Chapter 2

Overview of bank filtration in India and the need for flood-proof RBF systems

Cornelius Sandhu, Thomas Grischek, Medalson Ronghang, Indu Mehrotra, Pradeep Kumar, Narayan C. Ghosh, Yellamelli Ramji Satyaji Rao, Biswajit Chakraborty, Pooran Patwal and Prakash C. Kimothi

2.1 INTRODUCTION

In some towns and cities in India, existing riverbank filtration (RBF), or simply bank filtration (BF), systems (mainly on rivers, but also at some lakes) currently serve as sustainable alternatives and supplements to existing surface water and groundwater sources for public water supply (Sandhu & Grischek, 2012). The application of BF has certain regionally specific advantages. For instance, most urban drinking water production systems in the hilly parts of the north Indian state of Uttarakhand, but also in other hilly regions of India, are typically supplied by directly abstracted surface water from springs, rivers and streams with a highly variable seasonal discharge. These surface water abstraction systems face two major recurring problems with respect to quantity and quality for drinking water production:

- In the pre-monsoon, especially the hot-dry summer season (March–May), the discharge of spring-fed streams and small rivers decreases considerably, thereby significantly reducing the quantity of drinking water produced and making such schemes drought-prone resulting in a drinking water production-deficit. During this period, the BF systems continue to operate sustainably by abstracting the sub-surface flow in the riverbeds, e.g. in Satpuli (Kimothi *et al*., 2012; Ronghang *et al*., 2012).
- During monsoon (June–September), the rapid sand filters used currently in the conventional drinking water treatment plants are unable to remove the turbidity from the raw water and the subsequent conventionally-applied disinfection by chlorination does not guarantee the elimination of pathogens. Furthermore, silting of water supply pipes and damage to water abstraction structures from surface water treatment plants is common, especially by floods due to washing away of abstraction pipes, structural damage, and inundation of pumps and electrical installations. As a result surface water abstraction and treatment plants are rendered inoperable with consequent interruptions in water supply from 2–3 days to a few weeks. This is a ubiquitous issue experienced in many regions in India. In comparison, investigations of various BF systems in India have demonstrated their efficiency in the pre-treatment of raw water for drinking and especially the removal of pathogens and turbidity during monsoon (Dash *et al*., 2008, 2010; Ronghang *et al*., 2012; Sandhu & Grischek, 2012; Saph Pani D1.1, 2012, D1.2, 2013; see also Chapter 3).

The first aim of this chapter is to elucidate the importance of BF systems for potable water supply in India as a sustainable alternative to the direct abstraction of surface water followed by conventional post-treatment. In this context, an overview of the hydrogeology, design and water quality of some BF systems in India is given. BF systems also have weak points, being vulnerability to breakthrough of pathogens and contamination to wells from floods. Thus, the second aim is to evaluate the risk from floods to BF systems using the example of Haridwar and Srinagar in Uttarakhand. An assessment of the removal of bacteriological indicators in the context of floods was conducted by column studies under laboratory and field conditions and from field data collected from some RBF sites.

2.2 OVERVIEW OF BANK FILTRATION SYSTEMS IN INDIA

2.2.1 Summary of design-parameters of bank filtration systems in India

Data-collection field surveys and scientific studies from 2005 onwards (as cited in Table 2.1) of sites of drinking water supply organisations in the states of Uttarakhand, Bihar, Jharkhand, Andhra Pradesh and Gujarat have revealed the presence of various BF systems (Figure 2.1). These systems are located in different hydro-climatic and -geological settings, whose features and suitability for BF are summarised in Table 2.2. Most BF sites are located in regions having a substantial vertical and horizontal extent of alluvium, most prominently in the Indo-Gangetic Plain (IGP) (Figure 2.1). However, some BF sites are also located in hilly, hard rock and coastal areas, such as in the states of Uttarakhand, Jharkhand and coastal Andhra Pradesh. In these areas the alluvium is mainly confined to the river course and nearby areas and is also of limited thickness (3–7 m in Jharkhand and up to 20 m in Uttarakhand).

The hydro-climatic variations range from arid and semi-arid in the northwest, west and central India, to humid in parts of the Himalayas (north), the northeast and coastal regions. Hence, due to the topography and tropical monsoon climate influencing the country, major temporal (seasonal) and spatial variations in rainfall occur which significantly influence the surface run-off regime of all rivers. Most rivers that have a significant year-round discharge and flow through the IGP from the Himalayas are glacier-fed. In addition, these rivers also receive water from solely spring-fed tributaries from the north and south from the central Indian highlands (Deccan Plateau and Peninsular India) with significant seasonal fluctuations in discharge. According to Kale (2003), the southwest summer monsoon accounts for >80% of the annual rainfall over a major part of the Indian region, whereas the southeastern part of the Indian Peninsula and the northwest Himalaya receive <60%. Consequently, the average monsoon flows tend to be at least 1–2 orders of magnitude more that in the non-monsoon season. This variability of river flows affects the availability (quantity and quality) of raw surface water for treatment plants producing drinking water, especially for larger towns and cities in the IGP where the terrain is levelled, gradients are low and significant volumes of partially-to-untreated industrial and domestic wastewater are discharged into the rivers (e.g. Delhi, Mathura, Agra, Kanpur). In comparison, the BF systems in Uttarakhand and the IGP (Figure 2.1 and Table 2.1) are able to abstract relatively constant volumes of water year-round.

On the other hand, south-north flowing spring-fed tributaries of the Ganga in south Bihar and Jharkhand and rivers originating in the central highlands flowing towards coastal Andhra Pradesh and Gujarat experience peak flows during monsoon and minimum flow (in some cases no flow) in the dry pre-monsoon period. As the rainfall over the northern part of the Indian Peninsula including the Deccan Plateau and south IGP is strongly concentrated in the monsoon season, the rivers in this part have a seasonal discharge related to the monsoon (Kale *et al.*, 1997) and the rivers are generally incised in rock or alluvium and have stable channels (Kale, 2003). One notable feature is that at the locations of the BF schemes by these rivers (Figure 2.1 and Table 2.1), the riverbeds consist of medium to coarse sand and gravel and thereby exhibit a suitable hydraulic conductivity for RBF. Due to this and similar to spring-fed rivers in Uttarakhand, most of these rivers have a substantial sub-surface flow in their beds even during the summer pre-monsoon, when no or only negligible flow is visible on the surface. This feature allows the RBF systems to operate during the relatively dry non-monsoon period also, albeit with lower discharges and reduced operating hours. Nevertheless, considering the predominant hard-rock geology of the region with limited alluvium confined to the riverbed, in nearby river areas and in the plains of northern Jharkhand, the existing BF schemes are suitable means for production of drinking water, and in some areas the only viable options to obtain water compared to direct surface water or even groundwater. In this context, BF buffers the quantity of water required through bank-/bed-storage and can thus be considered as an element of managed aquifer recharge and integrated water resources management.

It has been observed that most of the older BF systems constructed in India prior to 2000 (Table 2.1) have been designed primarily to fulfil the target of obtaining water of improved quality (compared to direct surface water abstraction) in sufficiently high volumes. Considering this and the local hydrogeological conditions, the wells of the BF systems have been accordingly designed. Typically these are classical vertical production wells, large-diameter caisson wells, radial collector wells (RCW) and one or more RCW with shorter radials at shallower depths connected to a single collector well (Figure 2.2a–d). Vertical wells have been constructed in relatively thick-layered homogeneous fine to medium alluvium (Table 2.1 and Figure 2.2a; sites built in 2010 in Uttarakhand, Nainital, Bhimtal, Patna, Gaya and Delhi).

Table 2.1 Summary of design parameters of bank filtration systems in India listed in ascending order of production capacity.

Location (State)	Source Water Body	Well Type (Number of Wells)	Production Capacity [m³/d]	Depth [m]	Distance from Source Water [m]	Travel-time of Bank Filtrate	References
Muzaffar Nagar* (UP)	Kali	VFW (1)	29–300	8–15	68	n.d.	*a*
Dandeli (KA)**	Kali	VFW	55–220	20–23.7	52	~9 days	*b*
Dehradun, Sahaspur (UK)	Swarna	RCW(s)	210–570	laterals 3–4 m beneath riverbed		>150 min	*c*
Ray Bazaar (JH)	Saphi Nadi (n.p.)	CW (1)	225	3–6	within riverbed	minutes–hours	*own data*
Agastmuni* (UK)**	Mandakini	VFW (1)	>280	30	33	n.d.	*c, d*
Bhimtal (UK)	Lake Bhimtal	VFW (1)	>320	48	16	n.d.	*c*
Karnaprayag* (UK)**	Alaknanda	VFW (1)	>700	20	53	n.d.	*c, d*
Satpuli* (UK)**	East Nayar	VFW (1)	756	26	43–45	2 days–2 weeks	*c, d, e*
Srinagar* (UK)**	Alaknanda	VFW (1)	852–937	18	170	>2 years	*own data, d*
Japla, Hussainabad (JH)	Son	RCW (1)	900	laterals 1 m beneath riverbed		minutes–hours	*own data*
Gumla (JH)	Nagpheri (n.p.)	CW (2)	>1,800 (max. 12,000)	3–6	within riverbed	minutes–hours	*own data*
Mathura (UP)	Yamuna	RCW (1)	2,400	laterals 15.5 & 18 m beneath riverbed		1.5–3 days	*f*
Patna (Bihar)	Ganga	VFW (6)	>3,500	150–300	9–236	n.d.	*g*
Anakapalli (AP)	Sarada	RCW (4)	>4,000	10	within riverbed	minutes–hours	*own data*
Daltonganj (JH)	North Koel (n.p.)	RCW (3)	4,000–5,000 (max. 7,000)	1–6	within riverbed	minutes–hours	*own data*
Rishikesh (UK)	Ganga	CW (2)	7,200	13–16	15–25	n.d.	*own data*
Gaya, Dandi Bagh (Bihar)	Falgu	VFW (12)	~10,000	25	5–10	n.d.	*own data*
Nainital (UK)	Lake Nainital	VFW (9)	12,000–16,000	22–37	4–94	8 ≥ 30 days	*h*
Medinipur (WB)	Kangsabati	RCW (1)	15,900	laterals 6 & 11 m beneath riverbed		n.d.	*i*
Kharagpur (WB)	Kangsabati	RCW (1)	22,700	laterals 6 8 m beneath riverbed		n.d.	*i*
Visakhapatnam, Boni (AP)	Gosthani (n.p.)	RCW (5)	27,300	10	within riverbed	hours–days	*own data*
Haridwar (UK)	Ganga and UGC	CW (22)	59,000–67,000	7–10	4–110	2 ≥ 100 days	*j, own data*
Delhi, Palla	Yamuna	VFW (~90)	~100,000 (in, 2007)	45–54	few m to 600 m	few weeks	*k, l*
Ahmedabad (Gujarat)	Sabarmati	RCW (7)	110,000	laterals 10 & 11 m beneath riverbed		n.d.	*i*

*Water used primarily for irrigation. **constructed in 2008. ***constructed in 2010. UP: Uttar Pradesh; KA: Karnataka; UK: Uttarakhand; JH: Jharkhand; AP: Andhra Pradesh; WB: West Bengal; UGC: Upper Ganga Canal; CW: large-diameter (5–10 m) caisson well; VFW: vertical filter well; RCW: radial collector well; RCW(s): Koop well or small-scale radial collector well; n.d.: not determined; n.p.: non-perennial – extreme low flow in pre-monsoon season; *a*: Thakur *et al.* (2010); *b*: Boving *et al.* (2012); *c*: Sandhu and Grischek (2012); *d*: Kimothi *et al.* (2012); *e*: Ronghang *et al.* (2012); *f*: Singh *et al.* (2010); *g*: Sandhu *et al.* (2011a); *h*: see Chapter 3; *i*: Sandhu *et al.* (2011b); *j*: Bartak *et al.* (2015); *k*: Rao *et al.* (2007); *l*: Lorenzen *et al.* (2010).

This is invariably related to the economical and fast construction of such wells compared to the other types. Nevertheless, the presence of large cobbles and boulders in foot-hill and mountainous regions (e.g. of Uttarakhand; Kimothi *et al.*, 2012) can hinder the construction of vertical wells using conventional rotary borehole drilling techniques that allow more accurate grain size distribution and classification of the sub-surface material. While in the absence of large cobbles and boulders rotary borehole drilling techniques permit borehole diameters of up to 500 mm, field-experience from Uttarakhand has revealed that it is a comparatively time- and cost intensive technique. Furthermore, the availability of rotary drilling rigs capable of drilling larger diameter (>300 mm) boreholes is limited. To circumvent these practical difficulties, the "overburden drilling with excentric bit (ODEX)" method (Murphy, 1991) is favoured in practise and frequently used. Although the ODEX technique is comparatively faster and more economical than the rotary drilling technique, it can reduce the actual size of the grains of the aquifer material through the elliptical grinding motion of the drilling bit thereby causing an underestimation of the grain size and an inaccurate interpretation of the sub-surface. The diameter of the boreholes that can be drilled using the ODEX technique is also limited to a maximum of 200 mm. This highlights the importance of conducting a sub-surface geophysical exploration during the investigation of new RBF sites for an accurate interpretation of the sub-surface lithology. Additionally, the construction of an exploratory well using a rotary drilling technique is advantageous for accurately determining particle grain sizes required for dimensioning the well filter-screens.

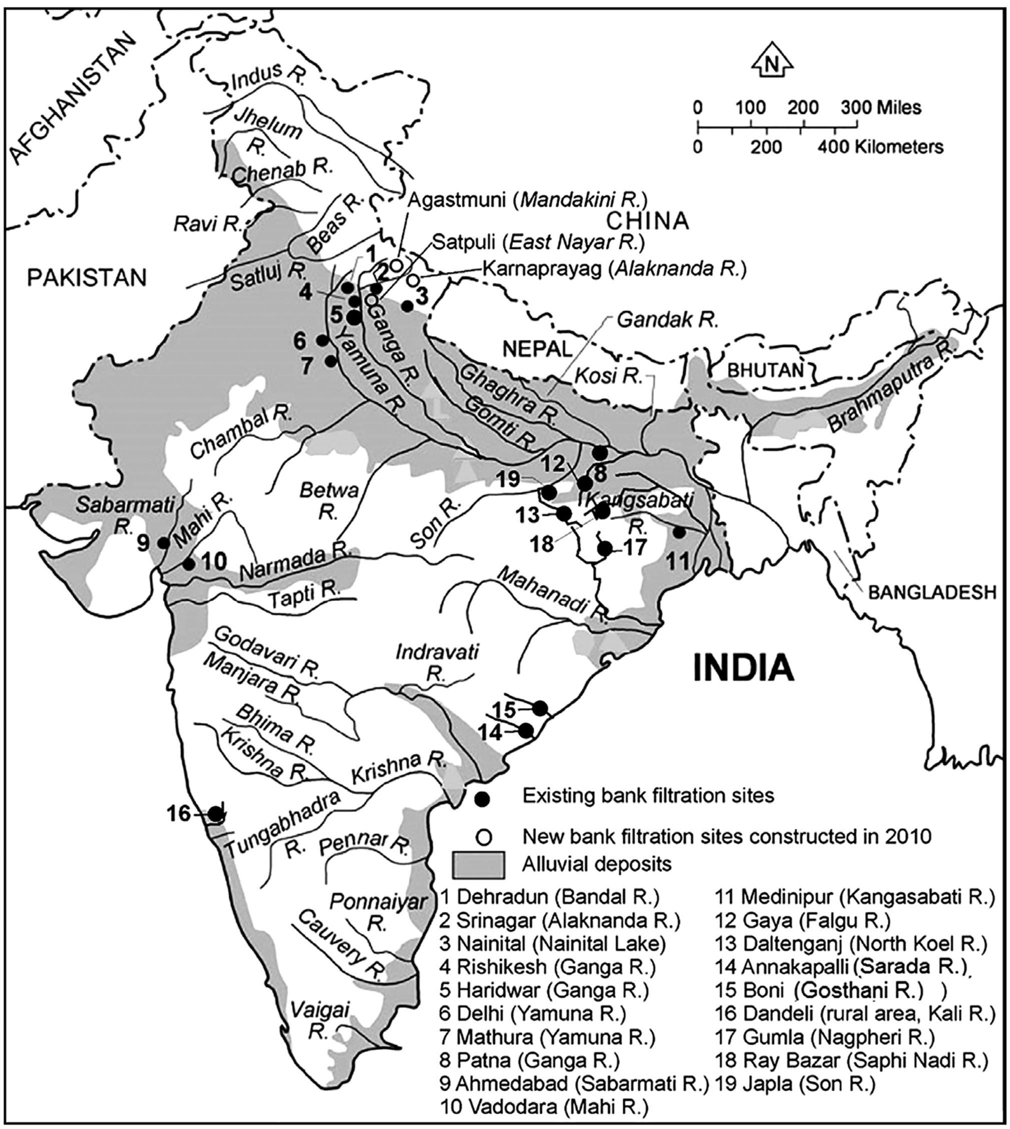

Figure 2.1 Existing bank filtration sites in India (adapted from Sandhu *et al.*, 2011b).

Table 2.2 Summary of hydrogeological features, advantages and issues of bank filtration sites in India.

BF site in Figure 2.1	General Features of BF Site location	Aquifers	Wells	Advantages of BF	Main Issues for BF
1–5	Hilly or foothill regions by perennial surface water bodies (snow-melt and spring-fed)	• Mostly shallow (up to ~20 m) • Medium to coarse sand & gravel • Presence of large fluvial boulders common (influences choice of drilling technique)	• Large-diameter caisson wells (7–10 m) • Vertical filter wells • Koop wells	• Removal of pathogens & turbidity • Year-round abstraction of water during monsoon & dry non-monsoon periods	• Construction of flood-proof wells • High sediment transport and turbidity in rivers during monsoon
6–8	Middle-lower courses of rivers in Indo-Gangetic Plain	• Mostly shallow to deep (>20 m) • Medium to fine alluvium	• Vertical filter wells typically 200–400 mm diameter • Radial collector wells located on riverbank and in riverbed	• Removal of pathogens, turbidity & organics • Year-round abstraction of water during monsoon & dry non-monsoon periods	• Partly extremely polluted surface water (sites 6 & 7) • Regulated river flow (sites 6 & 7) • Ambient landward groundwater contamination • Fine sediments in lower courses of rivers may impede surface water – groundwater interaction*
9–19	Peninsular India, east coast, semi-arid western India (Gujarat) and parts of South Ganga Plain	• Mainly hard rock aquifers in peninsular India. Limited alluvium deposits, partly confined to river courses • Medium to coarse sand and gravel riverbeds with thickness 3–20 m	• Radial collector wells in riverbed • Vertical wells (site 12,400 mm diameter) • Caisson well (site 11)	• Removal of pathogens & turbidity • Year-round abstraction of water during monsoon & dry non-monsoon periods • Abstraction during monsoon and post-monsoon is generally higher compared to dry pre-monsoon summer	• Construction of flood-proof wells • Relatively short travel time of bank filtrate to radial collector wells located in riverbeds, thereby possibility of breakthrough of turbidity and pathogens

*Possibility of presence of low-hydraulic conductivity layer which only partly cuts through the riverbed, local deposition of fines (e.g. site 8 in Patna).

Large-diameter (~10 m) caisson wells are used for BF systems designed to meet high water demands in areas with shallow groundwater tables (≤3 m below ground level) having medium to coarse alluvium containing cobbles and boulders (Table 2.1 and Figure 2.2b; Rishikesh and Haridwar). The caisson wells allow a significant storage capacity on account of their large-diameter. While simple in concept, caisson well construction requires specialised work and specific techniques involving significant manual labour and time (Herrick, 1996).

The BF sites in the cities of Ahmedabad, Baroda and Mathura are designed to abstract very large volumes of water using RCWs sited within the riverbed (Table 2.1 and Figure 2.2c). According to Kumar *et al.* (2012), the practise in India of siting the RCW within the riverbed is quite successful where groundwater is saline as there is little or no mixing of the filtered river water with the groundwater. However, the travel-time is relatively short and correspondingly moderate purification in terms of organics and microorganisms occur (Kumar *et al.*, 2012).

Examples of vertical filter wells and RCW systems at various BF sites in North America and Europe have been discussed in detail by Hunt *et al.* (2002) and Grischek *et al.* (2002). Accordingly, each well-type has its advantages and disadvantages.

Therefore the choice of the well-type for the BF system is site-specific and must consider the hydrogeological conditions of the aquifer and hydraulic conditions of the river, especially riverbed clogging.

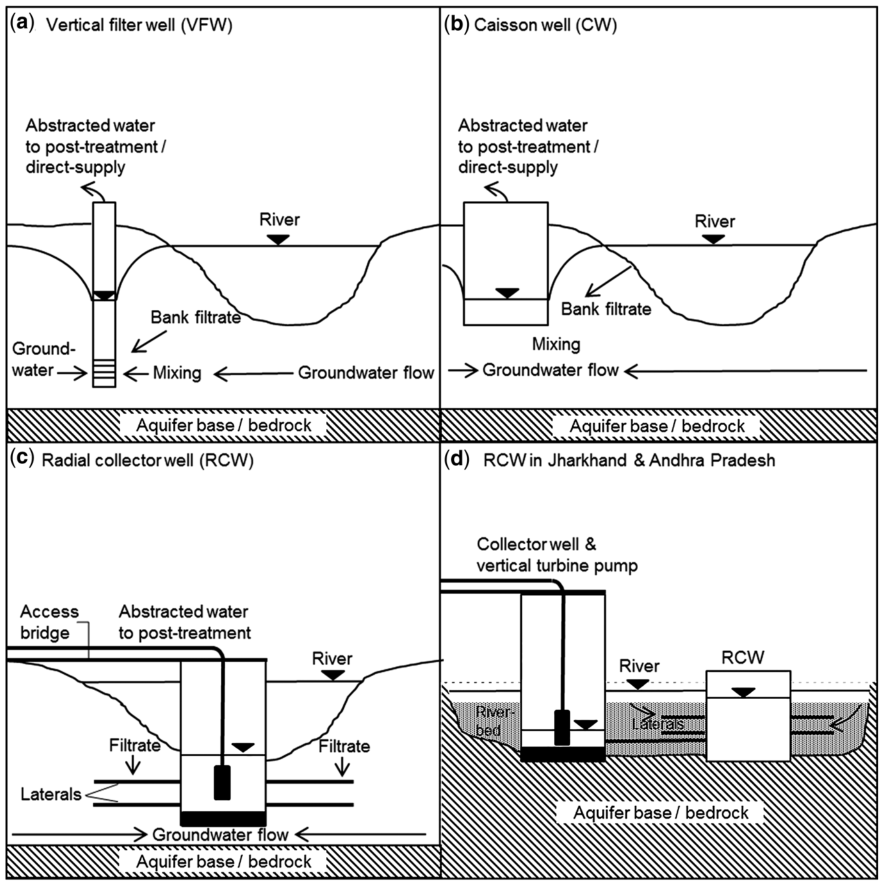

Figure 2.2 Schematic designs of typical wells at bank filtration sites in India.

2.2.2 Overview of water quality aspects at bank filtration sites

Water quality aspects for many BF sites in Europe and North America have been widely investigated. Consequently, while most BF sites in Europe are optimized for the removal of trace organic compounds, in North America BF is more often used to remove pathogens such as Cryptosporidium and, in limited settings, to minimize frequent clogging of costly membrane filters (Sandhu *et al*., 2011b). In light of the discharge of untreated to partially treated sewage into surface water, bathing of livestock and defecation along riverbanks, as well as the very high turbidity during monsoon in India, BF is considered to serve as an extremely important pre-treatment for the removal of pathogenic microorganisms from drinking water derived from surface water.

At the BF sites of Srinagar, Haridwar and Nainital, the $\log_{10}$ removal of total thermotolerant coliforms (TTC) is observed to be 2.1 to 4.4 (Table 2.3). At these sites, and also at the BF systems in Karnaprayag, Agastmuni and Satpuli in Uttarakhand, a very good removal of TTC is attained over short flow-paths of 4–170 m of bank filtrate despite short travel times of 2–8 days. This is also due to the relatively superior surface water quality in the hilly regions, in contrast especially to the Yamuna River between central Delhi and Mathura. This stretch of the river is infamous for its pollution (CSE, 2007) and 85% of the total pollution of the Yamuna is attributed to the discharge of partially to entirely untreated domestic sewage (CPCB, 2006). Nevertheless, according to Singh *et al.* (2010) and Kumar *et al.* (2012) the BF system in Mathura effectively attenuates organic contaminants, colour, UV-absorbance and TTC by around 50% and is thus a vital pre-treatment step to the necessary post-treatment by aeration, filtration and disinfection. Compared to the direct abstraction of river water followed by conventional treatment but with pre-chlorination in Mathura, the BF system reduces or eliminates the need for pre-oxidation or pre-chlorination (Kumar *et al*., 2012). Thus, according to Kumar *et al*. (2012) by using BF as a pre-treatment step, adsorbable organic halogenes, ammonia-chlorine complexes and disinfection by-products do not build up in the treated water.

Table 2.3 Removal of thermotolerant coliforms (TTC; *E. coli*) by BF at some sites in North India (Table 2.1).

BF Site (Reference)	TTC (*E. coli*) counts [MPN/100 mL]		Removal of TTC (*E. coli*)		Monitoring Period (n)
	Surface Water	BF Well	Log_{10}	[%]	
Srinagar (1)	104–6,570 (1,388)	<1	>3.4 (mean)	>99.96	Sep.–Nov. 2012 (5)
Haridwar (2,3)	4,298[a]–48,650[b]	1[a]–18[b]	3.5–4.4	99.97 ≥ 99.99	2005–2013 (129[a], 113[b])
Nainital (4)	141[c]	<2[c]	>2.1	>99.29	2011–2013 (18[SW], 116[well])
Mathura (5)	150–230,000	43–9,300	0.5–1.4	70–95	Nov. 2006–May 2007 (15[SW], 11[well])

1: Saph Pani D1.2 (2013); 2: Bartak *et al.* (2015); 3: Dash *et al.* (2010); 4: see Chapter 3 ; 5: Singh *et al.* (2010); MPN: most probable number; n: number of samples; [a]: Mean values for non-monsoon season; [b]: Mean values for monsoon season; [c]: median; [SW]: surface water, [well]: well water.

A study on the removal of human adenoviruses and noroviruses during the sub-surface passage of infiltrating Yamuna River water in central Delhi from December 2007 to March 2008 observed that although both viruses were present in the river water in the range of 10^5 genomes/100 mL, they were not detected in an observation well located 50 m from the river after a residence time of approximately 119 days (Sprenger *et al*., 2014). In the same study, the $\log_{10}$ removal of somatic coliphages between a transect of three observation wells each at a distance (from the river) of 1 m, 2.4 m and 3.8 m was determined to be around 3.3, 0.7 and 0.7 respectively.

At the other BF sites of Karnaprayag, Agastmuni and Satpuli in the Uttarakhand hills, sampling on three occasions at each site from November 2011 to May 2012 showed total coliform counts to be relatively low in the river water in the range of 23–900 MPN/100 mL. Some river water samples showed a positive presence for *E. coli*. In the water from the wells, total coliforms were not detected (detection limit ≤2 MPN/100 mL) and *E. coli* was absent in all the samples. The relatively low TTC counts at the hilly BF sites in Uttarakhand are due to the low population living upstream accompanied by enhanced biodegradation due to the relatively high dissolved oxygen content in the rivers and high river gradient allowing for enhanced aeration of the water. During the non-monsoon period, the turbidity in the river water was found to be below the 5 Nephelometric Turbidity Unit (NTU) drinking water limit (BIS 10500, 2012), except in Srinagar where it was 12 NTU. Under such favourable surface water quality conditions, including extremely low dissolved organic carbon concentrations of mostly ≤1 mg/L, the surface water treatment plants are able to produce potable water conventionally by flocculation, rapid sand filtration and disinfection. However, BF is advantageous for the year-round supply of water even in monsoon when the turbidity rises to up to 200 NTU (Dash *et al*., 2010), which conventional water treatment plants are unable to remove. The removal of TTC during monsoon has been observed to be greater than, if not equal to, the removal in non-monsoon due to greater TTC counts in surface water in monsoon at some BF sites such as Haridwar.

In hilly and sub-montane rural areas of Uttarakhand, these monsoon-associated problems necessitated the development of an economical and robust small-scale BF well called Koop (in Hindi: “well”) as an alternative to direct surface water abstraction structures built on smaller seasonal streams. The Koop assembly (made of mild steel), consisting of a vertical collector cylinder (1–2 m in length) and four perforated 0.05 m diameter radial pipes each around 0.5–1 m long, is installed 3–4 m below or beside the bed or bank of a stream. Bacteriological indicator counts in the filtrate abstracted by the conventionally built Koops are observed to be significantly lower but not completely eliminated on account of the very short travel time and flowpath (Dash *et al*., 2007; Sandhu & Grischek, 2012). While the travel time of the filtrate for a few conventionally built Koops was determined to be between 2 and 4 minutes only, it increased to more than 150 minutes for an experimental Koop constructed in 2008 using a sorted filter media and the additional installation of an extremely low permeability geotextile with the aim of increasing the length of the flow path and thereby the travel time (Sandhu & Grischek, 2012).

The BF wells in Jharkhand and coastal Andhra Pradesh, that are conceptually similar in design to Koop wells and are likewise located within the riverbed, also experience short travel time of the filtrate especially during monsoon (Table 2.1, Figure 2.2d, Section 2.2.1). Consequently a breakthrough of total coliforms was observed in these wells in monsoon 2014. However, at all these sites the abstracted filtrate is post-treated by aeration, flocculation, rapid sand filtration and finally disinfection.

Additional advantages of BF may also be seen principally in the removal of colour and organic compounds measured as UV absorbance and dissolved organic carbon (DOC). All sites produce bank filtrate that meets the acceptable limits of most of the general ionic water quality parameters of the Indian Standards (BIS 10500, 2012). An exception is found in Srinagar, where nitrate in the abstracted water from the BF well exceeds the 45 mg/L limit (BIS, 10500, 2012). There the abstracted water is diluted prior to distribution. At one location in Jharkhand, in Gaya and Mathura, the abstracted filtrate showed elevated manganese and iron concentrations as observed during a snap-shot screening of water quality at the peak of the dry pre-monsoon season in early June 2014 and in monsoon in late June 2013.

BF, however, does not present an absolute barrier to other substances of concern (e.g. ammonium) and some inorganic trace elements may even be mobilized. This has been observed in Delhi, which has poor surface water quality, and where extensive post-treatment is applied to remove high levels of ammonium (Groeschke, 2013). Elevated manganese concentrations were also observed in the water abstracted by the wells during the pre-monsoon in May 2014.

2.2.3 Mitigation of risks to bank filtration sites in India

Minimizing health-risks due to the use of BF systems and a commitment to protect the environment (aquifer or ambient groundwater resources) from any undesirable effects through induced BF are important considerations when using BF. In this context, water safety plan measures consistent with the WHO have been developed using the BF site in Haridwar as a case-study (Bartak *et al.*, 2015) to manage risks associated with BF sites in India. After the risk assessment of the BF site, it was concluded that risks from inorganic chemicals, salinity, nutrients and turbidity were acceptable in Haridwar. Furthermore, the quantitative microbial risk to human health from bacterial pathogens is below the reference risk used in this study. However, the quantitative microbial risk assessment was limited due to lack of data on virus and protozoa concentrations in source water (Bartak *et al.*, 2015). However, high removal capabilities even for viral and protozoan pathogens are reported in BF literature (e.g. in Sprenger *et al.*, 2014) albeit these risks need improved characterisation, in a longer-term assessment. General recommendations include the need for well head protection as a sanitary measure and to safeguard the well from floods, characterization of both source and groundwater quality, and management of monsoon effects (Bartak *et al.*, 2015; Saph Pani D1.2, 2013).

2.3 RISKS FROM MONSOON FLOODS TO BANK FILTRATION SYSTEMS IN INDIA

2.3.1 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 in the Indian subcontinent. As described in section 2.1, the disruption of drinking water production during monsoon is also common, especially for those towns and cities dependent on raw water that is directly abstracted from rivers. Unprecedented floods in June 2013 and other preceding extreme events as observed in August-September 2010 and 2011 in Uttarakhand and other parts of North India, accompanied with simultaneous inundation of the floodplain caused widespread deposition of sediments and structural damage to the drinking water production units and water-pipe distribution networks. Such an event potentially results in faecal contamination of drinking water. Faecal contamination is one of the most common 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). Various incidences of waterborne disease outbreaks in India from 1990–2011 that can be directly linked to the drinking water supply reveal that viral hepatitis, gastroenteritis, typhoid and diarrhoea were frequent, thereby underlining the fact that viruses even in small concentrations 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 the post-treatment, which is usually disinfection by chlorination. Gastroenteritis, typhoid, cholera and diarrhoea outbreaks across India are linked to the faecal contamination in the drinking water distribution system (leakages and low pressure in pipelines) resulting from wastewater, overland run-off due to extreme rainfall and flood water coming into contact with drinking water (Bhunia *et al.*, 2009; Sailaja *et al.*, 2009; Bhunia & Ghosh, 2011; Shah *et al.*, 2012).

2.3.2 Risks to riverbank filtration sites from floods

In India, wells used for the production of drinking water are at risk of microbial contamination during floods. There is also a risk of interruption of power supply, both of which lead to disruptions in drinking water supply. This occurs in Europe too, where floods are already the most common natural hazard and are expected to increase in frequency and severity resulting in rise in damages (Rambags *et al.*, 2011). 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 observed. Increased numbers 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 rapid increase in the surface water level. Numerical simulation studies on virus transport during RBF for flood scenarios in large rivers connected to shallow unconfined sandy gravel and gravel fluvial aquifers indicate that for river level increases of 1 to 5 m, 2- to 4-log higher virus concentrations in groundwater can be found accompanied with up to 30% shorter travel times that are attributed to higher advection during rising river levels and more dispersion (Derx *et al.*, 2013). It is thus hypothesized that the risk to raw water 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 riverbank where no protective clogging layer exists; thereby causing 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 shorter travel times of the bank filtrate towards the well until confining conditions are reached.
- Seepage of the flood water into the upper sub-surface and unsaturated zone, whereby microbial pathogen loading in the bank filtrate may be observed even many months after the flood 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.

2.3.3 Flood-risk identification at the RBF case study sites of Haridwar and Srinagar

Description of RBF site and extreme flood event in Haridwar

The potable water to the main city of Haridwar is supplied by 22 RBF caisson wells that have a total daily capacity of 59,000–67,000 m^3 (Table 2.1). The RBF wells are located on the west-bank of the Ganga River in the north, on Pant Dweep Island and on a narrow stretch of land between the Upper Ganga Canal (UGC) and the Ganga River in the southern part of the city (Figure 2.3). The abstracted water is disinfected with sodium hypochlorite at the well prior to being distributed to the consumer directly or being pumped into storage reservoirs that are also disinfected.

Along the area where the RBF wells are located, the unconfined aquifer comprises fluvial deposits of fine to coarse sand mixed with pebbles and boulders (Saph Pani D1.2, 2013). Beneath these deposits, the aquifer-base consists of a clay layer. This lithology is generally consistent with the more detailed lithological information available for Pant Dweep Island, where according to Dash *et al.* (2010) a 19 m thick unconfined alluvial aquifer comprising mainly poorly graded sand (0.0075–4.75 mm) in the upper 14 m, is followed by a 5 m thick silty sand layer. The hydraulic conductivity of the aquifer varies from 16 to 59 m/d. The aquifer is in hydraulic contact with the adjoining Ganga and UGC, whose bed sediments are made of silt (mainly within Bhimgoda Barrage reservoir and New Supply Channel; Figure 2.3), fine sand, coarse gravel, cobbles and boulders.

The highest extreme monsoon flood event that was ever recorded in Haridwar occurred on 19 September 2010 (CWC, 2014). 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 296.3 m above sea level. During August–September 2010, most of the abstraction structures that pump water directly out of rivers in Uttarakhand were also submerged. From 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 2.3). 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 severe danger from the approaching flood water). After the flood water had receded, a visual inspection by Uttarakhand State Water Supply and Sewerage Organisation (Uttarakhand Jal Sansthan – 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 turbidity was visible.

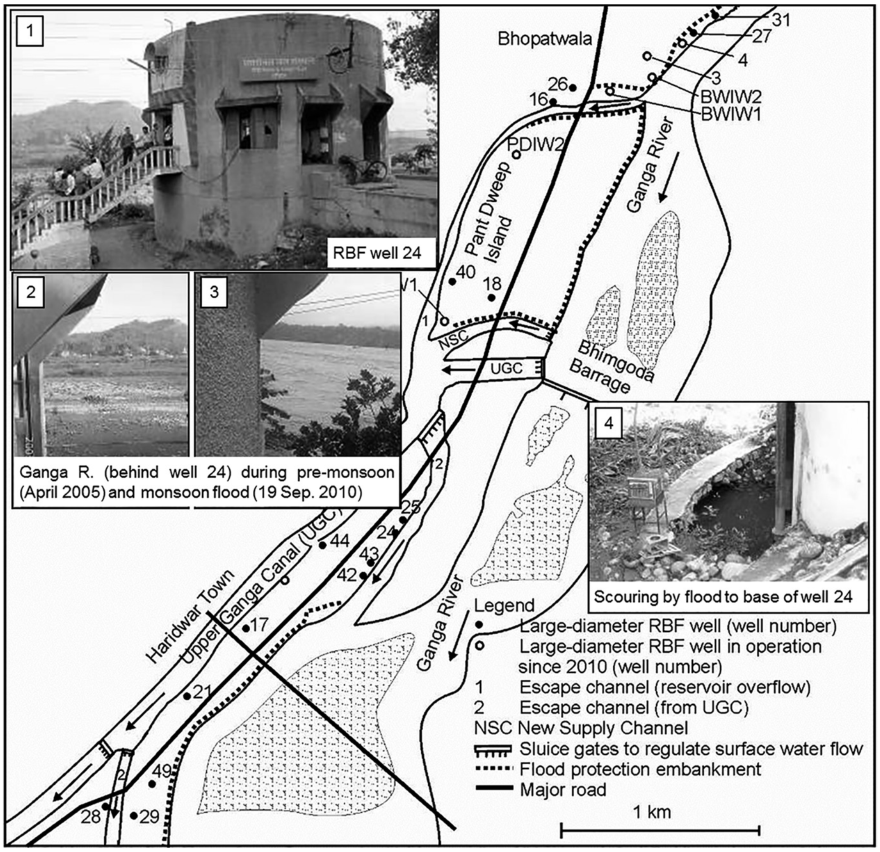

Figure 2.3 Layout of RBF system, flood protection embankment and flood-damage to RBF wells in Haridwar (Base map: Sandhu, 2015; Photo credits: (1) D. Schoenheinz, 2005; (2) T. Grischek, 2005; (3 & 4) S. Kumar, 2010).

Description of RBF site and extreme flood event in Srinagar

The direct abstraction of water from the Alaknanda River followed by conventional treatment accounts for around 80% of the potable water production for Srinagar and the town of Pauri (Saph Pani D1.2, 2013). The remainder is supplied by one RBF well (Table 2.1; Figure 2.4; designated as PW-DST) and some groundwater abstraction wells. The RBF well is located 170 m from the riverbank and is 18 m deep (Kimothi *et al.*, 2012). At the location of the RBF well, the aquifer is around 21 m deep and consists of medium-coarse sand. The mean seasonal discharge of the Alaknanda river increases nearly 10 times from a minimum of around 121 m^3/s in the winter months (January-March) to a maximum of nearly 1,200 m^3/s in monsoon, with peak monsoon discharges of up to 1,815 m^3/s (Chakrapani & Saini, 2009).

During the unprecedented flood from 15–17 June 2013 in the Alaknanda River catchment, the river level rose to around 15 m above its mean level in Srinagar thereby submerging the RBF site in nearly 8 m deep flood water (Figure 2.4). The adjacent area was also submerged. After the flood subsided, the receding water deposited a 1.5–3 m thick fine sand layer over the RBF site, the access road to the site, the adjacent Srinagar-Rishikesh main road and numerous buildings. The RBF site remained inaccessible for several weeks for vehicles and heavy equipment until the sand was cleared from the connecting roads.

In order to get an estimation of the bacteriological contamination to the wells that were inundated by the flood, two water samples (diluted to different concentrations with sterile water for improved accuracy) were collected on 2 July 2013 each from the production well Silk Farm located around 100 m to the landward (East) side of the RBF well PW-DST (Figure 2.4) and from a hand pump located around 100 m to the South of PW-DST. The samples were analysed in the laboratory of UJS in Srinagar for total coliforms and *E. coli* using the Colilert-18 method of IDEXX (Table 2.4).

From Table 2.4 it is evident that the water abstracted by the production well Silk Farm and the hand pump, both in the vicinity of the PW-DST, show a significant and high bacteriological contamination. The magnitude of bacteriological indicator counts is similar in the samples from the identical source indicating a high confidence in the results of the analyses. However, no turbidity was visible in any of the samples.

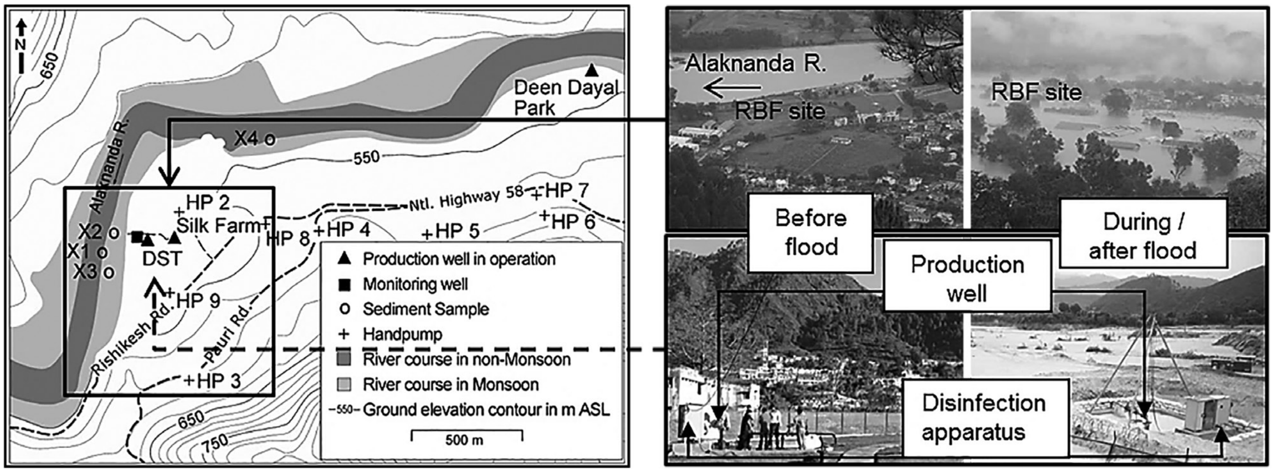

Figure 2.4 Location of RBF site in Srinagar before and after the unprecedented flood in June 2013 (Sandhu, 2015).

Table 2.4 Bacteriological indicator counts in well water in Srinagar on 2 July 2013 after the flood (Sandhu, 2015).

Location	Total Coliform Count [MPN/100 mL]		*E. coli* Count [MPN/100 mL]	
	Sample 1	Sample 2	Sample 1	Sample 2
Well Silk Farm	2,586	2,613	375	495
Hand pump	959	1,439	107	189

Summary of identifiable risks and existing flood protection measures

Taking the highest ever recorded flood event in September 2010 in Haridwar and the unprecedented flood of June 2013 in Srinagar as references, the risks to the RBF sites are summarised in Table 2.5. It is evident that most risks associated with the location of the RBF wells and their designs are applicable.

Table 2.5 Summary of risks from floods to RBF sites in Haridwar and Srinagar (Sandhu, 2015).

Risks	Haridwar	Srinagar
Risks associated to location of RBF site		
– Unconfined aquifer	X	X
– Inundation of land around RBF well and direct contamination	X	X
– Seepage of the flood water into the upper sub-surface and unsaturated zone	X	X
– Shorter travel times of the bank filtrate towards the well	X	X
Risks associated with RBF well design above ground level		
– Insufficient geodetic elevation of well head	X	X
– Inappropriate sealing of well head (Srinagar) or area around caisson well (Haridwar)	X	X
– Direct entry of flood water through improperly sealed well head and fissures in well caisson → direct contamination of well	X	X
– Inaccessibility to wells due to inundation of area around wells → difficulty to start backup power supply (e.g. generators)	X	X
Location of control system for pump operation	n/a	X
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 sub-surface 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.

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 (Figure 2.3). The elevation of the top of the embankment ranges from south to north between 279 and 302 m above sea level and is thereby largely above the normal ground surface elevations where the 22 RBF wells are located. While 15 RBF wells are located to the west (behind) of the embankment and are thereby protected from an extreme flood, seven wells are unprotected. The extreme flood in 2010 inundated the ground at the base of the caissons of these wells (Figure 2.3). The RBF site in Srinagar is also protected by an embankment. However a portion of it was damaged by the flood in 2011. Consequently embankments have to be inspected after each monsoon and repaired before the onset of the next monsoon.

Failure of main power supply and contingency measures

On Pant Dweep Island in Haridwar, only the RBF well 18 has a generator that provides backup electricity to the pumps and disinfection system. Of the remaining wells, only 24, 25, 42 and 43 are provided with backup electricity by diesel generators. However, as these wells are not protected by a flood embankment, during the extreme flood in September 2010 these generators could not be accessed/operated because they were also inundated. This highlights the fact that extreme flood events and subsequent direct contamination and inaccessibility of the wells are a risk for some wells in Haridwar. Accessibility to the wells during a flood in Haridwar and Srinagar, as well as at 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 and to ensure uninterrupted disinfection.

2.4 ASSESSMENT OF RISKS TO BANK FILTRATION WELLS

2.4.1 Design of wells and direct contamination

There is a significant difference in the design of the RBF wells in Haridwar and Srinagar (Saph Pani D1.2, 2013). 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 would not be expected. However, if the wellheads are insufficiently protected such that flood water inundates the area around the wells or enters the wells directly through cracks/fissures present in the caisson wall around or below ground level, then these provide a pathway for contamination of the well (Figure 2.5).

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. This hypothesis was tested by simulating the seepage of flood water, using a sodium chloride (NaCl) solution as a tracer, into the ground around the caisson of the wells IW40, 49 and 21 (Figure 2.6). A tap that is supplied by water from the RBF well is also located near the caisson of well IW40. The tap is used by the public for bathing and washing. There is no appropriate drainage for the wastewater into a sewer or drain and consequently it seeps into the ground. Well IW49 is neither protected by a perimeter wall nor by a concrete seal around the periphery of the well.

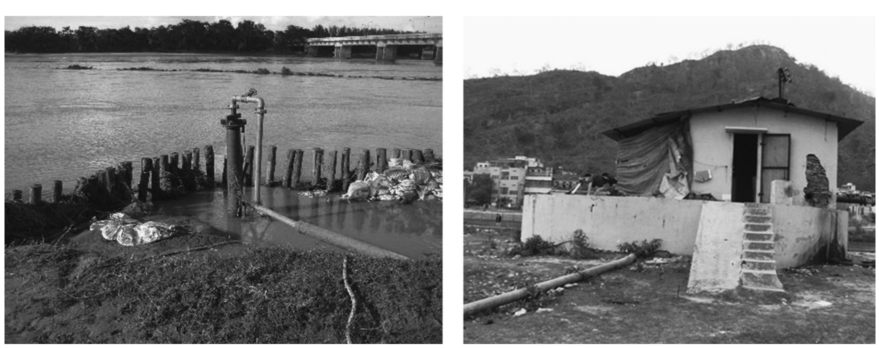

Figure 2.5 Unprotected wellhead (left) and cracks/fissures in the caisson as well as bathing and washing activities (right) can lead to contamination of the well by direct entry of water from the ground surface.

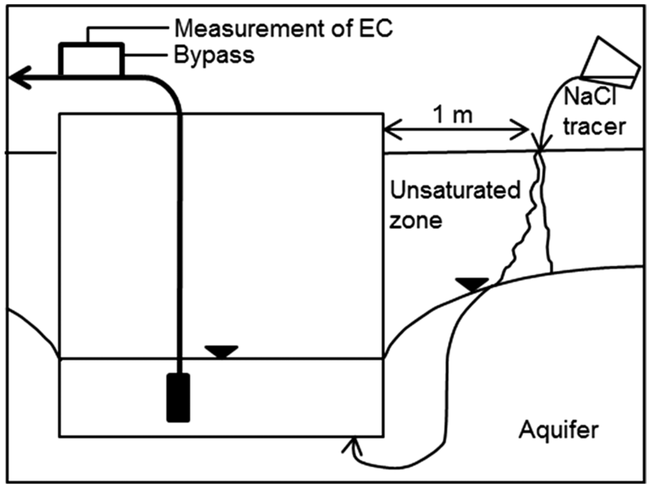

Figure 2.6 Principle of using a NaCl solution as a tracer to illustrate the pathway of contamination to a caisson well due to seepage of surface water.

In comparison, the immediate area within a radius of at least 5 m around well IW21 is protected from encroachment by a perimeter wall and the periphery around the well caisson is protected by a concrete seal (width ~1 m).

Two tests (1 and 2) were performed on well IW40 in December 2013. For the test 1, a NaCl tracer solution having an average electrical conductivity (EC) of 112 mS/cm was poured onto the ground at a distance of around 1 m from the outer edge of the caisson. Test 2 was performed in a slightly different manner by pouring four NaCl tracer solutions, at an interval of 30 minutes, each having an average EC of 260 mS/cm similar to a pulse injection. In both tests the EC of the abstracted water from the well was simultaneously measured using a sensor attached to a potable instant parameter measurement device (WTW Multi 350i). The EC sensor was immersed into a container fed by the abstracted water at a sufficient flow rate from the well via a bypass (Figure 2.6).

In test 1, the EC of the abstracted water from the well IW40 began to increase from its ambient value of 477 µS/cm after ~3 hours after the start of the application of the tracer. The EC then peaked at 489 µS/cm around 4 hours after the start of the experiment. In test 2, an increase in the EC from an ambient value of 473 µS/cm was observed already 10 minutes after the start of the experiment that attained an initial peak at 491 µS/cm after 45 minutes. Thereafter the EC gradually increased marginally and attained a steady value of 496 µS/cm after 4.5 hours of the experiment had elapsed. While a detectable initial peak in the EC is already observed after 45 minutes (test 2), the EC values in both tests 1 and 2 attain a maximum value after 4–4.5 hours elapsed since the start of the experiment. The earlier breakthrough during test 2 could be the result of the tracer flowing into the well along a preferential flow path, e.g. along the caisson of the well. On the other hand, the depth to the groundwater level around the well during test 1 could have been greater (deeper), and thus the tracer arrived later in the well. Thus it may be concluded that for a caisson well, taking well IW40 as an example, water that accumulates on the ground surface within 1 m of the caisson as a result of an intense rainfall event or flood, can take 45 minutes to 4.5 hours to come into contact with the groundwater and eventually flow into the well. Furthermore, the possible seepage of surface water along preferential flow paths (such as the outer wall of the caisson) and shallow depth to the groundwater table may result in shorter travel times for the potentially contaminated water from the surface to arrive in the well.

Two further tests were conducted on wells IW49 and IW21 using a NaCl solution. In case of IW49, having no periphery concrete seal around the caisson, the EC was observed to increase steadily and linearly albeit also marginally by only 10 µS/cm from 300 µS/cm after 100 minutes had elapsed, to 310 µS/cm after 200 minutes had elapsed. But in case of well IW21 that has a concrete seal around the periphery of the caisson, the breakthrough of the tracer was not detected even after 5.5 hours had elapsed since the start of the test. This highlights the importance of sealing the periphery at the base of the caisson wells and also ensuring a well-head protection zone where human encroachment and domestic activities by the public (bathing, washing) are prohibited.

In comparison, the RBF vertical filter well in Srinagar was fitted with a sanitary sealing prior to the flood. 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. Thus, disinfection is a required post-treatment step.

2.4.2 Field investigations on the removal of bacteriological indicators

During the last phase of the monsoon and onset of the post-monsoon period in 2012 (27 September to 7 November), water samples from the production wells PW-DST and PW5 and monitoring wells MW-DST and MW5 as well as the Alaknanda River in Srinagar were taken regularly and analysed for total coliforms, *E. coli* and on one occasion for Enterococci using IDEXX's Colilert-18 Quanti-Tray®/2000 and Enterolert-DW MPN method (Table 2.6). PW5 and MW5 were located between the Alaknanda River and production well PW-DST in Figure 2.4, but both wells were permanently damaged by the flood in June 2013 but were operational till then. 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 other RBF sites (e.g. Haridwar, Patna and Mathura) along the Ganga River and its tributaries (Sandhu and Grischek, 2012). 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 specified by the Central Pollution Control Board (CPCB) of India for drinking water sources for which conventional treatment and disinfection is necessary (Saph Pani D1.2, 2013).

Table 2.6 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 during September–November 2012 (Saph Pani D1.2, 2013).

Parameter	Sampling Location*				
	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 (7,554)	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) [MPN/100 mL]	2	<1	<1	<1	<1

*n = 5 samples were taken at each sampling location for the total coliform and *E.coli* counts, n = 1 sample was taken at each sampling location for the Enterococci analysis.

On the other hand, 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 2.6). It is observed that the production well PW5 that was located only 5.4 m from the normal monsoon water line of the Alaknanda, had 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 that do not need conventional treatment but must use disinfection (Saph Pani D1.2, 2013). On one hand this highlights the benefit of RBF as a natural water treatment technology which provides an environmental ecosystem service in terms of a significant natural pre-treatment of raw water. On the other hand, considering the dynamic change of the water line of the river during monsoon and non-monsoon periods, it also highlights the importance of the travel time of the bank filtrate as a critical parameter in order to determine the distance at which the RBF well should be located from the river bank.

In Figure 2.7, 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. As the post-monsoon period progresses the total coliform counts of the Alaknanda River decrease. 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 when 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.

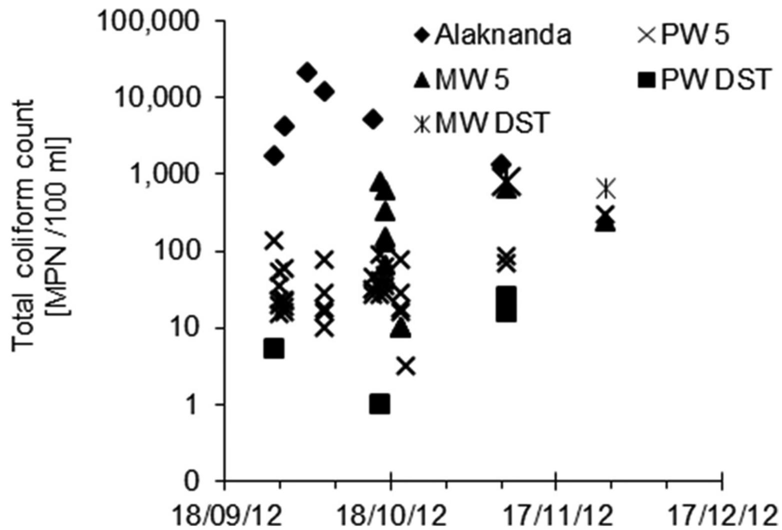

Figure 2.7 Total coliform counts in the Alaknanda River and wells at the Srinagar RBF site (Saph Pani D1.2, 2013).

Considering that the *E. coli* count in PW5 and MW5 is consistently low (<10 MPN/100 mL, Figure 2.8), 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 (Saph Pani D1.2, 2013) and from field measurements in well 40 in Haridwar (see modelling of RBF in Chapter 14), it is likely that the breakthrough is due to increased bank filtrate flow velocity (shorter travel time) and seepage through the previously unsaturated aquifer. In case of PW5 and MW5, the possibility of a short circuit of the flood water along the annulus between the casing of the monitoring well and the aquifer is less likely because both wells have a sanitary sealing and an inundation of the area where the wells are located occurred more than one year previously. Furthermore, no anthropogenic activities (personal hygiene) occur at these wells so that the contamination due to seepage of wastewater at the well is also unlikely.

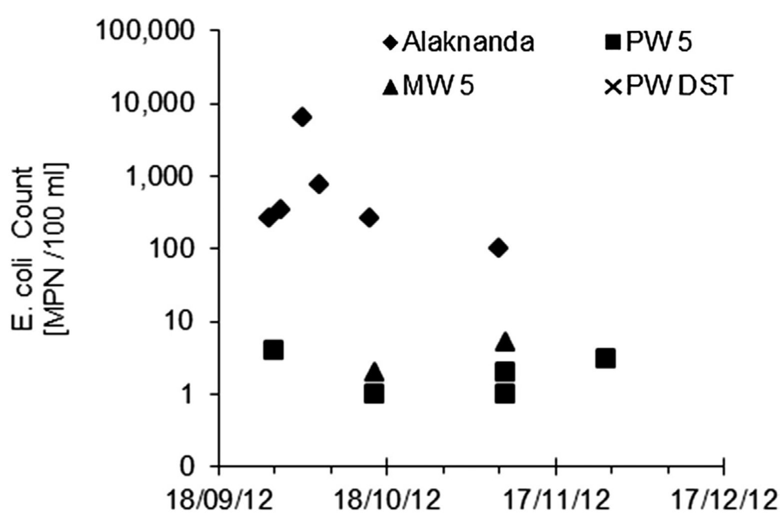

Figure 2.8 *E. coli* counts in the Alaknanda River and wells at the RBF site in Srinagar (Saph Pani D1.2, 2013).

2.4.3 Removal of coliforms under field conditions simulated for the river-aquifer interface

An assessment of the breakthrough of bacteriological indicators was also conducted for the river-aquifer interface by simulating the removal of total coliform and *E. coli* within the first 0.45 cm of flow of surface water through different sub-surface media filled into columns and fed directly with fresh Elbe River in Dresden (Germany) water for a continuous 31 day period at atmospheric temperature (Saph Pani D1.2, 2013). Four columns were filled with glass beads (C1), medium-coarse sand from the artificial recharge basin in the Waterworks Dresden-Hosterwitz (C2), sand and gravel Elbe riverbank material (C3) and a combination of sand and gravel and finer Elbe riverbank material taken adjacent to the Waterworks Dresden-Tolkewitz (C4, Table 2.7). The glass beads (diameter 1.7–2.1 mm) were used to represent well-rounded coarse sand to fine gravel. The discharge ($Q_{outflow}$) was measured once a day on 9–11 days at the outflow of the columns. Accordingly the infiltration rates (I) were calculated as a function of column area for

$$I = \frac{Q_{\text{outflow}}}{A_{\text{column}}} \tag{2.1}$$

The resulting ranges and mean values are summarised in Table 2.7. The residence times (range and median) of the Elbe River water was calculated for each column for the range and median values of their respective effective porosities (Table 2.7).

Table 2.7 Characteristics of materials used to determine coliform removal under field conditions (Saph Pani D1.2, 2013).

Parameter*		**Column 1 (C1)**	**Column 2 (C2)**	**Column 3 (C3)**	**Column 4 (C4)**
Material filled in column[1]		Glass beads (to represent well-rounded coarse sand- fine gravel)	Medium to coarse sand	Natural sand and gravel riverbed 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[d]
Effective porosity n_e*		0.30–0.35 (0.325)[a]	0.30–0.35 (0.325)[b]	0.20–0.30 (0.25)[c]	0.25–0.35 (0.29)
Infiltration rate* [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*	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.

[1]Length of each column: 45 cm; diameter of each column: 10 cm; n_e: effective porosity, n.d.: not determined; [a]Soares (2015); [b,c]: median after Bartak (2011) and Grischek (2003) respectively; [d]: 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); *mean values for infiltration rates are presented in parenthesis; median values for effective porosity and residence time are presented in parenthesis; **an effective porosity of 0.29 is used instead of 0.30.

The log removal rates for total coliforms and *E. coli* for the infiltration rates over a length of 0.45 m of the material used in the columns C1 to C4 (Figure 2.9), together with the travel time of water (Table 2.7), indicates that generally greater average removal is achieved for material having lower effective grain size diameters and consequently lower infiltration rates and longer travel times.

To summarise, for a RBF site where the riverbed material characteristics and travel times are similar, or are expected to be similar to those presented in Table 2.7 and for a range of infiltration rates shown in Figure 2.9, 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 representing well-rounded coarse sand to fine gravel and medium-coarse sand respectively for a travel time ranging from a few minutes up to around 10 hours. On the other hand, for riverbed sediment (C3) with a lower effective grain size diameter (0.28 mm), a greater log 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 travel time of 2 to 18 hours, with a median of 6–9 hours (Table 2.7, Figure 2.9). 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.

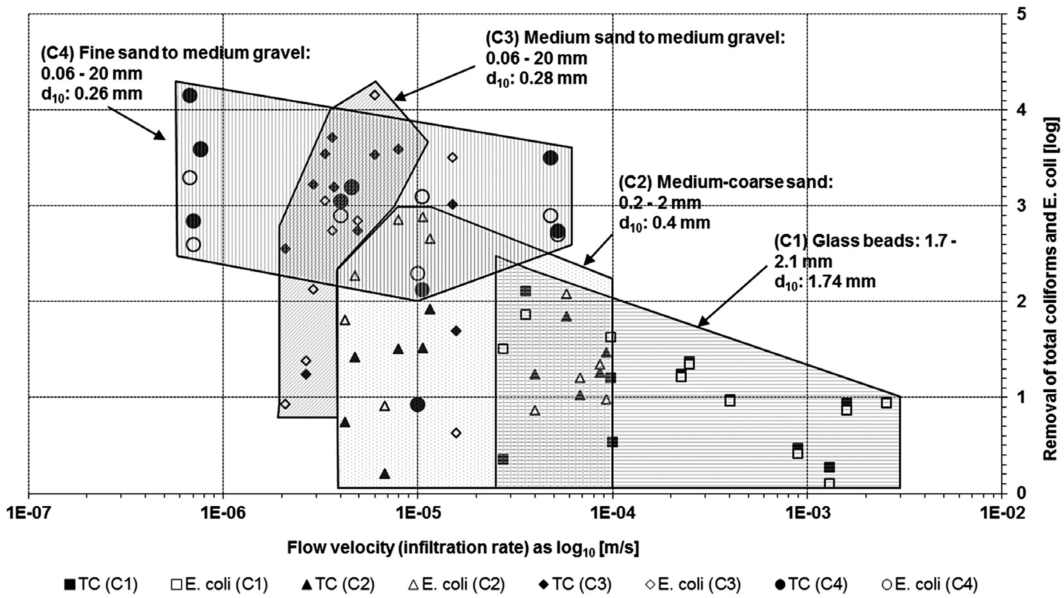

Figure 2.9 Removal of total coliforms and *E. coli* as a function of infiltration rates in different material (Saph Pani D1.2, 2013).

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 could be expected for medium-coarse sand (artificial recharge basin material, column C2) having a size of 0.2–2 mm (medium to coarse sand) during a travel 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 has also been observed at an RBF site in 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.

2.5 MITIGATION OF FLOOD-RISKS AT RBF SITES

2.5.1 Risk management plans for RBF sites in Haridwar and Srinagar

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 2.8. 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 and June 2013 in Srinagar, more elaborate long-term measures have to be introduced.

Table 2.8 General flood-risk management plan for RBF wells in Haridwar and Srinagar (Saph Pani D1.2, 2013).

Aspect	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

Health aspects

Additional measures in the formation of a World Health Organisation water safety plan can be implemented prior to engineered post-treatment options that include monitoring and measurement of disinfection residuals throughout the distribution system, and regular sanitary surveys around the well heads, bore holes and well houses, well maintenance, and prohibition of well house housing, public washing, cattle and defecation in or around the wells (Bartak *et al*., 2015). 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. 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 events 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, water supplied in the tap may not be suitable for direct ingestion and needs to be boiled.

2.5.2 Need for construction of flood-proof RBF wells

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 the highest ever recorded flood of June 2013 in Srinagar, and in order to guarantee high-quality abstracted water by minimising the entry of contaminants, suspended matter and pathogens, the production wells PW5 and PW-DST in Srinagar (Uttarakhand) that were submerged and subsequently buried beneath a 3 m thick layer of fine sand provide a good example of a RBF site requiring flood-proof wells. 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 2.5. Consequently, considering the availability of local materials and site-specific conditions, the following criteria have been formulated to flood-proof the wells:

- 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 run-off 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.

Sanitary sealing of RBF wells

During the well construction process, especially in case of large-diameter caisson wells, the sub-surface material is always loosened. This favours the infiltration of contaminated surface water. Consequently, 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. Furthermore, the seal around the well has to protect the aquifer and the water abstracted from the well. Depending on the material used, the thickness and extent of the seal may vary, but must be sufficient.

For large-diameter RBF caisson wells such as those in Haridwar, very large quantities of seal materials are needed. To act economically, it is recommended to place a combination of an impermeable layer of high quality clay and to fill up the remaining space with inferior material like loam. A concrete plate should be placed on top (Figure 2.10).

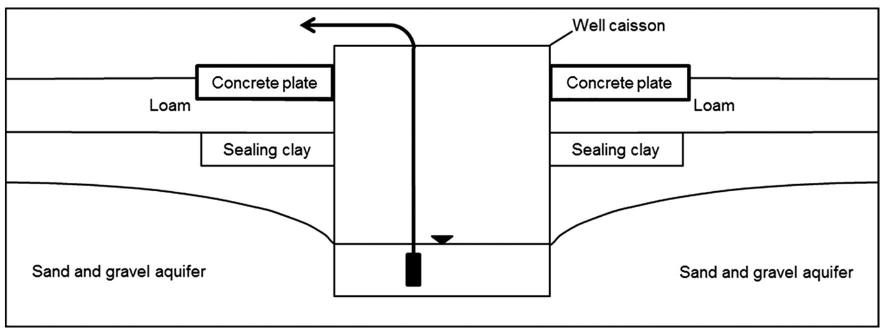

Figure 2.10 Sanitary sealing of a large-diameter well (adapted from Balke, 1999).

The installation of clay above the groundwater table requires the use of dried clay which is broken up and can become compacted through longer periods of compaction. Afterwards the layer has to be soaked very thoroughly, and consequently the clay swells thereby becoming an effective seal after some time.

For vertical filter wells and based on practical experiences in India, it is suggested to excavate an area of at least 1 m^2 (with the well at the centre) to a depth up to the mean groundwater level during the dry pre-monsoon period and fill (seal) the excavation with a commercially available product specifically for well sealing high plasticity, such as bentonite pellets. Thereafter the sealing should be compacted thoroughly. The sealing should subsequently be covered by a concrete plate or a water-tight well-head chamber. This type of sanitary sealing is demonstrated in Saph Pani D1.2 (2013), and was already constructed for the RBF site in Srinagar in November 2011 by UJS. Nevertheless it must be noted that the sanitary sealing, while minimising and in the best case preventing the direct seepage of surface water from above ground near the well (e.g. from an intensive rainfall event), cannot prevent the direct entry of surface water in case of an extreme flood or complete inundation of the well.

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