004 (Swain et al., 2010) can be linked to the faecal contamination in directly abstracted surface water and subsequent insufficient removal of viruses by post-treatment, usually disinfection by chlorination. Gastroenteritis, Typhoid, Cholera and Diarrhoea outbreaks are linked to the faecal contamination in the drinking water distribution system (leakages and low pressure in pipelines) resulting from wastewater, overland runoff due to extreme rainfall and floodwater coming into contact with drinking water (Annex 1, Annex 2).

Thus during the monsoon floods and extreme flood events in India, there are multiple pathways to contamination of drinking water between the points of abstraction of raw water, through the treatment process and distribution network to the consumer.

However, when considering riverbank filtration (RBF) in the context of a multiple-barrier approach to prevent contamination of drinking water, RBF offers the first important barrier between the source of the water and point of abstraction in terms of a significant removal of pathogens and turbidity in India.

1.3 Review of risks to riverbank filtration sites from floods

In Europe, floods are the commonest natural hazard with an expected increase in frequency and severity and consequent rise in damages. Wells used for the production of drinking water are at risk of microbial contamination and interruption of power supply leads to disruptions in drinking water supply (Rambags et al., 2011). In India, floods are an annual occurrence regularly causing widespread damage.

Despite the numerous risk definitions to be found in literature (for a summary of some definitions see Kelman, 2003) there exists no common definition of risk as generally definitions vary depending on the context. Hazard is often discussed as a consequence and can include water velocity, depth of flooding etc. In a number of definitions vulnerability has also been considered. The IEC 300-3-9 (1995) defines risk as a combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event (Vatn, 2008).

In the context to this chapter, the main risk is the breakthrough of pathogens in RBF wells in consequence to floods and/or monsoon (Figure 1-1).

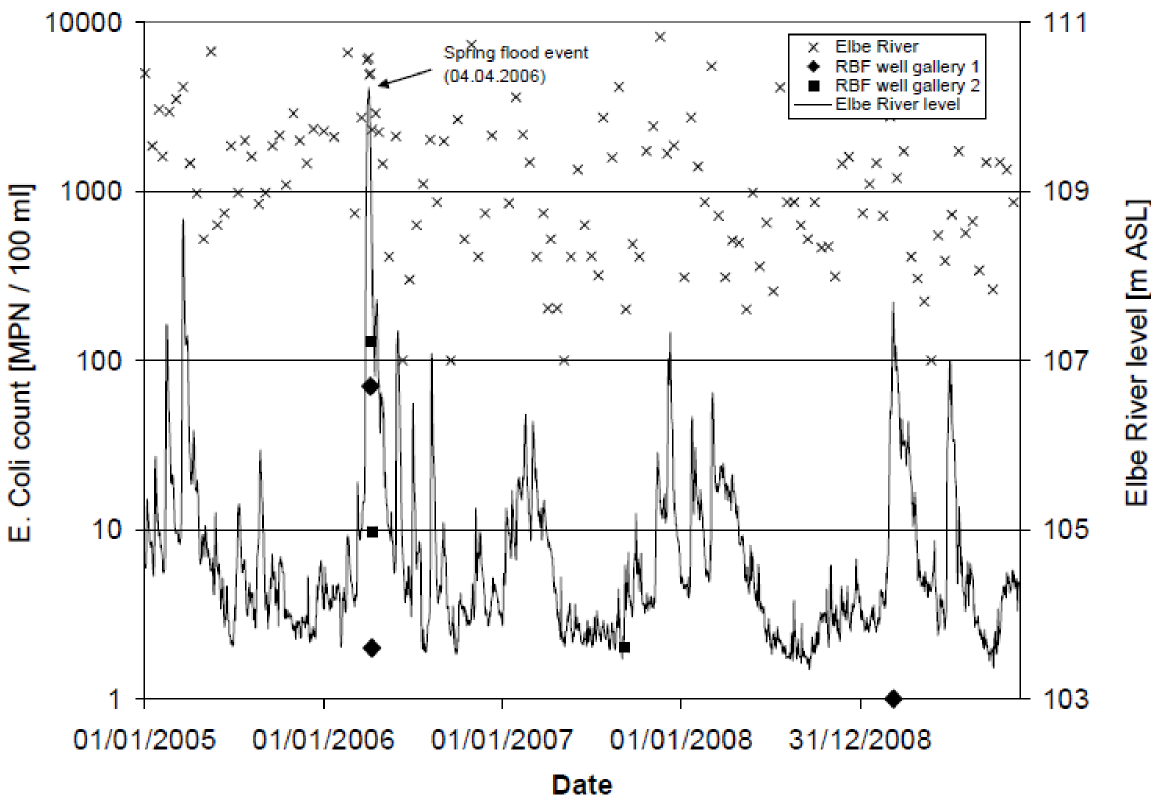


Figure 1-1 Escherichia Coli counts in the Elbe river and RBF wells at an anonymous site in Germany (Sandhu et al. 2013)

During the extreme monsoon flood event in August – September 2010 and the resulting high water level in the rivers of the Indian Subcontinent, most of the abstraction structures that pump water from rivers in the North Indian mountainous state of Uttarakhand were submerged leading to an interruption in water supply for at least two days. In Haridwar where 22 RBF wells are located, the Ganga River rose to the highest ever recorded level of 296 m above sea level on 19 September 2010 (CWC, 2010), thereby inundating the area around some of the RBF wells. It was observed that the water in the wells had become turbid. The abstraction from these wells had to be discontinued for at least 48 hours. Similarly, at the RBF site of Srinagar which has been in development since 2010, the monsoon flood in 2011 inundated the riverside area and directly entered the five boreholes being drilled for the construction of production wells.

Despite sparse data sets and temporal inconsistencies in the methodology used to investigate raw water quality at RBF schemes along some rivers in Germany (Elbe and Rhine), a correlation between flood events and a temporary influence on the bank filtrate quality in terms of an increase in coliform counts and turbidity of the bank filtrate has been revealed. An increased number of bacteria and viruses have been reported in bank filtrate at the Rhine River during floods (Schubert, 2000).

A high probability of a breakthrough of pathogenic microorganisms in bank filtrate was identified for a sand and gravel aquifer in The Netherlands (Medema et al., 2000), whereby the residence-time of the bank filtrate in the aquifer decreased from 45 – 65 days to 10 – 14 days with a fast increase in the surface water level.

It is thus hypothesized that the risk to raw water from contamination by pathogenic microorganisms during floods is likely to be a result of:

- Damage to the biologically active clogging layer (effective filter layer) on the riverbed as a result of increased shear stress during floods,
- Infiltration of river water along areas of the river bank where no protective clogging layer exists; thereby transport of water in the upper part of the aquifer that was unsaturated before the flood resulting in poorer filtration,
- Changes in hydraulic pressure and faster travel-times of the bank filtrate towards the well until confining conditions are reached,
- Seepage of the flood water into the upper subsurface and unsaturated zone, whereby microbial pathogen loading in the bank filtrate may be observed even many months after the flood event has subsided,
- Direct contamination through unsealed/unprotected well (-heads) and observation wells.

Observations at different RBF sites along the rivers Elbe and Rhine showed that the changes in the hydraulic pressure as a result of the higher flood-water levels could lead to a release of already existing microorganisms in the sub-surface, which break through into the well before the younger bank filtrate from the flood reaches the well.

These risks shown in Table 1-1 below are summarised in relation to the various aspects of the location and design of a RBF well with specific reference to India. They build upon those outlined by Rambags et al. (2011).

Table 1-1 Risks to RBF wells from floods during monsoon in relation to various aspects of the location and design of wells (adapted from Rambags et al. 2011)

Aspects of RBF well / well-field	Associated risks
Location: - Unconfined aquifer - Topographic depression or extremely level terrain adjacent to river - Unsealed and abandoned or disused wells / boreholes in vicinity of RBF well - Upstream of a dam / reservoir and below the maximum attainable water level of the reservoir - Within the riverbank / channel area that is usually inundated by the annual high flood level of the river during monsoons	Increased risk of contamination by: - Inundation of RBF well and direct contamination - Seepage of the flood water into the upper subsurface and unsaturated zone - Faster travel-times of the bank filtrate towards the well
Design above ground level: - Insufficient geodetic elevation of well head, well head entrance or well head access door - Inappropriate sealing of well head entrance door (“leaky access doors / entrance”) - Inappropriate sealing of water-level gauge pipe of production well	- Inundation of well head → inaccessible well head - Direct entry of flood water through leaky access door and / or through cracks and fissures in well chamber → direct contamination of well and / or damage to power supply of well - Direct contamination of well-bore through armatures, valves, fittings and water level gauge pipe in case of power failure and interruption to pump operation
Design below ground level: - Insufficient sealing immediately below well head chamber (uppermost part of borehole) - Insufficient sealing of annulus (area between casing and subsurface material) where casing penetrates through confining layer of aquifer at ground level	Short-circuiting of flood water with groundwater and direct contamination to groundwater

1.4 Overview of tasks carried out

The preparation of these guidelines is primarily based on results from field work complemented by laboratory analyses and experiments.

Intensive field work was conducted from October 2011 to March 2013 at the two Saph Pani RBF case study sites of Haridwar (project partners NIH, HTWD, UJS, AJD) and Srinagar (project partners UJS, HTWD, IITR, AJD).

Simultaneously to the field work, water quality and isotope analyses were conducted for the Haridwar and Srinagar RBF sites by the National Institute of Hydrology (NIH Roorkee) and Environmental Engineering Section of the Department of Civil Engineering at the Indian Institute of Technology Roorkee (IIT Roorkee, water quality analyses only) respectively. To facilitate the analyses, two monitoring wells were constructed in Haridwar and one in Srinagar by AJD. An assessment of the health risk to the RBF site in Haridwar was conducted by CSIRO and HTWD.

Experiments were conducted to investigate the removal of bacteriological indicators (total and faecal coliforms) and turbidity after the passage of river water through columns filled with sediment. Thus, Ganga River water was induced through columns filled with aquifer material from the RBF site in Srinagar (IIT Roorkee), and Elbe River water was induced through columns filled with Elbe riverbed material and artificial recharge basin material from Dresden (HTW Dresden). The effect of floods on the removal of bacteriological indicators after RBF was simulated by inducing river water through the columns under various flow rates.

Finally, concepts to mitigate the flood risks were developed by HTWD.

2 Description of case study sites

2.1 Riverbank filtration site in Haridwar

2.1.1 General geography

The Census of India (2011) defines Haridwar as an urban agglomeration having a permanent population of 310,582 persons. The urban agglomeration (UA) of Haridwar is spread over the elongated topographically level flood-plain area (> 11 km) on the West bank of the Ganga River, where the Ganga exits from the Siwalik hill range (Lesser Himalayas) and enters the Northern fringe of the Indo-Gangetic alluvial plain and thereby transitioning from its upper into its middle course (Figure 2-1). The Haridwar UA comprises the main or "core" part of the city (that is administered by the municipal corporation – "*Nagar Palika Parishad*, NPP") and the suburban areas that include the industrial areas. The main city administered by the NPP has a permanent population of 225,235 persons.

2.1.2 Religious significance and impact on population numbers

Haridwar is one of the most important Hindu pilgrimage sites in the world ("*Haridwar*" can literally be translated as "the gateway to the Gods") by virtue of being located at the foot of the Himalayas that are regarded as the abode of the Gods in Hindu mythology. Consequently, in addition to its 225,235 permanent residents, the main part of the city has a "floating" population of around 200,000 persons who reside temporarily within the main city in religious retreat locations ("Ashrams") and hotels. Furthermore, an additional 400,000 – 500,000 persons (mainly pilgrims) are estimated to visit the main city every day (UJS, 2012).

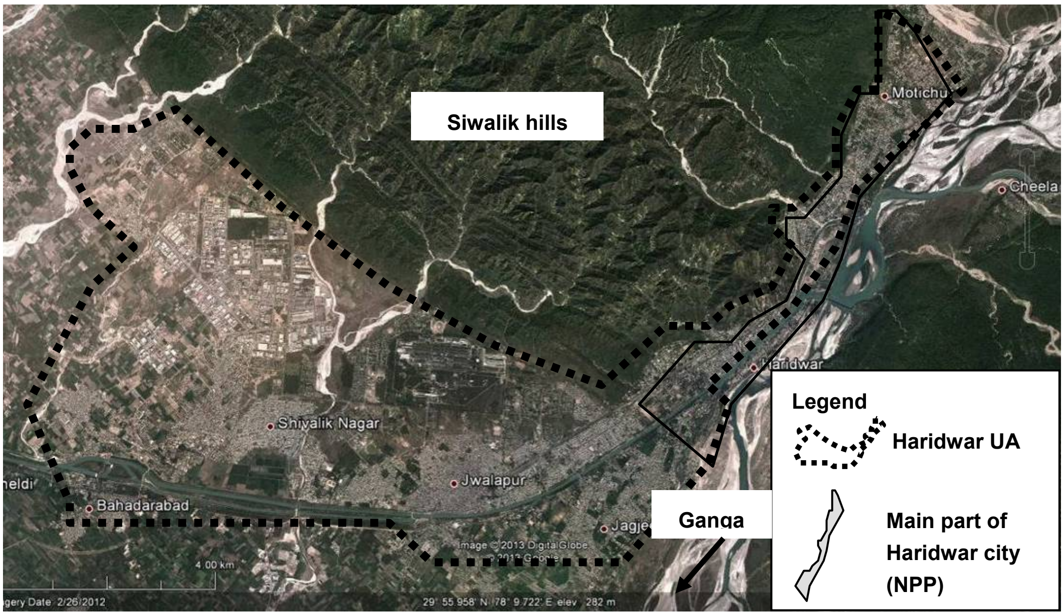


Figure 2-1 Overview of Haridwar (adapted from Google earth © Google, 2013)

2.1.3 Riverbank filtration scheme

Twenty two RBF wells (Figure 2-2) abstract a mixture of bank filtrate and groundwater from the upper unconfined aquifer, which accounts for nearly 68 % (> 43,000 m^3/day) of the total drinking water production of the entire population within the main city of Haridwar (Sandhu and Grischek, 2012). Groundwater abstraction through vertical production wells (colloquially called “tube” wells) from the deeper confined aquifer covers the remainder of the drinking water production in the main city. The 22 large-diameter (10 m) bottom-entry caisson RBF wells of 7-10 m depth are located in an area from 29°54’44” to 30°0’10” N and from 78°8’33” to 78° 12’ 33” E.

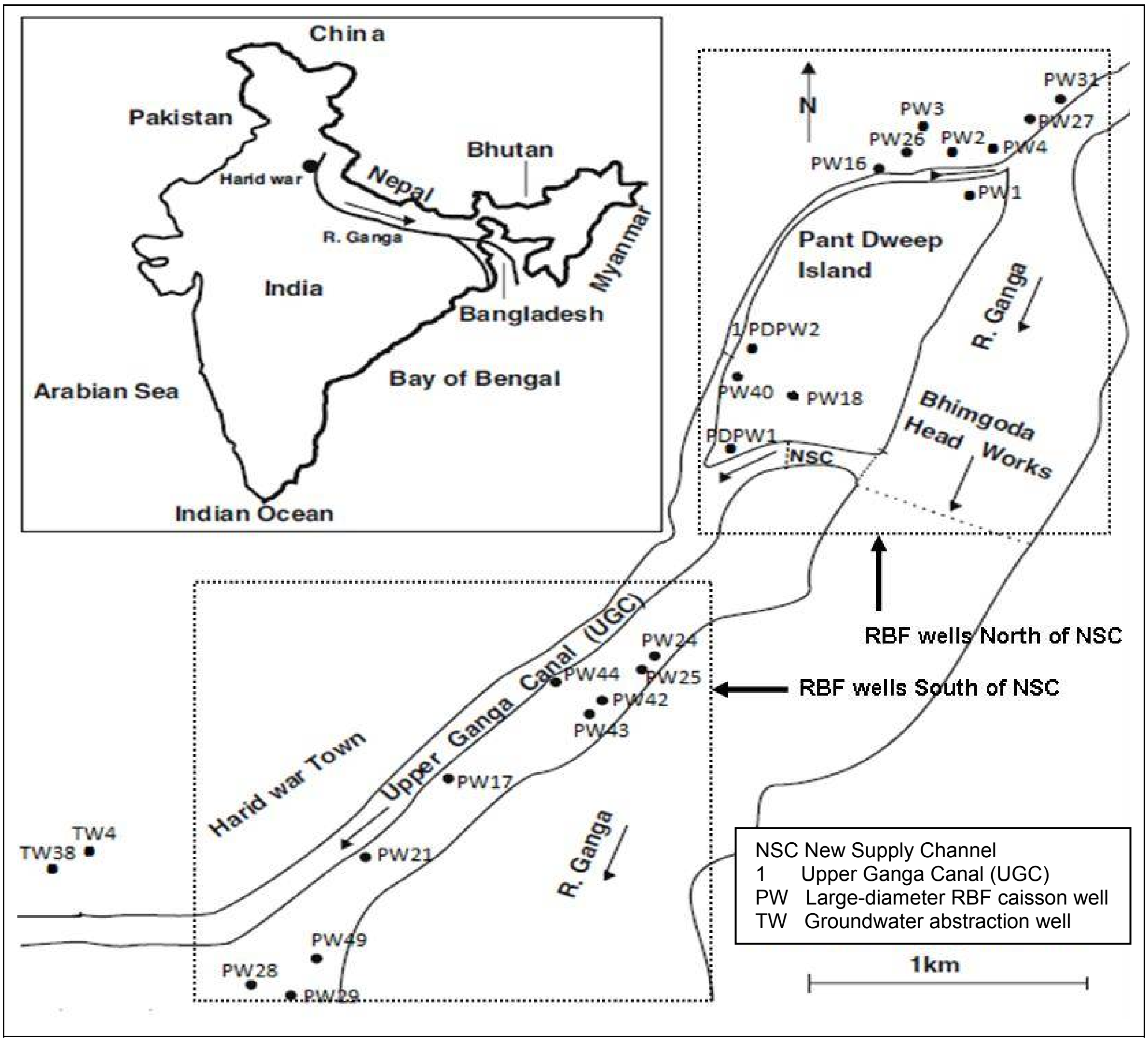


Figure 2-2 Location of large-diameter RBF wells in Haridwar (after Saini 2011)

The 22 RBF wells can be distinctly divided into two groups based mainly on the proportion of bank filtrate to groundwater abstracted. Those RBF wells located to the North of the New Supply Canal (NSC) on Pant Dweep island and in Bhupatwala abstract a comparatively lower portion of bank filtrate than those located to the South of NSC and in between the Upper Ganga Canal (UGC) and Ganga River (Figure 2-2). The NSC additionally diverts flow of the Ganga from the Bhimgoda barrage reservoir in a regulated manner into the UGC. The shortest distance from the RBF wells to the Ganga or the UGC varies between 50 m and 490 m from the centre of the respective water course (Annex 3). Normally, 12 – 13 wells are operated continuously (24 hours) with the remaining wells operating 9 – 19 hours per day using fixed-speed vertical line shaft pumps through 150 mm diameter impeller. The abstracted water is only chlorinated at the well using Sodium hypochlorite (NaClO).

Figure 2-3 Example of large-diameter RBF well adjacent to Ganga River, Haridwar (Photo: L. Rossoff, HTWD, 2011)

2.1.4 Hydrogeology

According to the geological formations as depicted on the map developed by Central Ground Water Board (CGWB 2009), most part of the study area particularly along the N-W, N-E, and S-E directions comprises the Siwalik group having sedimentary formations with conglomeration of sandstone and clay stone sequences. In the S-W part around the Haridwar city area, newer alluvium made up of fan and channel alluvium formations with sequences of brown to grey clay, silt and sand with pebbles and boulders are found.

The hydrogeological formation of the study area is interpreted from the borehole data of three exploratory wells (data source UJS) located along a NE-SW transect and extending almost across the entire length of the study area (Figure 2-4). The cross-sectional view of the sub-surface formations (Figure 2-5, X-X') showed that the uppermost layer of around 2 m comprises surface soil, which is underlain by fluvial deposits of fine to coarse sand mixed with pebbles and boulders. Furthermore, hydrogeological investigations conducted on Pant Dweep island concluded that the aquifer is hydraulically connected to the Ganga River and the UGC system under unconfined conditions (Dash et al., 2010). These fluvial deposits are underlain by sequences of relatively thick clay layers mixed with pebbles or boulders, which act as impervious strata with no sign of vertical and horizontal connectivity to the river, canal and the underlying confined aquifer. The depth to groundwater level varies from location to location as the area has a varying topography.

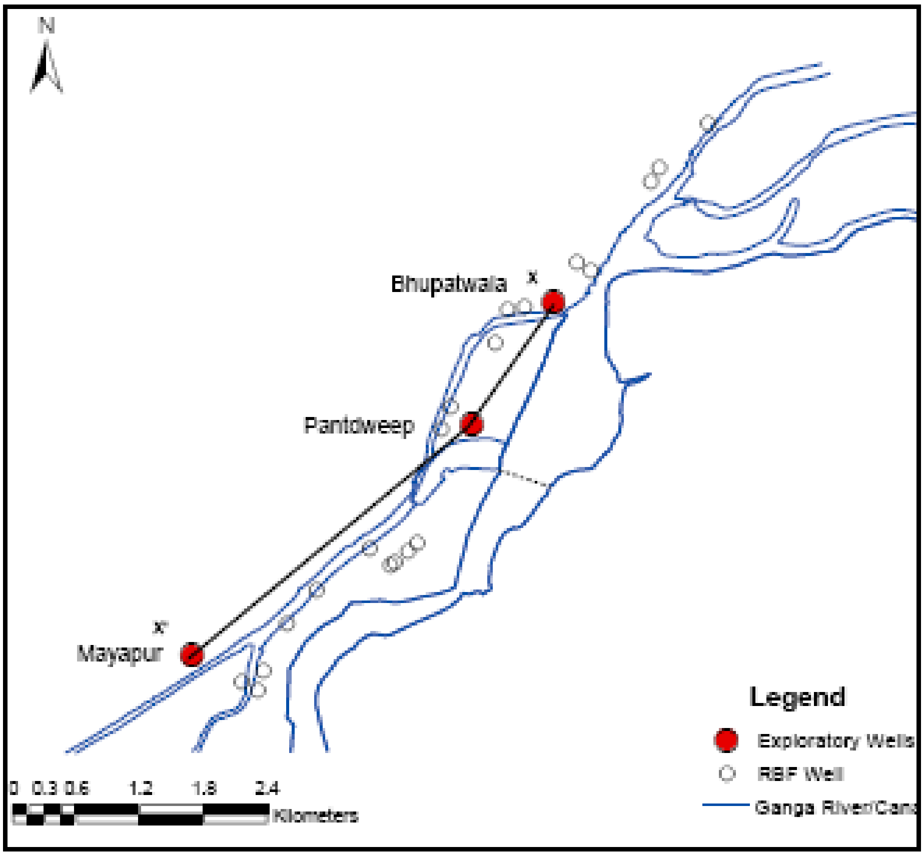


Figure 2-4 Transect X-X' connecting the exploratory wells used for aquifer characterisation

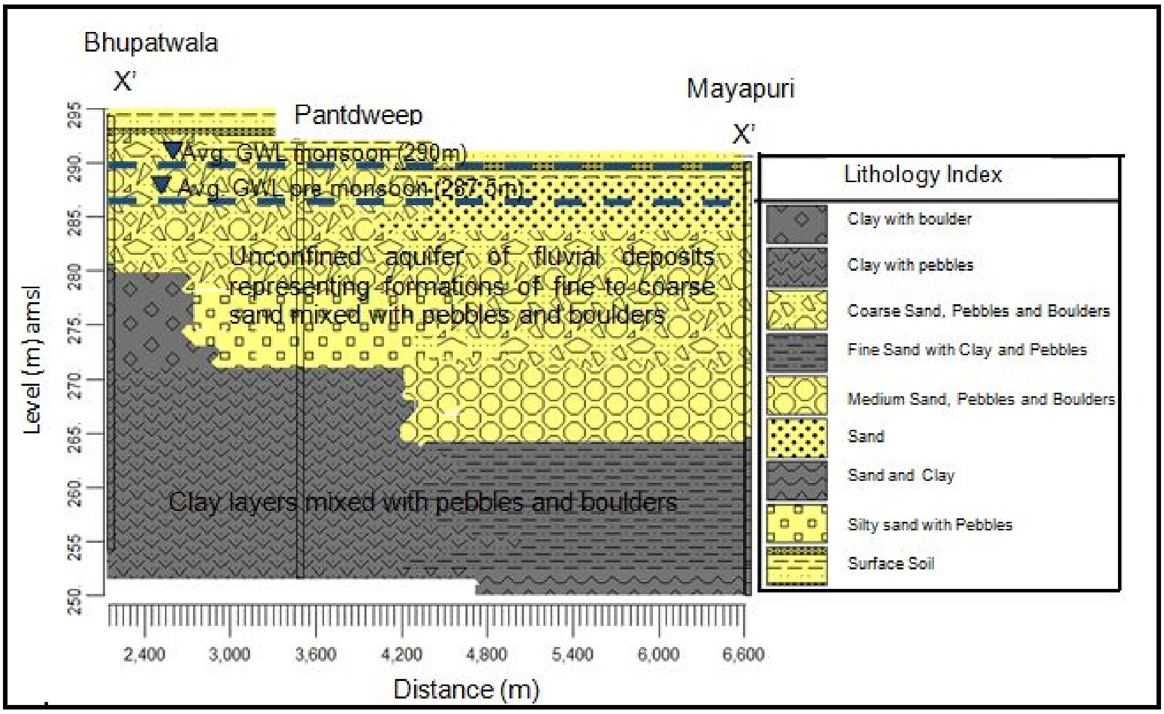


Figure 2-5 Cross-section of the study area along the X-X' transect in Figure 2-4 (NIH 2013)

During non-monsoon months the groundwater level occurs at a depth of 2.8 m below the lowest ground level (near IW3) and 9.35 m below the highest ground level (IW27) in the Bhupatwala region (northern part of study area). There, the average depth of groundwater is 6.25 m below the normal ground surface level. In terms of elevation, the average groundwater table during non-monsoon months occurs at 288.75 m above mean sea level (mASL). During monsoon, the groundwater level increases by an average of 1.25 m and attains an average level of 290 mASL. The normal groundwater flow direction is from the Siwalik hills towards the Ganga River (NW-SE).

All the 22 RBF wells are constructed in the upper unconfined aquifer having a thickness ranging from 14 m below ground level (BGL) in the North to around 38 m BGL in the South. The hydrogeological formations represented by this unconfined aquifer have very good hydraulic properties representing a hydraulic conductivity (K) value ranging from 16 - 50 m/day (Dash et al., 2010).

In the Northern part of the study area, the Ganga River and UGC form a natural boundary to the East and South-East respectively for the RBF wells in the Bhupatwala area (IW31, IW27, IW4, IW3, IW2, IW 26, IW16). For all other RBF wells located further downstream on Pant Dweep Island and to the island’s South, the UGC and the Ganga River form hydraulic boundaries to the West and East respectively. Consequently, these boundaries cause a natural groundwater flow direction from West to East and also affect the portion of bank filtrate abstracted, as indicated from water quality (Saini, 2011), isotope and groundwater flow modelling investigations. In this context, Saini (2011) observed a different water quality pattern by analysing the electrical conductivity, alkalinity, total organic carbon (TOC) and major ions for the RBF wells in 2011. 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 to the South of the NSC. 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 portion of bank filtrate compared to the South.

2.1.5 Historic flood event in Haridwar

The highest extreme monsoon flood-event (in terms of surface water discharge and level of the Ganga and corresponding wide-spread inundation of river-side land) that was ever recorded occurred on 19 September 2010 (CWC 2010). Water levels recorded at the gauging station of the Central Water Commission (CWC) located approximately 1 – 2 km upstream of Pant Dweep Island in Haridwar reached 296 mASL. During that monsoon (August – September 2010), most of the abstraction structures that pump-out water directly from rivers in the North Indian mountainous state of Uttarakhand, were also submerged. Around the period 18 – 21 September 2010, the area around some of the RBF wells in Haridwar (from North to South: IW 31, 27, 42, 43, 25, 24) was inundated by the flood-waters of the Ganga (Figure 2-6).

Figure 2-6 RBF well IW 24 in Haridwar (left photo), (1) view of the Ganga River in the background in April 2005 (pre-monsoon), (2) flood-water of Ganga inundates the base of well on 19/09/2010 and (3) damage by scouring to base of well no. 24 (photos from L to R: Schoenheinz and Grischek (2005), Subodh & Kumar (2010))

During inundation the wells ceased operation. This lead to an interruption of the water supply for at least 2 – 3 days as the well operators were forced to abandon the wells and shut down the pumps (due to the inclement danger from the approaching flood-water). After the flood-water had receded, a visual inspection by UJS revealed some damage to the base of the wells. It was also visually observed that the water in the wells had become turbid, presumably due to direct seepage of the flood-water down the well shaft, or through cracks and fissures in the wall of the caisson. The turbid water was pumped out of the wells via a bypass, until no more visible turbidity was observed.

2.2 Riverbank filtration site in Srinagar

2.2.1 General geography

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 (Sandhu et al., 2011), 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., 2011). The town is the main commercial and administrative centre of the district of Pauri in Uttarakhand, and is one of the largest towns along the Alaknanda River.

2.2.2 Drinking water production

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 located at an altitude of around 1660 mASL) was around 3,750 m^3/day in 2010 while the demand has been estimated 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, the current surface water abstraction system is likely to become inoperable due to severely reduced flows in the Alaknanda along the 4 km stretch where the current abstraction takes place (Sandhu et al., 2011).

2.2.3 Riverbank filtration scheme

In May 2010, one production and one monitoring well (PW-DST & MW1) were constructed in the South-West part of the town (Figure 2-7) as part of a separate project by UJS (Ronghang et al., 2011; Kimothi et al., 2012). These wells are located 170 m from the riverbank and were drilled up to a depth of 20 m BGL. With the objective to cater for current and future increases in demand, two additional boreholes were drilled for the construction of production wells PW1 and PW5 on the lower level of a public park (administered by the Municipal Corporation of Srinagar) located in between the existing PW-DST and the river in August 2011 (Figure 2-7). Currently only PW5 has a temporary submersible pump for testing purposes within the Saph Pani project. Another monitoring well (MW5) was constructed by AJD between PW5 and the Alaknanda River in May 2012 (Figure 2-7, Annex 10).

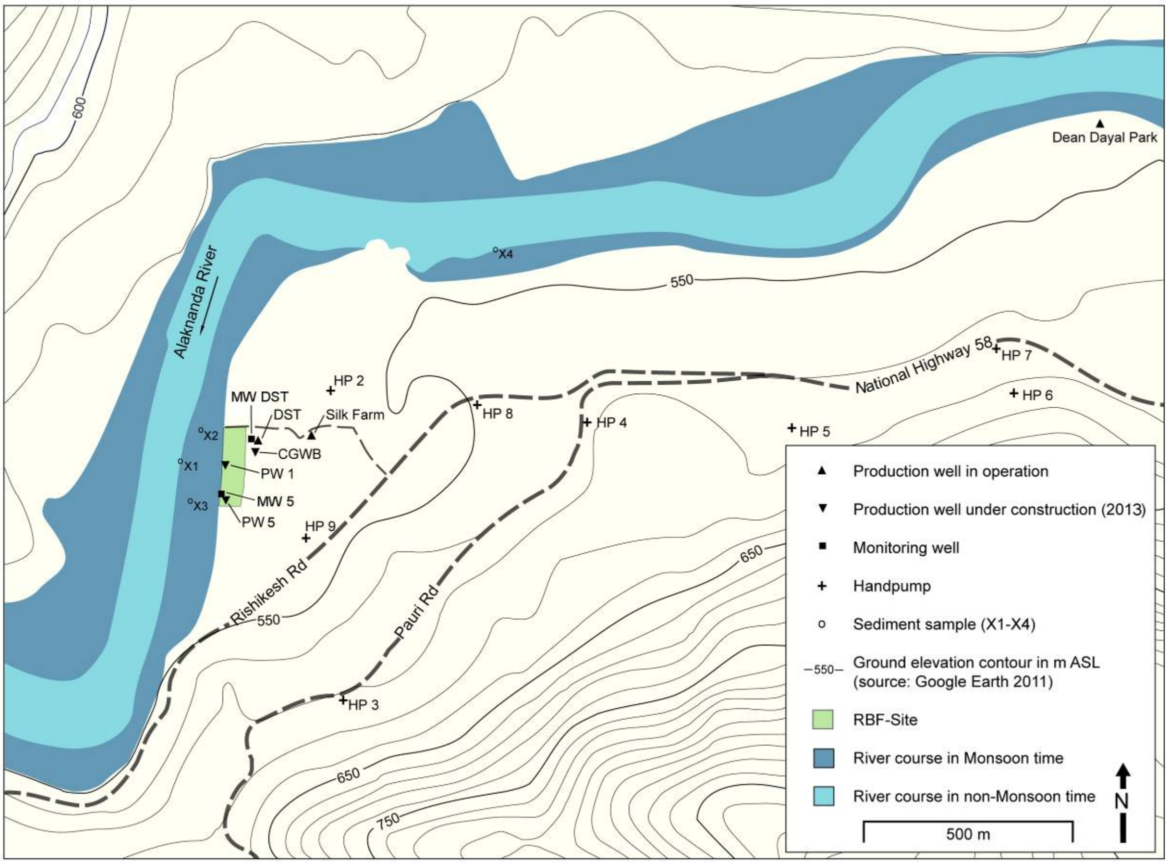


Figure 2-7 RBF well field in Srinagar under development since May 2010 (HTWD and UJS 2012b)

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 of the aquifer to be in the range of 1.3×10^{-3} – 4.0×10^{-3} m/s (HTWD and UJS, 2012a). 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).

2.2.4 Hydrogeology

Srinagar lies in a localised flood plain of the Alaknanda River, after the river emerges from a relatively narrow valley. Fluvial terraces on either side of the river indicate the presence of mainly matrix supported gravels of debris flow origin, clayey silt and fine sand (Jha, 1992). This alluvium is constituted of relict lake sediments (Sundriyal et al., 2007). The thickness of the aquifer at the RBF site was determined to be 21 m as interpreted from borehole logs of the production wells PW-DST, silk farm, PW1 and PW5 (Figure 2-8).

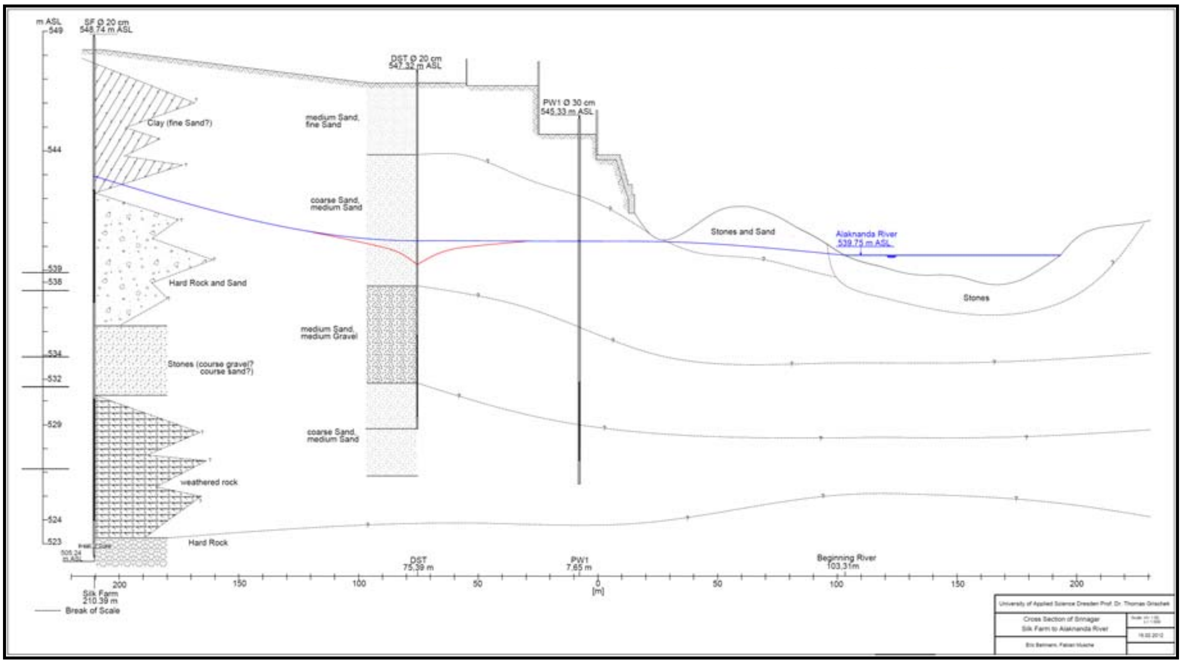


Figure 2-8 Subsurface cross section of RBF site in Srinagar (HTWD and UJS 2012b)

The top soil and upper unsaturated subsurface is mainly made of fine to medium sand. The post-monsoon depth to the groundwater table in the monitoring well MW DST, based on a reference day measurement in December 2011, was around 7 m BGL. The saturated aquifer material has a medium to coarse sand layer followed by medium sand to medium gravel beneath which a medium to coarse sand layer is again found. The base of the aquifer is made up of consolidated and unconsolidated rock. The mean hydraulic conductivity of 4.5×10^{-2} m/s for the riverbed material was obtained after *Beyer* from sieve analyses of sediment taken from four different locations along the river (Figure 2-7, sediment sample locations X1…X4, HTWD and UJS 2012b). Information obtained from a report of the construction of a dam a short distance upstream of Srinagar, indicates that a thin layer of topsoil covers a predominantly hard rock layer mostly in areas with a steep topography further upstream of the RBF site.

2.2.5 Historic flood event in Srinagar

The RBF site in Srinagar where the drilling of the boreholes for the production wells PW1 and PW5 commenced in the beginning of August 2011 was flooded on 12 August 2011 (Figure 2-9 and Figure 2-10).

Figure 2-9 Potential RBF site under development in Srinagar inundated by the monsoon flood of the Alaknanda (facing upstream) in August 2011 (Photo: J. Ebermann, HTWD, 2011)

Figure 2-10 Production well PW5 (under construction) in the background (encircled) inundated by the monsoon flood of the Alaknanda (facing downstream) in August 2011 (Photo: J. Ebermann, HTWD, 2011)

The flood water rose to around 0.7 m above the ground level at the site. At the time of the flood, the RBF site was under construction with only the casing pipe and filter section for the production well PW5 having been installed. However the flood water did not enter the borehole of PW5 because the top of the casing pipe remained above the flood level (Figure 2-10). Due to the sudden onset of the flood, more enhanced measures other than temporarily covering the top of the casing of PW5 were not possible as the site had become inaccessible, especially for equipment required for enhanced sealing of wells (e.g. welding a cover onto the casing). The boreholes for PW1 and PW5) were drilled after the flood receded. The reoccurrence of the flood was witnessed again during the monsoon in 2012, with the flood water attaining a level below 0.7 m (above ground level of the RBF site). As the area in the vicinity around the site is sparsely populated, no previous eye-witness accounts of the highest flood level attained by the Alaknanda in this particular location were available before the site-selection and construction of the wells.

3 Flood-risk identification at the RBF sites of Haridwar and Srinagar

3.1 Overview of identifiable risks

Based on the highest ever recorded flood of 2010 in Haridwar and 2011 in Srinagar, the risks to the RBF sites are summarised in Table 3-1, using Table 1-1 as a reference. It is evident that most risks associated with the location of the RBF wells and their designs are applicable as presented in Table 3-1. However, for the design below ground level, there is no apparent shortcoming.

Table 3-1 Summary of risks to RBF sites in Haridwar and Srinagar (Sandhu et al. 2012)

Risk	Haridwar	Srinagar
Risks associated to location of RBF site		
- Unconfined aquifer & level terrain with low gradient of riverbank - Inundation of land around RBF well and direct contamination - Seepage of the flood water into the upper subsurface and unsaturated zone - Faster travel-times of the bank filtrate towards the well - Inaccessibility to wells due to inundation of area around wells	X	X
Risks associated with RBF well design above ground level		
- Insufficient geodetic elevation of well head - Inappropriate sealing of well head / area around caisson well - Direct entry of flood water through improperly sealed well head and fissures in well caisson → direct contamination of well - Inaccessibility to wells due to inundation of area around wells → difficulty to start back-up power supply (e.g. generators)	X	X
Location of control-system for pump operation	n/a	n/a
Design below ground level		
- Insufficient sealing immediately below well head chamber (uppermost part of borehole)	X	n/a[1]
- Insufficient sealing of annulus (area between casing and subsurface material) where casing penetrates through confining layer of aquifer at ground level	n/a	n/a
X risk applicable; n/a risk not applicable; [1] sanitary sealing measures were implemented after the August 2011 flood		

3.2 Existing flood protection measures

Generally, as a rule in many parts of India, the banks of rivers that experience, or are at risk of serious flooding, are fortified by flood-protection measures. Such measures include stone and boulder filled galleries reinforced with wire-mesh, concrete blocks and permanently constructed stone and concrete embankments as well as dykes. As such, along the Ganga River's West bank in Haridwar, there is a flood protection embankment (red line in Figure 3-1; Annex 4). The wells are located on both sides of this embankment. The top surface elevation of this flood protection embankment that ranges between 279 and 302 mASL is largely above the normal ground surface elevations where these 22 RBF wells are located.

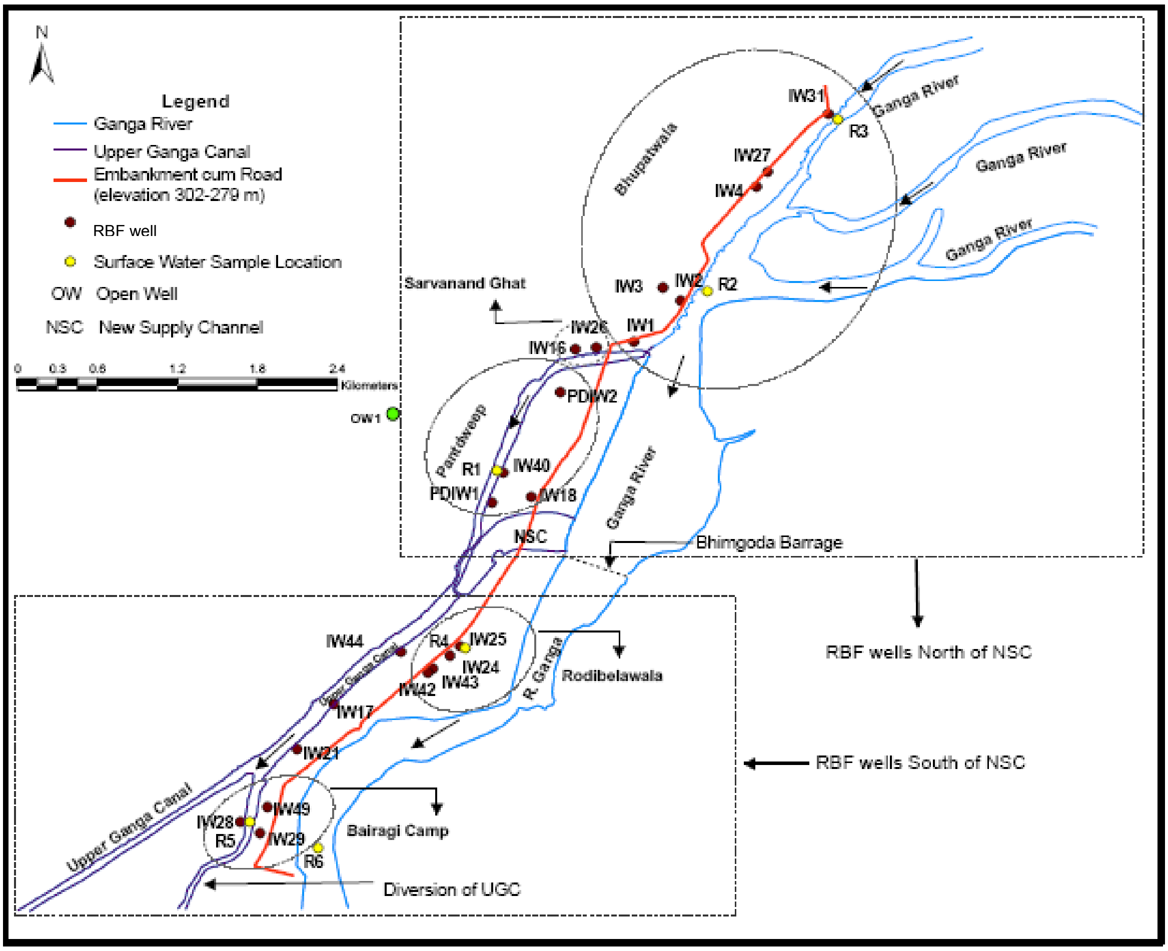


Figure 3-1 Flood protection embankment cum road (red line) (NIH 2013)

The river-side boundary of the park in Srinagar where the RBF wells are located has a permanent stone and concrete retaining wall. To protect the retaining wall (and the park) from flooding, a flood-wall exists towards the river a few metres away from the retaining wall (Figure 3-2 and Figure 3-3). During normal monsoons, the river water level reaches the flood wall. However, during the monsoon in August 2011, the flood damaged the downstream end of the flood wall and the retaining wall as a consequence of which a portion of the land around well PW5 subsided (Figure 3-4).

Figure 3-2 View of flood-wall (left) and retaining wall (right) of the lower level of the park where the RBF site in Srinagar is located (Photo: M. Ronghang, IITR, 2011)

Figure 3-3 Intact retaining wall at the downstream-end of the RBF site in Srinagar at the onset of the monsoon flood in August 2011 (Photo: J. Ebermann, HTWD, 2011)

Figure 3-4 Damaged retaining wall of the RBF site in Srinagar after the monsoon flood of August 2011 (facing upstream) (Photo: T. Voltz, HTWD, 2012)

3.3 Design of wells and direct contamination

Furthermore there is a significant difference in the design of the RBF wells in Haridwar and Srinagar. The caisson well design of the wells in Haridwar implies that the well head or the ceiling of the caisson on top of which the vertical turbine pumps and associated armatures, valves and electrical installations are installed is at a sufficient elevation above ground level so that the entry of flood water from directly above is not possible (Figure 3-5). However, if cracks / fissures are present in the caisson wall around or below ground level, then these provide a pathway for direct entry of flood water into the well. In case of some of the RBF wells in Haridwar, the area around the caisson at ground level is not sufficiently sealed with a concrete base or clay layer to prevent flood water (or water from an intense precipitation event) seeping down along the outer wall of the caisson to the groundwater table.

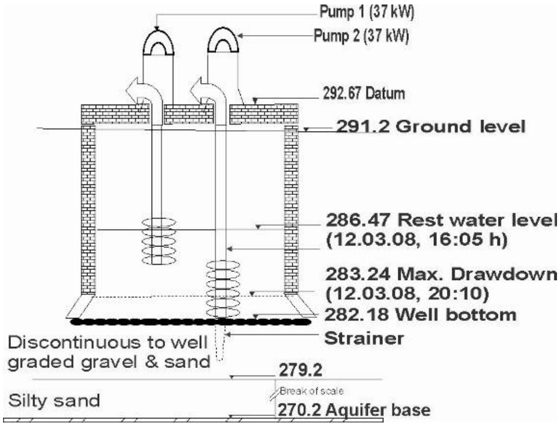


Figure 3-5 Cross-section of a typical large-diameter caisson RBF well (IW18) in Haridwar (Sandhu, 2013)

Figure 3-6 A RBF well in Kharagpur (Kang-sabati River, West Bengal) at risk of contamination by floods (Photo: C. Sandhu)

In comparison, the wells PW5 and MW5 in Srinagar that were affected by the flood in August 2011 underwent a sanitary sealing after the flood (Figure 8-1). The sanitary sealing includes the construction of a concrete and / or clay seal in the immediate vicinity of the well base. Its purpose is to prevent the seepage of water into the ground and along the annulus between the well casing and the aquifer material to the groundwater table ("short-circuiting"). In the event that a sanitary sealing is constructed, and as long as the casing pipe and well head remain above the flood level, the risk of direct entry of flood water through the well head or short circuiting along the well casing is lessened but not eliminated. Even if a sanitary seal may exist, the flood-water nevertheless comes in direct contact with the casing and thus potential contamination by damage from floating debris or entry of flood-water through impervious seals cannot be excluded (Figure 3-6).

3.4 Failure of main power supply and contingency measures

On Pant Dweep Island in Haridwar, only the RBF well IW18 has a generator that provides back-up power to the pumps and disinfection system. Of the remaining wells, only IW24 and 25 are provided back-up power together from one generator (the wells are located close to one-another) and IW42 and IW43 are together provided back-up power by another generator. However, during that flood these generators could not be accessed / operated because they were also inundated by the flood. This highlights the fact that extreme flood events and subsequent direct contamination and inaccessibility of the wells are a risk in Haridwar. Accessibility to the wells during a flood in Haridwar and Srinagar, as well as all other RBF sites in India, is important because currently there are no known examples of on-line systems installed to monitor microbial contamination and turbidity peaks in time.

4 Field investigations to assess flood-risk at RBF site in Haridwar

4.1 Enhancement of monitoring network

Two monitoring wells (MW 1 & 2) were constructed in Haridwar (Bhopatwala) in May 2012 for the Saph Pani project (Figure 4-1). They are located between the RBF well BWIW2 and the Ganga River. The construction was carried out by the project partner Akshay Jaldhara (AJD), with logistical and technical support from the project-partners Uttarakhand State Water Supply and Sewerage Organisation (Uttarakhand Jal Sansthan - UJS) and the Dresden University of Applied Sciences (HTWD). The RBF well is situated at a distance of 46 m from the Ganga River. MW1 is 14.7 m deep and built at a distance of 2.9 m from the well. MW2 is 5.2 m deep and built at a distance of around 4.9 m from the well. The MWs will be used to measure water levels and to observe the quality of the bank filtrate originating from the Ganga River.

Figure 4-1 Construction of monitoring wells at the RBF site (IW2) in Haridwar by Akshay Jaldhara (Photo: K. Heinze & M. Lesch, HTWD, May 2012)

4.2 Water level and flow analyses of Ganga River in Haridwar

4.2.1 Time-series analyses of Ganga River stage and discharge

To analyse flood risk and flood hazards on the RBF wells, 11 years (2002 – 2012) of daily stage and discharge data of the Ganga River, collected by the UGC authority, who measured the river level upstream of Sarvanand Ghat, have been used. For the estimation of discharge, a stage versus discharge rating curve has been used.

The daily stage and discharge data of the Ganga River for the year 2002 – 2012 have been analysed to compute monthly minimum, maximum, mean, median and quantiles of water level and discharge series. Figure 4-2 (box-and-whisker plot) presents the monthly water level for different years showing a vertical line, a box and horizontal lines, respectively representing the minimum and maximum values by the bottom and top of the vertical line, quantiles (25 % and 75 %) by the bottom and top of the box and the mean and medium by the horizontal lines. A box-and-whisker plot shows the distribution of a set of data along a number line, dividing the data into four parts using the median and quantiles. It also indicates which way the data sways. For example, if there are more high flow values than low flow values, the median is going to be higher or the top whisker would be longer than the bottom one. Basically, it gives a good overview of the data distribution. The spacing of the different parts of the box helps indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

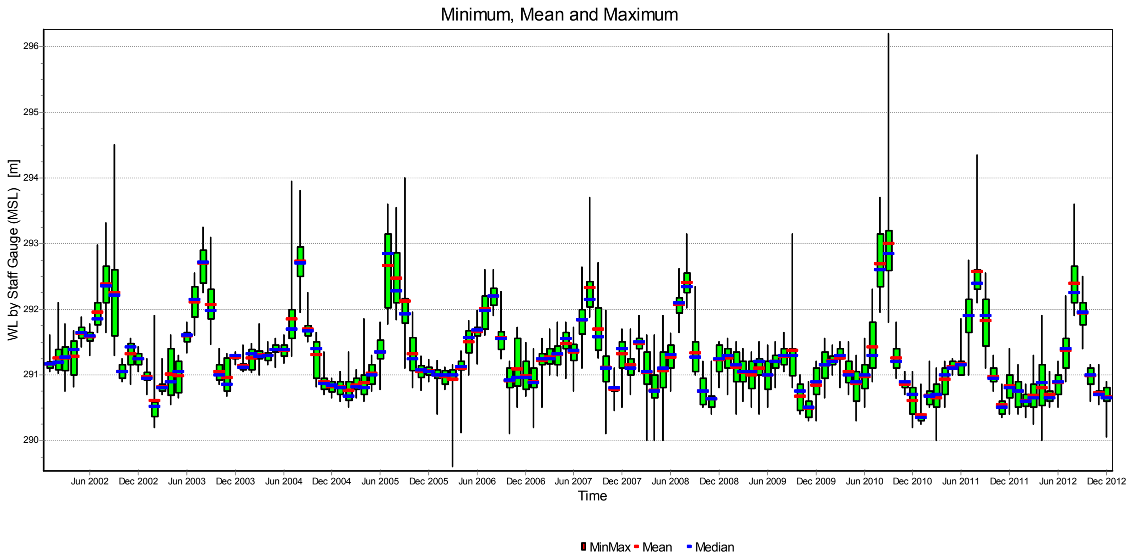


Figure 4-2 Box and whisker plot of water level at monthly interval (NIH 2013)

For the data series 2002 – 2012, the minimum water levels generally remain above 290 mASL (Figure 4-2), except the minimum level of 289.60 mASL recorded in March 2006. The maximum average monthly water level is observed mostly below 294 mASL except in 2002 and 2011 and the maximum level of 296.2 mASL recorded in September 2010. The minimum and maximum level of monthly average is observed to be 290.85 mASL and 292.38 mASL, respectively with an annual average of 291.29 mASL. The monthly minimum, monthly maximum and monthly average level for the data series of 2002 – 2012 are given in Table 4-1.

Table 4-1 Ganga River at Sarvanand Ghat - monthly minimum, maximum and monthly average water level in mASL 2002-2012 (NIH 2013)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Year
Average of monthly minimum												
290.2	290.2	289.6	290.0	290.0	290.5	290.8	291.0	290.8	290.1	290.3	290.0	289.6
Average of monthly maximum												
291.7	292.1	291.78	291.9	291.9	291.98	293.9	294.3	296.2	291.9	291.7	291.7	296.2
Average of monthly average												
291.0	291.0	291.0	291.0	291.2	291.3	291.9	292.4	291.9	291.0	290.6	291.0	291.3

The average monthly minimum discharges corresponding to the average monthly minimum water levels variation of 290 mASL and 291 mASL are observed to be between 196 m^3/s and 1,503 m^3/s. The discharge of flow corresponding to the minimum level of 289.6 mASL is 17 m^3/s. The maximum flood discharge corresponding to the maximum water level of 296.2 mASL observed in 2010 is 12,400 m^3/s. Further it is observed that the water level in the river Ganga reaches its maximum during August and September (Figure 4-2.) Table 4-2 gives average monthly minimum, maximum and monthly average discharge values for the data series 2002 – 2012.

Table 4-2 Ganga River at Sarvanand Ghat - average monthly minimum, maximum and average discharge in m^3/s 2002-2012 (NIH 2013)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Year
Average of monthly minimum												
203	208	189	200	224	373	893	1503	841	365	194	196	189
Average of monthly maximum												
377	517	554	430	774	1303	2902	3997	4143	1066	481	407	4143
Average of monthly average												
270	295	296	302	455	721	1630	2402	1728	623	318	286	777

The minimum, mean and maximum discharges at yearly interval indicate that the maximum discharge of flow was observed during the year 2010 and minimum during the year 2006. Further, it is also clearly evident that the high flood peaks, as observed in the year 2010, are very rare and normally the peak discharge is found < 5,700 m^3/s.

4.2.2 Analyses of flood return periods using annual maximum series

To find flood values for different return periods, a flood frequency analysis using the annual maximum series (AMS) has been carried out. The AMS model has been used to arrive at a return period flood growth curve that is eventually used for deriving a flood q (T) for a specific return period (T). It is to be mentioned here that the AMS models are generally used for a series of length 30 years or more. In the present case, data for a period of 11 years were available. Floods for different return periods computed using the Extreme Type-2 distribution are given in Table 4-3. The 25 year and 50 year floods are predicted to have a discharge of 10,427 and 12,860 m^3/s, respectively. These correspond to a water level of 295.14 mASL and 295.57 mASL, respectively.

While the RBF wells at the Rodibewala area are also at risk from floods of the lower return periods, all other wells are located behind the flood protection embankment (dyke) of the Ganga and the UGC, and are therefore at low risk from flooding for return periods up to a 50-year event (see Section 4.6.1).

Table 4-3 Return period flood using Type-2 distribution (NIH 2013)

Return period (years)	Probability (xi<x) p	Discharge Q m^3/s	Standard deviation Q m^3/s	Confidence Intervals	
				lower	upper
2	0.50	4487	473	3649	5518
5	0.80	6290	1019	4579	8640
10	0.90	7867	1634	5235	11820
25	0.96	10435	2809	6157	17687
50	0.98	12869	4067	6926	23911

4.3 Water quality monitoring

4.3.1 Methodology for water quality sampling and analyses

The locations from where water samples for quality and isotope analysis were collected from May 2012 to February 2013 are shown in Figure 4-3. The samples were collected monthly, except in July when no samples were taken. Two sampling campaigns were conducted in September, and thus a total of 10 sampling campaigns were undertaken. For the assessment of water quality, samples from 29 locations (22 RBF wells, 3 locations on the Ganga River, 3 locations on the UGC and one sample from an open well (OW), to get a representation of the ambient groundwater quality were collected. The samples were analysed in the water quality laboratory of NIH, Roorkee.

Each sample was analysed to determine temperature, pH, EC, TDS, turbidity, alkalinity, hardness, Na, K^+, Ca^{2+}, Mg^{2+}, HNO_3^-, Cl^-, SO_4^{2-}, NO_3^-, and BOD), total coliform and faecal coliform, Fe and Mn. The water samples were collected in clean polyethylene bottles preserved by adding an appropriate reagent (Jain and Bhatia, 1988; APHA, 1992). The water samples for trace element analysis were collected in acid leached polyethylene bottles and preserved by adding ultra pure nitric acid (5 ml/l). Samples for bacteriological analysis were collected in sterilized high density polypropylene bottles covered with aluminium foil. All the samples were stored in sampling kits maintained at 4°C and brought to the laboratory for detailed chemical and bacteriological analysis.

All general chemicals used for analysis were of analytical reagent grade (Merck/BDH). Standard solutions of metal ions were procured from Merck, Germany. Bacteriological reagents were obtained from HiMedia. De-ionized water was used throughout the study. All glassware and other containers used for trace element analysis were thoroughly cleaned by soaking in detergent followed by soaking in 10% nitric acid for 48 h and finally rinsed with de-ionized water several times prior to use. All glassware and reagents used for bacteriological analysis were thoroughly cleaned and sterilized before use.

The physico-chemical and bacteriological analysis was performed following standard methods (Jain and Bhatia, 1988; APHA, 1992). Details of analytical methods and equipment used in the study are given in Annex 5. The error in the ionic balance for majority of the samples was within 5 %.

Metal ion concentrations were determined by atomic absorption spectrometry using Perkin Elmer Atomic Absorption Spectrometer (Model 3110) using air-acetylene flame. Operational conditions were adjusted in accordance with the manufacturer's guidelines to yield optimal determination. Quantification of metals was based upon calibration curves of standard solutions of respective metals. These calibration curves were determined several times during the period of analysis. The detection limits for iron and manganese are 0.003 mg/L and 0.001 mg/L respectively.

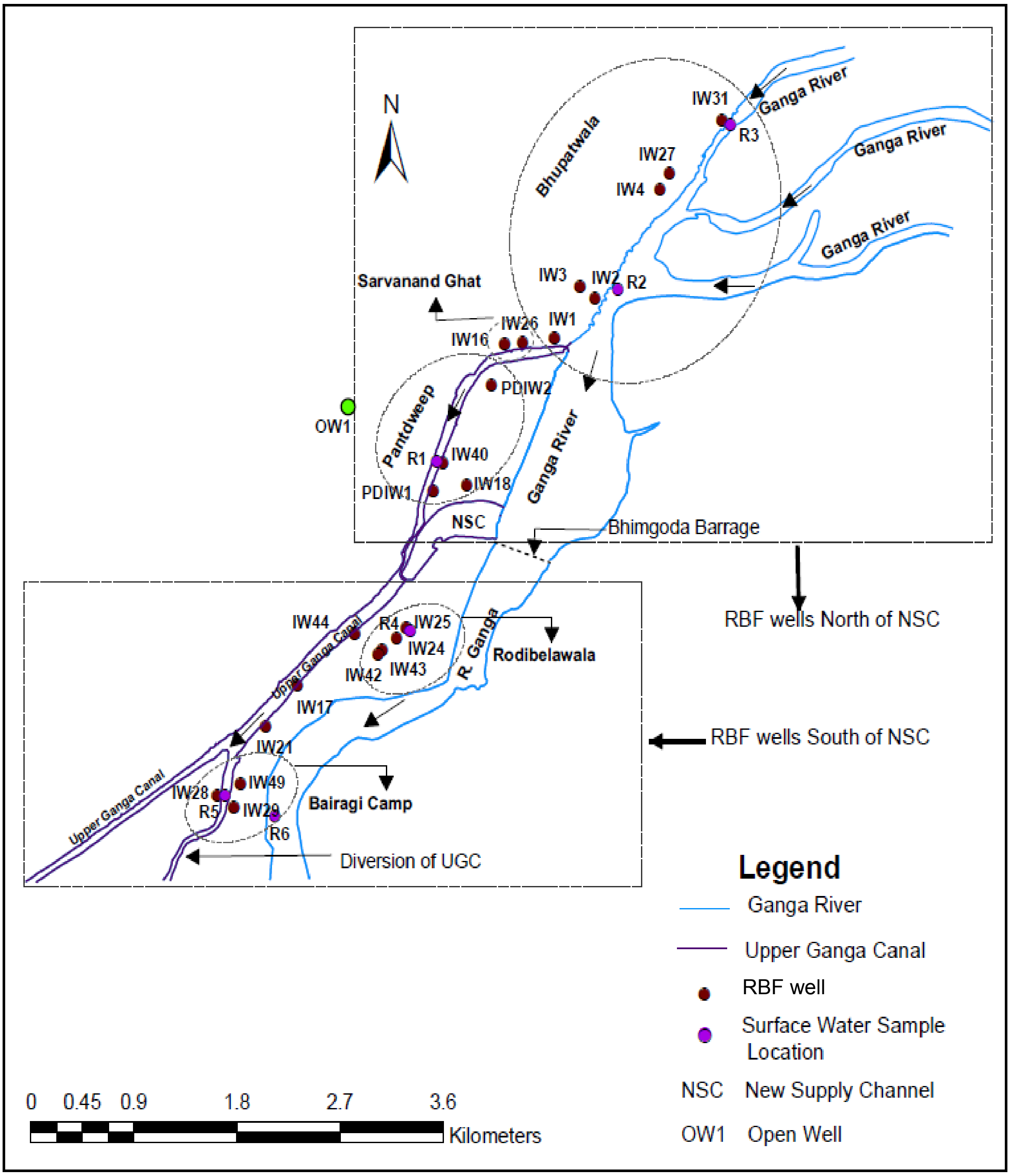


Figure 4-3 Locations of 22 RBF wells, surface water bodies, the flood protection embankment and points for sampling for water quality and isotope analysis

4.3.2 Water quality evaluation

A summary of the range of values of all water quality parameters analysed for the monsoon and non-monsoon months is provided in Annex 6 and Annex 7 respectively. Due to the relatively low impact of industries along the Ganga River upstream of Haridwar (compared to downstream) and along the stretch of the UGC where the RBF wells are located, the main anthropogenic impacts on surface water quality are from partially to untreated domestic sewage. Furthermore, previous studies (Dash et al., 2010, Sandhu et al., 2011) report that all other water quality parameters are mostly within the limits prescribed by the Indian Standard IS 10500 (1991). Thus water quality parameters of concern for bank filtrate in study site are mainly pathogens and turbidity.

4.4 Isotope analyses

4.4.1 Isotopic characteristics of water

The isotopic method provides a mean for identifying the actual mass transport of water. It is based on the fact that the surface water system normally has a different stable isotopic composition than that of recharged water from local precipitation. In case of a river, the transported water that originates from precipitation at higher elevations shows an altitude effect in the isotopic composition (Kumar and Nachiappan, 1992) which differs from the precipitation recharged to groundwater locally.

In case of a river contributing to the groundwater regime, there are two possible sources of recharge to groundwater, viz. infiltration of local precipitation and infiltration of river water. In such conditions, the accuracy of the estimate of the proportion of infiltrated river water depends upon the accuracy of the estimates of stable isotopic indices of these two potential sources of recharge and the difference between these indices. An estimate of the river index is made on the basis of river water samples. This should be done at different times and especially at high river stages to ascertain variations in stable isotopic composition. If variations are evident the mean value weighted for discharge should be used. The preferable approach is to sample groundwater close to the river where piezometer indicates river water as the source of recharge. The estimation of the index for recharge by infiltration by local precipitation is based on measurements of groundwater away from the influence of the river or, if sufficient data are available, on the peak value of the skewed frequency distribution. If the errors in estimates of the indices of the two potential sources of recharge are not greater than the analytical error, then the accuracy in the estimate of the proportion is better than 10 %. In practice the limitations of the method are not in the method itself, but in the availability of meaningful samples.

4.4.2 Sampling locations and frequency

A total of 28 sampling locations which include 25 sites for subsurface water samples, 2 sites for the river Ganga water samples, and 1 for Upper Ganga canal water had been identified for isotopic analysis (Figure 4-3, Annex 8).

Water samples have been collected ten times during May 2012 and February 2013 from the selected locations, two times before monsoon (May and June 2012) and three times during the monsoon season (August, twice in September), and 5 times in the post monsoon season (October, November, December, January and February). The samples collected from the Haridwar experimental site have been analysed for isotopic composition of oxygen ($\delta^{18}O$) and hydrogen (δD). The results of the isotopic analysis are given in Annex 9.

4.4.3 Methodology

The approach is based on the fact that the river originates at higher altitudes. The river Ganga normally has a different stable isotopic composition than that of groundwater recharged by infiltration from local precipitation. The isotopic composition for $\delta^{18}O$ in precipitation changes between -0.2 and -0.3 ‰ per 100 m with altitude. Thus, the stable isotopic composition of the river water is found more depleted than that of groundwater derived from infiltration of local precipitation in plains. This distinct difference helps in identifying the contribution of one to the other. The studies carried out by Rai et al. (2009) and few others have revealed that the river Ganga has stable isotopic signatures ($\delta^{18}O$) in the range of -9.5 ‰ to -13 ‰. In the areas, where groundwater recharge due to precipitation dominates, $\delta^{18}O$ values in the Haridwar area have been found to vary between -7 ‰ to -9 ‰. Therefore, stable isotopes of oxygen have been used to determine the contribution of river water in the well water at selected locations in the study area using the following equation, which conform to the law of mass conservation:

$$m_r = m_1 + m_2 \tag{4.1}$$

$$m_r C_r = m_1 C_1 + m_2 C_2 \tag{4.2}$$

where *m* is the quantity of components expressed in fraction, *C* is the tracer concentration, the subscript r denote admixture at the point of interest, and the subscripts 1 and 2 denote the two components that contribute to the water. In the absence of volumetric data, m_r could be assumed to be equal to one and the m_o and m_n could be expressed as ratio to the total water at a particular time. Rewriting equation (4.1), we get:

$$m_1 = 1 - m_2 \tag{4.3}$$

Substituting equation (4.3) in (4.2) and rearranging, we get:

$$m_2 = \frac{C_1 - C_r}{C_1 - C_2} \tag{4.4}$$

Equations (4.1) and (4.4) could be used to compute the fraction of the two components of the stream flow at a given point in space and time.

4.4.4 Results of isotope analyses

Isotopic composition of the rivers in the snow free catchments reflects the isotopic composition of the rainfall. But in a glaciated catchment, the isotopic composition of the river water in summers reflects the isotopic composition of the snow and ice (Rai et al, 2009). But in the catchments with large water storages, small events of rain and snow and ice melting are mixed with stored water and are lost. Variation in isotopic composition of the Ganga River is shown in Figure 4-4.

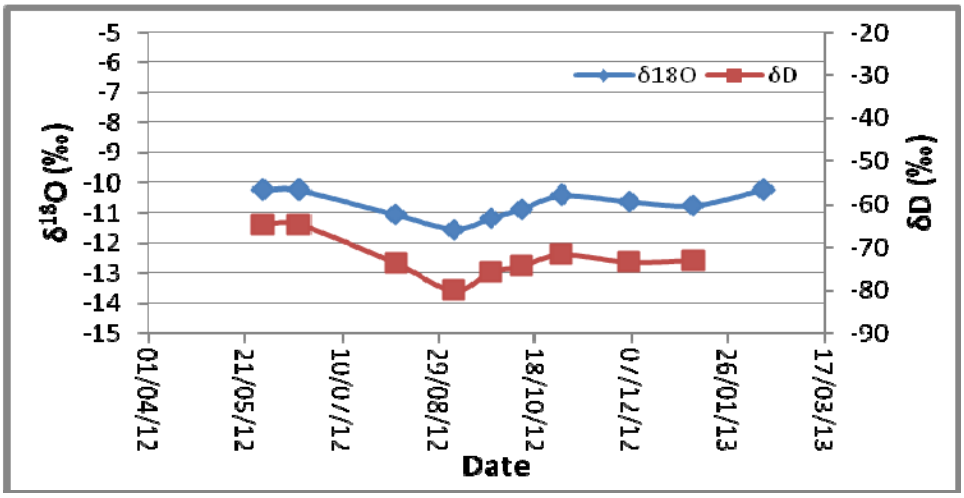


Figure 4-4 Isotopic characteristics of Ganga River water at Haridwar (NIH 2013)

Figure 4-4 indicates that during the period of investigations, the isotopic values varied from -64.8 to -80.1‰ and -10.19 to -11.68 ‰ for δD and δ^{18}O, respectively. With the advancement of the monsoon, the isotopic values get depleted due to enhanced melting of snow and ice (Rai et al., 2009). After the monsoon, it again gets enriched, with relatively higher contribution of groundwater generated due to monsoon rains.

Isotopic variation (δ^{18}O) in infiltration and other groundwater wells indicate that the groundwater in those wells is recharged from river water as well as from rainwater in different proportions depending on the location.

For determining the component of river water in the IWs and the open wells, the groundwater isotopic indices and the isotopic indices of river water have been used. For determining the groundwater indices, the maximum isotopic value of the month has been considered, whereas for determining the isotopic indices of the river water the average of the river isotopic value has been considered. As the Ganga River is very wide and not very deep in the area, the isotopic composition of the near surface water or slow flowing water may get enriched due to evaporation. Considering this fact, the minimum of the isotopic value observed in the wells has been taken as the river water index for that month. The indices for the different sampling dates are given in Table 4-4.

Table 4-4 Isotopic indices (δ^{18}O) of groundwater and river water (NIH 2013)

Date	30-May-2012	18-Jun-2012	07-Aug-2012	06-Sep-2012	25-Sep-2012	11-Oct-2012	01-Nov-2012	06-Dec-2012	08-Jan-2013	13-Feb-2013
Indices										
Groundwater	-7.5	-7.6	-7.5	-7.1	-7.2	-7.5	-7.5	-7.1	-7.2	-7.4
River water	-10.8	-10.7	-11.1	-11.7	-11.3	-11.1	-11.2	-10.8	-10.9	-10.7

Based on these indices, the proportion of the river water in groundwater wells has been computed and is given in Table 4-5.

Table 4-5 Relative proportion of river water in well water in Haridwar site (NIH 2013)

		2012								2013	
Lo-cation	Well No.	30.05.	18.06.	07.08.	06.09.	25.09.	11.10.	01.11.	06.12.	08.01.	13.02.
Bhupat wala	IW31	0	4	0	3	0	0	0	0	0	0
	IW27		0	15	0	15	1	13	14	12	8
	IW4		14	19		13	4	7	18	19	14
	IW3	27	23			46	10	2	18	19	29
Bhupat wala	IW2	74	88	47	40	68	75	54	70	81	84
	IW1		83	60	51	54	48	43	60	67	70
Sarvan and Ghat	IW26	56	65	66	38	31	39	26	30	36	42
	IW16	39	46	35	28	27	27	19	26	29	
Pant-dweep	PDIW 2		81		63	51	61	39	46	58	66
	IW40	75	84	77	58	68	66	72	73	68	78
Pant-dweep	PDIW 1		91	82	68	81	84	87	87	88	91
	IW18	100	98		47	63	72	80	82	80	91
Rodibe lawala	IW25	97	100	84	73	77	87	87	97	93	96
	IW24		89	84	62	76	80	88	94	95	99
	IW43		97	96	68	76	88	80	100	100	97
	IW42		96	95	70	69	85	85	96	98	97
	IW44	95	95	83	81	76	95	90	97	98	97
Ala-knanda Hotel	IW17	95	93	81	69	85	96	93	93	95	100
	IW21	98	95	83	84	89	100	84	94	96	96
Bairagi Camp	IW49		95	75	74	90	95	92	98	97	99
	IW29	95	94	86	87	100	96	100	96	95	98
	IW28	90	90	89	84	93	89	96	95	93	87
Kabir Ash-ram, Bhupat wala	OW1			7	8	19	10	2	26	24	16
Jhanda Chowk Jawala pur	OW2		25	24		40	33		51	54	56
Firahe diyan Jawala pur	OW3		42	39	26	36	31		33	38	30
Colour code	Dark green	>75%	Light green	50-75%	Light blue	25-50%	Pink	<25%			

Figure 4-5 indicates that the samples from IW31, IW27, IW4 and OW-1 are mostly groundwater generated locally and have almost negligible component of river water. The sample from IW3 indicates that at this location river water recharge is dominant only during monsoon, after that groundwater recharge is the predominant component. The samples from IW2 and IW1 indicate a mixed recharge of river water and groundwater.

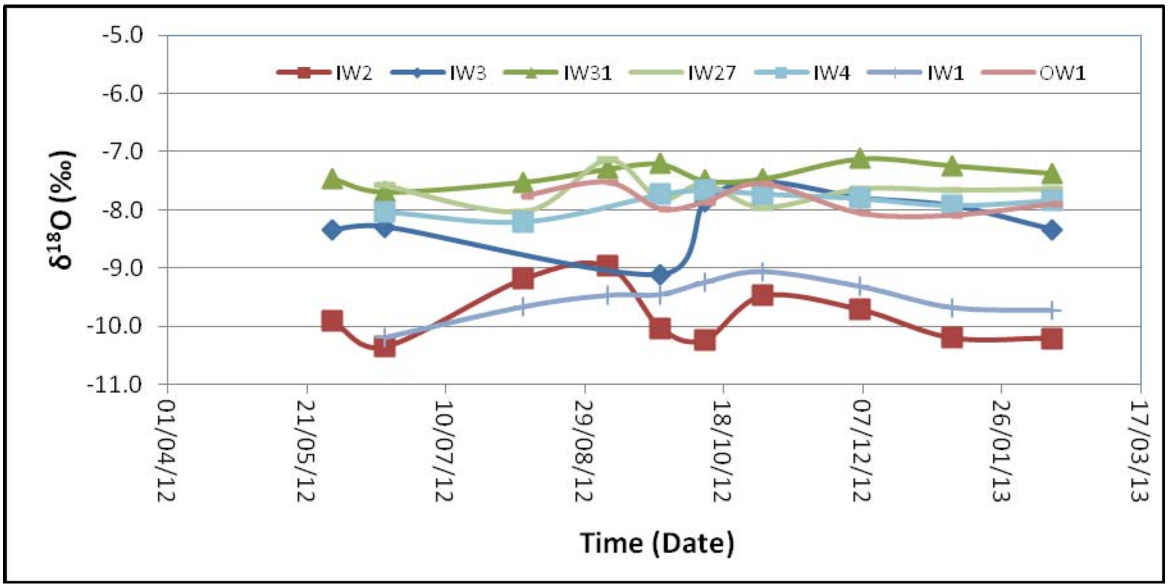


Figure 4-5 Isotopic (δ^{18}O) variation in Bhupatwala area (NIH 2013)

Moving South further downstream, samples from IW16 and IW26 have been collected. The isotopic (δ^{18}O) variation with time for the well water of this area is shown in Figure 4-6. Figure 4-6 indicates that in both wells there is little interaction with river water. The contribution of river water is less than 50 %. The interaction is more pronounced in IW26 than in IW16.

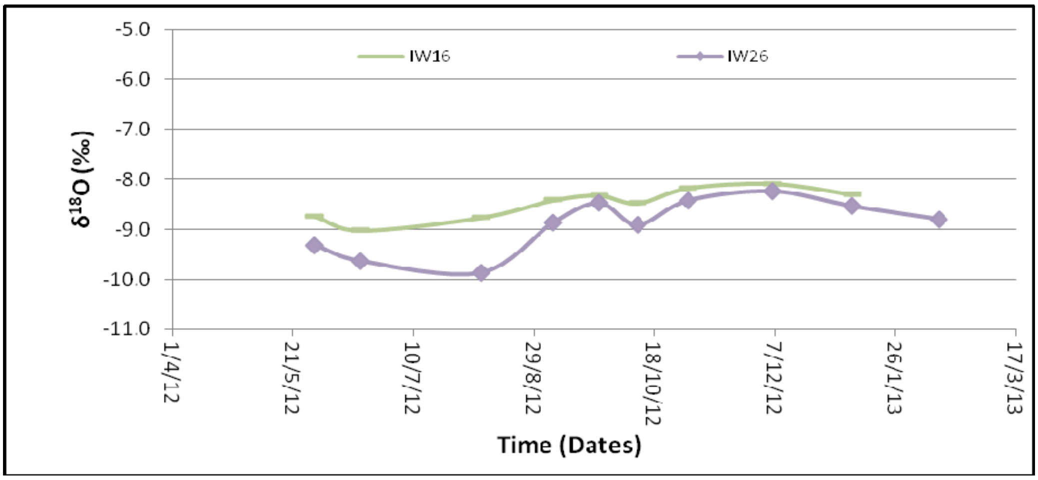


Figure 4-6 Isotopic (δ^{18}O) variation in Bhupatwala area (NIH 2013)

In the Pantdweep area, samples from 4 IWs (IW18, IW40, PDIW2 and PDIW1) have been collected. Isotopic (δ^{18}O) variation with time in the well water is shown in Figure 4-7. Figure 4-7 indicates that all the four wells receive water from the river Ganga at different proportions. Samples of IW18 and PDIW1 indicate more river water and show depleted signatures which are similar to the river water characteristics.

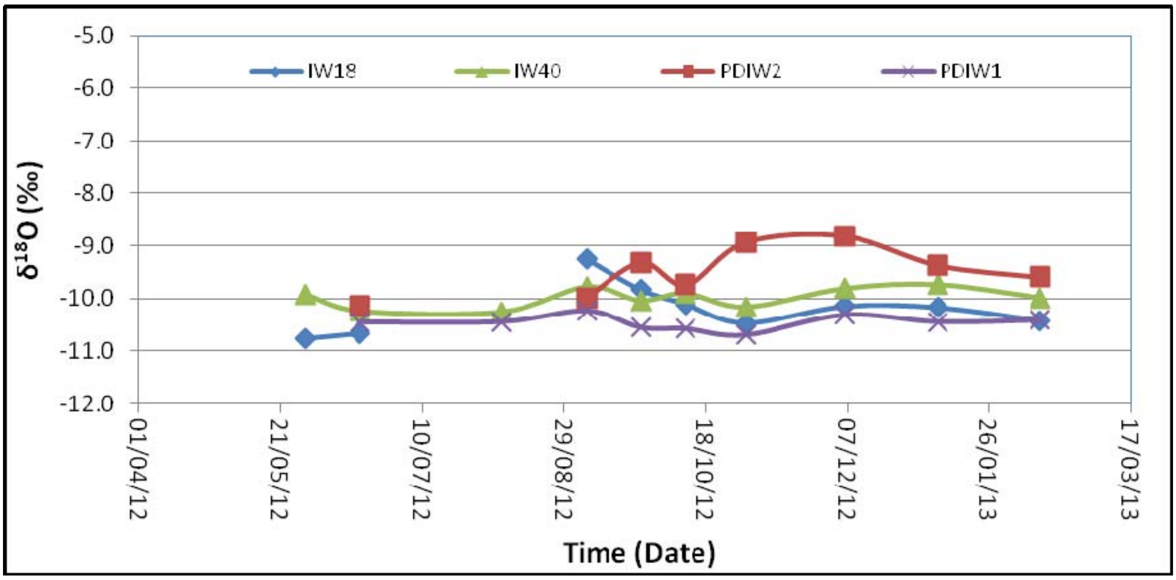


Figure 4-7 Variation of δ^{18}O with time in Pantdweep area (NIH 2013)

From this area, samples from five locations, i.e. IW25, IW44, IW24, IW43, and IW42 had been collected. All these infiltration wells lie between the UGC and the Ganga River. The isotopic (δ^{18}O) variation with time in the well water is shown in Figure 4-8. The isotopic data in Figure 4-8 show that all the wells receive a large proportion of river water (>75 %).

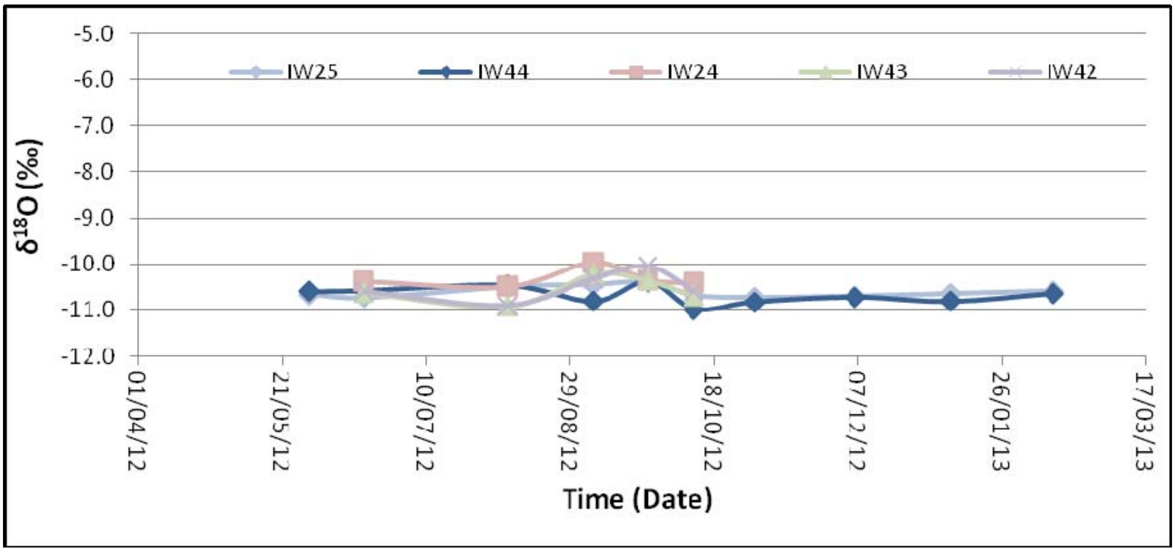


Figure 4-8 Variation of δ^{18}O with time in Rodibelwala area (NIH 2013)

This area represents two sampling sites; IW21 and IW17. The area lies between the River Ganga and very close to the UGC. The isotopic variation (δ^{18}O) at different times is shown in Figure 4-9.

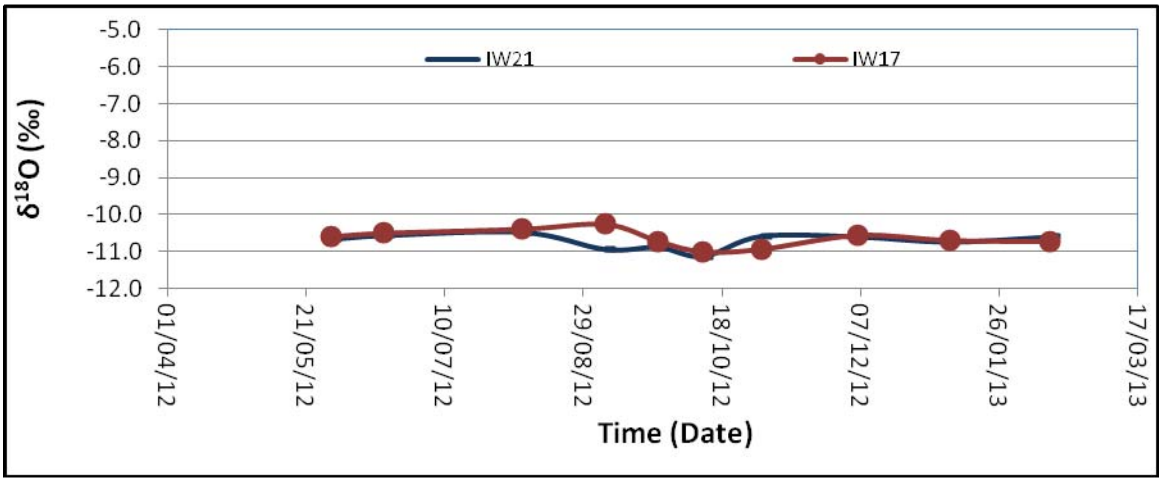


Figure 4-9 Variation of δ^{18}O with time in Alaknanda Hotel area (NIH 2013)

Figure 4-10 shows almost constant value of δ^{18}O with time and is very close to the isotopic values of the river / canal water, which indicates that the wells in this area are predominantly recharged by the canal water.

Three sampling sites (IW29, IW28 and IW49) are located near the Bairagi Camp and Mahila Milan. The area lies between the River Ganga and near to the UGC. The isotopic variation as shown in Figure 4-10 indicates that the IWs in this area also receive water from the river Ganga or the UGC. Almost all water is contributed by the UGC.

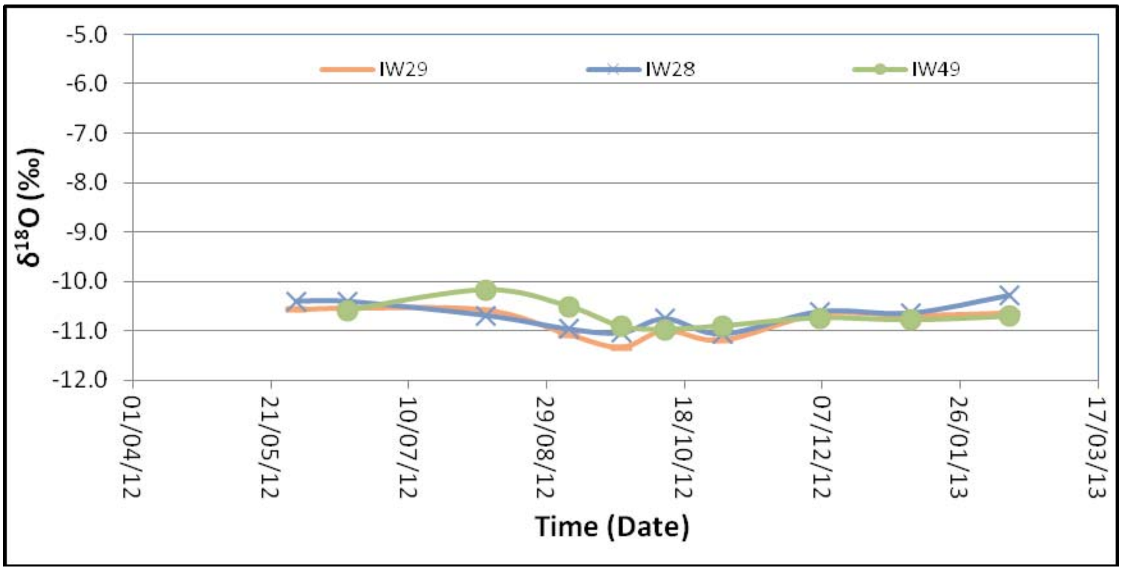


Figure 4-10 Variation of δ^{18}O with time in area near Bairagi Camp (NIH 2013)

The Jwalapur area lies far away from the river and is located to the North of the UGC. The isotopic variation recorded for two open wells (OW2, OW3) is shown in Figure 4-11. These wells are chosen to examine source of recharge to undisturbed groundwater in the surrounding area. Isotopic analysis shown in Figure 4-11 indicates that both the wells do not get any water from the river, and are recharged by the local precipitation only.

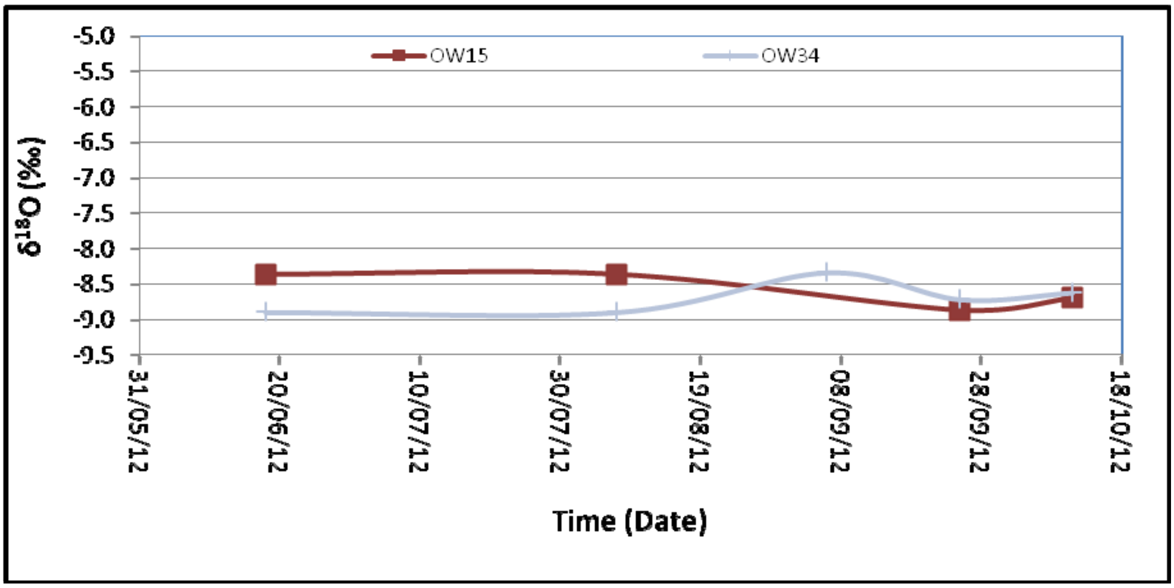


Figure 4-11 Variation of $\delta^{18}O$ with time for open wells in the Jawalapur area (NIH 2013)

4.5 Field investigations on removal of pathogens in Haridwar

During monsoon months (July – October), the total and faecal coliform counts and turbidity of the surface water (Ganga River and UGC) by the RBF wells are significantly higher than during non-monsoon periods (Table 4-6), the monsoon month are shown in grey). Turbidity levels in all the RBF wells monitored are quite low (< 7 NTU) in most of the cases except in some samples, and are within the range of the Indian Standard (IS 10500, 2012). The total and faecal coliform counts in the majority of the water samples from the RBF wells are quite low compared to the surface water. Accordingly, a significant removal of turbidity, total and faecal coliform counts is observed in the bank filtrate water. Total and faecal coliform counts in the UGC and the River Ganga are observed to be very high (mostly > 2400 MPN/100 mL) during the period from May to February. The monitored bank filtrate has shown a significant higher quality compared to directly abstracted surface water from the River Ganga and UGC. In some of the wells (IW4, IW2, IW1 and IW27 in the Bhupatwala area, IW16 and IW26 in the Sarvanandghat area, IW43 and IW42 in the Rodibelawala area, IW17 and IW21 in the Alaknanda hotel area) the occasional presence of total and faecal coliforms range between 240 to and 2400 MPN/100mL. A small number of these wells, namely, IW2, IW16, IW27, IW17, and IW21 are located very close to the Ganga / UGC, and the immediate area around these wells is exposed to significant human activity, including disposal of refuse. The ambient groundwater quality of the area, as observed from the samples of open well (OW1), also showed a fairly high value of total and faecal coliform counts.

Table 4-6 Turbidity, Total and Faecal Coliform count in surface water compared to bank filtrate from May 2012 to February 2013 (NIH 2013)

Parameter	Month &Year	Surface water (Ganga River and UGC)	RBF well
Turbidity (NTU)	May,2012	15.6 – 38.9	0.76 – 4.71
	June,2012	56.5 – 64.0	0.96 – 3.16
	August,2012	346 – 440	2.62 – 6.67
	September,2012	86 – 147	0.80 – 7.17
	September,2012	21 – 51	0.92 – 3.00
	October,2012	14 – 66	1.20 – 24.0
	November,2012	1.86 – 2.25	0.85 – 2.45
	December,2012	2.61 – 7.33	1.00 – 3.62
	January,2013	8.2 – 31.0	0.80 – 31.0
	February,2013	6.29 – 8.15	0.80 – 4.04
Total Coliform Count (MPN/100 mL)	May,2012	> 2400	ND – < 2400
	June,2012	> 2400	ND – 240
	August,2012	> 2400	ND – < 2400
	September,2012	> 2400	ND – < 2400
	September,2012	> 2400	-
	October,2012	> 2400	ND – < 2400
	November,2012	> 2400	ND – < 2400
	December,2012	> 2400	ND – < 2400
	January,2013	> 2400	< 3 – < 2400
	February,2013	23 – > 2400	ND – < 2400
Faecal Coliform Count (MPN/100 mL)	May,2012	-	-
	June,2012	460 – > 2400	ND – 240
	August,2012	> 2400	ND – < 2400
	September,2012	> 2400	ND – < 2400
	September,2012	-	-
	October,2012	460 – > 2400	ND – < 2400
	November,2012	> 2400	ND – < 2400
	December,2012	1100	ND – < 2400
	January,2013	460 – > 2400	< 3 – 460
	February,2013	23 – 150	ND – 460

4.6 Summary of results of field investigations in Haridwar

4.6.1 Likelihood of inundation at the RBF sites

The water levels upstream of Sarvanand Ghat corresponding to the magnitude of 25 year and 50 year floods are predicted to be 295.2 mASL and 295.6 mASL, respectively. These levels are expected to reach near to the wells IW31, IW27 and IW4 in the Bhupatwala area (Northern most upstream part of Haridwar), where the top of the well caissons are at an elevation of around 301.33 m and the average ground surface elevation is 299 mASL. Thus the expected risk of submergence of the wells and their nearby ground surface in the Bhupatwala area by the extreme flood event corresponding to the water level of 295.6 mASL is very low.

The average slope of the river bed in the stretch between the Bhupatwala area and Bairagi camp (7 km) is around 2 ‰. The discharge of the UGC and NSC at their full supply levels is around 298 m^3/s (10,500 ft^3/s). This implies that if during a peak flood in the Ganga, the UGC and NSC are allowed to flow at their full capacities, the flood discharge in the Ganga downstream of the Bhimgoda Barrange would be 298 m^3/s less than its upstream discharge. The 25 year and 50 year return period flood in such a case at the downstream side would be equal to 10,427 and 12,860 m^3/s, respectively; and the water level corresponding to these discharges at the stage-discharge site are estimated to be 295.2 mASL and 295.6 mASL. The approximate water levels in the Ganga at the Rodibewala area with an average bed slope of 2 ‰, for the distance of 5 km from the Bhupatwala area, for the 25 year and 50 year flood are predicted to be 285.2 mASL and 285.6 mASL, respectively. The top surface elevations of the well number IW25, IW24, IW43, IW42, and IW44 in the Rodibewala area vary between 288.65 mASL and 289 mASL and the average level of flood embankment is approximately 286 mASL. It indicates that for lower return periods up to a 50 year flood event the RBF wells at the Rodibewala area are at some risk from direct entry of flood waters into the wells through the top of the caisson.

All other wells are located behind the flood protection embankment (dyke) of the Ganga and the UGC, and therefore the possibility of direct entry of flood water into the wells by the high flood water level in the river Ganga is beyond expectation unless the flood embankment breaches or regulation of canal water supply system collapses.

4.6.2 Water quality issues during flooding

During monsoon months, the total and faecal coliform counts and turbidity of the surface water (Ganga River and UGC) by the RBF wells are significantly higher than during non-monsoon periods. Turbidity levels of the abstracted water from the IWs for both monsoon and non-monsoon period have been found low compared to the Ganga and the UGC water. Total and faecal coliform counts in the UGC and the River Ganga have been observed to be very high (mostly > 2400 MPN/100 mL) during the period from May to February while bank filtrate water has shown a significant higher quality (except in few IWs) compared to directly abstracted surface water from the River Ganga and UGC. The ambient groundwater quality of the area showed a quite high value of total and faecal coliform counts. Therefore, the transport of pathogens from the surface sources to the groundwater through RBF cannot be ruled out.

Out of the twenty five wells studied for isotopic composition of the groundwater samples taken from the infiltration wells / open wells, only 16 wells (only IW2 in the Bhupatwala area; IW1 in the Sarvanand Ghat area; IW18, IW40, PDIW1 and PDIW2 in the Pantdweep area; IW25, IW24, IW43, IW42 and IW44 in the Rodibelawala area; IW21 and IW17 in the Alaknanda hotel area; IW49, IW29, and IW28 in the Bairagi cam area) have good interaction with the river Ganga/UGC water. The remaining nine wells (IW31, IW27, IW4 and IW3 in the Bhopatwala area; IW16, and IW26 in the Sarvanand Ghat area; OW-1 in the Kabir Ashram area; OW2 and OW3 in the Jawalapur area) have very limited interaction with the river Ganga /UGC and recharge is predominantly from groundwater.

4.6.3 Health risk assessment

In cooperation with work package 6 – “Integrated sustainability assessment” of the Saph Pani project, a health risk assessment for Haridwar was conducted separately based on the field investigations conducted in Haridwar (Bartak et al., 2013). Accordingly, the risk for diarrhoeal diseases associated with rotavirus is above the adopted health target of 5E-03 disability adjusted life years (DALY's) in this study. The highest estimate of risk is associated with rotavirus. According to the calculated DALY's an additional $\log_{10}$ removal of 0.5 to 2.8 $\log_{10}$ units are required for rotavirus during monsoon. However, this figure may vary significantly depending upon the assumptions taken as discussed in Bartak et al. (2013). The risk associated with *E. coli* O157:H7, which numbers was converted from direct thermotolerant coliform measurements in the RBF wells, is far below the national and regional diarrheal incidence but above the WHO (2011) reference level of risk for advanced countries.

5 Field investigations to assess flood-risk at RBF site in Srinagar

5.1 Enhancement of monitoring network

Within the framework of the Saph Pani project, a monitoring well (MW5) was constructed in May 2012 by the project partners Akshay Jaldhara and Uttarakhand Jal Sansthan in between PW5 and the river (Figure 5-1, Figure 5-2 and Annex 10). MW5 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 PW5. 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 faecal coliform counts of the abstracted water from PW5 and the Alaknanda, was conducted from September to December 2012.

Figure 5-1 Monitoring well MW5 (left) constructed in between PW5 (right) and Alaknanda, Srinagar (Photo: HTWD, 2012)

Figure 5-2 Pumping test and sampling being conducted on MW5 and PW5, Srinagar (Photo: V. Nguyen, HTWD, 2012)

5.2 Water level investigations

5.2.1 Aim and execution

The objective was to get an improved understanding of the effect of the monsoon on the surface and groundwater levels at the RBF site. Water levels were measured regularly in all the wells and the Alaknanda River from 18.09.2012 to 26.11.2012. The distance between the retaining wall of the park and the receding water line of the river was always measured from a fixed reference point, in this case the revolving door at the gate to the park (Figure 5-3). Groundwater levels were measured with a water level tape from pre-determined reference points (bench marks) on the wells and surface water levels were measured using a levelling instrument (Dumpy level) and staff by transferring the elevation from the top of the revolving gate (bench mark) at the park entrance (Figure 5-3).

Figure 5-3 (from left to right) Levelling instrument (dumpy level), staff and the revolving door used as a datum (benchmark) for surface water level measurements

5.2.2 River and groundwater level measurements

The surface and groundwater levels are summarised in Figure 5-4. The decrease in the Alaknanda River's water level is accompanied by a progressive retreat of the rivers water line from the bank of the river (Figure 5-5).

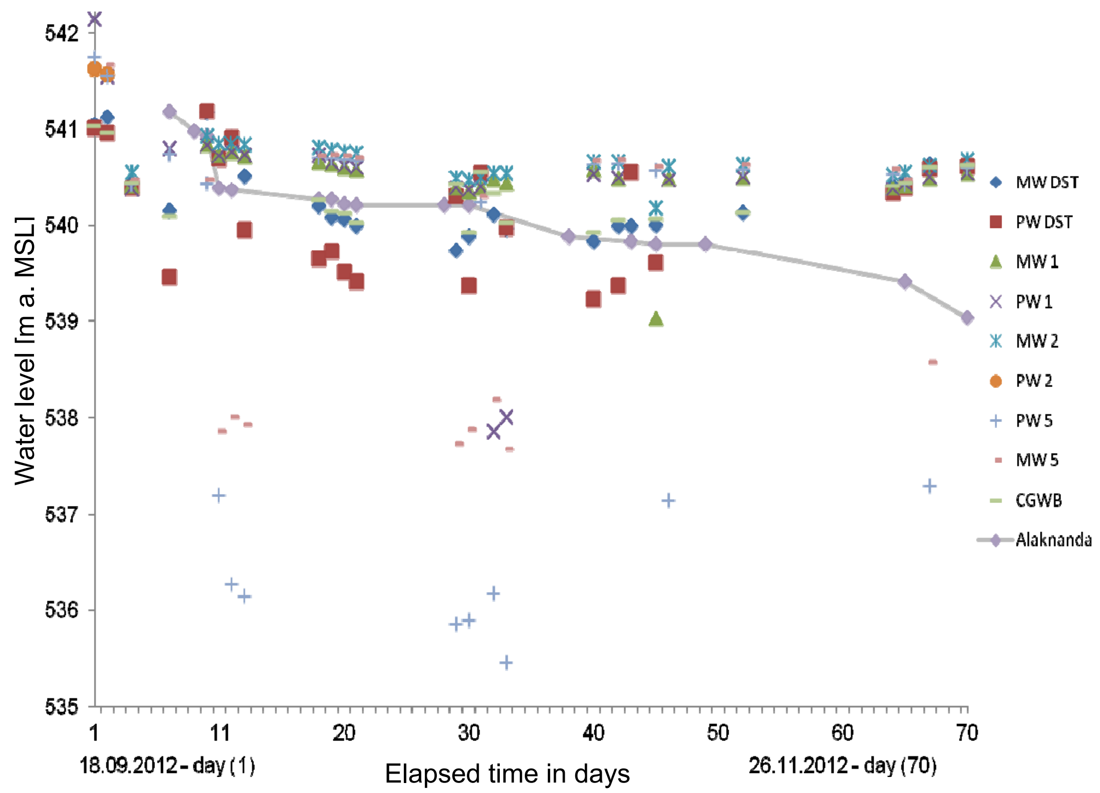


Figure 5-4 Water levels of RBF wells and Alaknanda during monsoon and post-monsoon in Srinagar (HTWD and UJS 2013)

Figure 5-5 Retreat of the Alaknanda River's water line from September to November 2012 (HTWD and UJS 2013)

It is apparent that the water levels of the wells PW-DST and MW-DST that are located around 170 m away from the river's bank (river-side edge of the park's lower level) do not consistently decrease with a decrease in the river's water level, and on certain occasions especially as the post-monsoon period progresses (November 2011), are even higher than the Alaknanda River's water level. This is due to the fact that under natural conditions (when no abstraction of water takes place from the RBF well field) the river is gaining groundwater. Also, the production well PW-DST abstracts a larger proportion of groundwater from the landward side compared to bank filtrate because the radius of influence of PW-DST only extends up to the Alaknanda during the monsoon. During the pre- and post-monsoon the well abstracts mainly groundwater that originates from the start of a meander located upstream to the North East of the RBF site (Figure 5-6). On the other hand, the production well PW5 and monitoring well MW5 located on the parks lower level and closer to the river consistently have lower water levels than the adjacent river. Thus, amongst all the wells at the RBF site, the wells closest to the river that are located on the parks lower level abstract the highest proportion of bank filtrate. Due to this, and by virtue of having an insufficient geodetic elevation, they face the greatest risk from floods.

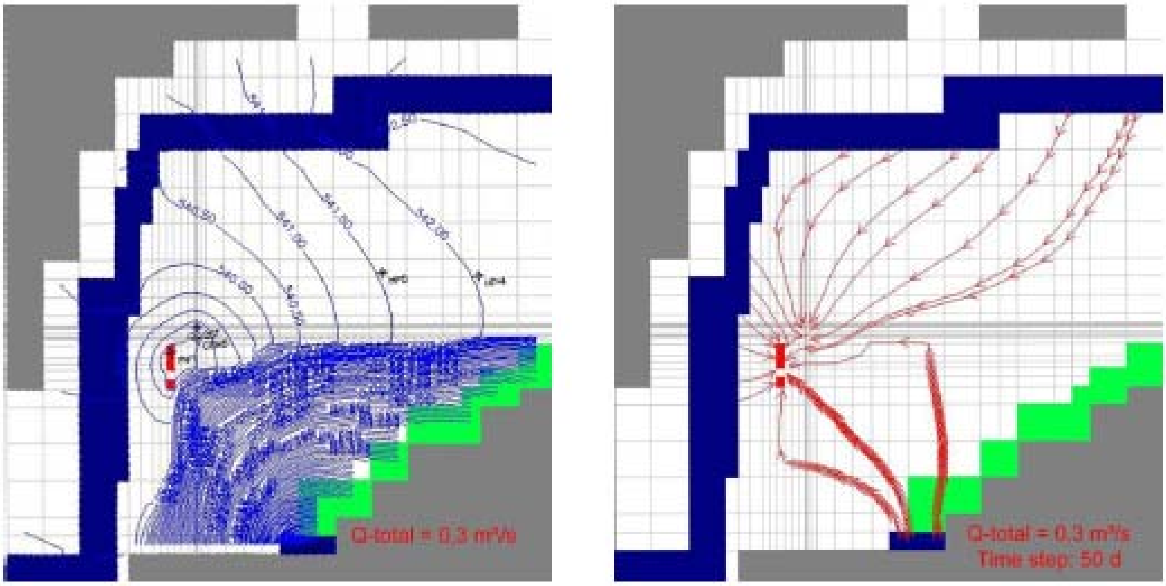


Figure 5-6 Simulated groundwater contours, travel time and flow path for the RBF well field in Srinagar (HTWD and UJS, 2012b)

5.3 Field investigations on removal of bacteriological indicators in Srinagar

5.3.1 Methodology

During the period September to November 2012, samples from the production well PW5, monitoring well MW5 and the Alaknanda River were taken regularly and analysed for Total Coliforms, E. coli and on one occasion Enterococci. Samples were directly collected from the sampling point at the outflow of each column in 100 ml sterile containers and stored in a thermo-box at 4 – 7°C. After all samples were collected, they were transported to the UJS laboratory in Srinagar where they were analysed (Figure 5-7). Samples were introduced into IDEXX colilert trays and incubated overnight (18 to 19 hours) at 35°C±0.5°K. Cell numbers in the samples were determined using IDEXX's *51-Well Quanti-Tray MPN Table* or *Quanti-Tray®/2000 MPN Table*. The most probable number (MPN) method is a probabilistic test that assumes cultivable bacteria meet certain growth and biochemical criteria. The procedure for the preparation of the samples for Enterococci is similar. However, the reagent used was Enterolert-DW and the samples were incubated for 24 hours.


Figure 5-7 Preparation of water samples and enumeration of coliform counts using the IDEXX Colilert-18 method (HTWD and UJS 2013)

5.3.2 Evaluation

Table 5-1 provides a summary of the range and mean values for Total Coliform, E. coli and Enterococci counts in the Alaknanda River and the production and monitoring wells of the RBF site in Srinagar from samples taken from 27 September to 7 November 2012. It is observed that while the total coliform counts in the Alaknanda River can attain a maximum of nearly 21,000 MPN/100 ml, it is yet considerably lower compared to total coliform counts reported for RBF sites (e.g. Haridwar, Patna and Mathura) along the Ganga River and its tributaries (Sandhu and Grischek, 2012).

Table 5-1 Range and mean Total Coliform and E. coli counts, and snap-shot analyses of an Enterococci count, in the Alaknanda River and RBF site in Srinagar (HTWD and UJS, 2013)

Parameter	Sampling location (n = 5 for all sampling locations, except Enterococci n = 1)				
	Alaknanda River	Production well PW 5	Monitoring Well MW 5	Production well PW-DST	Monitoring Well MW-DST
Total Coliform counts [MPN/100 ml] (mean)	1,300 – 20,980 (7554)	3.1 – 292 (45)	9.6 – 770 (229)	1 – 25 (12)	649 – 770 (710)
Mean Log removal of TC	-	2.2	1.5	2.8	1.0
E. coli count [MPN/100 ml] (mean)	104 – 6,570 (1,388)	1 – 4 (2.2)	2 – 5.2 (3.6)	<1	<1
Mean Log removal of E. coli	-	2.8	2.6	>3.4	>3.4
Enterococci (n=1)	2	<1	<1	<1	<1

The same applies also for E. coli counts. The relatively low indication of bacteriological contamination is due to the considerably low effect of population upstream of Srinagar accompanied with enhanced biodegradation due to the relatively high dissolved oxygen content in the river and high gradient allowing for enhanced dilution. The mean total coliform and maximum E. coli counts of >7,500 MPN/100 ml and >6,500 MPN/100 ml in the Alaknanda River are however higher than the environmental limit of <5,000 MPN/100 ml determined (by the CPCB - Central Pollution Control Board of India) for drinking water sources for which conventional treatment and disinfection is necessary.

The total coliform and E. coli counts found in the production wells at the RBF site (PW5 and PW-DST) are significantly lower although not completely absent (Table 5-1). It is observed that the production well PW5 that is located only 5.4 m from the normal monsoon water line (park boundary) of the Alaknanda, has a significantly lower mean total coliform and E. coli count of only 45 MPN/100 ml and 2.2 MPN/100 ml compared to the Alaknanda River. These mean values, as also those for the production well PW-DST located around 170 m from the normal monsoon water line and with even lower coliform counts, lie within the environmental limit of <50 MPN/100 ml determined by the CPCB for drinking water sources without conventional treatment but using disinfection. While on one hand this highlights the benefit of RBF as a natural water treatment technology which provides an environmental ecosystem service, it nevertheless underlines the fact that RBF wells under the influence of monsoon flooding (only PW5 and not PW-DST) are prone to contamination.

In Figure 5-8, the higher end of the range of total coliform counts in the Alaknanda River corresponds to the period when the monsoon begins to retreat (rainfall events lessen in frequency and intensity coupled with receding water line from the riverbank) and passes over into the post-monsoon period (Figure 5-8). As the post-monson period progresses the total coliform counts of the Alaknanda River decrease.

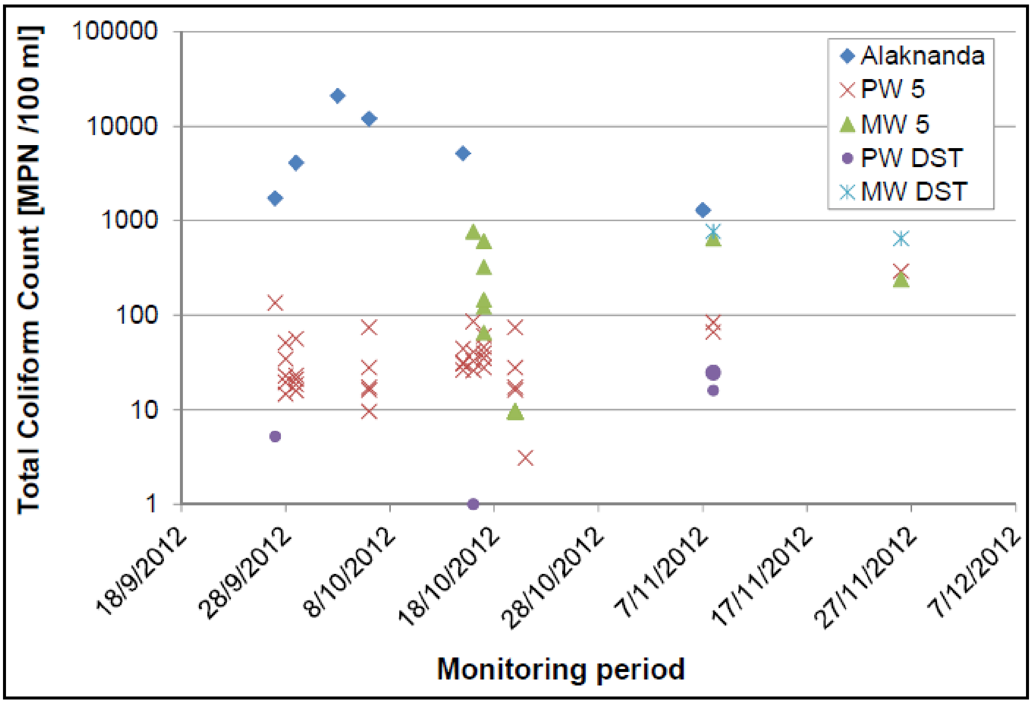


Figure 5-8 Total Coliform counts in the Alaknanda River and wells at the RBF site in Srinagar during the period September – November 2012 (HTWD and UJS 2013)

However the magnitude of the total coliform counts in the monitoring and production wells remains consistent, especially for PW5 and MW5. Considering that the area around these wells was flooded in August-September 2012 (up to before the sampling commenced) along with a possible direct entry of flood water into MW5, a breakthrough of coliforms into the wells can be attributed to either or all of the following:

- seepage of flood water from above ground through the previously upper unsaturated aquifer,
- short-circuit of the flood water along the annulus between the casing of the monitoring well and the aquifer, or
- breakthrough of coliforms due to increased bank filtrate flow velocity accompanied with very short travel-time.

But considering that the E. coli count in PW5 and MW5 is consistently low (<10 MPN/100 ml, Figure 5-9), and comparing the breakthroughs to those of a similar magnitude attained during column experiments conducted in the field and in the laboratory simulating a flood (chapter 6), it is more likely that the breakthrough is due to increased bank filtrate flow velocity and seepage through the previously unsaturated aquifer.

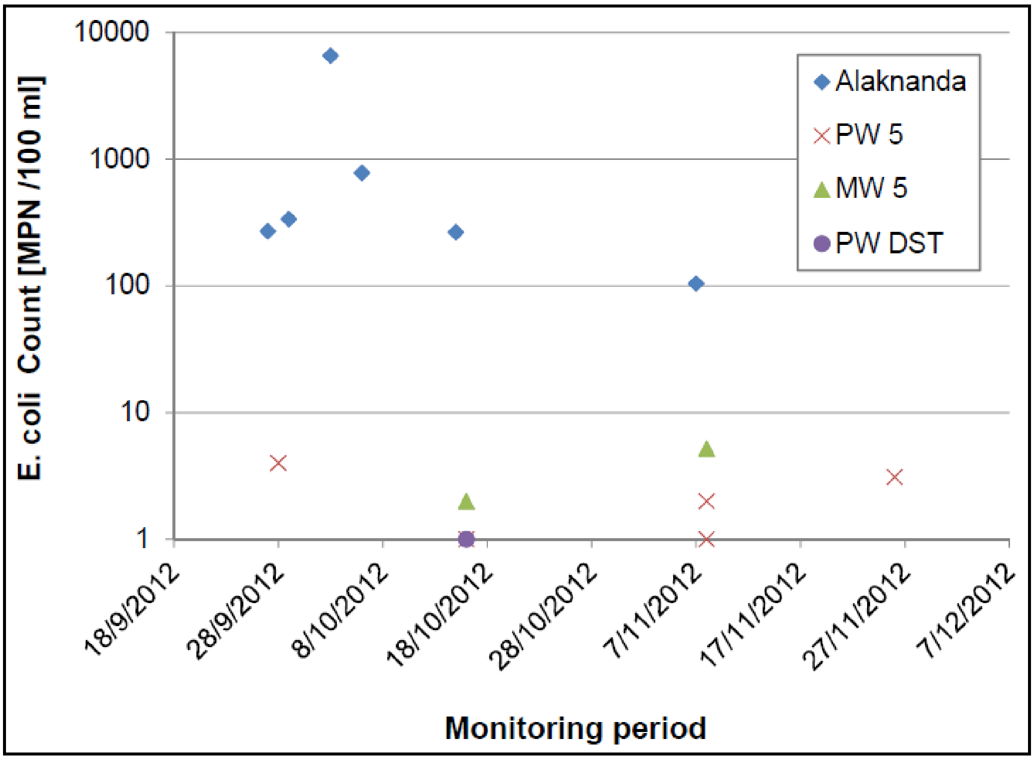


Figure 5-9 E. coli counts in the Alaknanda river and wells at the RBF site in Srinagar during the period September – November 2012 (HTWD and UJS 2013)

6 Laboratory column studies using aquifer material from RBF site in Srinagar

6.1 Objectives

Column studies were conducted using aquifer material from the borehole of the production well DST, located at the RBF site in Srinagar (see Figure 2-7). The ultimate aim of the experiments is to improve the understanding of the relationship between the river flows, in particular during flood conditions and the quality and quantity of the water produced at the RBF wells.

6.2 Materials and methods

Aquifer material from a depth of 16 – 20 m below ground level, the depth at which the filter-screen of the production well is located, was used for the column studies. Four columns, composed of the same aquifer material, were operated with an inflow of ~1, 5, 10 and 20 cm^3/min respectively, for 72 days. The flow rate and quality of the filtered water were monitored regularly. Four stainless steel columns were filled with aquifer material ranging in grain size from 0.212 – 0.425 mm. The grain size analysis of the oven dried aquifer material was carried out as per the Indian Soil Classification 1498 (1970). The column specifications and characteristics of the aquifer material are given in Table 6-1. Column filling and operations were carried out in accordance with the procedure given by Oliviera et al. (1996), Jin et al. (1997), Simon et al. (2000), Powelson and Mills (2001), Mahvi et al. (2003), and Lewis and Sjöstrom (2010).

Table 6-1 Column specifications and aquifer characteristics (Ronghang et al. 2013)

Column	A	B	C	D
Length (cm)	45.7	45.7	45.3	45.3
Internal diameter (cm)	4.5	4.5	5.4	5.4
Area of cross section (cm^2)	15.9	15.9	22.9	22.9
Volume (cm^3)	727	727	1037	1037
Bulk density (g/cm^3)	1.33	1.42	1.61	1.59
Porosity $^{++}$ (%)	49.7	46.5	39.2	40.1

Mean grain size determined from grain size distribution analyses: 0.30 mm; Coefficient of uniformity * (C_u): 1.5; Particle size used: 0.212 – 0.425 mm; Hydraulic conductivity after Hazen (1893), K=1.14 x10^{-4} m/s;
$^{++}$ from density and bulk density.

Two polyethylene meshes (0.1 mm and 0.2 mm) were placed at both ends of the column. The slurry of the aquifer material was added from the top and water was pumped from the bottom (Oliviera et al., 1996; Sakaguchi et al., 2005; Lewis and Sjöstrom,. 2010). This was done to avoid air bag/pockets between the grains of the aquifer material and wall of the column (Sentanac et al., 2001; Sakaguchi et al., 2005; Zlotnik et al., 2007). The tap water was pumped from the bottom through columns for one week to check any leakage and to stabilise the flow rate in each column. The schematics of the experimental setup indicating operation of a single column is shown in Figure 6-1.

Experiments were carried out in a temperature controlled cabinet (Aqualytic, Liebherr model FKS 3602) maintained at 20° C. Around 60 liters of water were collected daily from the Upper Ganga canal in Roorkee that originates from the Ganga River in Haridwar, and was stored in a reservoir from where it was pumped through these columns. Water in the reservoir was continuously stirred using a magnetic stirrer (Remi, Model 1MLH) to avoid settling of suspended solids. An air bubble separator was used to remove entrapped air bubbles.

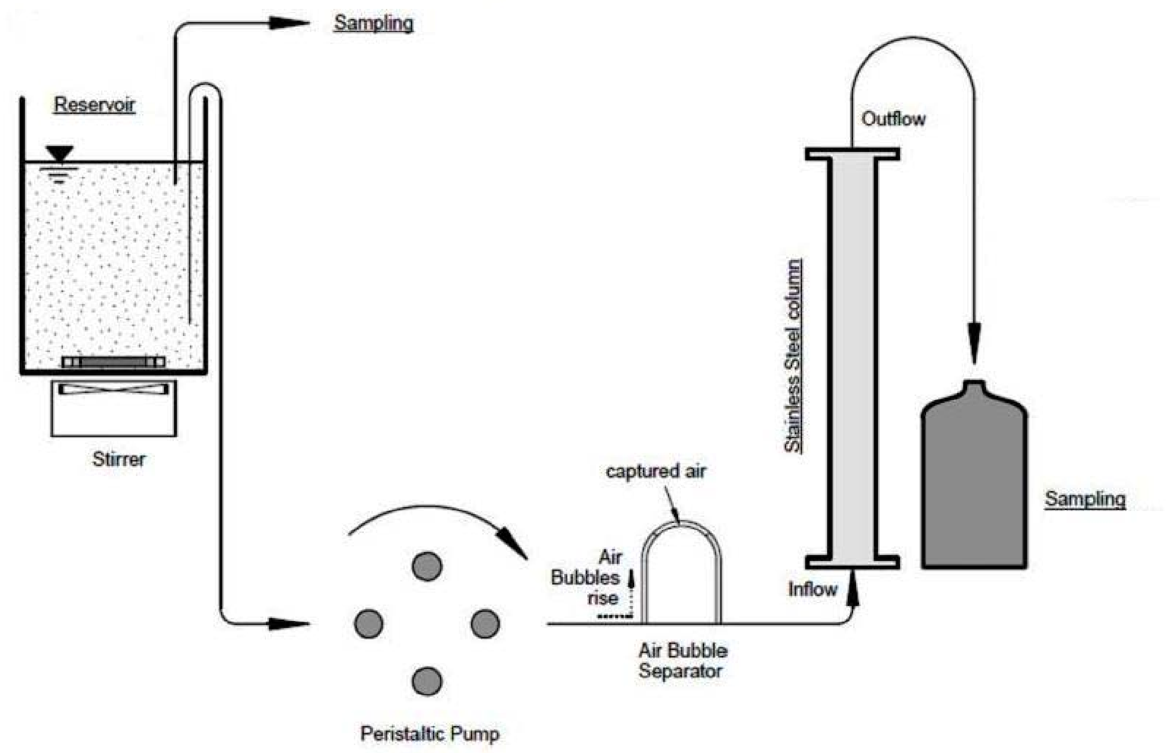


Figure 6-1 Schematics of the setup for the column experiment (Ronghang et al. 2013)

The column inflow water from the canal and the filtered outflow water were analysed for electrical conductivity (EC), pH, UV absorbance (UV-A), coliforms (total and faecal coliform) and turbidity. Turbidity, pH, EC, and flow rate were measured twice a day. UV-A and coliforms had initially been recorded once a day and subsequently at intervals of 3 – 4 days.

Effective porosity of each column was determined by a tracer test prior to and after the column operation. Sodium chloride dissolved in tap water (1g/L) was used as a tracer and electrical conductivity was monitored in the outlet water.

EC and pH were monitored by using HACH USA model HQ 40d. UV-A was measured at 254 nm by HACH, USA model DR 5000. Total coliform and faecal coliform were determined by multiple tube fermentation technique using lauryl tryptose broth (LTB) and EC medium (Eaton et al., 2005). Peristaltic pumps (Miclins, Model PP20 EX) were used to feed the canal water/ sodium chloride solution into the columns.

6.3 Results and discussion

6.3.1 Tracer test

Tracer tests were conducted to find out the flow regime and effective porosity of the aquifer material in columns. Conductivity of the filtered water was measured at regular intervals. Breakthrough curves were obtained by plotting fractions (C/C_0=0.5) of the input concentrations (C_0) as a function of time (t). Effective porosity was estimated from Eq. 6.1.The t_{50} values of different columns are given in Table 6-2.

Table 6-2 Summary of tracer tests (Ronghang et al., 2013)

Particular	Column A		Column B		Column C		Column D	
	Before[1]	After[2]	Before[1]	After[2]	Before[1]	After[2]	Before[1]	After[2]
Flow rate[3] Q (cm^3/min)	1.1	0.7	5.1	2.6	10	4.7	20.6	1.8
Specific velocity v (cm/min)	0.14	0.09	0.71	0.38	1.10	0.69	2.27	0.23
Effective contact time t_{50} (min) (Values computed from Eq. 6.2)	324 (327)	468 (461)	66 (65.4)	120 (126)	42 (32.7)	66 (69.6)	18 (15.9)	195 (182)
Effective porosity (%)	49.2	45.4	45.4	43.1	38.6	29.9	39.7	33.9
% decrease in porosity	7.7		5.1		22.5		14.6	
% decrease in discharge	35.2		48.6		73		81.4	

[1] at start of the experiment; [2] before terminating the experiment i.e. after 72 days; [3] flow rate at which the tracer test was conducted.

The midpoint (C/C_0=0.5) of the sigmoidal curve corresponding to one pore volume is indicative of uniform plug flow through homogenous packed porous media (Marlow et al., 1991).

$$\phi = \frac{Q \cdot t_{50}}{V} \tag{6.1}$$

Where ϕ is the effective porosity of the material used in the column,

t_{50} is the effective contact time i.e. time at which C/C_0 = 0.5,
Q is the outflow of the column experiment [L^3T^{-1}] and
V is volume of the column [L^3].

Perusal of the data in Table 6-2 suggests the effect of flow rate (i.e. pumping rate) on breakthrough of the solute. The effective porosity from the tracer test and the porosity calculated from the bulk density before the start of the experiment were found to match well (Table 6-1).

Both initial porosity and flow rate were reduced during operation by 5 – 22 % and 35 – 81 % respectively in the four columns. The reduction in porosity and flow rate, increased with the flow rate from 1 to 20 cm^3/min or flow velocities from 0.1 to 2.3 cm^3/min. The time (t_{50}) for 50 % solute response (C/C_0 = 0.5) conformed to Eq. 6.2 (Figure 6-2).

$$t_{50} = \frac{45.4}{v} \text{ or } \frac{327}{Q} \qquad (6.2)$$

Where *v* is the velocity at which the tracer test is conducted (cm/min).

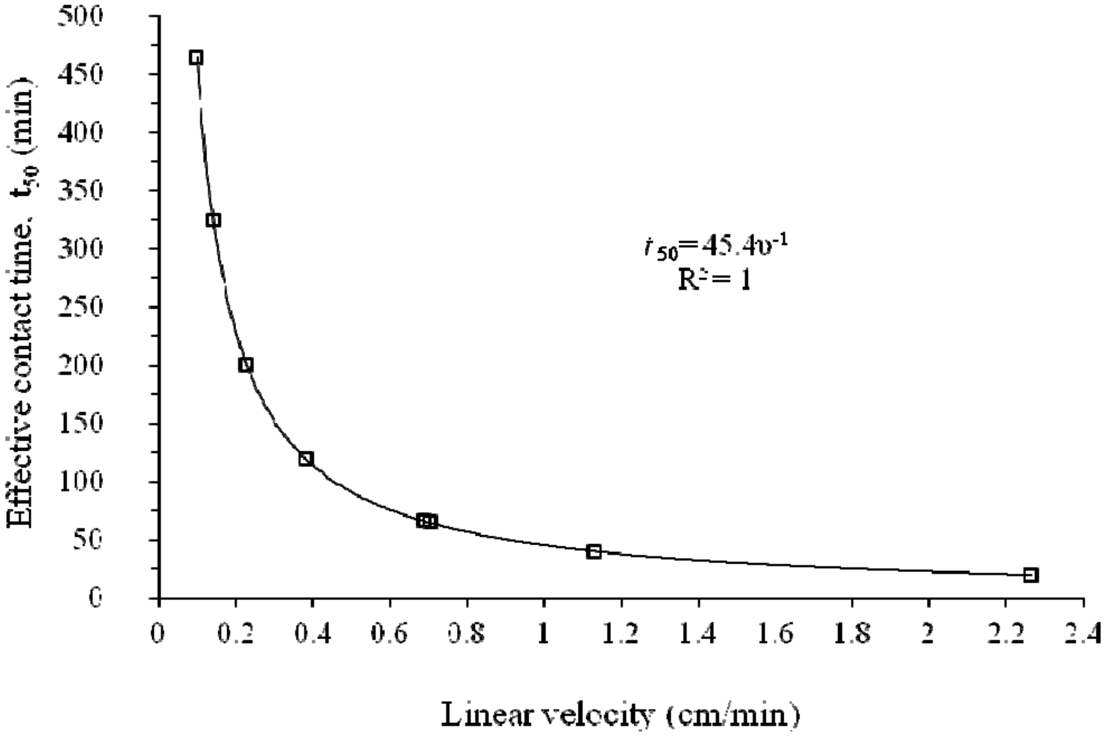


Figure 6-2 Flow velocity and effective contact time (Ronghang et al., 2013)

6.3.2 Discharge

Temporal variation in discharge through all the columns for 72 days is shown in Figure 6-3 (A) to (D). The initial discharge of 1.05 cm^3/min in column A was reduced to 0.7 cm^3/min on day 72. Likewise, in all the other columns the discharge was also reduced.

The reduction in flow given in Table 6-2 increased with the inflow rate. In column A the flow gradually reduced and reduction in flow conformed to linear relation given by Eq. 6.3

$$Q = 1.0 - 0.005t \qquad (6.3)$$

Where *Q* is the predicted discharge at time *t*

The flow rate through the other columns declined in 15 to 25 days of operation and at the end of operation, i.e. after 72 days the porosity was reduced. The percentage reduction in discharge and porosity after 72 days of column operation is given in Figure 6-4.

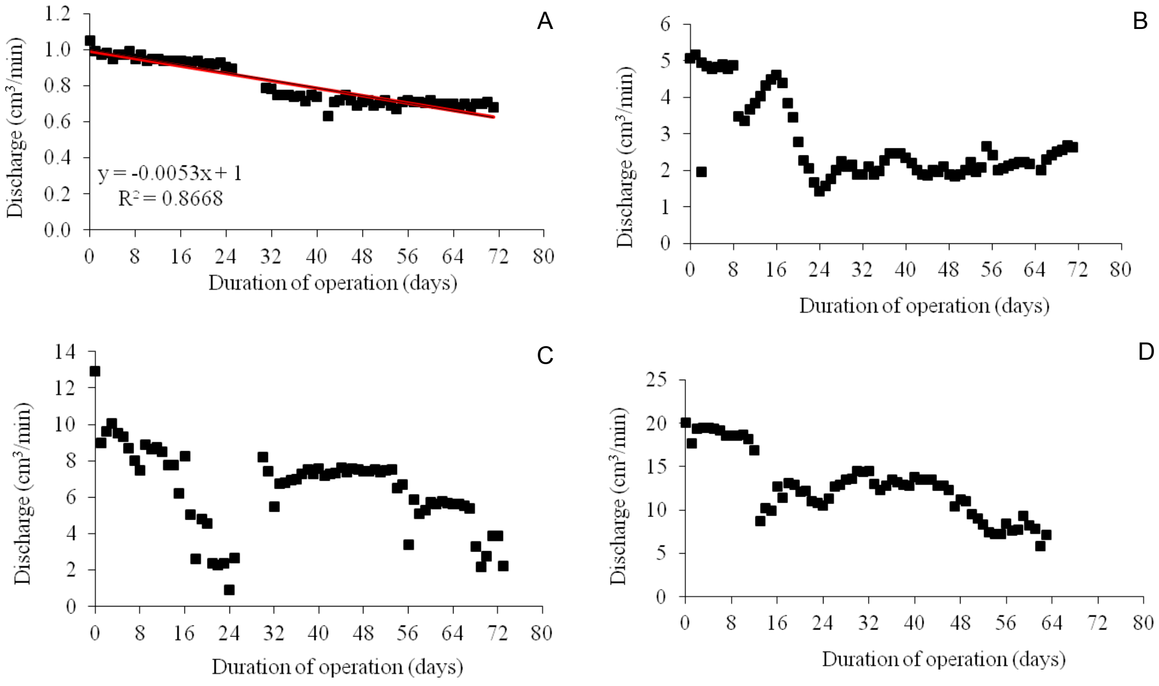


Figure 6-3 Temporal variation in flow rate (A – D represents column A – column D) (Ronghang et al., 2013)

The reduction of porosity and the subsequent reduction of flow is the result of clogging. As the porosity is reduced, there is a progressive increase in clogging of column material resulting from the reduction in pore size which depends on the loading of suspended solid (SS), the flow rate, biological processes etc. The SS loading increased with increase in inflow rate.

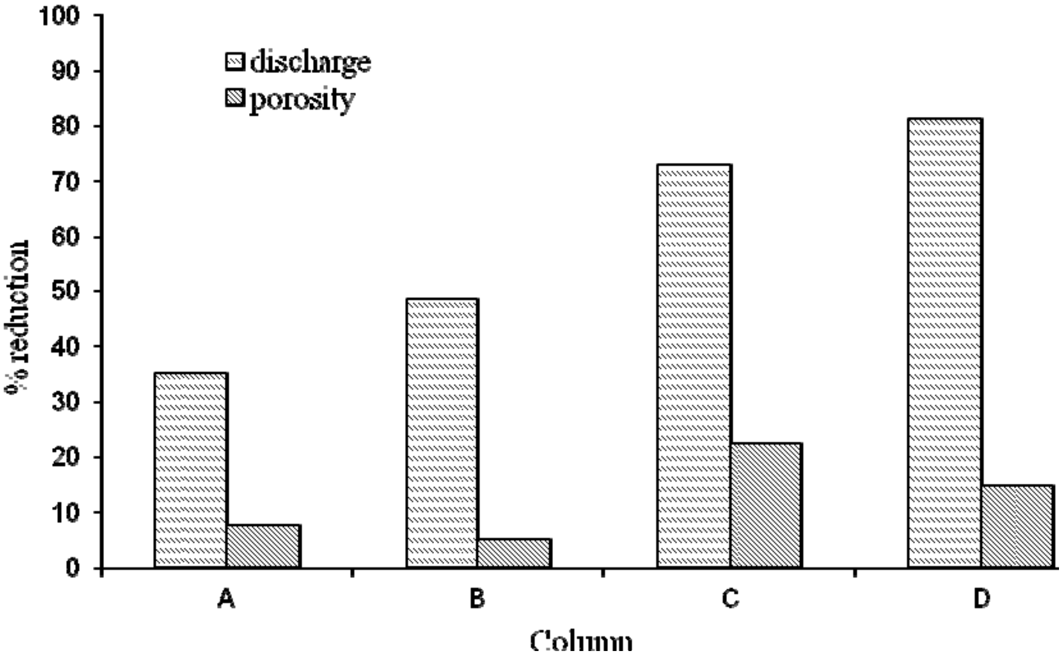


Figure 6-4 Percentage reduction in discharge and porosity (Ronghang et al. 2013)

The decreased flow rate or reduced porosity of the columns operating at higher inflow rate may be due to deposition of SS at the filter water interface, and/or particle intrusion into the aquifer material (Mauclaire et al., 2004). These observations therefore suggest that water abstraction from a RBF well induced by pumping is likely to clog the aquifer. Ideally, water abstraction should be compatible with the water recharge into the well.

6.3.3 Water quality

Performance of the four columns operating at different inflow rates was assessed by monitoring EC, pH, UV-A, turbidity, total coliform and faecal coliform of the source water and filtered water. Results are summarised in Table 6-3.

Table 6-3 Column performance: quality of inlet and outlet water (Ronghang et al. 2013)

Column		pH mean±sd [a]	EC, (μS/cm) mean±sd [a]	UV-A (cm^{-1}) mean±sd [a]	Turbidity (NTU) mean±sd [a]	Coliform(log removal) min-max (average)[b]	
						Total	Faecal
A	Inlet	7.9±0.08	266±30	0.04±0.03	20.6±25.7	2.9-2.8 (3.1)	2.3-4.6 (3.7)
	Outlet	7.8±0.09	278±27	0.02±0.01	0.8±0.7		
B	Inlet	7.9±0.09	257±44	0.02±0.005	24.1±25.8	2.7-3.6 (3.3)	2.3-4 (3.5)
	Outlet	7.8±0.08	267±41	0.02±0.006	1.3±1.6		
C	Inlet	7.9±0.08	237±35	0.02±0.03	23.6±17.4	2.1-3 (2.3)	1.9-1.6 (2.1)
	Outlet	7.8±0.23	243±30	0.01±0.01	0.4±1.9		
D	Inlet	7.9±0.09	238±36	0.02±0.006	14.3±15.1	2.4-2 (2.4)	2.1-2.7 (2.8)
	Outlet	7.8±0.08	243±34	0.02±0.005	1.2±1.5		

a & b: number of samples; a= 128 & b =22

Perusal of the data in Table 6-3 does not indicate any significant change in pH of the inlet and outlet water. The conductivity of the outlet water was 3 – 4 % higher than that of the inlet water. Though it is a marginal increase, it occurs consistently in all the columns.

Change in UV-A, an indicator of natural organic matter (NOM), is not consistent in the four columns. The mean value of UV-A of outlet water from column A and C is 50 % of the inlet water where as there is no change in absorbance in water from other two columns. This discrepancy may be due to the very low UV-A of the feed water. Reduction in NOM during column operation and RBF has been reported by Worch et al. (2002) and Kolehmainen et al. (2009). Turbidity of inlet water was considerably reduced after filtration irrespective of the flow rates and initial turbidity. All the outlet water samples from all the columns had turbidity <2 NTU. Similar observations have been recorded by Mahvi et al. (2003) and Jenkins et al. (2011).

Graphs of total and faecal coliforms are presented in Figure 6-5 and Figure 6-6, respectively. The outlet water from column A was observed to be devoid of faecal coliform (FC) bacteria. The faecal coliforms (TC) were noticed for the first 10 days only. Following this initial period the samples did not respond to the MPN test.

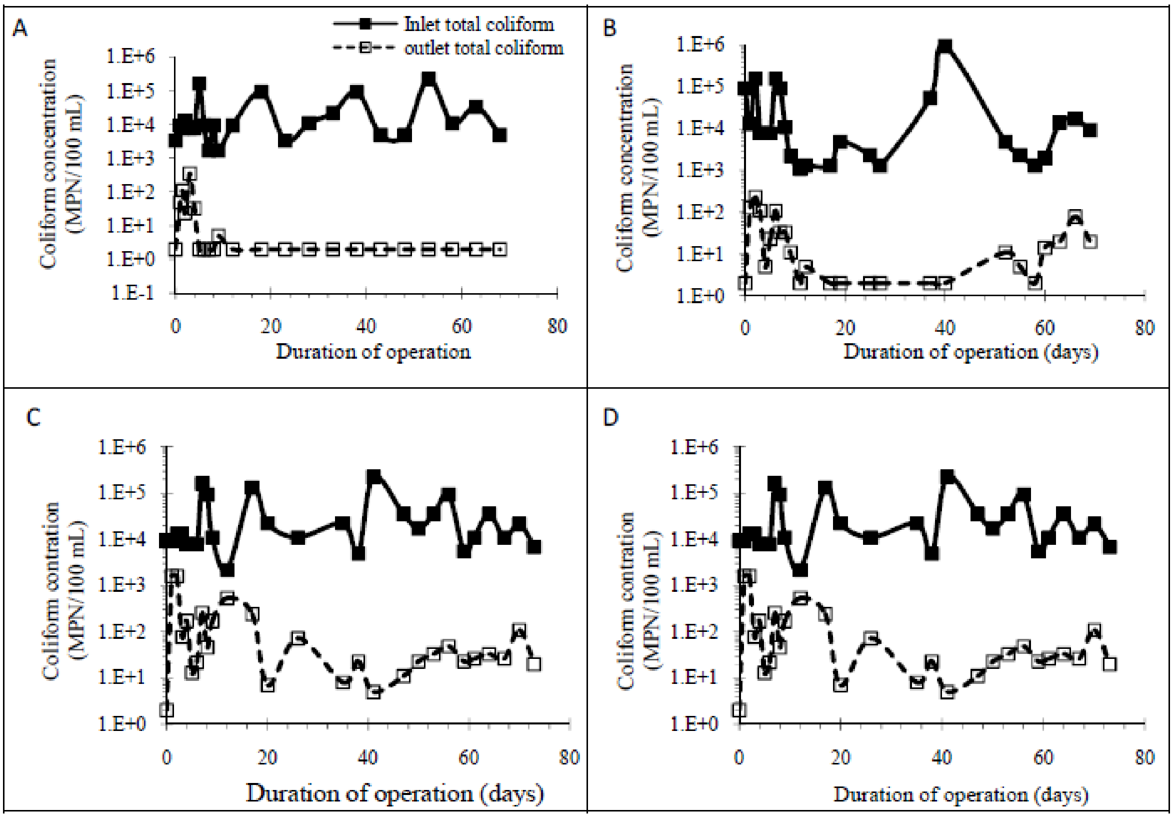


Figure 6-5 Total coliform counts in the four columns (dot line inlet water; full line outlet)

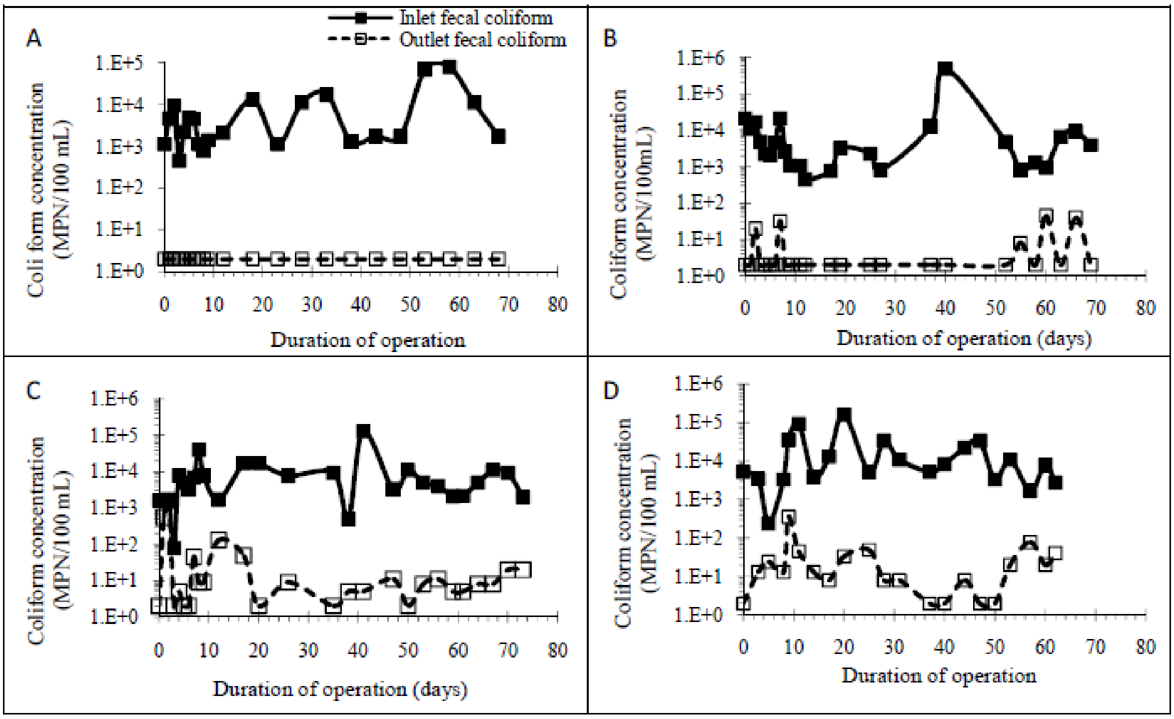


Figure 6-6 Faecal coliform counts in the four columns (dot line inlet water; full line outlet)

Initial deposition of SS at water soil interface combined with low water velocity (0.14 cm/min) does not facilitate bacterial transport through the column A (Syngouna and Chrysikopoulos, 2012). The performance of column B was satisfactory for a short duration between 10-40 days i.e. the column yielded safe water for a few days. The removal of TC and FC in column C was ~ 2.1 – 3 log and 1.6 – 1.9 log respectively. Outlet water without TC was rarely observed in column D. Maximum removal of TC and FC was observed in column A.

The probability of response to MPN test is shown in Figure 6-7. About 26 % of the outlet water samples were positive to total coliform test and none of the samples were positive to the faecal coliform test. The elimination of faecal coliform in column A is 100 % whereas the reduction in flow over a period of 72 days is only 35 %. The improvement of the water quality in column A is assumed to result from the combined effect of filtration and straining of the particles and to high retention time (~ 5.5 h) because of low flow rate (Marlow et al., 1991; Mahvi et al., 2003; Foppen and Schijven, 2006).

The filtered water from columns B to D, always responded to the MPN test. It is reported that bacterial travel through the aquifer depends on groundwater flow velocity, survival rate, initial concentration, dilution and dispersion of groundwater, and the sensitivity of the method used to detect bacteria (Pekdeger and Matthess, 1983; Sharma et al., 1985; Smith et al., 1985; Stevik et al., 2004). In the present scenario the flow velocity is the only variable effecting coliform transport.

The suspended solid loading in columns B, C and D was more than in column A. The output water from all columns had the same clarity (i.e. turbidity <2 NTU). As the discharge through the columns is reduced from A to D, these observations suggest that column D is more clogged than column C, B and A.

Despite increased clogging, the flow velocity through columns B, C and D is more than the velocity in column A. The breakthrough in column A did not take place even after 72 days of operation or the exchange of 319 pore volumes of water (calculated on the basis of initial flow and initial porosity). The low velocity of 0.23 cm/min in the clogged column D was not sufficient to completely immobilize bacteria by any of the mechanisms suggested by Marlow et al. (1991) and Lawrence and Hendry (1996).

As suggested by Lewis and Sjöstrom (2010), factors which affect microbial transport are the size of suspended solids causing turbidity in the input water and the concentration of SS and bacteria in the input water. However, in the present study, both size and concentration of SS in the input water were not monitored.

The frequency of positive response of total coliform in column B was about 68 % where as in column C and D it increased up to 96 – 100 % (Figure 6-7).

The inference drawn from this study is that a flow velocity up to 0.14 cm/min is able to immobilise coliform through a clogged river bed of hydraulic conductivity of 0.68 cm/min.

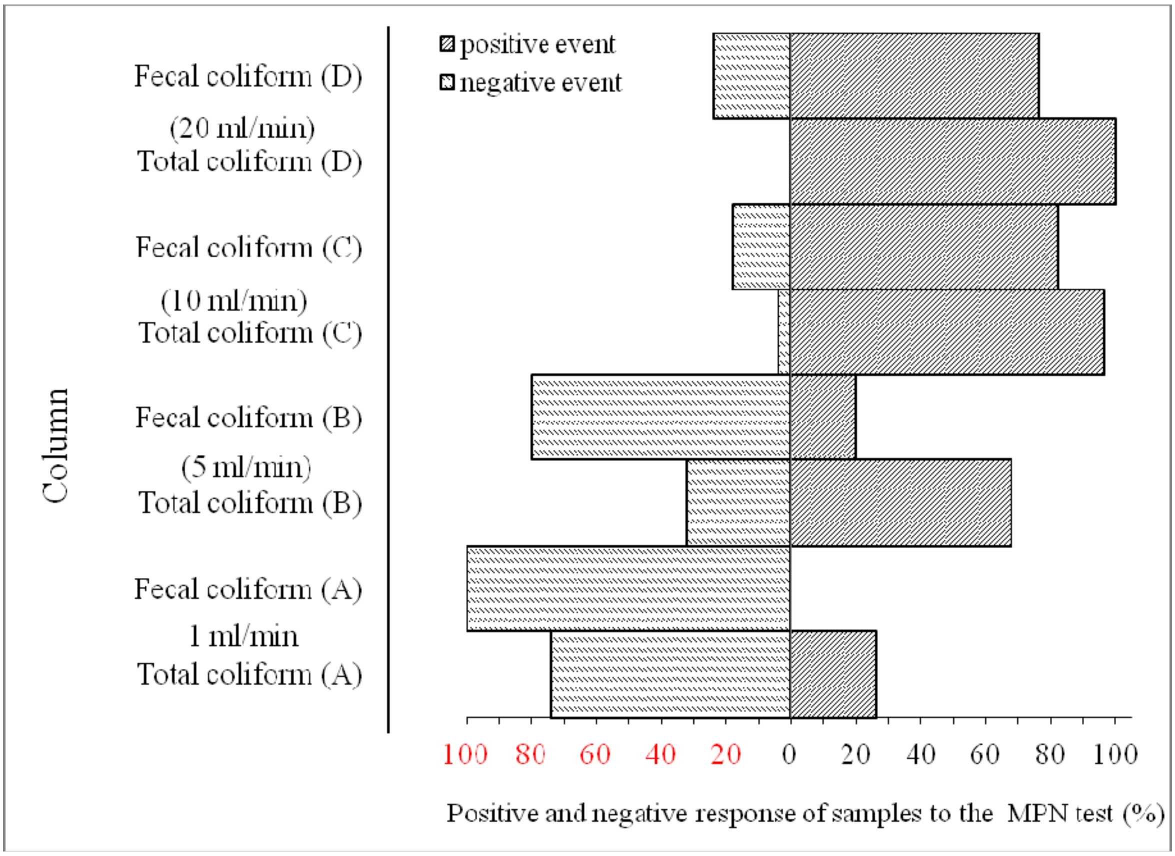


Figure 6-7 Distribution of the test results on coliform analysis (Ronghang et al. 2013)

6.4 Mechanism of bacterial transport

The convective diffusion equation suggested by Yao et al. (1971) for the filtration of colloids in saturated media has been used for predicting the transport of microorganisms by Harvey and Garabedian (1991) and Murphy and Ginn (2000). This colloid filtration theory was also applied by Schijven et al. (2002) to calculate the removal of coliforms in an artificial recharge dune. Accordingly, the coliform removal at steady state with no dispersion, no die-off and negligible growth can be expressed by Eq. (6.4) and Eq. (6.5).

$$v\frac{\partial C}{\partial x} + K_C C = 0 \qquad (6.4)$$

$$\text{or } \frac{C}{C_0} = \exp\left(-\frac{K_C}{v}L\right) \qquad (6.5)$$

Where, C and C_o are the counts of coliforms in the outlet and inlet water, respectively, K_C is the deposition coefficient, v is the interstitial pore velocity and L is the length of the column.

The deposition coefficient depends on the diameter of the collector (mean grain size), porosity, attachment efficiency and single-collector efficiency (Tien et al., 1979). Physical factors and constants such as gravitational effect, van der Waals effect, Peclet Number, aspect ratio, Hamaker constant etc. affect the single collector efficiency or bacterial deposition (Martin et al., 1992; Hijnen et al., 2004 and Schijven et al., 2002).

The bacterial deposition coefficient, K_C for columns A, B, C & D has been computed at the start and at the end of the experiment. Values are given in Table 6-4. The deposition coefficient has been found to linearly vary with velocity (Figure 6-8). The model (Eq.6.5) has primarily been developed on the basis of average concentration of coliform in the inlet and outlet water. Therefore temporal fluctuations are not accounted for. The mean size of the single collector changes with duration of operation due to deposition of the suspended solids from the inlet water, an effect which has also not been considered in the model.

Table 6-4 Values for the calculated bacteria deposition constant, K_C (Ronghang et al., 2013)

Particular		Deposition coefficient(sec^{-1}) x10^{-3}			
		computed	observed	computed	observed
		Before[1]		After[2]	
Column	A	0.37	0.44	0.25	0.3
	B	1.9	2.1	1.0	1.1
	C	2.2	2.0	1.3	1.2
	D	4.5	5.2	0.48	0.55

[1] at start of the experiment; [2] before terminating the experiment (after 72 days)

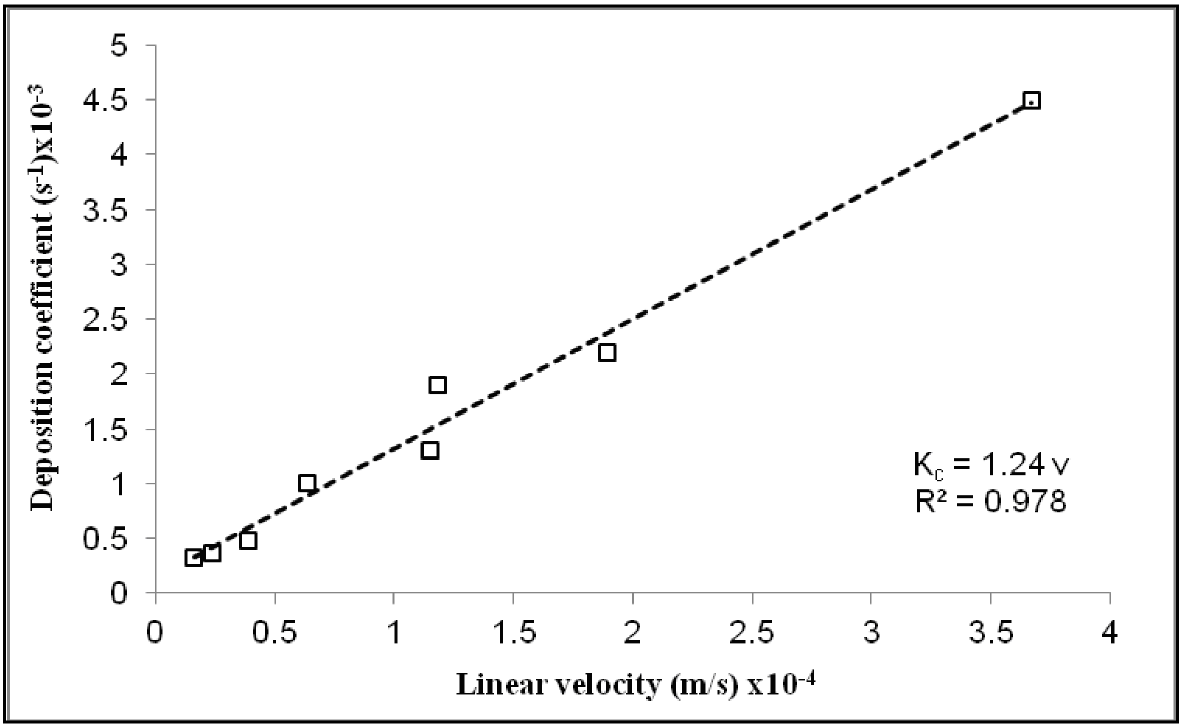


Figure 6-8 Correlation between flow velocity and deposition coefficient (Ronghang et al., 2013)

6.5 Conclusion

This study aimed at improving the understanding of the effect of variable pumping rates on the quality and quantity of filtered water at RBF sites.

The performance of the column D with the highest inflow rate of 20 cm^3/min was not satisfactory in terms of coliform removal. Moreover the column was considerably clogged.

The results suggest that water abstraction through induced pumping is likely to

- clog the natural filter and
- adversely affect the coliform removal.

There is a need to explore the performance of the columns during monsoon season when high river levels coincide with significant increases in turbidity and a reduction in water quality.

7 Assessment of the risk of pathogen breakthrough during RBF on the basis of column experiments in specific context to floods

7.1 Objectives

The increase in coliforms numbers in the river water and the potential subsequent increase in the RBF wells during the monsoon has been discussed in previous chapters. Chapters 4 and 5 indicate that a breakthrough of coliforms has been observed in some RBF wells during normal high-flow events in India. The risk for diarrhoeal diseases associated with rotavirus exceeds the adopted health target. Increases in turbidity have been observed during extreme flood events in India (during monsoon floods). Also, increases in turbidity, bacteria and viruses have been observed at RBF sites in Germany. The risk of breakthrough of pathogenic microorganisms has been also been identified in the Netherlands. Thus, floods are a risk to RBF sites. Consequently, adequate post-treatment, technical and operational measures should be in place in order to minimise this risk. For this, the identification, analysis and evaluation of the risks to RBF sites resulting from high flow events are necessary.

The aim of this chapter is to identify and analyse the risks from normal high flow and extreme high flow (floods) events at RBF sites based on the breakthrough of pathogen indicators in column experiments under different boundary conditions.

7.2 Methodology

7.2.1 Field experiments on columns filled with different media

Apparatus and execution

Column experiments were conducted by the HTW Dresden with assistance from IIT Roorkee by the Elbe River for a continuous 31 day period at atmospheric temperature. Four stainless-steel columns, each 0.45 m long were installed in a covered trailer at a pier in the Port of Dresden by the Elbe River (Annex 11). Water was pumped from the river (depth 2 m) adjacent to the pier using a submersible pump (model AL-KO TDS 1001/3) into an overhead tank fitted on the roof of the trailer (Figure 7-1). The water was allowed to flow from the overhead tank by gravity into the columns installed in the trailer. The hydraulic head in each column was determined using piezometers (attached to the door of the trailer) connected to the inlet and outlet of the column. Pipes were connected to the outlet of the columns, from which samples for bacteriological analyses were taken.

Discharge, hydraulic gradient, turbidity, electrical conductivity and water temperature were observed nearly daily during the 31 day period. The total and faecal coliform counts were determined from samples taken on 11 days (2 – 3 days between each sample). The discharge was measured at the sampling point after the column outlet manually using a stopwatch and measuring cylinder. The turbidity was measured with clean vials by using a calibrated 2100P Hach turbidity-meter.

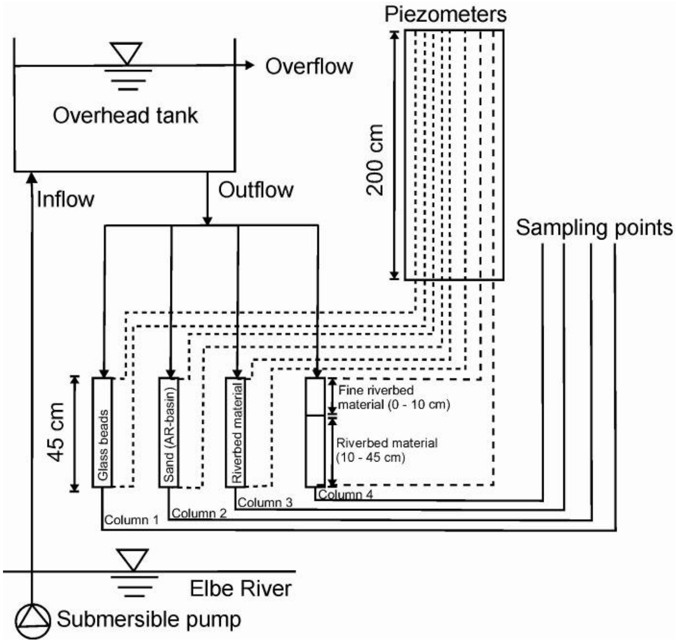


Figure 7-1 Column-apparatus to determine the breakthrough of coliforms under field conditions (Sandhu et al., 2013)

Composition of columns

The four columns were filled with (1) glass beads (procured from Sigmund Lindner GmbH), (2) medium-coarse sand from the artificial recharge basin in the Waterworks Dresden-Hosterwitz, (3) sand and gravel Elbe riverbank material and (4) a combination of sand and gravel and finer Elbe riverbank material taken adjacent to the Waterworks Dresden-Tolkewitz (Table 7-1). The glass beads (grain size 1.7 – 2.1 mm) were used to represent well-rounded coarse sand to fine gravel. The intention was to investigate the physical effects of clogging and to exclude geochemical effects, especially geochemical heterogeneity, on the removal of coliforms.

Table 7-1 Characteristics of material contained in columns (Sandhu et al. 2013)

Parameter	Column 1	Column 2	Column 3	Column 4
Material filled in column	Glass beads (to represent well-rounded coarse sand- fine gravel)	medium to coarse sand	Natural sand and gravel river-bed material	Layered combination of finer material (upper layer: 0-10 cm) above natural riverbed material similar to column 3 (10-45 cm)
Grain size distribution range [mm]	1.7 – 2.1	0.2 – 2.0	0.06 – 20	0.06 – 20
Effective grain size (d_{10}) [mm]	1.74	0.4	0.28	0.26 [e]
Effective porosity	0.30 – 0.35 [a] (0.325)	0.30 – 0.35 (0.325) [b]	0.20 – 0.30 (0.25) [c]	0.25 – 0.35 (0.29) [d]
Length of each column: 45 cm; diameter of each column: 10 cm; median values are given in parenthesis for the effective porosities; a: Eckis (1934); b & c: median after Bartak (2011) and Grischek (2003) respectively; d: effective porosity assumed to be similar to columns used in laboratory as same material used; e: depth-weighted mean of d_{10} = 0.18 mm (for upper layer: 0-10 cm) and d_{10} = 0.28 mm (for lower layer: 10-45 cm)				

The materials were filled into the columns up to a length (height) of 0.45 m gradually by wet-filling to avoid air being trapped in the voids between the grains and with minimal compaction. After the materials were built into the columns, they were fed with degassed tap water from the bottom to the top for 12 hours, in order to check for leakages and also to remove trapped air bubbles. The sampling points of the columns were located at a higher elevation than the column-outlets to avoid air entering them.

Determination of coliform counts

The inflow (Elbe river water) and each outflow sample were tested for E. coli and total coliforms. Samples were directly collected from the sampling point at the outflow of each column in 100 ml sterile containers and stored in a thermo-box at 4 – 7°C. After all samples had been collected, they were transported to the Division of Water Sciences laboratory at the Dresden University of Applied Sciences where they were analysed. Samples were introduced into IDEXX colilert trays and incubated overnight (18 to 19 hours) at 35^{o}C±0.5^{o}K. Cell numbers in the samples were determined using IDEXX's *51-Well Quanti-Tray MPN Table* or *Quanti-Tray®/2000 MPN Table*. The most probable number (MPN) method, a probabilistic test that assumes cultivable bacteria meet certain growth and biochemical criteria, was then applied.

7.2.2 Laboratory experiments on columns for different flow conditions

Apparatus

Column experiments using three stainless steel columns packed with riverbed material (sand 70 % & gravel 30 %) collected from the Elbe River at the Tolkewitz RBF site in Dresden (Germany) were conducted (Figure 7-2). The aim was to simulate the flow path of river water into the riverbed during the first meter of RBF.

Each column was 1 meter in length and had a 7.5-cm inside diameter, and was sealed at top and bottom with a metal mesh screen and a solid steel cap with a rubber seal. Source water samples were collected in 20 L plastic containers directly from the Elbe River at Pier 11 between the Carola Bridge and Albert Bridge in Dresden (Germany). The inflow water for samples to test the removal of coliforms (Table 7-3) was collected immediately prior to the test. These water samples were instantly pumped into the top of each column using an Ismatec pump and Teflon tubing (4.0 mm in diameter). The outflow of the columns were connected to a SKINTOP U231 flow-through cell (glass cylinder with an opening for multi-meter probes) using more of the same Teflon tubing. For the determination of coliforms, the samples were directly collected from the outflow of each column after the flow-through cell in 100 ml sterile containers. About 100 ml of Elbe river water was collected directly from the inflow containers using a sterile 100 ml Colilert jar. These samples were immediately stored at approximately 4^{o}C until bacteriological analysis could commence (but no longer than 12 hours).

Figure 7-2 Column-apparatus to determine the breakthrough of coliforms under laboratory conditions (Sandhu et al. 2013)

The pH, electrical conductivity, dissolved oxygen, and temperature of each inflow and outflow were observed daily. Samples were periodically taken for coliforms or redox parameter analyses. In order to test the temperature effects on pre-treated drinking water produced by RBF, each column was maintained at different temperatures (10°C, 25°C (room temperature), and 30°C). To test whether the effects of temperature on the performance of each column was due to temperature differences rather than a function of the column characteristics (e.g. differences in packing, porosity, soil), the 10°C column was switched to 30°C and the 30°C column was switched to 10°C on a certain date. To test the effects of increased and decreased infiltration velocities (as would be experienced during floods and droughts, respectively), the flow rates through the columns were varied at points throughout the experimental period. A timeline of major events during the column experiments is given in.

Tracer test to determine effective porosity

Tracer tests were conducted to determine the effective porosity and retention time of each column using a NaCl solution (Table 7-2). t_{50} represents the travel time for 50 % of the inflow concentration of tracer to reach the outflow. t_{50} for each column was initially determined by several tracer tests conducted at around 4 ml/min. The assumed t_{50} values used in these tests were determined by adjusting the tracer test's t_{50} by the new column flow velocity.

Table 7-2 Effective porosity, t_{50}, and Darcy velocity of columns used in the laboratory (Sandhu et al. 2013)

Column	Effective porosity	t_{50} (hours)			Darcy velocity (m/day)		
		Normal	Low	High	Normal	Low	High
C1	0.29	5.34	17.34	3.65	1.3	0.4	1.9
C2	0.32	5.78	19.27	3.21	1.0	0.3	1.8
C3	0.26	4.80	12.47	3.28	1.3	0.5	1.9

Simulation of normal and flood conditions

Five separate tests (test 1… test 5) were performed at different flow rates (Table 7-3 and Figure 7-3) to simulate the effect of floods, except scouring of the riverbed. Tests 1 and 2 were performed on three columns, each at around 30°C (column C1 in thermo-cabinet), ambient air temperature of 23.2 – 25.8°C (column C2) and around 10°C (C3 in thermo-cabinet). However, tests 3 to 5a were only performed on C1 and C3 (test 5b only on C1) because the ambient air temperature in the laboratory was closer to 30°C and thus the effect of temperature on C2 would not differ much to that of C1 (at 30°C). The five tests were not performed continuously one after the other i.e. the subsequent test did not commence immediately after the preceding test concluded.

Thus, **Test 1** was considered as the reference test, and after all subsequent tests (test 2…test 5), the conditions in the column were set back to those of test 1, and the columns were operated continuously under normal conditions till the start of the next test. Test 1 generally represented a RBF system during normal conditions. For all tests, inflow and outflow samples for the analyses of total coliforms and E. coli were collected at the beginning of each test (time = 0:00 hours), at t_{50} and thereafter at multiples of t_{50} ($\sim 2 \times t_{50}$, … $\sim 6 \times t_{50}$) depending on the travel-time through the column. Thus sampling was performed more often for shorter travel-times (higher flow rates). The samples were analysed following the procedure described in section 7.2.1 (*Determination of coliform counts*). The outflow samples were not diluted since very low or zero bacteria concentrations were expected. At the start of the test, it was assumed that there were no residual coliforms in the columns, thus the outflow concentration of bacteria would be zero, so no outflow coliform measurement at the beginning of the test was necessary. No coliform bacteria or E. coli were measurable when conducting a preliminary Colilert test that used river water collected four days prior. It was thought that coliform bacteria would die-off or become inactivated after a few days. Since there was a period of at least a week between tests, it was assumed that there were no residual coliforms in the columns.

Test 2 was designed to represent a RBF system during a normal high flow or normal flood when velocities would be higher due to increased river levels. To simulate flood conditions the flow velocity in each column was increased to about 1.5 times greater than normal flow velocity (test 1).

Test 3 was performed to simulate the effect of a sudden and very high increase in river levels. To represent such a scenario, the flow rates in the columns C1 and C3 were increased abruptly from around 5 ml/minute to 22.3 ml/minute.

Test 4a was designed to simulate an extreme flood event wherein very high flow rates were continuously maintained for a period of 4 hours. But due to no significant breakthrough of coliforms, this test was repeated with a higher flow rate (than used for test 4a) in **test 4b**.

Test 5a was designed to simulate the effect of seepage through an unsaturated zone at very high flow rates that would potentially shear-off dormant pathogens attached to the grains of the aquifer material and re-activate them once they are in an aqueous mobile phase. Again, due to no significant breakthrough in test 5a, this test was repeated as **test 5b** only on column 1 with a higher flow rate (than test 5a). In preparation for this test, the columns were allowed to drain freely by gravity for more than two weeks immediately after test 4. Then, from an initial "no-flow" condition, fresh river water was pumped through the columns at a very high flow rate of 24.3 – 26.6 ml/minute.

Table 7-3 Summary of column tests performed to observe removal of coliforms under different flow rates (Sandhu et al., 2013)

Test	Column	Test duration [hours]	Flow rate [ml/min]	Mean residence time (t_{50}) [min	Pore velocity [m/day]	Sampling interval [min]	No. of samples (n)	
							Inflow	Outflow
1: normal flow conditions	C1	27.67	3.9	320	3 – 5	0, 330, 702, 1662	4	3
	C2		3.4	347			4	3
	C3		4.1	288			4	3
2: high flow or normal flood (normal monsoon scenario)	C1	8.75	4.5	219	5 – 7	0, 45, 285, 525	3	3
	C2		5.3	193			3	3
	C3		5.8	197			3	3
3: change-over normal flood to extreme flood	C1	2.5	22.3	58	25 – 28	0, 30, 60, 150	1	4
	C3		22.3	52			1	4
4a: Extreme flood	C1	4.0	26 – 29.7	46	29 – 31	0, 30, 60, 120, 180, 240	1	6
	C3		24.0	49			1	6
4b: Repeat of extreme flood	C1	2.5	40.3	37	34 – 39	37, 74, 111,148	3	5
	C2		29.8	42			3	5
	C3		34.3	38			3	6
5a: Change-over from unsaturated to saturated conditions	C1	5.0	24.3 – 26.6	50	29 – 31	60, 120, 180, 240, 300	1	5
	C3		24.7 – 25.4	46			1	5
5b: Repeat: unsat.→ sat.	C1	1.63	38.2	37	39	19, every 3 min	1	14

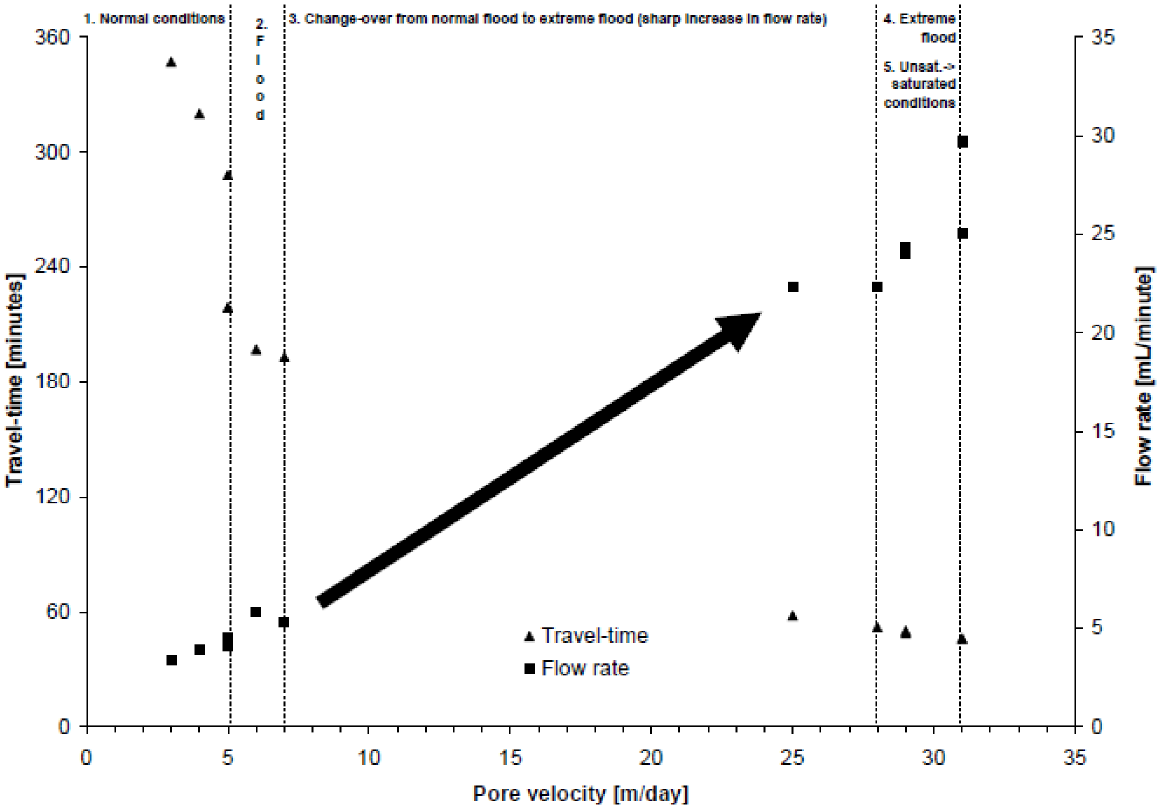


Figure 7-3 Concept for column tests performed (data from Table 7-4) to investigate the effect of different flow rates as an equivalent representation of increased hydraulic pressure (due to floods) on pathogen removal (Sandhu et al., 2013)

7.3 Results

7.3.1 Removal of coliforms and turbidity for different material under field conditions

Infiltration rates and residence times of Elbe water in different column-filled material

For the four columns filled with glass beads (C1), medium-coarse sand (C2), river bed sediment (C3) and river bed sediment topped with a 10 cm thick layer of finer material (C4), respectively, which were operated under field conditions with fresh water pumped directly from the Elbe river, the discharge ($Q_{outflow}$) was measured once a day on 11 days (9 days for C4) at the outflow of the columns. Accordingly the infiltration rates (I) were calculated as a function of column area for

$$I = \frac{Q_{outflow}}{A_{column}} \qquad (6.1)$$

The resulting ranges and mean values are summarised in Table 7-4. Consequently the residence times (range and median) of the Elbe river water was calculated for each column (Table 7-4) for the range and median values of their respective effective porosities as given in Table 7-2.

Table 7-4 Infiltration rates and residence times of Elbe river water in columns filled with different media under field conditions (Sandhu et al. 2013)

Parameter		Column (outflow)			
		Glass beads [C1] (n=11)	medium-coarse sand [C2] (n=11)	Elbe river bed sediment [C3] (n=11)	Finer sediment layer (10 cm thick) filled above Elbe river bed sediment layer (35 cm thick) [C4] (n=9)
Infiltration rate (*I*) [m/s]		9.9×10^{-5} … 2.5×10^{-3} (6.8×10^{-4})	4.2×10^{-6} … 9.3×10^{-5} (3.6×10^{-5})	2.1×10^{-6} …1.6×10^{-5} (6.2×10^{-6})	6.8×10^{-7} …5.2×10^{-5} (1.4×10^{-5})
Travel time [minutes or hours]	$n_e = 0.20$	n. d.	n. d.	2 … 12 hours (6)	n. d.
	$n_e = 0.25$	n. d.	n. d.	2 … 15 hours (7.5)	1 … 46 hours (17)
	$n_e = 0.30$	1 … 82 min (18)	0.4 …<9 hours (3.3)	2 … 18 hours (9)	1 … 54 hours (20) *
	$n_e = 0.325$	2 … 89 min (22)	0.4 …<10 hours (3.6)	n. d.	1 … 57 hours (24)
	$n_e = 0.35$	1 … 95 min (23)	0.5…10.3 hours (3.9)	n. d.	n. d.

n_e: effective porosity; n.d.: not determined; * an effective porosity of 0.29 (from Table 7-1) is used instead of 0.30; mean values for infiltration rates are presented in parenthesis; median values for residence time are presented in parenthesis

The infiltration rates range across at least one to two orders of magnitude for each column during the course of the 31 day experiment (Table 7-4). The higher infiltration rates are generally observed at the start of the experiment. As time elapsed, the infiltration rate progressively decreased as a function of clogging of the columns as fresh Elbe water was continuously pumped through them. The highest infiltration rate of 2.5×10^{-3} m/s was observed in C1 (glass beads), the lowest rate of 6.8×10^{-7} m/s was observed in C4 (Table 7-4).

As the effective porosity (n_e) of each column was not determined by means of a tracer test, a range of effective porosities was assumed for each column and the residence time of the water that passed through each column was then calculated accordingly. The effective porosities listed in Table 7-2 (based on references from literature) were taken as a median within a range of ± 5 %. Accordingly, the residence time for column C3 (Elbe river bed sediment) was calculated for porosities ranging from 0.2 – 0.3, and for glass beads (C1) and medium-coarse sand (C2) ranging from 0.3 – 0.35. For columns C1 and C2, the median effective porosity of 0.325 has been taken into consideration. For C3 and C4, median effective porosities of 0.25 and 0.29 respectively have been taken into account. Of all materials used in the columns, the residence time is shortest for glass beads (C1). For an effective porosity range of 0.3 – 0.35 the median residence time in column C1 is < 25 minutes, with a maximum of 95 minutes (1.5 hours). The residence times for the columns 2, 3 and 4 (C2, C3 and C4) increases with the corresponding decrease in effective grain-size diameter. Thus for medium-coarse sand (C2), and also using a porosity range of 0.3 – 0.35, the median residence time is between 3 – 4 hours over a range from around 30 minutes (0.4 – 0.5 hours) to around 10 hours. For Elbe river bed sediment (C3), the residence times vary from 2 to a maximum of 18 hours over a range of effective porosities from 0.2 to 0.3 (Table 7-4). Over the same range of effective porosities, the median residence time lies between 6 to 9 hours. The longest residence times are observed for column C4, with medians of 17, 20 and 24 hours for effective porosities of 0.25, 0.29 and 0.35.

Magnitude of removal of coliforms and turbidity

Over the duration of the 31-day experimental period, a consistent removal of total coliforms, E. coli and turbidity from Elbe river water after passage through all four columns (Figure 7-4) was observed.

While a breakthrough of coliforms was observed consistently for the columns containing the glass beads (C1) and medium-coarse sand (C2), a very low total coliform count of <1 MPN/100 ml was determined on 2 – 3 occasions for the columns containing the riverbank material (C3) and the column containing the riverbank material topped with fine sediment (C4). For C3 and C4, a minimum of <1 MPN/100 ml of faecal coliforms was determined on 5 and 8 occasions respectively.

For statistical analyses, a coliform count of <1 MPN/100 ml was taken as 0 MPN/100 ml. The justification for this is that when all wells react negatively to the presence of coliforms, for samples analysed by the quantitray IDEXX Coliert-18 method, then a value of 0 MPN/100 ml lies within the lower 95 % confidence interval. Furthermore for a sample-size of 11 measurements, a value of 0 or 1 MPN/100 ml for samples having a coliform count <1 MPN/100 ml has an insignificant effect on the magnitude of mean values.

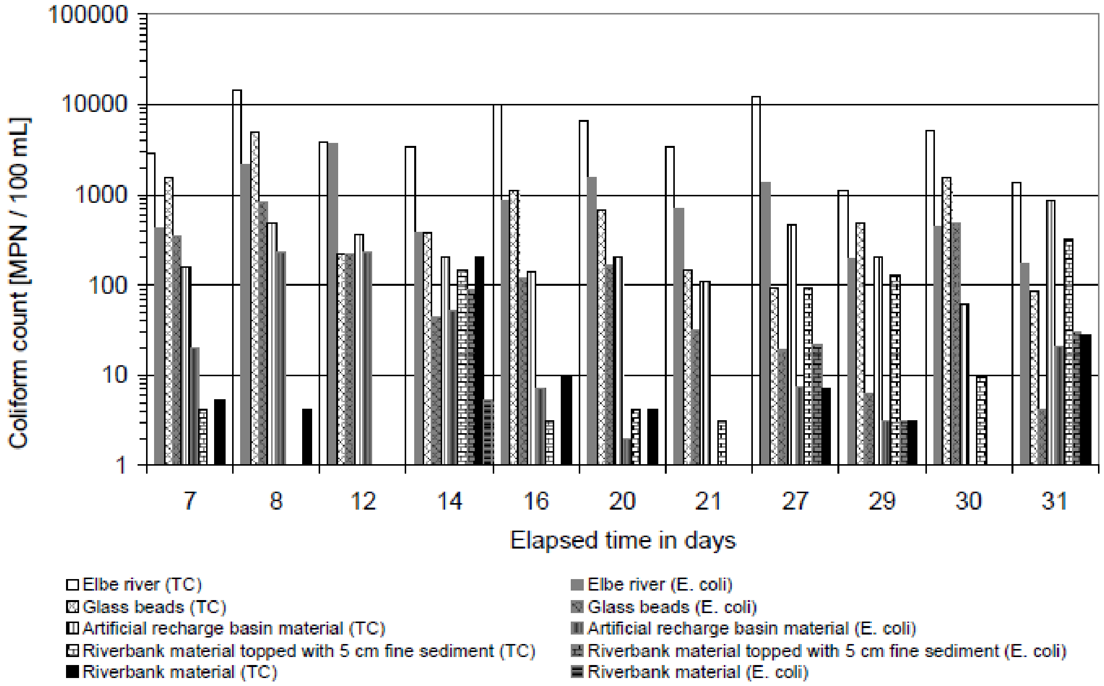


Figure 7-4 Coliform counts of samples taken at outflow of columns in operation under field conditions (Sandhu et al., 2013)

The range and mean values of the coliform counts and turbidity measured at the inflow of the columns (Elbe river water) and their outflows, as well as their respective log (base 10) removal rates of the columns have been summarised in Table 7-5. It is evident that the lowest mean log removal of 0.9, 1.0 and 0.7 for total coliforms, E. coli and turbidity is observed for the glassbeads (C1), on account of an effective grain size diameter of 1.74 mm which is significantly larger than the effective grain sizes of the material used in the other columns that range from 0.18 to 0.4 mm (Table 7-1). Columns C2, C3 and C4 exhibit a higher removal of these parameters, with column C4 having a 10 cm thick finer layer (above the natural riverbed material) with the smallest mean effective grain size diameter of 0.26 mm showing the highest removal of 2.5 and 1.2 log orders respectively for E. coli and turbidity (Table 7-5).

The mean coliform and turbidity counts determined in the outflow of column C1 filled with glass beads, are around five times lower than in the Elbe river water. This highlights that even after a short flow path and consequently short median travel time of < 25 minutes, as simulated by the columns with a length of 0.45 m, straining and attachment are important processes for the removal of coliforms.

Table 7-5 Summary of coliform and turbidity counts, and log removal rates, for different column-filled material under field conditions (Sandhu et al. 2013)

Parameter	**Elbe river** (n=11)	**Column (outflow)**			
		Glass beads [C1] (n=11)	medium-coarse sand [C2] (n=11)	Elbe river bed sediment [C3] (n=11)	Combined finer sediment (35 – 45 cm) with Elbe river bed sediment (0 – 35 cm) [C4] (n=11)
TCC [MPN/100 ml]	1112 – 14163 (5803)	86.2 – 4884 (1017)	62.4 – 866 (295)	<1 – 200 (24)	<1 – 323 (64)
Log removal of TC with reference to Elbe river water	-	0.3 – 2.1 (0.9)	0.2 – 1.9 (1.3)	1.2 – >3.7 (>3.5)	0.9 – >4.2 (2.9)
E. coli counts [MPN/100 ml]	175 – 3654 (1087)	4.1 – 845 (208)	1 – 228 (52)	<1 – 88.5 (13)	<1 – 5.3 (<1*)
Log removal of E. coli with reference to Elbe river water	-	0.03 – 1.9 (1.0)	0.9 – 2.9 (1.8)	0.6 – >4.2 (>2.5)	2.3 – >3.6 (>2.9)
Turbidity [NTU]	11 – 23.5 (14.8)	0.6 – 9.5 (3.8) $^{n=9}$	0.3 – 2.1 (1.4)	0.7 – 2.5 (1.3)	0.5 – 1.9 (1.1) $^{n=8}$
Log removal of turbidity	-	0.3 – 1.4 (0.7)	0.8 – 1.7 (1.1)	0.8 – 1.4 (1.1)	0.8 – 1.6 (1.2)
TCC: Total coliform counts; * median value; n: number of samples					

By comparing the removal rates observed for the other columns, it can be confirmed that the removal of coliforms and suspended matter progressively increases with smaller effective grain size diameter, because as stated by Foppen et al. (2007) the attachment rate coefficient increases with decreasing bead size. Another aspect which can be reaffirmed from the results is that a significant removal of total coliforms and E. coli (maximum 4.2 and 3.6 log orders respectively in C4) occurs within the first half-meter of flow path of the bank filtrate.

Removal of coliforms in relation to residence times and infiltration rates

An analyses of the log removal rates for total coliforms and E. coli with the residence time of water over a length of 0.45 m of the material used in the columns C1 to C4 indicates that generally greater average removal is achieved for material having lower effective grain size diameters (Figure 7-5) and consequently longer residence times. The correlation presented for columns C1 and C2 show that a comparatively lower removal (than C3 and C4) of a maximum of 2 and 3 log orders can be achieved for the glass beads and medium-coarse sand respectively for a residence time ranging from a few minutes to < 2 hours (Figure 7-5A and Figure 7-5B). On the other hand, for riverbed sediment (C3) with a lower effective grain size diameter (0.28 mm), a greater removal ranging from a mean of > 2.5 (E. coli) to > 3.5 (total coliforms) to a maximum of > 4.2 (E. coli) to > 3.7 (total coliforms) is achieved within a residence time of 2 to 18 hours (Figure 7-5C), with a median of 6 – 9 hours. Similarly high removal rates of 2.9 log orders (total coliforms) and greater (E. coli) can be observed for the riverbed material covered with finer sediment (Figure 7-5D).

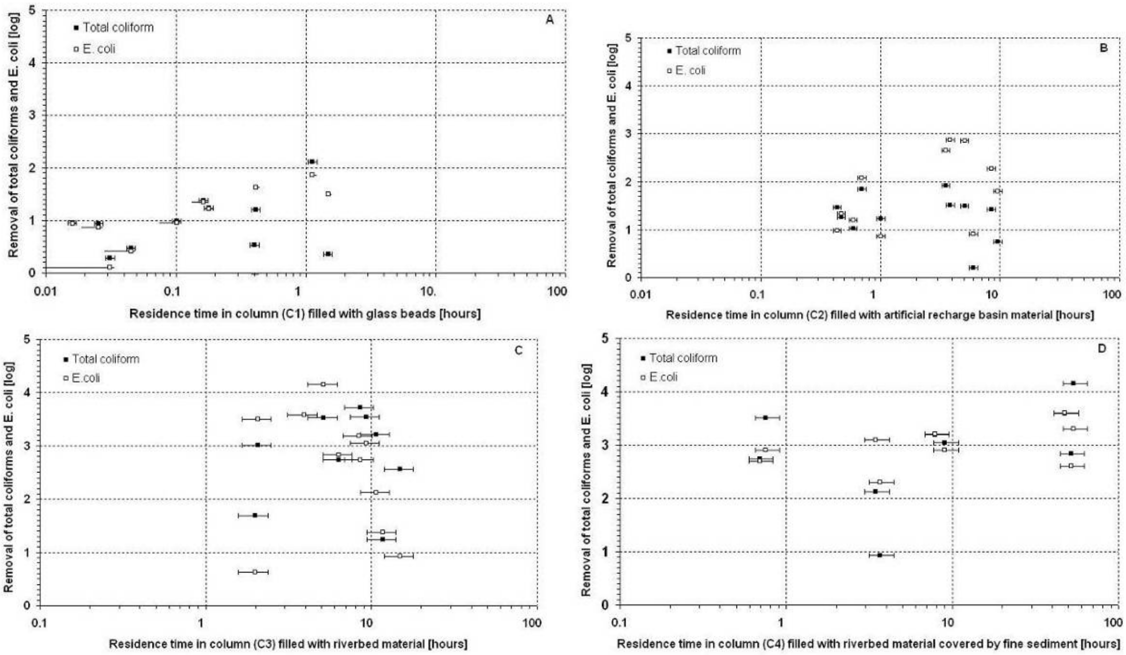


Figure 7-5 Removal of total coliforms and E. coli as a function of residence time in different material (Sandhu et al. 2013)

A clear relationship is not visible by correlating the removal of coliforms with infiltration rates (Figure 7-6), because the observed magnitude of removal is similar over a range of infiltration rates for a specific material. Although during the course of the experiment there was a general decrease in infiltration rates due to clogging of the columns, there were some incidences where increases in the infiltration rates were observed. This was due to the erratic flow of water from the submersible pump in the Elbe river (which choked due to weeds) that in turn caused fluctuations in the hydraulic head of the overhead tank from which the columns were supplied by gravity.

However as stated earlier, a more pronounced correlation is observed between the grain sizes of the material and the removal rates that indicates greater removal for smaller effective grain sizes.

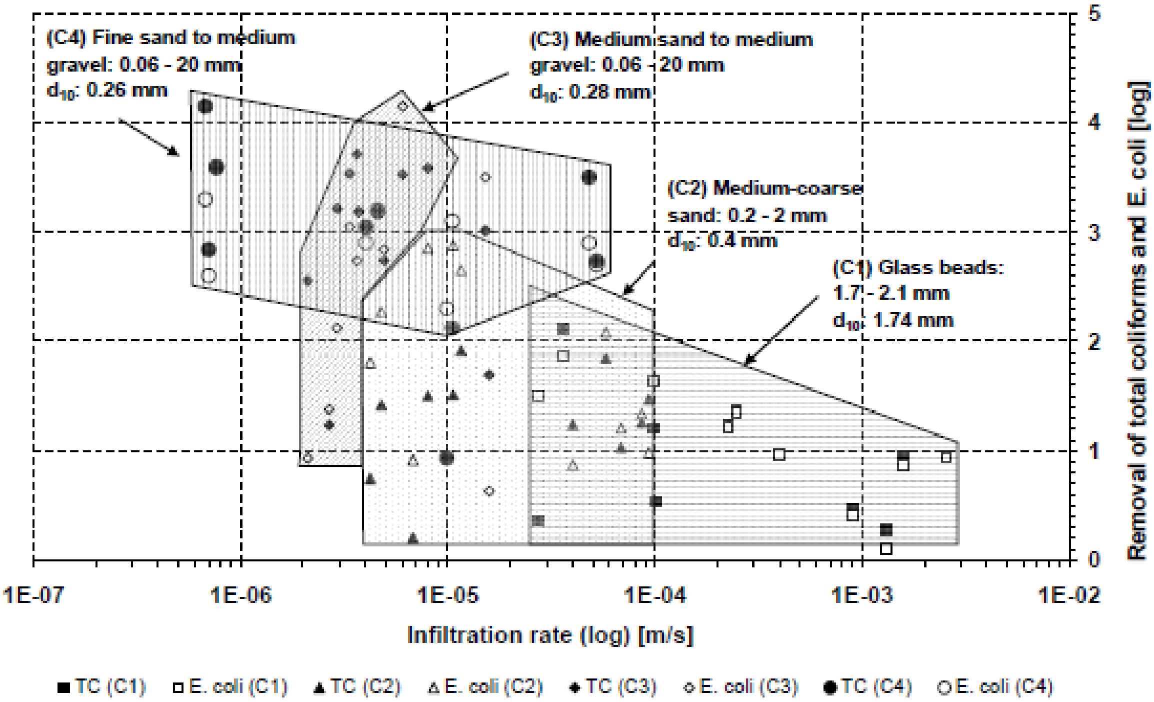


Figure 7-6 Removal of total coliforms and E. coli as a function of infiltration rates in different material (Sandhu et al. 2013)

Discussion of removal of coliforms for different material under field conditions

For a range of infiltration rates from 10^{-2} to 10^{-4} m/s a maximum removal of coliforms of up to around 2 log orders is observed for well-rounded or spherical grains (glass beads, column C1) having a size of 1.7 – 2.1 mm (coarse sand to fine gravel) during a residence time ranging from minutes to around 1.5 hours. In a series of experiments with columns of limited height (2 – 5 cm) with glass beads of various micro sizes (0.038 – 0.425 mm), Foppen et al. (2007) found that attachment of E. coli decreased hyper-exponentially, or, on logarithmic scale in a bimodal way, as a function of the transported distance from the column inlet. They attributed this to microscopic chemical heterogeneities on the surface (and thus the surface charge) of the grains. Consequently they concluded that the sticking efficiency within a population of E. coli bacteria may vary at least 100-fold, resulting in different deposition patterns. Furthermore, they concluded that when the beads were large, or column heights were too limited, dual mode deposition, as a result of attachment heterogeneity among members of the E. coli population, was completely masked, because in such cases just one type of (fast) deposition dominated, resulting in log-linear retained bacteria masses.

In comparison, larger spherical beads of 1.7 – 2.1 mm (C1) diameter to represent coarse sand to fine gravel were used under much higher flow rates of 13 – 1200 ml/min (17 – 26 ml/min were observed towards the end of the 31 day experimental period). The observed removal after 0.45 m column passage from 175 – 3654 MPN/100 ml in Elbe river water down to 4.1 – 845 MPN/100 ml at the outflow of column C1 can most likely be attributed to straining and deposition, especially in the top most 5 cm of the column.

After the conclusion of the experiment, the glass beads were extracted from the column carefully and visually assessed for clogging (Soares, 2011). It was observed that the top-most 5 cm of the column had retained a significantly larger amount of suspended matter from the Elbe river water. It is likely that the low variation of grain sizes resulted in significant inter-particle pore spaces that were able to trap or “strain-out” the suspended matter. It is now known that within the pore structure thus created, there are also regions of stagnant pore water due to very low pore water velocity, which can lead to storage of biocolloids and consequent retention of E. coli (Foppen et al., 2007). This can lead to subsequent attachment or deposition onto the grains or even die-off in case of longer retention times.

For a range of infiltration rates from 10^{-4} to 10^{-5} m/s a maximum removal of coliforms of up to around 3 log orders is observed for medium-coarse sand (artificial recharge basin material, column C2) having a size of 0.2 – 2 mm (medium to coarse sand) during a residence time ranging from around 0.5 to 10 hours.

The infiltration rates of 10^{-5} to 10^{-6} m/s occur for the fine sand to medium gravel column (C3) having a grain size of 0.06 – 20 mm, whose purpose is to represent a natural river bed immediately after a flood as a consequence of which the overlying clogging layer (finer sediment layer) has been scoured away. A similar range of infiltration rates have also been observed at an RBF site by the Enns river (Austria) during a flood event, as a consequence of which the seepage rate in the riverbed changed from around 8.3×10^{-6} to 1.2×10^{-5} m/s (Wett et al., 2002).

In contrast, column C4 is intended to represent a natural riverbed immediately before a flood when the naturally formed clogging layer (made-up of finer sediment) is still present. Thus the infiltration rates are also lower in the range of 10^{-7} m/s during the first 12 days of the experiment. Thereafter, it is likely that preferential flow may have led to an increase in infiltration rates because on an average they are higher compared to column C3 (Table 7-4). For C3 a greater mean removal for total coliforms at > 3.5 log and for E. coli at > 2.5 log is observed for residence times ranging from 2 to a maximum of 18 hours that are considerably less than those for C4. A greater average removal of E. coli of > 2.9 log is observed for fine sand to medium gravel covered by a layer of finer sediments (C4). But the average removal of total coliforms at 2.9 log orders is lower compared to > 3.5 log for C3. The higher removal of E. coli in C4 could be explained due to an increased effect of straining, attachment and eventually die-off especially in the upper 10 cm thick finer layer. Consequently this phenomenon would be in accordance with the finding by Foppen et al. (2007) that attachment of E. coli decreases hyper-exponentially with increasing distance from the column inlet.

7.3.2 Column experiments in the laboratory under controlled flow conditions and temperatures

For **test 1** that was intended to represent **normal flow conditions**, columns 2 and 3 had breakthrough of total coliforms but no breakthrough for E. coli (Table 7-6). The outflow concentration in column 2 was higher than column 3, even though the inflow concentration of column 3 was higher than column 2. This means column 3 effected a greater removal of coliforms than column 2. This can be explained by the effective porosity of column 2 being greater than column 3. The lower effective porosity in column 3 could have resulted in more attachment and straining, resulting in greater removal efficiencies. Column 3 was able to remove more coliforms despite having a lower temperature which would be expected to reduce die-off or inactivation rates. This result indicates that for these columns attachment and straining played a larger role in total removal than inactivation did.

For **test 2** that was intended to represent **high flow or normal flood conditions** by marginally increasing the flow rate through the columns, none of the columns showed any breakthrough of total coliforms or E. coli. This result is not corroborated by the theory that shorter travel times worsen removal efficiency by allowing less time for die-off and adsorption to occur. However, the inflow concentrations of coliform bacteria in test 2 were slightly lower than in test 1. It is possible that a breakthrough could have occurred if coliform bacteria concentrations in test 2 were as high as in test 1.

For **test 3** that was intended to represent **a change-over from normal flood conditions to extreme flood conditions** by rapidly increasing the flow rate through the columns to 22.3 ml/min, no breakthrough of coliforms was observed (a cell count of < 1 /100 ml is the most probable number when all wells using the IDEXX Quantitray method are negative) despite the high inflow concentration.

However, a very minor breakthrough of total coliforms of up to 2 MPN/100 ml was observed for slightly higher flow rates of 24 – 29.7 ml/min in both columns C1 (30°C) and C3 (10°C) in **test 4a intended to represent an extreme flood**. In a repetition, with higher flow rates of 29 to 40 ml/min and correspondingly short residence times (t_{50}) of 37 – 42 min, a noticeable yet small breakthrough of 19.9 – 59.1 MPN/100 ml total coliforms and 3.1 – 5.2 MPN/100 ml for E. coli was observed for C1 at 10°C. C2 and C3 in contrast displayed minor breakthroughs of total coliforms of up to 3.1 and 6.3 MPN/100 ml. Considering that the inflow coliform counts in all columns were similar, the effect of higher temperatures of 20°C and 30°C (compared to C1 with 10°C) caused greater die-off and inactivation of coliforms.

Tests 5a and b were designed to simulate the effect of drying, or un-saturation, of a previously flooded riverbank or near-well area over a few months and then **followed by a sudden wetting, or re-saturation due to floods.** The aim was to observe whether sudden high pore water velocities could shear-off or dislodge coliforms that may have attached themselves to the grains of the aquifer material. For this purpose the fully saturated (~100 %) columns were first let to drain by gravity until a saturation of around

30 % was achieved. Thereafter sterile chlorine-free water was pumped into the columns at high flow rates of 24.3 to 26.6 ml/min (test 5a), and subsequently 38.2 ml/min (test 5b). The results of test 5a, with a residence time of 46 – 50 min and a pore water velocity of 29 – 31 m/day, resulted only in a minor breakthrough of up to 2 MPN/100 ml for total coliforms and E. coli (only 10°C column). In comparison, a repetition of the experiment as test 5b (after a 5 month drying-period), with residence time of 37 min and a pore water velocity of 39 m/day, resulted in a higher breakthrough of up to 42.9 MPN/100 ml for total coliforms only. Comparable to test 5a, no breakthrough of E. coli occurred.

Table 7-6 Summary of coliform counts and removal efficiencies for all tests using 1m-long columns (Sandhu et al. 2013)

Test	Column	Total coliform counts [MPN/100 ml]		Log removal	E. coli counts [MPN/100 ml]		Log removal	Mean residence time (t_{50}) [minutes]	Pore water velocity [m/day]
		Inflow	Outflow		Inflow	Outflow			
1	C1 (30°C)	5446 – 852	0	2.9 – > 3.7 (> 3.3)	682 – 80	< 1	1.9 – > 2.6 (> 2.3)	320	3 – 5
	C2 (25°C)	7308 – 763	208 – 19	1.2 – 1.4 (1.4)	654 – 83	< 1	1.9 – > 2.6 (> 2.3)	347	
	C3 (10°C)	10344 – 2868	12 – 0	2.7 – > 3.5	576 – 200	< 1	2.3 – > 2.6 (> 2.5)	288	
2	C1 (30°C)	5794 – 2368	< 1 (0 – 3.7)	3.0 – > 3.7 (3.4 – 3.5)	546 – 274	< 1 (0 – 3.7)	2.1 - > 2.8 (2.6 – 2.7)	219	5 – 7
	C2 (25°C)	6620 – 2368	< 1 (0 – 3.7)	3.0 – > 3.5 (3.4 – 3.5)	473 – 356	< 1 (0 – 3.7)	2.2 – > 2.8 (2.5 – 2.6)	193	
	C3 (10°C)	4611 – 2779	< 1 (0 – 3.7)	3.1 – > 3.7	480 – 427	< 1 (0 – 3.7)	2.3 – > 2.9 (2.6 – 2.7)	197	
3	C1 (30°C)	> 10000 – 8260	< 1 (0 – 3.7)	3.9 – > 4.0	> 555	< 1 (0 – 3.7)	2.2 – > 2.7	58	25 – 28
	C3 (10°C)	> 10000 – 8260	< 1 (0 – 3.7)	3.9 – > 4.0	> 555	< 1 (0 – 3.7)	2.2 – > 2.7	52	
4a	C1 (30°C)	6131 – 3654	< 1 – 2 (0 – 3.7)	3.5 – > 3.8	53 – 51	< 1	> 1.7	46	29 – 31
	C3 (10°C)	10462 – 6131	< 1 – 1	3.8 – > 4.0	530 – 512	< 1	> 2.7	49	
4b*	C1 (10°C)	9930	19.9 – 59.1	2.2 – 2.7	758 – 698	3.1 – 5.2	2.1 – 2.4	37	34 – 39
	C2 (20°C)	9930 – 7766	< 1 – 3.1	3.4 – > 4.0	897 – 646	< 1 – 1	2.8 – 3.0	42	
	C3 (30°C)	7766 – 6499	< 1 – 6.3	3.0 – 3.9	835 – 825	< 1 – 1	2.9	38	
5a	C1 (30°C)	0	< 1 – 2	n. a.	0	< 1	n. a.	50	29 – 31
	C3 (10°C)	0	< 1 – 2	n. a.	0	< 1 – 2	n. a.	46	
5b	C1 (10°C)	0	1 – 42.9 (0.3 – 62.5)	n. a.	0	< 1 (0 – 3.7)	n. a.	37	39

In test 5a & b, chlorine-free sterile water was used as inflow water; The outflow range of coliforms of 0 – 3.7 MPN/100 ml is for the lower 95 % to upper 95 % confidence interval as interpreted when all large *Quantitray* wells are negative or “0” equivalent to a MPN of <1 count per 100 ml; n. a.: not applicable as the effect of survival of coliforms in the unsaturated zone was investigated with subsequent release due to re-saturation following a flood; 4b*: for this test a solenoid-driven diaphragm pump (ProMinent ® gamma/L) was used to achieve higher flow rates.

7.4 Summary and conclusions

In general, the coliform removal experiments conducted on different media contained in columns lead to the conclusion that significant log removal rates of coliforms ranging from a mean of > 2.5 up to a maximum of 4.2 occur under normal flow conditions within a short flow path of 0.45 m and residence times of up to 1 – 2 days and even less. Furthermore, a greater removal of coliforms can be achieved for well graded sand and gravel mixtures, such as fine sand to medium gravel (e.g. naturally occurring riverbed material), as compared to uniformly graded mixtures (e.g. medium – coarse sand). The effective grain size diameter (e.g. d_{10}) of the riverbed is however more important than the infiltration rate. Consequently, it can be concluded from the experiments that sediment mixtures having a low effective grain size diameter are more effective in removing coliforms over short flow paths and residence times.

The column simulations (tests 1 to 5) confirm the hypothesis of the potential risks of floods to RBF wells with regard to the breakthrough of pathogens, but only at a laboratory-scale and that too the breakthrough is very low. The measured breakthrough at very high flow rates in the columns is lower than the observed breakthrough for production wells at a RBF site by the Elbe river (Figure 1-1) in Germany during a flood but is almost of the same order of magnitude as observed for production well PW5 in Srinagar, but lower than monitoring well MW5 (Table 5-1, Figure 5-8 and Figure 5-9). One possible explanation is that the breakthrough of coliforms in the column experiments is underestimated due to the frequency of sampling at the outflow of the columns. In this context, it could be that "peaks" in the outflow concentration were missed. More frequent sampling (than that already done for these tests) is difficult due to the cost and time factor involved. Thus this advocates the use of online-monitoring of coliforms, especially in practise. The removal of pathogens by RBF is also largely dependent on their concentration in the source water body (Schijven, 2002).

For the coliform removal and breakthrough experiments conducted under controlled flow and temperature conditions in the laboratory, the results appear to corroborate the theory that die-off and inactivation rates generally increase with temperature although the magnitude of the measured effect is marginal. This could be the result of the difference in scale of the columns used to determine such effects in works by other authors (e.g. Foppen et al., 2007), where comparatively very short columns of a length of 0.25 to 5 cm have been used. The pH value and dissolved oxygen are considered to have had negligible effects on die-off and inactivation. A significant portion of removal is thought to be attributable to attachment.

From the above, the most likely and frequent cause of contamination is a direct entry of flood water into a well due to inundation or flooding of the area directly around the well and seepage and entry of flood water along preferential flow paths into the well. In this context, flood proofing measures of RBF, especially in India, is extremely important.

8 Mitigation of flood risks at RBF sites

8.1 Risk management plans for RBF sites in Haridwar and Srinagar

8.1.1 Operational and technical aspects

The breakthrough of pathogens in RBF wells has been identified as the most severe probable risk associated with normal monsoon high flow events as well as extreme flood events. A general management plan to address the risk is presented in Table 8-1.

Table 8-1 General flood-risk management plan for RBF wells in Haridwar (that are not protected by flood embankments or dykes) and Srinagar (Sandhu et al. 2012)

	Annual monsoon high flow event (normal flood)	Extreme flood
Travel-time of bank filtrate	2 – 50 days	<1 day to 30 days
Expected risks	Breakthrough of pathogens	- Breakthrough of pathogens and increased turbidity - Failure of power supply - No access to wells - Damage to water supply pipelines and installations
Immediate additional remedy measures	Controlled disinfection	- Back-up power supply - Alternative disinfection measures
Long-term remedy measures	Online-monitoring	- Online-monitoring & inline-electrolyses - Sealing of surface near periphery of wells in Haridwar with clay - Construction of dykes to prevent direct contamination to flood-prone wells - Construction of new flood proof wells in Srinagar

The most important aspect is to ensure adequate disinfection at all times. This can only be achieved if a back-up power supply is permanently available. Furthermore, disinfection measures should be installed at certain points along the drinking water supply distribution network in order to guarantee a residual chlorine concentration of 0.2 mg/l. In the event of an extreme flood, like those experienced in September 2010 in Haridwar and in August 2011 in Srinagar, more elaborate long-term measures have to be introduced as described in the following sections.

8.1.2 Health aspects

Additional treatment steps can be applied to the source of contamination, water distribution network or at the tap. Watershed protection such as reducing sewer overflow and limiting discharge of untreated wastewater or human excreta into the Ganga River can reduce pathogen numbers by 0.5 to 1 $\log_{10}$ (NHMRC, 2011). Another 1 to 2 $\log_{10}$ unit removal can be achieved by primary and secondary wastewater treatment (NRMMC–EPHC–AHMC, 2006). Currently, around 80% of wastewater upstream from Haridwar is discharged untreated into the Ganga River. Well head protection zones, improved well sanitation and protection of well heads against direct contaminations is further necessary as pollution by on-site facilities is a major threat in terms of pathogen related risks. During longer religious festivals (e.g. *Kumbh Mela*), when widespread tented accommodation is provided to pilgrims, temporary sanitation facilities are also constructed at many places (e.g. on Pant Dweep island). Human excreta are first collected in a pit with a cemented wall, and the overflow is then allowed to seep into the ground through a soak pit. Such soak pits close to RBF wells, especially in areas having a shallow groundwater table (Pant Dweep island), also pose a high risk. The pathogens can easily be transported into the groundwater and then directly to the well. Optimized well operation during flood event such as increasing abstraction rate of wells with longer travel distance and reduction of abstraction rates at wells along the riverbank is also a potential operation philosophy to minimise risk. Currently when there is contamination with flood water or a loss of disinfection, mains water is not suitable for direct ingestion and needs to be boiled.

8.2 Design of technical elements for flood protection of RBF wells

8.2.1 Criteria for flood protection measures of RBF wells

Taking into account the reoccurrence of the monsoon flood of August 2011 again in the monsoon of 2012, and in order to guarantee high-quality abstracted water by minimising the entry of contaminants, suspended matter and pathogens, the production wells PW1 to PW5 in Srinagar provide a good example of a RBF site requiring flood-proof wells. The wells PW-DST, MW-DST and CGWB are not affected by floods as their site has a sufficient elevation.

Taking into account locally available materials and site-specific conditions, three designs for the protection of the RBF wells from floods were developed and are described in the following sections. The basis for designing the flood-proof wells was the monsoon water level of August 2011. The following criteria have been considered:

- Protection of the well against external factors and trespassing by unauthorised persons,
- Prevention against pollution of groundwater through the well,
- Prevention of rapid seepage of rainfall-runoff by providing adequate drainage measures,
- Low maintenance costs and use of non-toxic materials resistant to chemical corrosion and biological degradation,
- Easy access to well for authorised persons.

At the time the need for flood-proofing the wells was identified, the RBF site in Srinagar was attributed with some of the deficiencies and risks from floods listed in Table 1-1 and Table 3-1.

8.2.2 Sanitary sealing of RBF wells

It is absolutely necessary to seal all wells around their base to prevent the vertical seepage of water in the immediate vicinity of the well and particularly along the casing pipe as a precaution against short-circuiting of seepage water with groundwater. It is suggested to excavate an area of at least 1 m^2 (with the well at the centre) to a depth of

1 m and fill (seal) the excavation with a material of high plasticity, such as clay or concrete. Thereafter the sealing should be compacted thoroughly. The sanitary sealing is illustrated in Figure 8-1, and has already been executed at the wells PW5, MW5 and PW-DST at the RBF site in Srinagar in November 2011 by UJS (Annex 12).

Figure 8-1 Sanitary sealing of production wells PW-DST (left) and PW5 and MW5 (right) at Srinagar RBF sites implemented by UJS (photos: Heinze and Lesch 2012)

8.2.3 Design 1 – Reinforced concrete well-head chamber built on an elevated mound

This design (1) consists of a well-head chamber made of cement-concrete, built into the top of an elevated mound (Figure 8-2). The upper 1 m below ground level, where the abstraction pipe emerges, is first sealed with a 0.5 m thick clay layer above which a 0.5 m thick concrete layer is placed in order to prevent vertical seepage of flood water into the well casing (similar to sanitary sealing shown in Figure 8-1 and Annex 12).

The well chamber is constructed of reinforced concrete, with a base located approximately 2.25 m above ground level. The chamber has a fully-waterproof cover. All the important armatures such as the bypass, valve, flow meter, backflow flap (non-return valve), the lid of the water level gauge pipe as well as the electricity supply are placed in the 2.8 m long and 1.3 m high well chamber. The entire well chamber is surrounded by an inclined earth mound that extends from the top of the well chamber to the ground level. During a monsoon flood, the flood water will flow around the mound and thus not come in direct contact with abstraction pipe, armatures and electricity supply system. This will provide sufficient protection against the hydro-dynamic effects of the flood, other mechanical forces and trespassing by unauthorised persons.

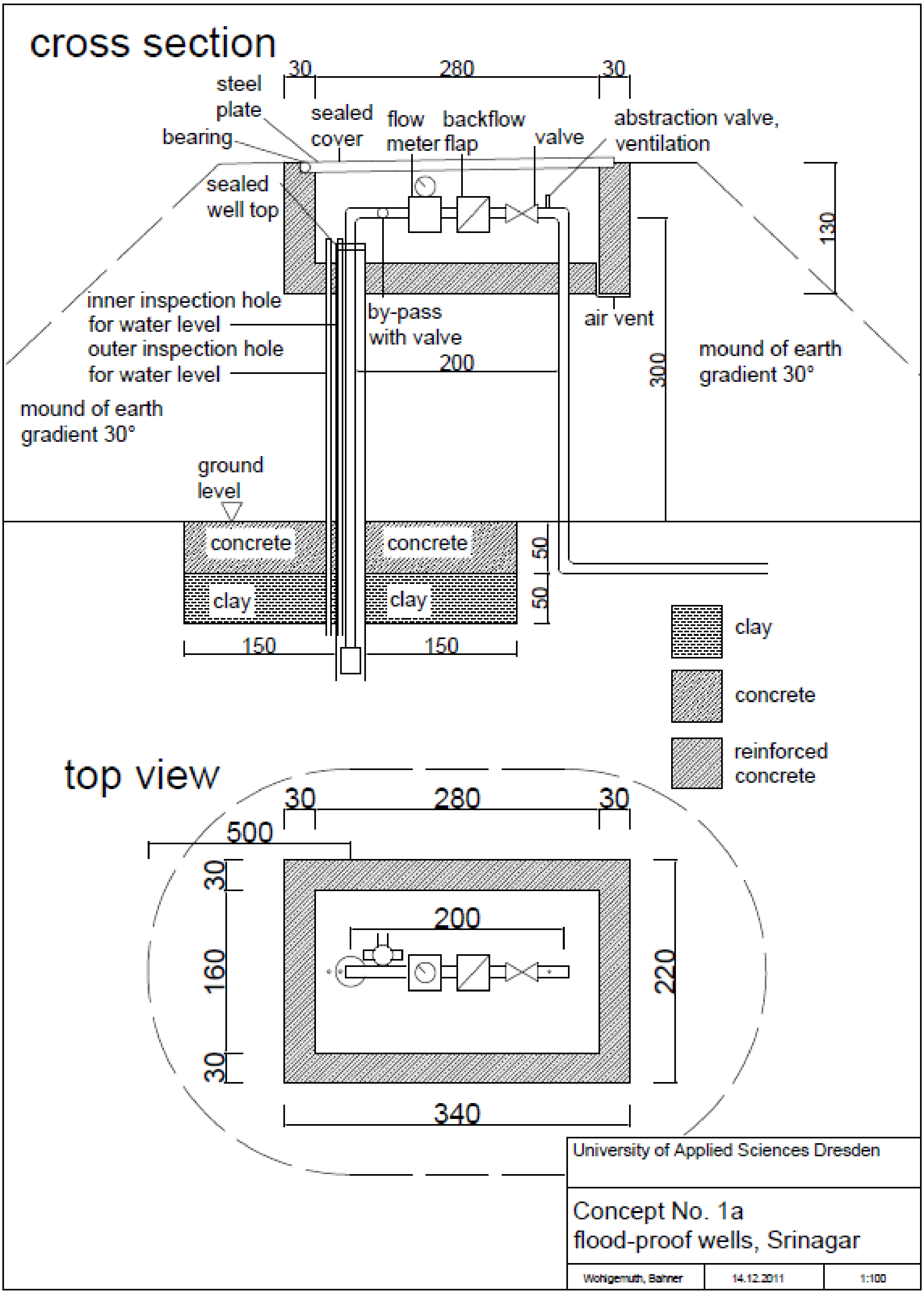


Figure 8-2 Design 1 - Cement-concrete well-head chamber built on elevated mound (HTWD and UJS 2012a)

8.2.4 Design 2 - Elevated platform

In this design (2), the abstraction and the casing pipe are elevated on a platform located at a level that remains unaffected by the flood water. The armatures, valves and electrical installations are placed on this platform (Figure 8-3). Similar to the conceptual design 1 the upper 1 m below ground level, where the abstraction pipe and casing pipe emerge, is first sealed with a 0.5 m thick clay layer above which a 0.5 m thick concrete layer is placed in order to prevent vertical seepage of flood water into the well casing. The well top is welded onto the casing pipe to prevent water entering. The abstraction pipe rises vertically up to 3 m above ground level and is then laid horizontally for 2 m. Thereafter the abstraction pipe returns vertically to the ground and leads away from the RBF site below ground level. In the horizontal 2 m pipe section, the bypass, valve, flow meter and backflow flap (non-return valve) are installed. At an elevation of around 2 m above ground, an approximately 5 m^2 steel platform is placed to enable a person to stand to operate, inspect and maintain the armatures. While the two vertically placed water abstraction and supply pipes will be exposed directly to flood water, all other sensitive equipment will be placed on the platform. Although the two vertical pipes are at risk of being damaged by floating debris, this would be a low risk as the area lies in the spill-over region (of the full channel under extreme floods) and does not lie directly in the path of the main flood water. Therefore the velocities are relatively low compared to the main channel. Furthermore the site is protected towards the river by a railing which will eventually provide some resistance against floating debris flowing towards the wells.

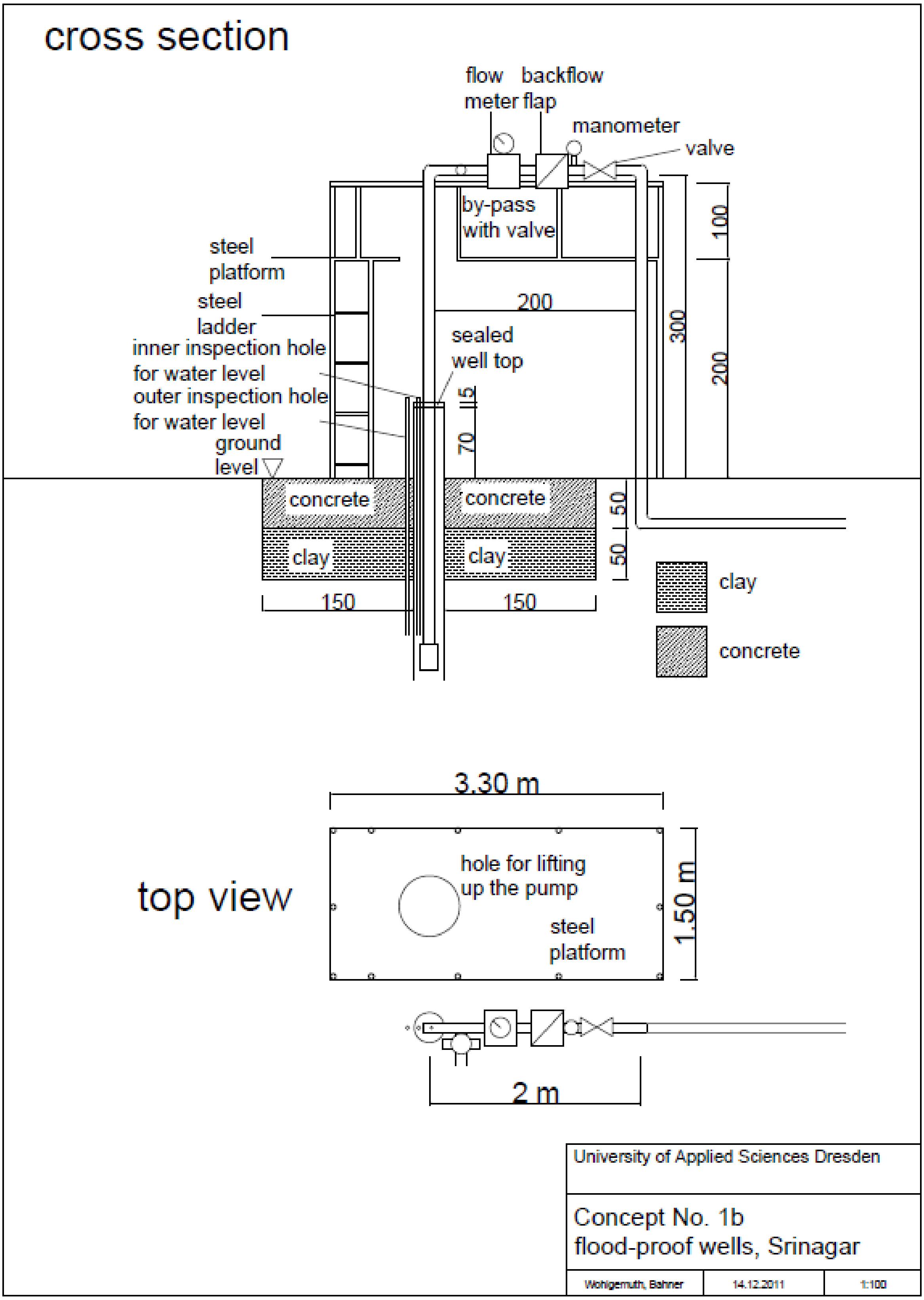


Figure 8-3 Design 2 – Elevated platform (HTWD and UJS, 2012a)

8.2.5 Design 3 – Subsurface reinforced concrete well chamber

In this design (3), the well chamber is constructed of reinforced concrete and built completely below ground level so that the top of the well chamber is around the same level as the surrounding ground surface (Figure 8-4).

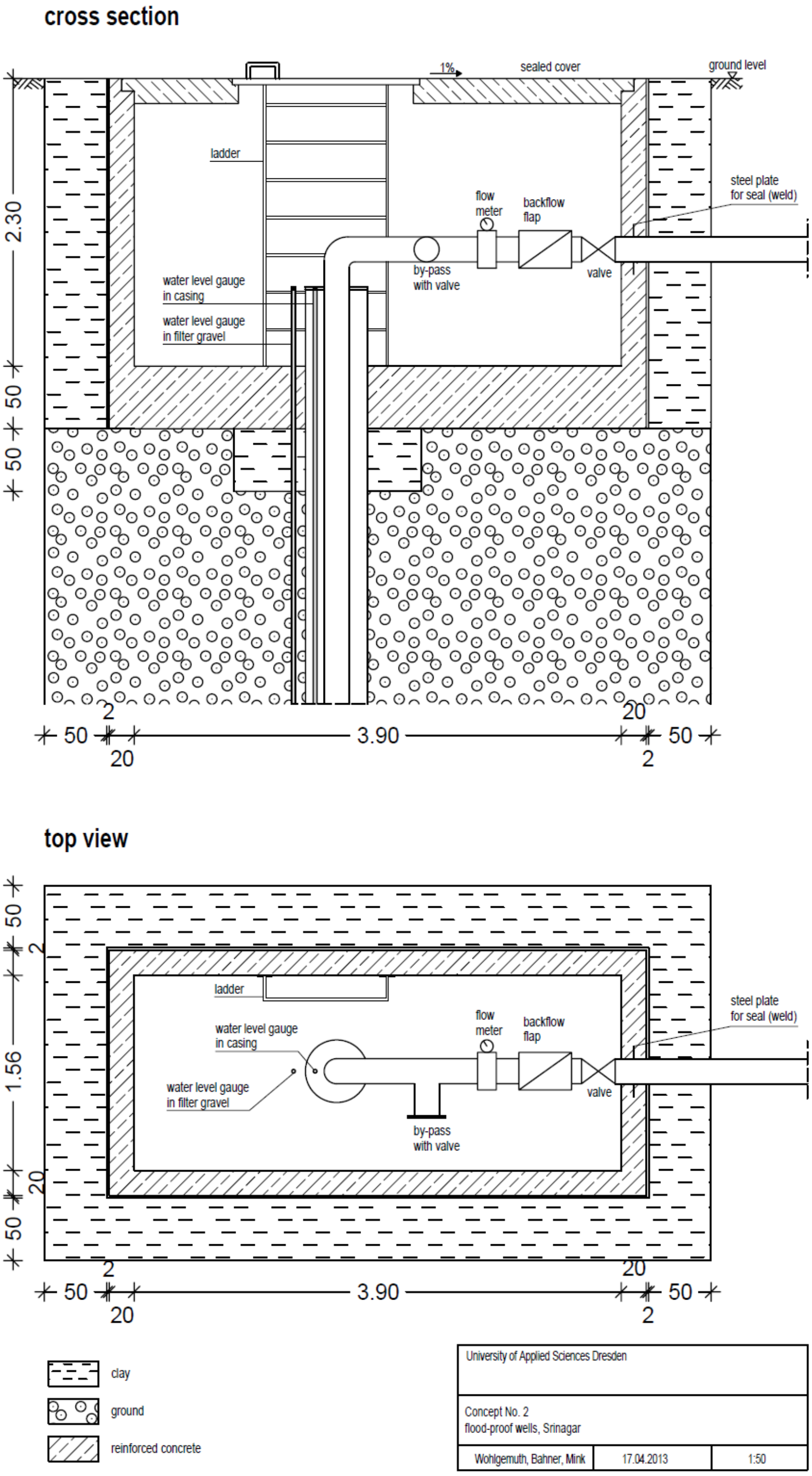


Figure 8-4 Design 3 – Subsurface reinforced concrete well chamber (HTWD and UJS 2012a)

At a depth of 2.80 m in the chamber, the casing of the well is sealed by clay that is compacted into another smaller 0.50 × 0.50 × 0.50 m excavation around the casing. Then either a prefabricated reinforced concrete box (20 cm wall thickness) is placed into the excavation or the walls of the well chamber are constructed in situ. The internal dimensions (length × height × width) of the well chamber are 3.90 × 2.30 × 1.56 m. The chamber must have openings for the well casing and for the outlet supply pipe, as well as for the electricity cables. These opening can be sealed with a bitumen based emulsion (e.g. "coal tar"). In order to avoid the accumulation of water on top of the well chamber, the cover (e.g. steel) of the entrance to the chamber has to be water tight and be inclined with a gradient of 1 %. All armatures and valves are placed in the well chamber. Although during a flood the well chamber is under water and cannot be accessed, the water tight cover to the entrance of the chamber and the bitumen and clay sealing provide complete protection against the external water pressure.

8.2.6 Comparison of conceptual design for flood protection of RBF wells

A comparison of the three conceptual designs is presented in Table 8-2. While the design 1 is a typical choice for RBF sites in Germany (e.g. in Görlitz by the Neisse River) and in areas prone to flooding in The Netherlands and is also aesthetically appealing, it is costly to construct and regular maintenance checks and subsequent maintenance have to be conducted. Yet it provides the best barrier against direct entry of flood water into the well.

The design 2 requires less maintenance and is easier to construct under local conditions especially in Srinagar as it does not require too much additional land compared to that required for the earth mound of design 1. However, the elevated platform (design 2) may not be aesthetically appealing and it will attract public attention that may have negative effects (e.g. vandalism).

Design 3 will attract least attention (including less risk of vandalism) and is safe from damage by floating debris, but it requires a certain level of expertise to construct the water-tight doors and seals to the entrance of the well-chambers.

Table 8-2 Comparison of flood protection options (HTWD and UJS 2012a)

	Advantages	Disadvantages
Design 1	- pipe fully protected against mechanical impacts and human intervention - no flood proof cover required	- prone to erosion - high expenditures - requires continuous maintenance (vegetation growth, erosion)
Design 2	- low maintenance - no flood proof cover required - easy access	- not protected from vandalism, damage and manipulation as fencing is not feasible - Prone to corrosion from weathering - not protected from mechanical damage (e.g. by floating debris)
Design 3	- fully protected against floating debris and vandalism - easy access - no visual impact on landscape	- high expenditures - complicated construction which requires some expertise - flood proof cover required

8.3 Designs for retaining walls to protect riverbanks from erosion at RBF sites

The motivation for investigating protection measures of the river banks at RBF sites arises following the damage through scouring recently experienced at the Srinagar RBF site (Figure 3-4). Erosion of banks, especially where deeply incised channels exist or the ground level of the RBF site is at a comparatively higher elevation to the river channel, is potentially dangerous to the RBF well. The erosion of the bank can cause the ground around the well to subside, reduce the length of flow-path and consequently lessen travel-time of bank filtrate to the well and eventually cause the entire well structure (well head, chamber and casing pipe) to collapse. In this context various designs for retaining walls to protect riverbanks from floods at RBF sites have been developed (Table 8-3). The individual designs are appended in the respective annexes. The specific design for an individual site depends on the site characteristics and the severity of the risk if the retaining wall collapses.

Table 8-3 Comparison of designs for flood-protection walls (HTWD and UJS 2013)

Flood-protection wall structure (example for RBF site, Srinagar)	Advantages	Disadvantages
Steel piling (Annex 13)	- nearly impermeable - fast installation - good mechanical stress-bearing characteristics - durable	- requires additional support (e.g. anchors) below a certain depth - expensive - supporting soil need special stability - difficult to install at riverbanks with boulders - can affect subsurface water flow (to the RBF well) below a certain depth
Retaining wall with bricks (Annex 13)	- simple construction - low cost - simple to upgrade/repair	- not so suitable against mechanical stress - occupies large space - mortar is prone to damage - water uptake by bricks
Angular retaining wall (Annex 14)	- precast elements durable - good mechanical stress-bearing characteristics - impermeable - protection from subsurface erosion and under-currents by the river - narrower than a concrete gravity wall	- expensive - large excavation required
Concrete wall with anchors (Annex 14)	- possibility to prestress (anchors) - durable - impermeable - less material required	- not every subsurface material is suitable - correct backfilling necessary - suitable drainage of water from backfill required
Concrete gravity wall (Annex 15)	- good mechanical stress-bearing characteristics - durable - impermeable	- expensive - bigger than an angular retaining wall - instability
Retaining wall with gabions (Annex 15)	- fast and simple construction - low cost	- occupies large space - not impermeable (geotextile or backfilling behind the gabions is necessary)

References

AJD (2012) Report on construction of monitoring wells for Saph Pani Project in Haridwar and Srinagar. *Akshay Jaldhara* (AJD), well drilling company, Dehradun, India.

APHA (1992) Standard Methods for the Examination of Water and Waste Waters. American Public Health Association, 18th Edition, Washington, DC.

Bartak R (2011) *Untersuchungen zur Rohwasserbeschaffenheit im Wasserwerk Hosterwitz im Hochwasserfall* (in German – "Investigations of the raw water quality at the Waterworks Hosterwitz in the event of a flood"). Graduate degree ("*Diplom*") thesis, Faculty of Forestry, Geo- and Hydrosciences, Institute of Groundwater Management, Dresden University of Technology.

Bartak R, Page D, Sandhu C, Dillon P, Grischek T (2013) Haridwar risk assessment: Managed Aquifer Recharge and Water Safety plan. CSIRO, Australia.

Census of India (2011) Cities having population 1 lakh and above. Provisional Population Totals, Census of India 2011. Office of The Registrar General and Census Commissioner, India, Ministry of Home Affairs, Government of India. Available: http://www.censusindia.gov.in/2011-prov-results/paper2/data_files/India2/ Table_2_PR_Cities_1Lakh_and_Above.pdf; Accessed: 25.07.2012

CGWB (2009) Groundwater brochure of Haridwar District, Uttarakhand. Central Ground Water Board, Ministry of Water Resources, Government of India, Uttarakhand region, Dehradun.

Available: http://www.cgwb.gov.in/District-Profile/Uttarakhand/Haridwar.pdf

CWC (2010) River stage gauge and flood forecasting station Haridwar. Central Water Commission (CWC), Ministry of Water Resources, Government of India.

Dash RR, Bhanu Prakash EVP, Kumar P, Mehrotra I, Sandhu C, Grischek T (2010) River bank filtration in Haridwar, India: Removal of turbidity, organics and bacteria. Hydrogeol. J. 18(4), 973–983.

Eaton AD, Clesceri LS, Rice EW, Greenberg AE (2005) Standard method for examination of water and wastewater. 21st edition, American Water Works Association, 949–956.

Eckis R (1934) Geology and groundwater storage capacity of valley fill, South Coastal Basin Investigation. California Department of Public Works Division of Water Resources, 273 pp.

Foppen JWA, Schijven JF (2006) Evaluation of data from literature on the transport and survival of *Escherichia coli* and thermotolerant coliforms in aquifers under saturated conditions. Water Research 40(3), 401–426.

Foppen JWA, van Herwerden M, Schijven JF (2007) Transport of Escherichia coli in saturated porous media: dual mode deposition and intrapopulation heterogeneity. Water Research 41(8), 1743–1753.

Harvey RW, Garabedian SP (1991) Use of colloid filtration theory in modelling movement of bacteria through a contaminated sandy aquifer. Environ. Sci. Technol. 25(1), 178–185.

Hazam RK, Singla R, Kishore J, Singh S, Gupta RK, Kar P (2010) Surveillance of hepatitis E virus in sewage and drinking water in a resettlement colony of Delhi: what has been the experience? Archives of Virology 155(8), 1227–1233.

Hazen A (1893) Some physical properties of sands and gravels. Massachusetts State Board of Health, 24th Annual Report

Hijnen WAM, Schijven JF, Bonne P, Visser A, Medema GJ (2004) Elimination of viruses, bacteria and protozoan oocysts by slow sand filtration. Water Science and Technology 50(1), 147–154.

HTWD, UJS (2012a) *Durchführung und Auswertung von Pumpversuchsdurchführungen und Ertüchtigung von hochwassersicheren Brunnen an Uferfiltratstandorten in Uttarakhand* (in German – "Execution and evaluation of pumping tests and strengthening flood-safe wells at riverbank filtration sites in Uttarakhand"). Report by Bahner P, Wohlgemuth T, Patwal PS, Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany, and Uttarakhand State Water Supply and Sewerage Organisation – *Uttarakhand Jal Sansthan* (UJS), Riverbank Filtration Cell, Jal Bhawan, Dehradun, India.

HTWD, UJS (2012b) *Uferfiltrations-Standorterkundung in Srinagar am Alaknanda Fluss und in Haridwar am Ganges in Indien* (in German – "Riverbank filtration site-investigations in Srinagar by the Alaknanda River and in Haridwar by the Ganga River in India"). Report by Musche F, Ballmann E, Patwal PS, Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany, and Uttarakhand State Water Supply and Sewerage Organisation – *Uttarakhand Jal Sansthan* (UJS), Riverbank Filtration Cell, Jal Bhawan, Dehradun, India.

HTWD, UJS (2013) Hydrogeologische und Wasserbeschaffenheitsuntersuchungen an Uferfiltrationsstandorten in Srinagar und Haridwar in Uttarahand, Indien (in German – "Hydrogeological and water quality investigations at the riverbank filtration sites in Srinagar and Haridwar in Uttarakhand, India"). Report by Lattke J, Nguyen VDA, Patwal PS, Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany, and Uttarakhand State Water Supply and Sewerage Organisation – *Uttarakhand Jal Sansthan* (UJS), Riverbank Filtration Cell, Jal Bhawan, Dehradun, India.

IEC 300-3-9 (1995) Risk analysis of technological systems. Dependability management, application guide. International Electrotechnical Commission. In: Røstum J, November V, Vatn J (2008) COST Action C19 – Proactive Crisis Management of

Urban Infrastructure. Publ. European Science Foundation, COST Office, and SINTEF Byggforrsk. ISBN 978-82-536-1003-0.

Indian Standard IS 10500 (1991) Indian Standard Specifications for Drinking Water. Bureau of Indian Standards, New Delhi, India.

Indian Standard IS 10500 (2012) Indian Standard Specifications for Drinking Water. Bureau of Indian Standards, New Delhi, India.

Jain CK, Bhatia KKS (1988) Physico-chemical Analysis of Water and Wastewater. User's Manual, UM-26, National Institute of Hydrology, Roorkee.

Jenkins MW, Tiwari SK, Darby J (2011) Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: Experimental investigation and modeling. Water Research 45(18), 6227–6329.

Jha VK (1992) Aerial remote sensing as an aid to engineering geologic investigation—A case study from Srinagar Hydel Project, Garhwal, UP. J Ind. Soc. Remote Sensing 20(4), 199–205.

Jin Y, Yates MV, Thompson SS, Jury WA (1997) Sorption of viruses during flow through saturated sand columns. Environ. Sci. Tech. 31(2), 548–555.

Kaur R, Kendall T (2008) Myth of power. Down To Earth 17(8), 28–32.

Kelman I (2003) Defining Flood Risk. FloodRiskNet Newsletter, Issue 2, Winter 2003.

Kimothi PC, Dimri DD, Adlakha LK, Kumar S, Rawat OP, Patwal PS, Grischek T, Sandhu C, Ebermann J, Ruppert M, Dobhal R, Ronghang M, Kumar P, Mehrotra I, Uniyal HP (2012) Development of Riverbank Filtration in Uttarakhand. J. Indian Water Works Association, Special Issue on RBF, July–September, 13–18.

Kolehmainen RE, Kortelainen NM, Langwaldt JH, Puhkka JA (2009) Biodegradation of natural organic matter in long term, continuous flow experiments simulating artificial ground water recharge for drinking water production. Journal Environmental Quality 38(1), 44–52.

Kumar B, Nachiappan RP (1992) Study of stream-aquifer interaction along River Ganges between Hardwar and Narora using isotope techniques. Technical Report TR-150, National Institute of Hydrology, Roorkee, India.

Lawrence JR, Hendry MJ (1996) Transport of bacteria through geologic media. Canadian Journal of Microbiology 42(4), 410–422.

Lewis J, Sjöstrom J (2010) Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments. Journal of Contaminant Hydrology 115(1-4), 1–13.

Mahvi AH, Sheikhi R, Naddafi K (2003) Total coliforms and turbidity removal of water in the continuous sand filter. Iranian Journal Public Health 3(32), 7–13.

Marlow HJ, Duston KL, Wiesner MR, Tomson MR, Wilson JT, Ward CH (1991) Microbial transport through porous media: The transports of hydraulic conductivity and injection velocity. Journal of Hazardous Materials 28(1-2), 65–74.

Martin RE, Bouwer EJ, Hanna LM (1992) Application of clean-bed filtration theory to bacterial deposition in porous media. Environ. Sci. Technol. 26(5), 1053–1058.

Mauclaire L, Schürmann A, Thullner M, Zeyer J (2004) Sand filtration in a water treatment plant: biological parameters responsible for clogging. Journal of Water Supply: Research and Technology—AQUA 2(53), 93–108.

Medema GJ, Juhàsz-Holterman MHA, Luijten JA (2000) Removal of micro-organisms by bank filtration in a gravel-sand soil. In: Jülich W, Schubert J. (eds.) Proc. Int. Riverbank Filtration Conference, Düsseldorf, 2-4 November 2000, 161–168. ISBN 90-707671-27-1.

Murphy EM, Ginn TR (2000) Modelling microbial processes in porous media. Hydrogeology Journal 8(1), 142–158.

Naik SR, Aggarwal R, Salunke PN, Mehrotra NN (1992) A large waterborne viral hepatitis E epidemic in Kanpur, India. Bull. of the World Health Organization 70(5), 597–604.

NHMRC (2011) Australian drinking water guidelines Paper 6 National Water Quality Management Strategy. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

NIH (2013) Hydrogeological evaluation of bank filtration case study site Haridwar: water quality, isotope and flood analysis. Report, National Institute of Hydrology (NIH) Roorkee, Ground Water Hydrology Division, Roorkee 247 667, Uttarakhand, India.

NRMMC–EPHC–AHMC (2006) Australian guidelines for water recycling (Phase 1): Managing Health and Environmental Risks, Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and Australian Health Ministers’ Conference, Canberra.

Oliviera BI, Demond AH, Salehzadeh A (1996) Packing of sands for the production of homogeneous porous media. Soil Science Society of America Journal 60(1), 49–53.

Pekdeger A, Matthess G (1983) Factors of bacteria and virus transport in groundwater. Environmental Geology 5(2), 49–52.

Powelson DK, Mills AL (2001) Transport of Escherichia coli in sand columns with constant and changing water contents. Journal of Environmental Quality 30(1), 238–245.

Rai SP, Kumar Bhishm, Singh Pratap (2009) Estimation of Contribution of South-West monsoon rain in Bhagirathi River near Gomukh, Western Himalayas, India, using stable isotope (δ18O). Current Science 97(2), 240–245.

Rambags F, Raat KJ, Leunk I, van den Berg GA (2011) Flood proof wells: Guidelines for the design and operation of water abstraction wells in areas at risk of flooding. PREPARED project report 2011.007, deliverable number 5.2.1.

Ronghang M, Sandhu C, Grischek T, Kumar P, Mehrotra I, Voltz TJ, Kimothi PC, Adlakha LK, Dobhal R, Rawat OP, Patwal PS (2011) Development of Riverbank Filtration in Hill Regions for Sustainable Solution for Quality and Quantity Problems of Drinking

Water in Uttarakhand. Intermediate Project Report: March 2010 – December 2011, funded by "Water Technology Initiative" of the Department of Science and Technology, Government of India (DST-WTI).

Ronghang M, Kumar P, Mehrotra I (2013) Column Studies: Effect of flow rates on the quality and quantity of filtrated water. Report, Environmental Engineering Section, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667.

Saini B (2011) Water quality improvement during riverbank filtration at Haridwar. Master thesis, Environmental Engineering Section, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667.

Sakaguchi A, Nishimura T, Kato M (2005) The effect of entrapped air on the quasi-saturated soil hydraulic conductivity and comparison with the unsaturated hydraulic conductivity. Vadose Zone Journal 4(1), 139–144.

Sandhu C (2013) Ph. D. Thesis. in preparation, Dresden University of Technology, Institute of Waste Management and Contaminated Site Treatment, and Dresden University of Applied Sciences, Faculty of Civil Engineering / Architecture, Division of Water Sciences.

Sandhu C, Grischek T (2012) Riverbank filtration in India – using ecosystem services to safeguard human health. Water Sci. Tech. 12(6), 783–790.

Sandhu C, Grischek T, Kumar P, Ray C (2011) Potential for Riverbank filtration in India. Clean Techn Environ Policy 13(2), 295–316.

Sandhu C, Voltz T, Grischek T (2012) *Nutzung von Aufenthaltszeiten für die Erarbeitung eines Hochwasserschutzkonzeptes für Uferfiltratfassungen in Indien* (in German – "Use of residence times to develop flood safety concepts for bank filtration sites in India"). FH-DGG conference, Dresden, 16–20 May 2012.

Sandhu C, Voltz TJ, Ronghang M, Soares M, Grischek T, Macheleidt W (2013) Assessment of the risk of pathogen breakthrough during RBF on the basis of column experiments in specific context to floods. Report, Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany.

Schijven J (2002) Virus removal by soil passage at field scale and groundwater protection. In: Ray C (ed.) (2002) Riverbank Filtration: Understanding Contaminant Biogeochemistry and Pathogen Removal. NATO Science Series 4: Earth and Environmental Sciences – Vol. 14. Kluwer Academic Publishers, The Netherlands, 55–84. ISBN 1-4020-0954-2.

Schijven J, Berger P, Miettinen I (2002) Removal of pathogens, surrogates, indicators, and toxins using riverbank filtration. Ray et al. (eds), Riverbank Filtration, Kluwer Academic Publishers, The Netherlands, 73–116.

Schubert J (2000) *Entfernung von Schwebstoffen und Mikroorganismen sowie Verminderung der Mutagenität bei der Uferfiltration* (In German – "Removal of particles and microorganisms and reduction of mutagenicity during bank filtration"). gwf Wasser Abwasser 141(4), 218–225.

Sentenac P, Lynch RJ, Bolton MD (2001) Measurement of a side-wall boundary effect in soil columns using fibre-optics sensing. International Journal of Physical Modelling in Geotechnics 4, 35–41.

Sharma MM, Chang YI, Yen TF (1985) Reversible and irreversible surface charge modification of bacteria for facilitating transport through porous media. Colloids and Surfaces 16(2), 193–206.

Simon R, Colon D, Tebes-Stevens CL, Weber EJ (2000) Effect of redox zonation on the reductive transformation of p-cyanonitrobenzene in a laboratory sediment column. Environ. Sci. Technol. 34(17), 3617–3622.

Smith MS, Thomas GW, White RE, Ritonga D (1985) Transport of Escherichia coli through intact and disturbed columns. Journal of Environmental Quality. 14(1), 87–91.

Soares M (2011) Recovery of infiltration rates in columns filled with different media and using Elbe river water after a drought period and type of clogging. Internal report, Division of water Sciences, University of Applied Sciences Dresden, Germany.

Stevik TK, Ausland G, Hanssen J (2004) Retention and removal of pathogenic bacteria in wastewater percolating through porous media: a review. Water Research 38(6), 1355–1367.

Sundriyal YP, Tripathi JK, Sati SP, Rawat GS, Srivastava P (2007) Landslide-dammed lakes in the Alaknanda Basin, Lesser Himalaya: Causes and implications. Curr. Sci. 93(4), 568–574.

Swain SK, Baral P, Hutin YJ, Rao TV, Murhekar M, Gupte MD (2010) A hepatitis E outbreak caused by a temporary interruption in a municipal water treatment system, Baripada, Orissa, India, 2004. Trans. of the Royal Soc. of Tropical Medicine and Hygiene 104(1), 66–69.

Syngouna VI, Chrysikopoulos CV (2012) Transport of biocolloids in water saturated columns packed with sand: Effect of grain size and pore water velocity. Journal of contaminant hydrology (special issue - Sorption and Transport Processes Affecting the Fate of Environmental Pollutants in the Subsurface) 129-130, 11–24.

Tien C, Turian RM, Pendse H (1979) Simulation of the dynamic behaviour of deep bed filters. American Institute of Chemical Engineers 25, 385–395.

UJS (2012) Verbal communication. Executive Engineer for drinking water supply to Haridwar, Uttarakhand State Water Supply & Sewerage Organisation – *Uttarakhand Jal Sansthan* (UJS), Haridwar.

Vatn J (2008) Introduction to risk analysis. In: Røstum J, November V, Vatn J (eds.) COST Action C19 – Proactive Crisis Management of Urban Infrastructure. Publ. European Science Foundation, COST Office, and SINTEF Byggforrsk. ISBN 978-82-536-1003-0.

Wett B, Jarosch H, Ingerle K (2002) Flood induced infiltration affecting a bank filtrate well at the River Enns, Austria. J. Hydrol. 266(3-4), 222–234.

Worch E, Grischek T, Börnick H, Eppinger P (2002) Laboratory tests for simulating attenuation processes of aromatic amines in riverbank filtration. J. Hydrol. 266(3-4), 259–268.

World Health Organization (WHO) (2011) Guidelines for drinking-water quality: Volume 1 Recommendations 3rd ed. World Health Organization, Geneva.

Yao K, Habibian MT, O'Melia CR (1971) Water and wastewater filtration: concepts and applications. Environ. Sci. .Technol. 5(11), 1105–1112.

Zlotnik VA, Eisenhauer DE, Schlautman DJ, Zurbuchen BR, Van Peursem D (2007) Entrapped air effects on dipole flow test in sand tank experiments: Hydraulic conductivity and head distribution. J. Hydrol. 339(3-4), 193–205.

Annexes

Annex 1 Some incidences of waterborne disease outbreaks in India and their reported cause (Sandhu 2013)

Location (district, state) [reference]	Reporting period	No. of reported cases	Clinical diagnosis (no. of positive cases of detected pathogens)	Reported cause of outbreak
Lalpur (Jamnagar, Gujarat) [a]	12/2010 – 01/2011	330	Gastroenteritis (+ Vibrio Cholerae: 19 cases)	Ten leakages in drinking water supply network
Rural area in Sundarban block (West Bengal) [b]	End 05/2009	1076	Diarrhoea (+ Vibrio Cholerae: 2 cases)	Piped water and stored drinking water samples were positive for faecal contamination
South Dumdum municipality (Kolkatta, West Bengal) [c]	02 – 05/2007	103 (suspected)	Typhoid [+Salmonella (enterica) Typhi: 1 of 4 cases were positive]	Intermittent supply of non-chlorinated water in pipe adjacent to open drain connected with sewerage system. Positive faecal contamination in water.
Hyderabad (Andhra Pradesh) [d]	03 – 12/2005	1611	Viral Hepatitis (HEV)	Significantly high attack rate where water supply pipes crossed open drains. Crossing water pipe-lines were repaired & attack rates declined.
Baripada (Orissa) [e]	01 – 03/2004	538	Viral Hepatitis (+IgM antibodies to HEV: 47 out of 48)	Untreated water originating from river supplied in pipes (due to strike of waterworks employees)
Gokulpuri (New Delhi) [f]	01/2000 – 03/2003	141	Viral Hepatitis (+HEV: 41)	Faecal contamination of piped drinking water
Chennai [h]	10/1992	~9000	Gastroenteritis (+Rotavirus: 7)	Cross-contamination of water in a corroded water distribution system with sewers, and surface run-off during the monsoon from overflowing cesspools.
Kanpur (Uttar Pradesh) [i]	12/1990 – 04/1991	790091 (estimate)	Viral Hepatitis (HEV)	The incidence of hepatitis was higher in those city wards that were supplied with drinking-water consisting of a mixture of surface water (directly abstracted from Ganga) and groundwater, than in those wards supplied only with groundwater. The first peak was probably caused by faecal contamination of river water, indicated by water analysis data, and the second, by inadequate chlorination of water in a reservoir. There was no evidence of secondary intrafamilial spread.

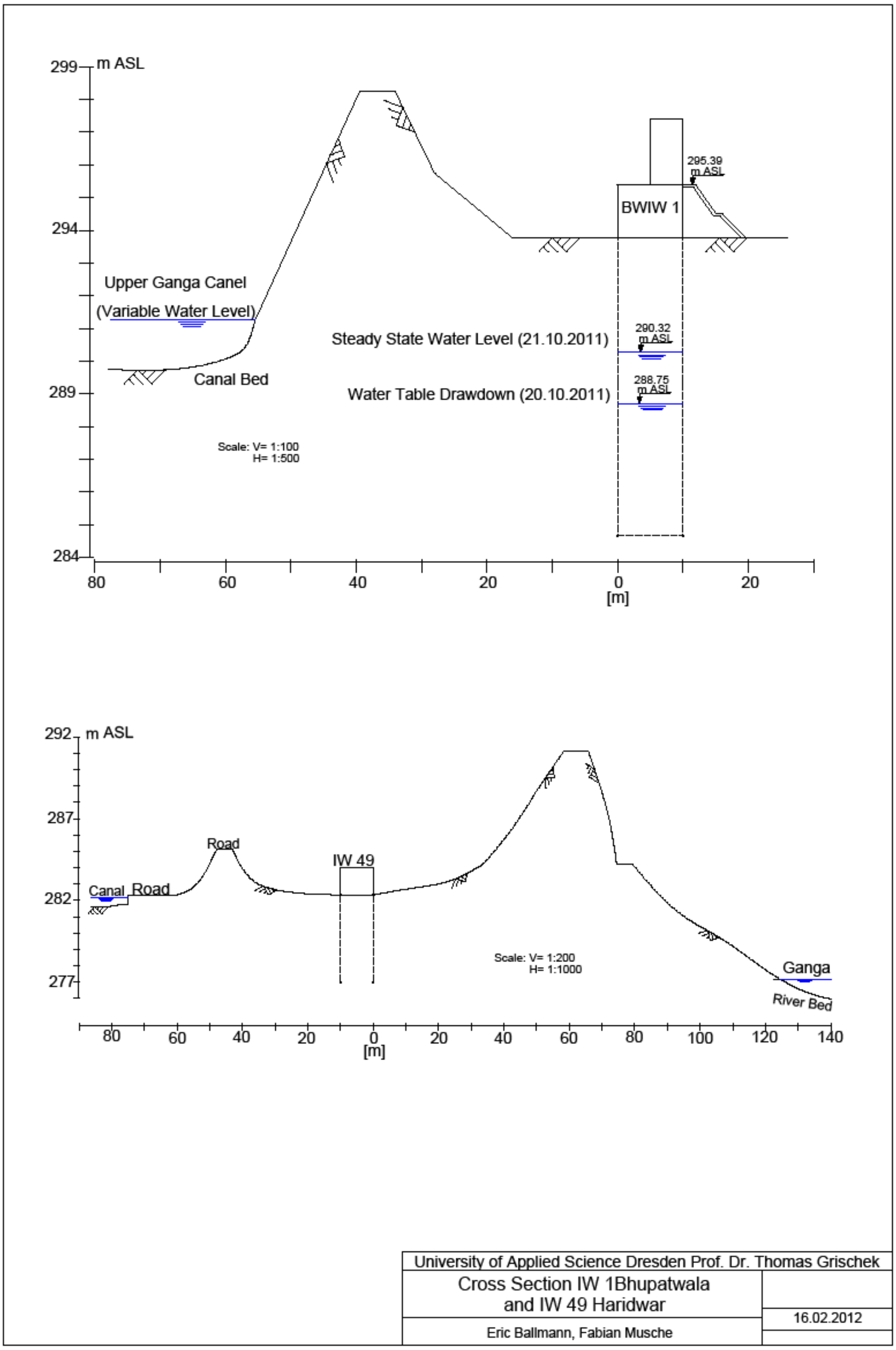
[a] Shah et al. (2012); [b] Bhunia & Ghosh (2011); [c] Bhunia et al. (2009); [d] Sailaja et al. (2009); [e] Swain et al. (2010); [f] Hazam et al. (2010); [h] Jothikumar et al. (1994); [i] Naik et al. (1992)

Annex 2 Points (encircled) where sections of drinking water pipes (across a seasonal stream) have been washed away as a result of a flood due to an extreme rainfall event during the monsoon in Haridwar and subsequent repair (lower row) (Photos: Subodh Kumar, Uttarakhand Jal Sansthan (14 – 18 August 2007)).

Annex 3 Well locations, ID and distance of the wells from the centre of the river Ganga and the Upper Ganga Canal (NIH 2013)

Location	RBF well identification number	Distance from river (m)	Distance from canal (m)	Width (m) GR-Ganga River; UGC-Upper Ganga Canal	River/canal boundary
North of New Supply Canal (NSC)					
Bhupatwala	IW31	102	-	GR: 107.4	GR (left side)
	IW27	238	-	GR: 67	GR (left side)
	IW4	239	-	GR: 102	GR (left side)
	IW3	333	-	GR: 311	GR (left side)
	IW2	139	-	GR: 239	GR (left side)
Sarvanand Ghat	IW1	315	102	GR: 266, UGC: 49	GR and UGC (left side)
	IW26	-	95	UGC: 80	UGC (left side)
	IW16	-	95	UGC: 75.4	UGC (left side)
Pantdweep	PDIW2	693	195	GR: 459, UGC: 103	UGC (right side) and GR (left side)
	IW40	985	50	GR: 796 UGC: 59	UGC (right side) and GR (left side)
	PDIW1	982	51	GR: 837, UGC: 54	UGC (right side) and GR (left side)
	IW18	743	288	GR: 868, Link Canal: 67	UGC (right side), Link canal (left side) and GR (left side)
South of New Supply Canal(NSC)					
Rodibewala	IW25	533	421	GR: 263, UGC: 147	UGC (right side) and GR (left side)
	IW24	586	491	GR: 255, UGC: 155	UGC (right side) and GR (left side)
	IW43	683	461	GR: 258, UGC: 150	UGC (right side) and GR (left side)
	IW42	672	464	GR: 264, UGC: 150	UGC (right side) and GR (left side)
	IW44	910	107	GR: 295, UGC: 137	UGC (right side) and GR (left side)
Near Alaknanda Hotel	IW17	1210	72	GR: 657, UGC: 133	UGC (right side) and GR (left side)
	IW21	545	110	GR: 257, UGC: 161	UGC (right side) and GR (left side)
Bairagi Camp	IW49	368	96	GR: 330, UGC: 70	UGC (right side) and GR (left side)
	IW29	371	83	GR: 241, UGC: 44	UGC (right side) and GR (left side)
	IW28	-	61 and 475	UGC1: 44, UGC2: 241	UGC both sides.

Annex 4 Cross-sections of flood embankment between Ganga River and RBF wells IW1 in Bhopatwala (top) and IW49 (bottom) in Haridwar (HTWD and UJS 2012b)



Annex 5 Analytical methods and equipment used for water quality analysis (NIH 2013)

S. No.	Parameter	Method	Equipment
A	**Physico-chemical**		
1.	pH	Electrometric	pH Meter
2.	Conductivity	Electrometric	Conductivity Meter
3.	TDS	Electrometric	Conductivity/TDS Meter
4.	Turbidity	Turbidimetric	Turbidity Meter
5.	Alkalinity	Titration by H_2SO_4	-
6.	Hardness	Titration by EDTA	-
7.	Chloride	Titration by $AgNO_3$	-
8.	Sulphate	Turbidimetric	Turbidity Meter
9.	Nitrate	Ultraviolet screening	UV-VIS Spectrophotometer
10.	Sodium	Flame emission	Flame Photometer
11.	Potassium	Flame emission	Flame Photometer
12.	Calcium	Titration by EDTA	-
13.	Magnesium	Titration by EDTA	-
14.	BOD	5 days incubation at 20°C	BOD Incubator
15.	COD	Digestion followed by titration	COD Digestor
B	**Bacteriological**		
16.	Total coliform	Membrane Filtration (MF) technique	Filtration Assembly, Bacteriological Incubator
17.	Faecal coliform		
C	**Heavy Metals**		
18.	Iron	Atomic Spectrometry	Atomic Absorption Spectrometer
19.	Manganese		

Annex 6 Range of values of analyzed water quality parameters for the Haridwar site during monsoon months (August – October, 2012) (NIH 2013)

Location	Source	Temp.	pH	EC	TDS	Turbidity	Alk	Hard	Na	K	Ca	Mg	HCO3	Cl	SO4	NO3	BOD	Fe	Mn	Total Coliform	Faecal Coliform
		°C		mS/cm	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	MPN	MPN
IW-31	Saptrishi	27.3-32.6	6.8-7.1	472-542	302-347	0.94-3.21	226-244	201-240	19-31	0.38-5.7	37-60	19-28	276-298	6.4-12	12-14	13-18	0.5-1.6	0.74-1.592	0.002-0.025	9-240	9-240
IW-27	Bhupatwala	27.3-32.9	6.6-6.9	513-728	328-466	1.12-5.1	210-292	216-286	27-37	0.5-5.3	47-65	23-30	256-356	8.8-16	20-28	13-26	0.1-2.9	0.008-0.537	0.014-0.62	240-2400	240-2400
IW-4	Bhupatwala	27.1-30.9	6.7-6.9	533-802	341-513	1.29-3.72	208-240	226-246	35-47	0.6-5.6	54-59	21-25	254-293	16-31	29-37	7.5-11	0.2-3.3	0.054-0.13	0.005-0.074	21-2400	21-2400
IW-3	Bhupatwala	27.1-29	6.6-6.9	495-671	317-429	1.76-6.23	221-240	213-252	12-16	0.7-7.1	46-58	24-26	270-293	6.0-14.0	11-15	11-12	1.6-6.6	0.19-0.329	0.01-0.041	-	-
IW-2	Bhupatwala	27-32.9	6.8-7.2	342-508	219-325	1.0-3.37	182-226	180-235	15-27	0.7-9.9	35-48	19-28	222-276	4.0-8.0	20-27	11-18	0.1-2.4	0.03-0.697	0.012-0.034	2400-2400	2400-2400
IW-1	Bhupatwala	27.1-32.7	6.8-7.1	451-554	289-355	1.0-4.43	181-232	192-210	20-36	0.5-5.6	44-66	11-22	221-283	4.5-10.0	21-25	6.5-8	0.1-3.3	0.02-2.205	0.01-0.06	4.0-2400	4.0-2400
IW-26	Sarwanand Ghat	27-32.7	6.5-6.9	560-644	358-412	1.27-4.27	240-290	242-293	23-36	1.4-6.7	41-81	22-34	293-354	12-15	22-26	11-13	0.2-1.7	0.023-0.2	0.049-0.222	21.0-2400	21.0-2400
IW-16	Sarwanand Ghat	27-32.7	6.5-6.9	464-719	297-460	2.08-4.44	204-301	189-288	31-41	0.6-6.2	38-76	19-24	249-367	11-22	18-27	6.9-10	0.5-1.3	0.096-0.28	0.03-0.314	2400-2400	2400-2400
IW-2	Pantdweep	26.9-32.5	6.7-7.2	455-614	291-393	1.32-4.7	160-242	185-276	11-35	0.5-9.4	38-48	21-38	195-295	5.3-8.0	17-42	5.7-38	1.0-3.7	0.121-0.589	0.045-0.16	240-2400	240-2400
IW-40	Pantdweep	27.3-32.8	6.6-7.0	399-507	255-324	1.03-2.62	184-224	165-240	20-30	0.8-7.2	50-58	5.0-28	224-273	6.2-12	22-25	5.9-8.9	0.1-2.9	0.003-0.171	0.01-0.117	-	-
IW-1	Pantdweep	26.9-32.6	6.8-7.3	358-540	229-346	1.3-3.52	166-180	160-186	21-29	0.7-6.8	41-45	14-18	203-220	5.3-10	18-30	1.0-13.0	0.1-2.1	0.356-0.388	0.293-0.454	43-460	43-460
IW-18	Pantdweep	27.4-32.7	6.9-7.1	479-530	307-339	1.01-2.88	200-235	154-248	19-52	0.8-7.6	52-69	6.0-21.0	244-287	8 - 11	22-24	18-26	0.6-3.3	0.032-0.182	0.027-0.127	-	-
IW-25	Rodibelwala	27.2-32.4	7.1-7.3	283-378	181-242	1.24-7.17	112-136	114-170	17-21	0.7-5.6	26-40	12.0-17.0	137-166	5.1 - 8	22-26	10.0-24.0	0.5-1.6	0.033-6.152	0.027-0.027	2400-2400	2400-2400
IW-24	Rodibelwala	27.5-32.7	7.1-7.6	263-385	168-246	1.01-4.08	102-115	110-137	14-25	0.6-4.8	31-35	8.0-12.0	124-140	3.8-6	20-23	11.0-17.0	0.5-2.9	0.01-0.642	0.003-0.017	23-43	23-43
IW-43	Van Samadhi	27.2-32.8	7.2-7.4	286-396	183-253	1.22-6.67	116-142	119-168	6.0-21.0	0.28-6.9	32-43	6.0-19.0	142-173	4 - 6	22-26	7.1-15	0.5-4.5	0.048-0.188	0.007-0.402	2400-2400	2400-2400
IW-42	Van Samadhi	27-32.8	7.2-7.5	261-423	167-271	1.12-5.7	110-170	118-161	15-31	0.6-8.2	31-43	10.0-13.0	134-207	3.3-7	19-23	9.0-19.0	0.1-1.6	0.341-0.379	0.002-0.008	15-2400	15-2400
IW-44	Vishnu Ghat	27.2-	7.1-	226-	145-	0.96-3.6	94-	95-	17-	0.7-5	22-	8.0-	115-	4.3-	16-	11.0-	0.5-	0.092-	0.005-	23-23	23-23

		32.5	7.4	272	174		100	108	22		26	11.0	122	6.7	19	20.0	2.0	0.397	0.007		
IW-17	Laltarapul	27.4-32.6	7.1-7.5	252-342	161-219	1.14-9.0	96-116	100-126	15-21	0.4-3.8	28-37	6.0-13.0	117-142	3.7-8	17-20	7.7-19	0.2-2.1	0.012-1.18	0.001-0.76	9.0-2400	9.0-2400
IW-21	Alaknanda	27-32.6	6.9-7.4	206-305	132-195	1.27-2.95	88-126	90-146	13-15	0.3-4.1	28-32	5.0-16.0	107-154	2.0-6.0	15-19	5.5-9.5	0.2-1.3	0.128-0.26	0.013-0.029	2400-2400	2400-2400
IW-49	Bairagi Camp	27-32.8	7.1-7.6	304-465	195-298	0.92-4.37	126-192	139-195	14-24	0.4-5.0	38-50	9.0-17.0	154-234	2.0-4.0	16-24	8.1-45	0.8-3.3	0.041-0.281	0.01-0.038	240-1100	240-1100
IW-29	Bairagi Camp	27-32.5	7.2-7.4	268-292	172-187	1.03-3.13	112-122	114-130	17-21	0.5-4.5	25-34	7.0-15.0	137-149	2.2-6.0	17-24	7.1-8.3	0.9-2.1	0.033-1.013	0.01-0.01	23-2400	23-2400
IW-28	Mahila Milan	27-32.4	7.2-7.3	268-362	172-232	1.23-3.4	116-130	112-139	10.0-22.0	0.3-6.0	35-41	6.0-12.0	142-159	2.0-11.0	15.9-20	4.9-9.9	0.6-2.9	0.007-0.555	0.026-0.07	4.0-23	4.0-23
OW-15	Jawalapur, (GW)	26.9-28.9	6.7-6.9	623-739	399-473	1.15-4.2	160-160	221-228	24-27	1.5-2.4	54-55	21-22	195-195	30-32	41-48	21-23	0.2-0.8	0.022-0.022	0-0	-	-
OW34	Jawalapur, (GW)	27-33.1	6.7-6.9	660-794	422-508	0.8-24	221-284	261-300	42-61	0.4-3.3	57-84	22-30	270-346	22-32	30-35	45-60	0.4-2.1	0.004-0.012	0.003-0.003	-	-
R-1	UGC Sample	27.5-33.2	7.3-7.9	140-257	90-164	44-147	52-60	83-91	6.0-13.0	0.4-3.6	19-22	7.7-10	63-73	2.0-3.0	32-41	3.4-3.6	0.6-2.8	1.174-5.4	0.029-0.274	2400-2400	2400-2400
R-3	River Sample	27.3-33.1	7.4-7.8	146-348	93-223	14-346	62-94	76-115	4.8-16	0.3-6.0	24-31	4.0-10.0	76-115	2.0-3.0	20-38	3.1-4.3	1.0-4.1	0.097-6.896	0.029-0.632	2400-2400	2400-2400
R-5	UGC Sample	27.2-33.2	7.6-7.9	134-219	86-140	40-440	52-64	60-65	6.0-15.0	0.3-5.1	17-19	3.0-4.9	63-78	2.0-2.4	14-24	3.2-4.4	0.9-3.3	0.328-7.024	0.036-0.267	2400-2400	2400-2400
R-6	River Sample	27.3-33.1	7.6-8.0	174-228	111-146	38.7-116	60-64	58-80	5.1-16	0.3-2.5	14-22	5.7-6.7	73-78	2.0-2.2	19-24	3.4-4.4	1.0-2.1	0.021-12.339	0.001-0.313	2400-2400	2400-2400
OW-1	Kabir Ashram (GW)	27.2-33.1	6.6-6.8	1240-1554	794-995	1.85-48.1	470-564	517-590	58-95	1.1-9.8	110-159	34-64	576-688	42-50	44-61	71-137	0.1-0.8	0.052-3.994	0.253-0.714	2400-2400	2400-2400

Annex 7 Range of values of analyzed water quality parameters for the Haridwar site during non-monsoon months (May-June and November-February, 2012) (NIH 2013)

Location	Source	Temp.	pH	EC	TDS	Turbidity	Alk	Hard	Na	K	Ca	Mg	HCO3	Cl	SO4	NO3	BOD	Fe	Mn	Total Coliform	Fecal Coliform
		°C		mS/cm	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	MPN	MPN
IW-31	Saptrishi	10.3-35.2	6.9-7.48	445-544	284-348	0.76-8.1	210-246	202-266	16.56-24	2.78-17.5	33.7-62	18-28.7	256.2-300.1	7--16	12.5-20.7	10--18	0.9-2.2	0.013-0.357	0.013-0.357	4--2400	75-240
IW-27	Bhupatwala	10.6-35.3	5.4-7.6	521-686	333-439	0.8-2.1	154-310	162-321	17.95-31	3.29-8	40-80	15-29	188-378	12--26	12.5-26	7.5-29.2	0.1-3.8	0.015-1.716	0.004-0.035	150-240	43-240
IW-4	Bhupatwala	10.6-35.3	6.8-7.51	660-748	422-479	0.88-2.92	292-322	294-340	21.36-36	3.21-12.9	44.9-90.6	23-44.2	356-393	18-44	25-42	8.3-23	0.1-2.3	0.01-2.79	0.005-0.231	3--2400	3--2400
IW-3	Bhupatwala	10.5-35.2	6.8-7.25	80-808	51-517	0.85-3.9	302-376	190-400	22.4-37	0.7-7.4	47-106	18-44	368-459	11--28	24-40	11--22	0.5-5.9	0.021-0.8	0.026-0.179	150-1100	43-460
IW-2	Bhupatwala	10.3-35.2	6.08-7.57	291-453	186-290	0.69-2.75	146-220	140-223	5.79-13	1.4-8.3	35.3-63	8.7-16.5	178-268	2--14	19-23	4--23	0.1-2.9	0.011-4.2	0.012-0.345	210-2400	3--15
IW-1	Bhupatwala	10.9-35.2	7.1-7.44	369-529	236-339	1.16-3.88	162-250	174-267	11.1-20	4.2-10.2	28.1-66	22-30	198-305	7--28	20-28	5.3-13	0.7-4.5	0.011-0.192	0.052-0.149	4-210	4--75
IW-26	Sarwanand Ghat	10.4-35.2	6.8-7.34	448-684	286-438	0.86-14.4	212-290	194-300	19.3-32	5.05-6.9	23.3-84	18-43.3	259-354	10--24	21-33	5.4-14	0.7-4.6	0.054-1.068	0.144-0.67	21-2400	21-2400
IW-16	Sarwanand Ghat	10.4-35.2	6.75-7.37	523-761	335-487	1-6.8	236-336	238-351	22.5-37	5.4-8.9	20-93	25-51	288-410	12--30	18.5-31	7.1-13	0.1-5	0.044-0.638	0.108-0.584	93-2400	20-2400
IW-2	Pantdweep	10.8-35.2	6.96-7.59	479-588	307-376	0.87-3.62	224-260	212-298	11.1-23	4.1-7.2	29-75	20.4-34	273-317	11--22	24.5-38	1.4-15	0.1-7.3	0.005-0.61	0.035-0.248	3-240	3-240
IW-40	Pantdweep	10.3-35.2	6.89-7.53	381-491	244-314	1-2.34	182-220	176-235	11.7-19	3.74-10.5	41.7-64	9.2-20.8	222-268	7--16	19-27	0.7-16.6	0.1-4.2	0.012-0.381	0.03-0.181	240-240	3-240
IW-1	Pantdweep	10.9-35.2	7.1-7.98	337-438	216-280	0.8-6	158-190	142-196	9.6-22.1	4.2-8.7	30.5-57	9.2-23.3	193-232	4.0-22	17-28	0.1-12	0.2-4.1	0.0-1.185	0.0-0.416	3--2400	3--2400
IW-18	Pantdweep	10.6-35.6	6.6-7.64	363-587	233-376	1.2-2.24	178-216	182-256	6.5-12	4.3-6.6	28.1-57	16-29.6	217-264	4.0-10	20-27	1.8-16	0.1-4.2	0.0-0.512	0.0-0.133	93-460	4-460
IW-25	Rodibelwala	10.5-35.2	7.4-7.86	243-313	156-200	0.8-5	104-140	108-160	5.1-9.4	3.3-9.8	28.1-56	5.0-14.1	127-171	3.0-12	18-26	2.0-17	0.5-1.4	0.0-3.261	0.0-0.07	28-2400	15-2400
IW-24	Rodibelwala	10.7-35.3	7.3-8.01	215-256	138-164	0.9-9.1	80-110	96-144	3.8-6.9	2.5-17.2	21.7-34	6.0-16	97.6-134	5.0-12	19-25	4.7-14	0.1-2.7	0.0-0.647	0.0-0.106	23-2400	23-1100
IW-43	Van Samadhi	10.7-35.2	7.3-8.2	213-311	136-199	1.3-31	70-125	90-141	4.5-8	2.5-8.1	17.6-40	9.2-14	85.4-153	3.0-14	15-25	4.4-12	0.2-2.5	0.0-0.702	0.0-0.405	43-460	43-93

IW-42	Van Samadhi	10.8-35.2	7.4-8.1	214-318	137-204	1.1-5.7	88-126	96-150	4.5-8.6	2.5-17.3	21.7-38	8.3-14	107.4-154	6.0-16	16-23	0.8-11	0.5-2.1	0.0-1.625	0.0-0.023	28-240	4--93
IW-44	Vishnu Ghat	10.5-35.2	7.3-8.1	186-215	119-137	1.3-1.9	82-110	94-136	3.2-6.1	2.1-13.2	21.7-40	7.3-13.0	100-134	2.0-10	16-25.2	1.6-11	0.1-3.7	0.0-0.6	0.0-0.1	240-240	23-23
IW-17	Laltarapul	10.8-35.2	7.2-8.0	204-313	131-200	0.8-2.9	86-140	94-164	5.2-9.0	2.8-17.7	22.5-40	6.3-17.5	105-171	1.0-14	17-25	3.7-22	0.1-1.0	0.0-0.4	0.0-0.1	4--2400	4--75
IW-21	Alaknanda	10.6-35.1	7.3-8.0	184-278	118-178	1.0-22	80-126	76-130	3.2-8.0	2.2-15.6	19.3-40.1	6.3-8.0	97.6-154	1.0-12.0	16.5-24	2.4-12	0.2-10.7	0.0-0.3	0.0-0.1	460-1100	150-460
IW-49	Bairagi Camp	10.8-35.3	7.3-8.2	213-287	136-184	1.2-1.9	98-122	82-150	3.7-12	2.2-19.8	24-42	5.4-13	120-149	5.0-16	12--24	1.2-27	0.1-4.2	0.0-2.5	0.0-0.1	28-1100	20-240
IW-29	Bairagi Camp	10.3-35.2	7.0-8.1	214-264	137-169	0.6-1.9	92-120	102-136	3.1-9.0	2.3-13.9	26-48	4.0-11.0	112-146	1.0-8.0	18.4-23	1.9-12	0.5-2.6	0.0-0.3	0.0-0.3	4 -7	4- 4
IW-28	Mahila Milan	10.4-35.3	7.5-8.0	200-282	128-181	0.9-4.0	84-120	86-129	4.4-7.1	3.6-13.6	23-37	6.8-110	102.5-146	1.0-10.0	16.0-23	3--11	0.1-2.5	0.0-0.7	0.0-0.3	240-1100	93-1100
R-1	UGC Sample	10.9-19.4	7-8.1	136-217	87-139	6.6-22.6	58-96	80-102	3.9-11	1.9-3.2	16-26	6.7-9.7	70.8-117	0.0-16	15.5-24.1	1.3-9.4	0.5-2.6	0.0-0.4	0.0-0.0	240-2400	150-1100
R-3	River Sample	10.7-35.4	7.5-8.5	172-515	110-330	2.3-56.5	70-230	86-243	4.9-11.6	1.6-15	17.6-71	10--25	85-281	0.0-14	20-46	1.4-12	0.2-3.7	0.0-1.5	0.0-0.1	28-2400	28-2400
R-5	UGC Sample	10.9-35.3	7.4-8.3	128-188	82-120	6.5-64	56-80	62-92	3.2-4.8	1.8-19	15-23	3.9-11	68-98	1.0-10	15.6-23	1.4-9.4	0.1-3.7	0.0-3.0	0.0-0.1	23-2400	23-1100
R-6	River Sample	10.9-23.9	7.9-8.3	133-209	85-134	1.9-39	42-74	60-92	3.2-5.4	1.8-3.3	18.5-24	3.4-9.0	51-90	2.0-18	13-22	3.3-9.1	0.1-2.3	0.0-2.3	0.0-0.5	2400-2400	150-2400
OW-1	Kabir Ashram (GW)	10.9-24	6.8-7.6	1112-1189	712-761	1.1-1.9	430-454	454-491	45-78	6.9-8.6	94.6-129	32.1-60.8	525-554	56-60	26-45	0.4-63	0.2-4.5	0.0-0.2	0.0-0.2	2400-2400	460-2400

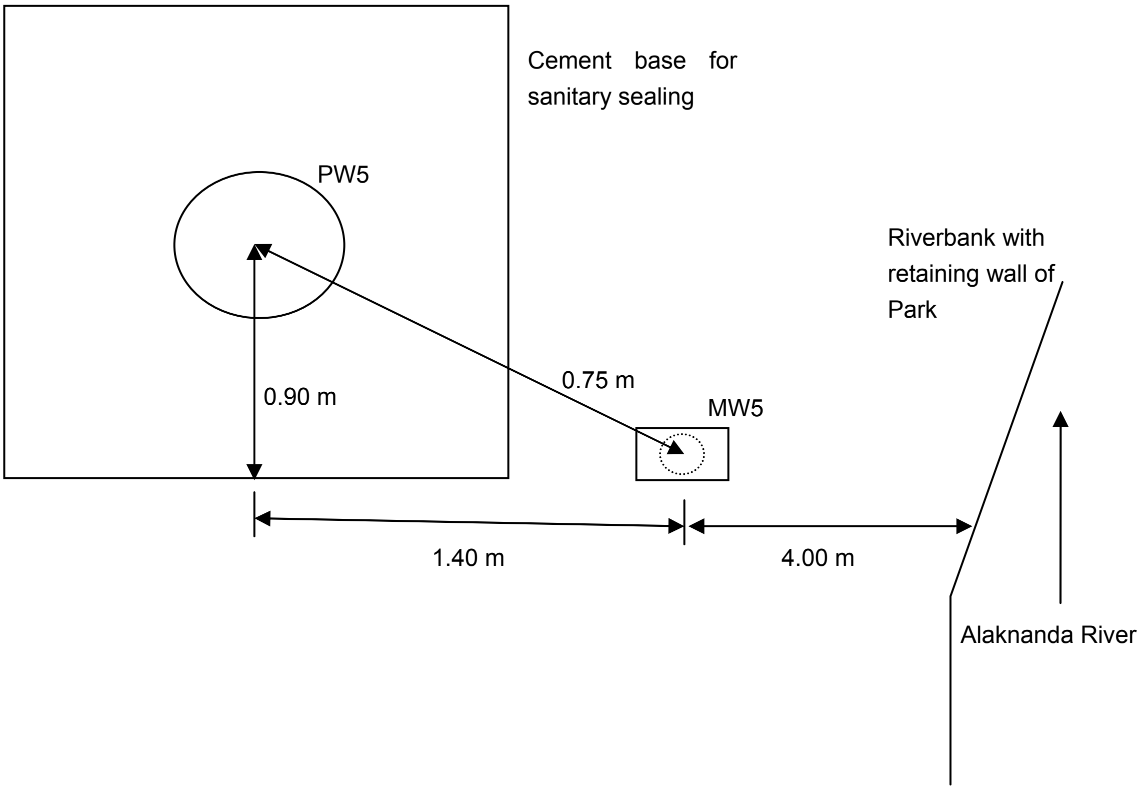
Annex 8 Sampling locations in Haridwar for water quality and isotopic analysis (NIH 2013)

Location	Well ID	Latitude (N)	Longitude (E)	Sampled water source
Bhupatwala	IW31	29.986983	78.196017	IW
	IW27	29.982867	78.191883	IW
	IW4	29.982200	78.191167	IW
	IW3	29.975100	78.184900	IW
	IW2	29.974317	78.186067	IW
Sarvanand Ghat	IW1	29.971567	78.182900	IW
	IW26	29.971233	78.180367	IW
	IW16	29.970983	78.178917	IW
Pantdweep	PDIW2	29.968167	78.177950	IW
	IW40	29.959667	78.174167	IW
	PDIW1	29.960800	78.173417	IW
	IW18	29.961150	78.175983	IW
Rodibelwala	IW25	29.951083	78.171200	IW
	IW24	29.950367	78.170467	IW
	IW43	29.949467	78.169317	IW
	IW42	29.949183	78.169000	IW
	IW44	29.950667	78.167183	IW
Near Alaknanda Hotel	IW17	29.947050	78.162667	IW
	IW21	29.944067	78.160183	IW
Near Bairagi Camp	IW49	29.940100	78.158183	IW
	IW29	29.938433	78.157733	IW
	IW28	29.939183	78.155000	IW
Kabir Ashram, Bhupatwala	OW1	29.974139	78.178389	OW
Jhanda Chowk, Jawalapur	OW2	29.923806	78.106694	OW
Firahediyan Jawalapur	OW3	29.926444	78.104778	OW
Ganga River	R3 near IW31			RW
Ganga River	R2 near IW2			RW
Ganga River	R6 near IW28			RW
UGC	R1 near IW40	29.959667	78.174167	CW
UGC	R4 near IW28	29.939183	78.155000	CW
UGC	R5 near IW29	29.938433	78.157733	CW

Annex 9 Range of values of isotopic composition determined from the samples collected from May 2012 to February 2013 (NIH 2013)

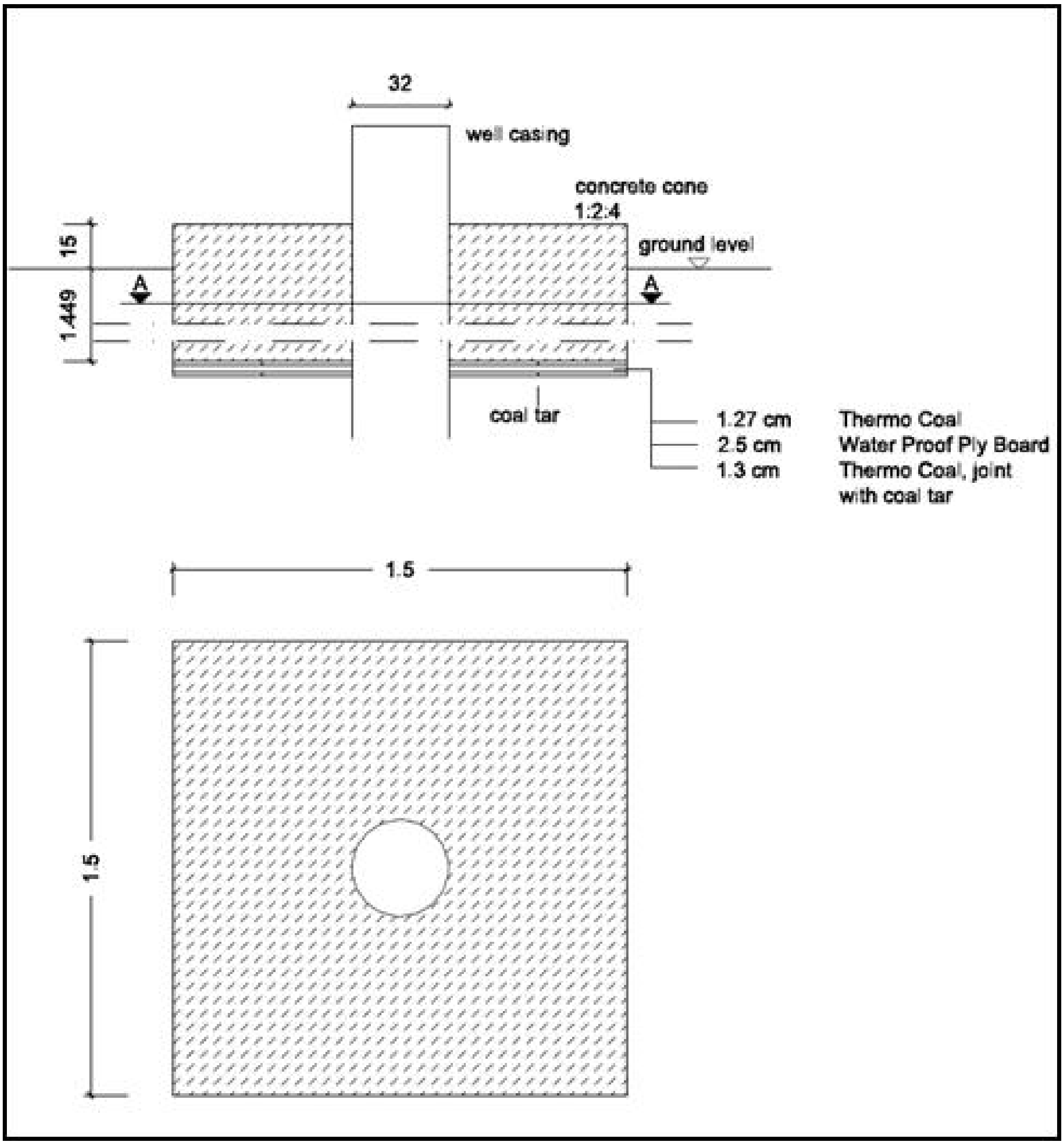
Location	Source water	$\delta^{18}O$	δD
Bhupatwala	IW31	-7.12 to -7.69	-49.12 to -51.2
	IW27	-7.14 to -8.04	-50.68 to -54.06
	IW4	-7.65 to -8.21	-52.39 to -62.59
	IW3	-7.80 to -9.11	-54.21 to -56.83
	IW2	-8.42 to -10.35	-61.40 to -74.50
	IW1	-9.06 to -10.19	-62.59 to -65.58
Sarvanand Ghat	IW26	-8.24 to -9.86	-57.20 to -64.62
	IW16	-8.08 to -9.02	-55.80 to -59.09
Pantdweep	PDIW-2	-8.81 to -10.13	-60.67 to -66.26
	IW40	-9.73 to -10.26	-65.41 to -68.45
	PDIW-1	-10.23 to -10.70	-68.14 to -72.09
	IW18	-9.26 to -10.76	-64.15 to -70.73
Rodibelawala	IW25	-10.39 to -10.73	-69.48 to -73.35
	IW24	-9.97 to -10.77	-67.66 to -73.86
	IW43	-10.22 to -10.92	-68.54 to -73.39
	IW42	-10.04 to -10.90	-67.93 to -72.12
	IW44	-10.36 to -10.98	-68.39 to -75.11
Alaknanda Hotel	IW17	-10.27 to -11.02	-68.40 to -74.14
	IW21	-10.48 to -11.15	-66.48 to -75.84
Bairagi Camp	IW49	-10.17 to -10.98	-66.96 to -75.35
	IW29	-10.55 to -11.34	-65.60 to -77.33
	IW28	-10.41 to -11.06	-66.48 to -75.84
Kabir Ashram, Bhupatwala	OW-1	-7.52 to -8.10	-52.93 to -56.44
Jhanda Chowk,Jawalapur	OW-2	-8.36 to -9.26	-57.21 to -61.72
Firahediyan, Jawalapur	OW-3	-8.34 to -8.90	-56.04 to -59.91

Annex 10 Site-map of new monitoring well (MW5) installed for production well PW5 at RBF site in Srinagar (AJD 2012)

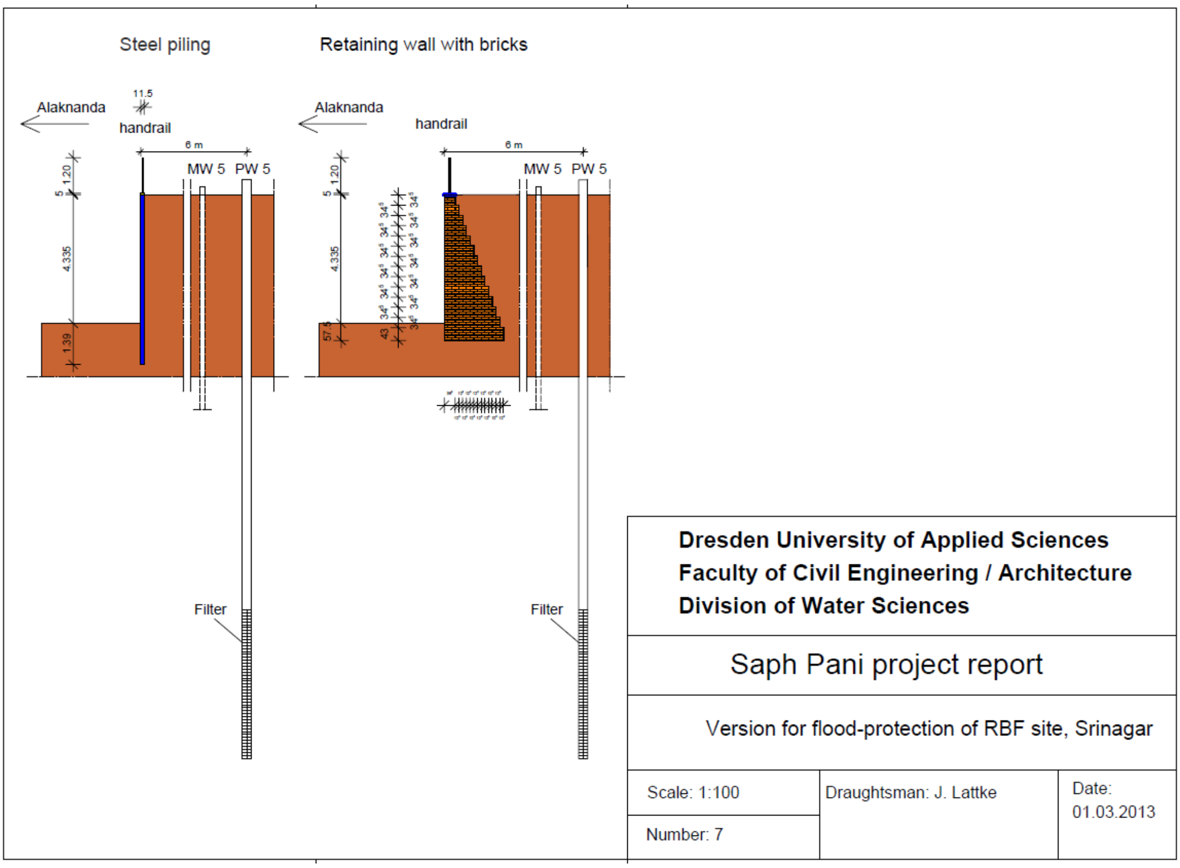


Annex 11 Column-apparatus to determine the breakthrough of coliforms under field conditions (Photos: C. Sandhu, HTWD, 2012)

Annex 12 Design of sanitary sealing for wells PW5 and MW5 at RBF site in Srinagar (HTWD and UJS 2012a)



Annex 13 Steel piling and retaining wall with bricks variants for flood proofing the embankment of the RBF site in Srinagar (HTWD and UJS 2013)



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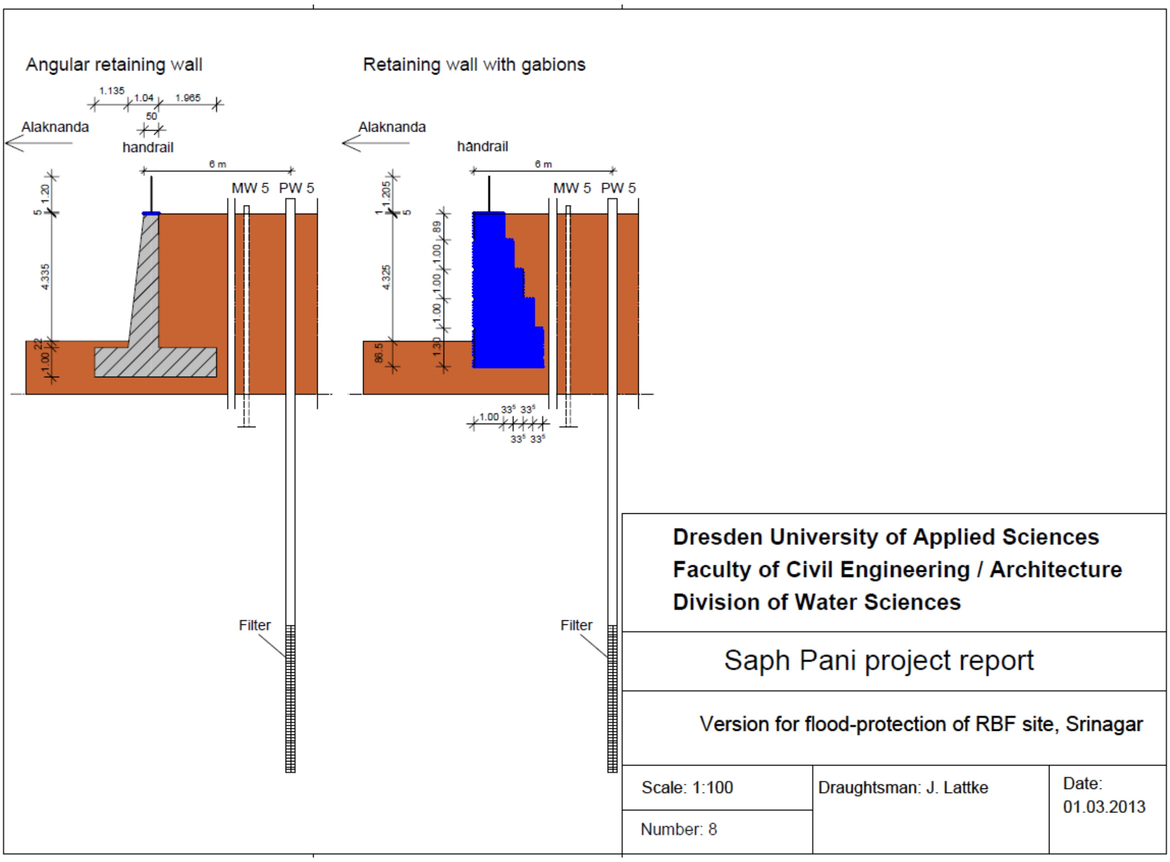
Annex 14 Angular and gabion retaining wall variants for flood proofing the embankment of the RBF site in Srinagar (HTWD and UJS 2013)



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Number: 8
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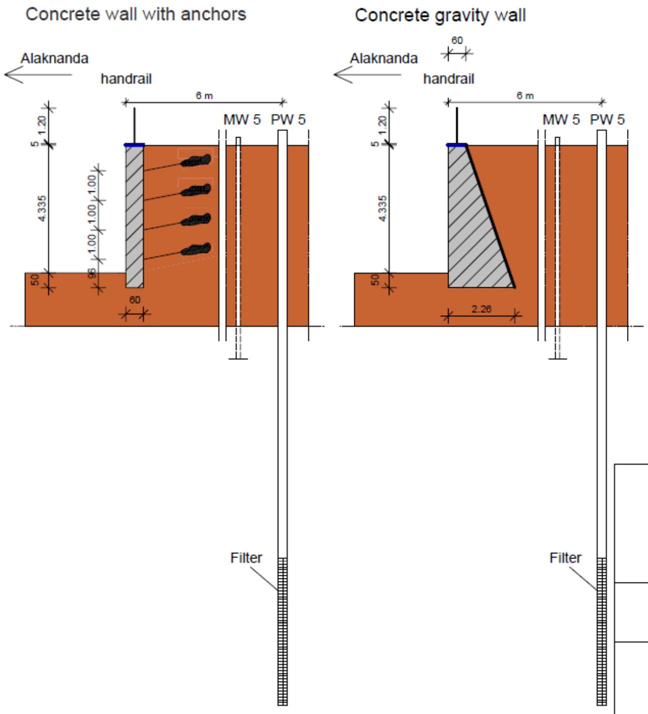
Annex 15 Concrete gravity wall and concrete wall with anchors variants for flood proofing the embankment of the RBF site in Srinagar (HTWD and UJS 2013)



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Version for flood-protection of RBF site, Srinagar

Scale: 1:100

Number: 9

Draughtsman: J. Lattke

Date:
01.03.2013