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# Application of risk-based assessment and management to riverbank filtration sites in India

Rico Bartak, Declan Page, Cornelius Sandhu, Thomas Grischek, Bharti Saini, Indu Mehrotra, Chakresh K. Jain and Narayan C. Ghosh

## ABSTRACT

This is the first reported study of a riverbank filtration (RBF) scheme to be assessed following the Australian Guidelines for Managed Aquifer Recharge. A comprehensive staged approach to assess the risks from 12 hazards to human health and the environment has been undertaken. Highest risks from untreated ground and Ganga River water were identified with pathogens, turbidity, iron, manganese, total dissolved solids and total hardness. Recovered water meets the guideline values for inorganic chemicals and salinity but exceeds limits for thermotolerant coliforms frequently. A quantitative microbial risk assessment undertaken on the water recovered from the aquifer indicated that the residual risks of 0.00165 disability-adjusted life years (DALYs) posed by the reference bacteria *Escherichia coli* O157:H7 were below the national diarrhoeal incidence of 0.027 DALYs and meet the health target in this study of 0.005 DALYs per person per year, which corresponds to the World Health Organization (WHO) regional diarrhoeal incidence in South-East Asia. Monsoon season was a major contributor to the calculated burden of disease and final DALYs were strongly dependent on RBF and disinfection pathogen removal capabilities. Finally, a water safety plan was developed with potential risk management procedures to minimize residual risks related to pathogens.

**Key words** | DALYs, quantitative risk assessment, riverbank filtration, water safety plan

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## INTRODUCTION

The United Nations Millennium Development Goals include ‘halving by 2015 the proportion of the people without sustainable access to safe drinking water and basic sanitation service’ (World Bank 2006). However, India’s growing population is facing an exponential water decline in per capita availability of water (Sandhu *et al.* 2011). In 2001, many Indian potable water distribution systems supplied water only a few hours per day, on average 2.9 h per day often late at night (World Bank 2006). About one-third of India’s urban population resides in large cities of more than a million people (World Bank 2006). While 62% of the urban population had access to toilets either connected to sewers, septic tanks or pit latrines in 2001, ranging from 52% in Delhi to 90% in Hyderabad, only 28% of the surveyed population was connected to sewerage facilities (World Bank 2006). In 2013, large volumes of untreated sewage were discharged into surface water bodies or leaked into shallow aquifers, making them unsuitable to use directly as a source of potable supply without treatment. Furthermore, some urban agglomeration centres such as Haridwar are experiencing declining groundwater levels (CGWB 2009) and surface water bodies are the main source of potable water for many riparian communities in India.

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The World Health Organization (WHO 2008) projects the risk associated with diarrhoeal diseases in South-East Asia by estimating the burden of disease in disability-adjusted life years (DALYs) to 0.00533 DALYs (baseline scenario) per person per year for 2015. The National Commission on Macroeconomics and Health (NCMH 2005) projects the burden of diarrhoeal diseases in India to be 0.0218 DALYs for 2016. This risk is significantly higher than the WHO projections for SE-Asia, and India is a major contributor to the regional burden of diarrhoeal diseases. Unsafe potable water or the absence of drinking water may not be the only reason for the high incidence of diarrhoeal diseases in India but is likely to affect many people without access to drinking water facilities, insufficient sanitation and the absence of water safety plans (WSP).

The usage of riverbank filtration (RBF) in India offers the benefit of a significant reduction in turbidity and coliform bacteria in the source water that is directly supplied after disinfection without the need for further extensive post-treatment (Sandhu & Grischek 2012). RBF can be used as water treatment at sites where hydrogeological conditions are favourable, the surface water requires extensive treatment or groundwater resources are limited. Furthermore RBF is recognized in India as a method to induce recharge into an aquifer by virtue of augmenting well yield (IS 15792). However, RBF as with other techniques can also involve hazards to the ambient water or create environmental risks under certain circumstances. The evaluation of risk from RBF schemes includes studies of hydraulics (e.g. clogging) and now incorporates a wider suite of hazards and hazardous events such as monsoons. RBF has been used in India in Haridwar (Ganga River), Srinagar (Alaknanda River) and Nainital (Lake Nainital) for urban water supply since the 1980s as an alternative to surface water abstraction and to supplement groundwater abstraction (Sandhu *et al.* 2011, 2012). Yet to date a structured management approach to assess risks to human health and the environment has not been implemented at RBF sites in order to make water supplies safer.

In 2006, the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006) were released and then extended among others with the second phase guideline: Managed Aquifer Recharge (MAR) for Recycling via the Aquifer ('MAR Guidelines') (NRMMC–EPHC–NHMRC 2009). This common holistic risk assessment framework applied to MAR, which provides a staged approach to assess the treatment capacity of the aquifer as part of the larger treatment chain in water recycling with the same rigour as previously applied to engineered water treatment components, is to date unreported in the literature. An RBF scheme in Haridwar, India provides a case study to apply the risk-based approach outlined in the Australian MAR Guidelines. The risk assessment is used to focus effort toward the highest priority hazards commonly encountered in MAR operations and provides a rationale for further risk-based management plans. Given the aim to produce water of a potable quality, it was necessary to undertake a thorough assessment of the potential pathogen risks to human health using quantitative microbial risk assessment (QMRA). Details of the QMRA approach for assessing human health risks for water recycling via aquifers are reported by Page *et al.* (2010). This is the first reported application of the risk assessment framework outlined in the Australian MAR Guidelines to an RBF site. The objectives of this study were: (i) to document the application of the Australian MAR Guidelines to the Haridwar RBF case study site; and (ii) to report the outcome of the risk assessment to human health and the environment. This novel methodology for RBF sites makes use of a risk management framework which is consistent with the WHO WSP (WHO 2011).

## METHODS

### Risk assessment stages

The risk assessment was performed following the four risk assessment stages reported by Page *et al.* (2010) shown in Figure 1. It is structured as though the Haridwar RBF facilities are being constructed, although they have primarily been in existence since 1980. Data from existing operations were used in this investigation. The staged approach allows a consistent risk assessment framework to be applied for new and existing RBF sites. An entry-level assessment (Stage 1) addresses the type and scale of the RBF project, the existence of a suitable aquifer, the availability of

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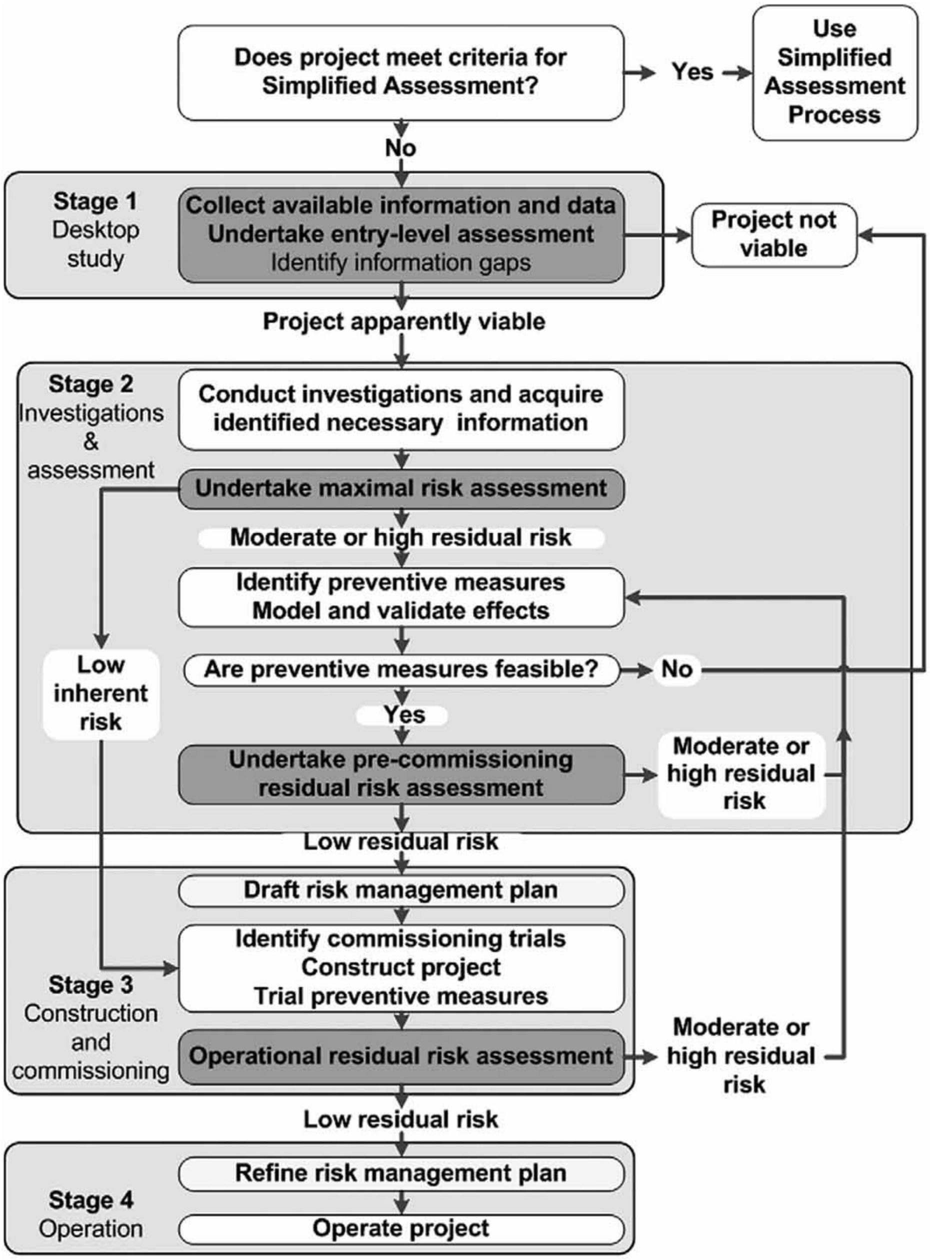

**Figure 1** | Risk assessment stages (after Page *et al*. 2010).

source water, and the intended uses of recovered water. Environmental values, management capability, and compatibility with catchment and groundwater management plans are also assessed.

The first part of an entry-level assessment is *viability assessment*. The second part of the entry-level assessment is to determine the *degree of difficulty* of the project which involves the collection of additional information, such as estimation of travel times, analysis of source and native groundwater quality, characterization of the reactive aquifer minerals, evaluation of other groundwater users, ecosystems and property boundaries and identifies any further investigations required in order to quantify the risk and appropriate treatment measures required. Investigations in

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Stage 2 included exploratory drillings, river bed sediment analysis, groundwater flow modelling, bank filtrate mixing calculations and ground- and surface water sampling during monsoon and non-monsoon season. Stage 2 semi-quantitative 'maximum risk assessment' was performed as outlined in the Australian MAR Guidelines (NRMMC–EPHC–NHMRC 2009). Water quality hazards were assessed in broad classes by comparing river source water and groundwater quality data for pathogens, inorganic chemicals, salinity and sodicity, nutrients, organic chemicals, turbidity and particulates, and radionuclides to the Indian standards for drinking water (IS 10500). For the environmental risk assessment, pathogen numbers in the Ganga were compared to Indian water quality targets for water sources according to the Central Pollution Control Board (CPCB) of $\leq$50 most probable number (MPN)/100 mL. No environmental guideline values exist for the physicochemical hazards, but where there is a commitment to protect the aquifer, Ganga water quality was compared to native groundwater values. Additional environmental hazards such as contaminant migration, aquifer matrix dissolution and well stability, impacts on groundwater ecosystems and energy usage were also considered and were assessed based on their potential impacts on the aquifer or the biosphere. The treatment efficiency of RBF was assessed in a 'pre-commissioning residual risk assessment'. The Stage 3 semi-quantitative 'operational residual risk' assessment for the Haridwar recharge system was performed using the same approach as for the maximal risk assessment but with inclusion of all the water treatment barriers with RBF as a natural treatment step and chlorine disinfection.

## Study site

Haridwar (population ~200,000) is situated 200 km north-east of New Delhi in the state of Uttarakhand. In addition to the permanent residents, ~50,000 visitors come to Haridwar daily with up to 8.2 million people during specific days such as Kumbh (Gangwar & Joshi 2004) to practise a ritual bathing in the Ganga. These bathing sites are in <50 m proximity to the municipal water supply RBF wells (Figure 2). The Haridwar potable water distribution network was built in 1927 with the construction of three groundwater wells and one storage reservoir. As water demand increased, RBF was recognized for its improvements of microbial and physical water quality parameters by subsurface treatment while enabling the construction of highly productive wells. Starting in 1965, the groundwater abstraction was supplemented with the first large diameter bottom entry caisson RBF well. From 1980 to 1998, 15 more wells were constructed and another six new wells commenced operation in 2010. As of 2013, around 59 to 67 Tm$^3$/d, respectively, during non-monsoon and monsoon, is sourced for drinking water production from the 22 RBF wells which receive 40–90% of their water as riverbank filtrate from the Ganga River (Dash *et al.* 2010, Sandhu *et al.* 2011, Sandhu 2014). These wells are 7–10 m deep, have a diameter of ~10 m and a productivity of 789 to 7,526 m$^3$/day. In non-monsoon season (~8 months/year), 10–11 wells are operated 20–24 h, with the remaining wells operating 10–16 h per day. During the monsoon season (June–September), around 16 wells can be operated for 20–24 h daily. Minimum flow distances vary between 4 and >490 m. Average minimum travel times are estimated to range from 30 to >88 days and decrease during monsoon to 2 to >77 days for some wells on Pant Dweep island (Figure 2). The extracted water is further chemically disinfected by adding sodium hypochlorite directly at the well heads and to the drinking water storage reservoirs prior to distribution.

The hydrogeological conditions can be summarized from previous investigations conducted mainly on Pant Dweep Island (Dash *et al.* 2010, Sandhu *et al.* 2010, 2011, 2012). Accordingly, the 19 m thick unconfined alluvial aquifer comprises mainly poorly graded sand (0.0075–4.75 mm) in the upper 14 m, followed by a 5 m thick silty sand layer. A clay layer underneath forms the base of the aquifer. The hydraulic conductivity of the aquifer is 16 to 50 m/d and it is in hydraulic contact with the adjoining Ganga River and Upper Ganga Canal (UGC). The Ganga and UGC bed sediments are made of silt, fine sand, coarse gravel, cobbles and boulders.

The Ganga River flow range is perennial and highly variable. Average discharge at Haridwar is 200 m$^3$/s from October to May (non-monsoon) and increases from June to September (monsoon) on average to about 1,500 m$^3$/s (Das Gupta 1975), with recorded extreme peak flows up to 12,400 m$^3$/s in September 2010 (Saph Pani 2013).

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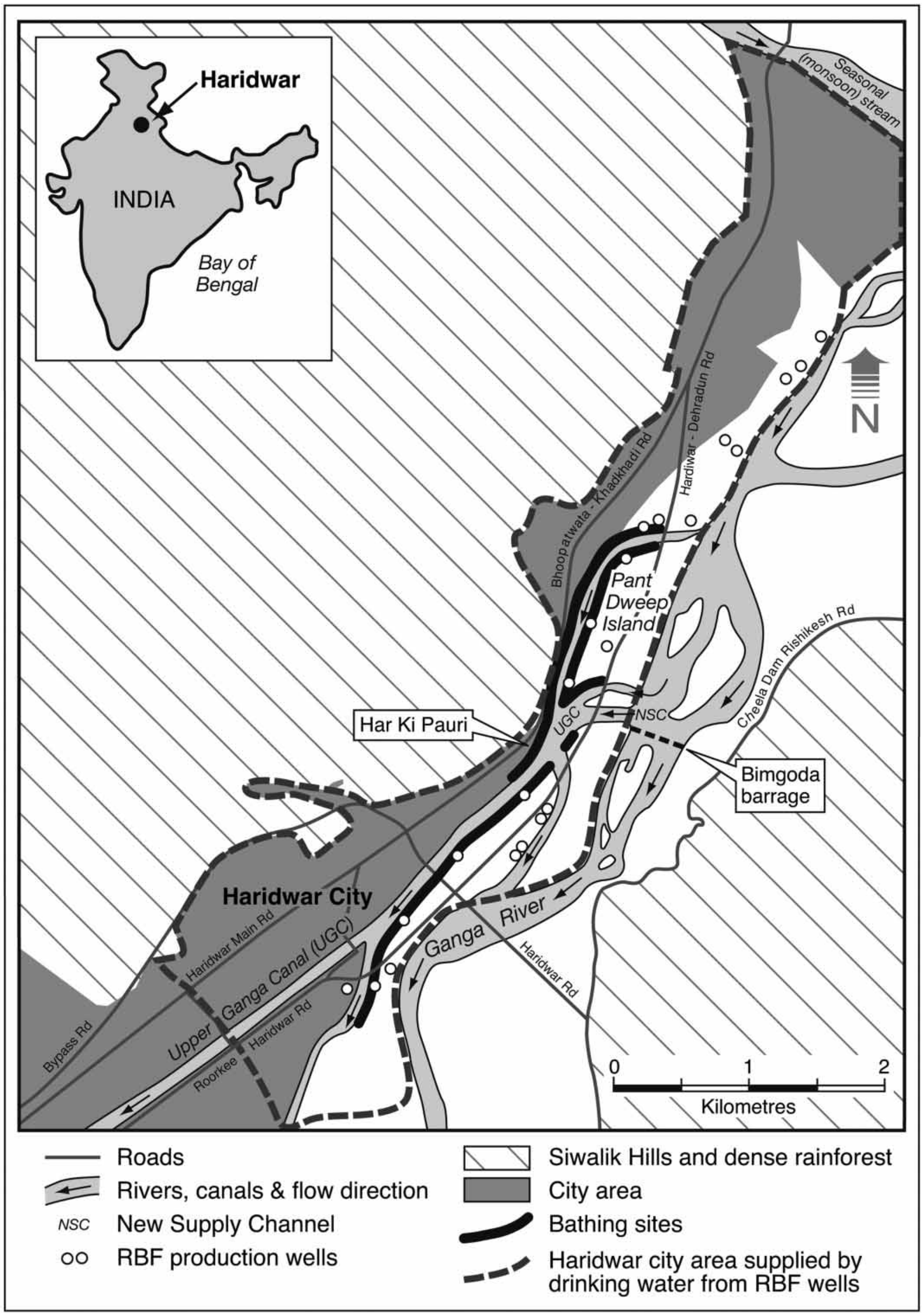

**Figure 2** | Site map of Haridwar RBF scheme including well locations.

## Water quality monitoring

Water quality monitoring was performed in 2005–2006 (Dash 2011, Sandhu 2014), from January to April 2011 (Saini 2011) and 2012–2013 (National Institute of Hydrology). Water samples were taken from 22 wells and analysed to determine temperature, pH, electric conductivity (EC), dissolved oxygen (DO), major ions, total dissolved solids (TDS), alkalinity, total hardness (TH), nitrate, phosphorus, metals, iron, manganese, total organic carbon (TOC), total coliforms (TC) and thermotolerant coliforms (TTC). Lognormal probability fit for microbial data

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were prepared by sorting bacterial numbers including 'no detection' or 'smaller as' values from lowest to highest and assigning each as a percentile value.

### Quantitative microbial risk assessment

The human health risk assessment of pathogens follows the approach outlined in WHO (2011). *Escherichia coli* (*E. coli*) O157:H7 was used to assess the risk of bacteria against a reference level of risk. WHO (2011) defines an upper tolerable reference level of risk of $10^{-6}$ DALYs per person per year as the health outcome target for WSP for locations where the overall burden of disease is mainly derived from waterborne exposure. However, this tolerable burden of disease target may not be achievable in the near future as the current incidence of diarrhoeal diseases in India is more than 4 $\log_{10}$ units above this target. In this study the WHO (2008) projection associated with diarrhoeal diseases in South-East Asia of 0.00533 DALYs (baseline scenario) was adopted as a less stringent, economically and technically more viable health outcome that is still consistent with the WHO goals of providing high-quality, safer water. Mean DALYs were calculated from 10,000 simulations (Table 1). It was assumed that 90% of the TTC detections were *E. coli* (Hamilton *et al.* 2005) and that 8% of all *E. coli* are pathogenic (Haas *et al.* 1999). The disease burden per case was calculated following the approach by Howard *et al.* (2006). Years of life lost due to death were assigned to the life expectancy at birth in India of 65 years for 2011 (World Bank 2012).

## RESULTS

### Stage 1: Viability and degree of difficulty assessment for RBF

The Stage 1 viability and degree of difficulty assessment applied to Haridwar demonstrated the scheme to be viable as there was sufficient supply and demand for the alternative water sources, source water readily available at a requirement of <0.4% of the Ganga base flow, an existing capture and treatment system, a suitable storage aquifer, and the capability to contract and operate a project of this nature. The *degree of difficulty* assessment revealed that groundwater has evidence of faecal contamination and Ganga water does not meet the guideline values for pathogens and turbidity of drinking water and the aquifer according to the CPCB. The aquifer and riverbed can contain ferrous or manganiferous sediment and variations in redox status and temperature may occur seasonally, potentially releasing iron and manganese. Source Ganga water is of poor quality with respect to suspended particles but clogging of the UGC bed is considered negligible because: (1) bed material is excavated annually; and (2)

**Table 1** | Stochastic QMRA model parameters for *E. coli* O157:H7

| Stochastic parameter | Mean | Distribution/comments | References |
|---|---|---|---|
| Numbers per 100 mL (mon) | Min = 4,300, Max = 93,000 | Uniform | Dash *et al.* (2010) |
| Numbers per 100 mL (non-mon) | $\mu = 4{,}297.5$, $\sigma = 2{,}908.8$ | Log-normal, truncated at 0 | Saini (2011) |
| *E. coli* fraction of TTC | Min = 0.84, Max = 1.04 | Uniform | Hamilton *et al.* (2005) |
| Pathogenic fraction of *E. coli* | Min = 0.07, Max = 0.09 | Uniform | Haas *et al.* (1999) |
| RBF removal (mon) | Min = 2, Max = 4.4, Mode = 3 | Triangular | Max by Dash *et al.* (2010) |
| RBF removal (non-mon) | Min = 2, Max = 3.5, Mode = 3 | Triangular | Max by Dash *et al.* (2010) |
| Removal through disinfection | Min = 0, Max = 3, Mode = 0 | Triangular | Sandhu (2014) |
| Ingestion in L/d | $\mu = 3.12$, $\sigma = 1.17$ | Normal | Hossain *et al.* (2012) |
| Dose–response | $\lambda = 0.49$, $\beta = 1.9 \times 10^5$ | Beta-Poisson | Haas *et al.* (2000) |
| Ratio of illness/infection | 0.25 | Based on *Shigella* | Haas *et al.* (1999) |
| Disease burden per case | 0.46 | Mortality based on Shigella | Havelaar & Melse (2003) |

Mon, monsoon season; non-mon, non-monsoon season; $\mu$, mean; $\sigma$, standard deviation; $\lambda$ & $\beta$, Beta distribution parameters.

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riverbed scour is sufficient to prevent external clogging as flow velocities are >1 m/s (Sandhu *et al.* 2010). Geological data indicate an unconfined aquifer, with intended use for drinking water supply, which may thus be vulnerable to urban land use, infiltrating waste and flood or storm water, and might affect or be affected by other groundwater users. Heavy monsoon rainfall and subsequent increase in Ganga flow by a factor of up to 60 was identified as a hazard to the existing water supplies and requires the investigation of riverbed scour, effect on travel times, and decrease of travel time during floods and characterization and identification of existing and future flood protection measures against inundation. In summary of the Stage 1 degree of difficulty assessment, water quality investigations, land use assessment, geochemical evaluation and effect of monsoon floods were identified as necessary in proceeding to Stage 2.

## Stage 2: Maximum and pre-commissioning residual risk assessment

During Stage 2, the dissolution of minerals in the aquifer storage zone and the mobilization of inorganic chemicals were studied by Dash *et al.* (2010); Ganga and groundwater quality were investigated by Dash *et al.* (2010), Saini (2011) and Sandhu (2014); travel times and groundwater mixing were estimated by Dash *et al.* (2010) and Sandhu *et al.* (2010, 2011); pathogen removal was studied in column experiments (Dash *et al.* 2010); effect of monsoon floods was investigated (Sandhu *et al.* 2010, Sandhu 2014); and land use was assessed in this study. Based on the collated results of these investigations, the maximal risk assessment indicated that risks from turbidity and presence of faecal indicator organisms (TTC) in Ganga water and from inorganic chemicals and salinity in groundwater (GW) were high if to be used for drinking (Table 2).

Mean total and thermotolerant coliform numbers in the Ganga were 7,824 and 4,298 per 100 mL (logN-fit, $n = 16$) during non-monsoon season and increase up to $10^5$ TTC/100 mL during monsoon (Dash *et al.* 2010). Ganga mean turbidity measured as nephelometric turbidity units (NTU) ranged from 17 NTU to 169 NTU in non-monsoon and monsoon, respectively. For the Ganga at Haridwar, the presence of organic chemicals including pesticides in the Ganga River was not detected by grab sampling non-target gas chromatography-mass spectrometry (GC-MS) screening in 2005 (Sandhu 2014).

In groundwater, average values exceed guideline values (IS 10500) for the desirable limit of TDS (523 mg/L), TH (368 mg $CaCO_3$/L), alkalinity (373 mg $CaCO_3$/L) and calcium (98 mg/L). Nitrate concentration is <10 mg/L and below the drinking water limit of 45 mg/L. High radionuclide concentrations are naturally found in fractured rock such as granite (Herczeg & Dighton 1998) but the absence of data only allows risk to be declared uncertain. The risk for aquifer and groundwater-dependent ecosystems is low due to an already existing natural Ganga River recharge into the alluvial aquifer. For greenhouse gases, the sustainable system uses natural attenuation processes to reduce surface treatment, energy and greenhouse emissions compared to direct surface water treatment. Results from Stage 2 laboratory investigations estimated ~3 $\log_{10}$ removal of TTC units after 5 days (Dash *et al.* 2010). Pre-commissioning at Haridwar assessed pathogen removal of 4.4 $\log_{10}$ units for TTC and 2.5 $\log_{10}$ units for turbidity based on limited samples (Dash *et al.* 2010). However, additional engineered treatment may be required for recovered water if pathogen attenuation in the riverbed and the aquifer is not sufficient to meet the microbial health based targets defined by the QMRA. This was investigated in Stage 3, the 'operational residual risk' assessment, when recovered water is used for drinking water.

## Stage 3: Operational residual risk management

The results of the water quality monitoring are shown in Table 3 as mean values or as range with respect to the Stage 3 assessment and the hazards defined by Page *et al.* (2010). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints and assessment of each of the risks to human health and the environment from the 12 hazards is discussed in the following sections.

### Pathogens

Mean TTC numbers measured in 22 RBF wells were 18 TTC/100 mL (logN-fit, $n_{mon} = 113$) during monsoon and 1 TTC/100 mL (logN-fit, $n_{non\text{-}mon} = 129$) during

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**Table 2** | Haridwar source water quality data

| | **Upper Ganga Canal**[a,b,c] | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Monsoon** | | **Non-monsoon** | | **GW**[a] | | |
| **Parameter/Location**<br>***Pathogens*** | ***n*** | **mean** | ***n*** | **mean** | ***n*** | **mean** | **IS 10500 limit** |
| TC (MPN/100 mL) | | **119,650**[d,e] | 16 | **7,824** (±3,751)[a,b] | 4 | < 2 | 0 |
| TTC (MPN/100 mL) | | **48,650**[d] | 16 | **4,298** (±2,909)[a,b] | 4 | < 2 | 0 |
| *Inorganic chemicals* | | | | | | | |
| TH (mg/L $CaCO_3$) | 25 | 81 (±16) | 32 | 94 (±18) | 4 | **368** (±101) | 300 |
| Alkalinity (mg/L $CaCO_3$) | 18 | 65 (±18) | 20 | 73 (±14) | 3 | **373** (±49) | 200 |
| $Ca^{2+}$ (mg/L) | 25 | 24 (±6) | 32 | 26 (±6) | 4 | **98** (±36.5) | 75 |
| $Mg^{2+}$ (mg/L) | 25 | 5 (±2) | 32 | 7 (±2) | 4 | **29** (±2.6) | 30 |
| $K^+$ (mg/L) | 22 | 5 (±5) | 30 | 3 (±2) | 4 | 4.3 (±4.1) | |
| $SO_4^{2-}$ (mg/L) | 25 | 26 (±14) | 32 | 23 (±7) | 4 | 41 (±6.6) | 200 |
| Fe (mg/L) | 1 | 0.1 | 2 | < 0.01 | | **0.25–0.37**[f] | 0.3 |
| *Salinity and sodicity* | | | | | | | |
| EC (µS/cm) | 25 | 160 (±22) | 31 | 205 (±46) | 4 | 957 (±57) | |
| TDS (mg/L) | 25 | 102 (±14) | 31 | 129 (±31) | 3 | **523** (±70) | 500 |
| $Na^+$ (mg/L) | 25 | 4 (±3) | 31 | 6 (±3) | 4 | 42 (±2.1) | |
| $Cl^-$ (mg/L) | 25 | 6 (±3) | 29 | 6 (±5) | 4 | 45 (±10.3) | 250 |
| *Nutrients* | | | | | | | |
| TOC (mg/L) | 1 | 1.0 | 4 | 0.8 (±0.2) | 4 | 1.5 (±1.8) | |
| $NO_3^-$ (mg/L) | 17 | 7 (±4) | 19 | 5 (±3) | | 2.2[f] | 45 |
| $NH_4^+$ (mg/L) | | n.d. | 2 | 0.02 | 4 | 0.005 (±0) | |
| *Turbidity and particulates* | | | | | | | |
| Turbidity (NTU) | 18 | 169 (±199) | 20 | 17 (±13) | 3 | 1.3 (±0.4) | 5 |

Standard deviation in brackets, n.d. not determined, bold values are above limits for drinking water.

[a] Saini (2011).

[b] Sandhu (2014).

[c] NIH.

[d] Dash *et al*. (2010).

[e] Mean from minimum and maximum numbers.

[f] Deepali & Namita (2012).

non-monsoon compared with $10^4$–$10^5$ TTC/100 mL in the Ganga. The presence of faecal indicators in groundwater wells was linked to areas where unsealed, temporary pit latrines are commonly used. Furthermore, the lack of source water/well head protection zones associated with social land use practices such as public bathing/washing at the well heads, well head housing, cattle in and around the RBF wells and unsanitary defecation practices were rated as high risks during a sanitary survey.

The risk from pathogens to the Haridwar RBF drinking water system was quantitatively assessed by performing a stochastic QMRA analysis. Mean Ganga TTC numbers are estimated to increase during monsoon by 1 $\log_{10}$ unit from 4,298 ± 2,900 (logN-fit, $n = 16$) to 4,300–93,000 TTC/100 mL (Dash *et al.* 2010) due to stormwater discharge and the changes in hydraulic connection when pits latrines/sewers become connected to the river. A RBF-removal rate of up to 3.5 to 4.4 $\log_{10}$ units during non-monsoon and monsoon was measured at Haridwar (Dash *et al.* 2010) and applied to *E. coli* O157:H7 (Table 1). Mean free chlorine concentration in the RBF distribution network was 0.11 (±0.12) mg/L and up to 2.0 $\log_{10}$ units reductions were added for

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**Table 3** | Haridwar mean RBF water quality (order of wells ascending with portion of bank filtrate)

| **Well #** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Well ID** | **BWIW03** | **BWIW04** | **IW16** | **IW26** | **IW27** | **BWIW01** | **PDIW02** | **IW40** | **BWIW02** | **PDIW01** | **IW18** | **IW31** | **IW42** | **IW17** | **IW21** | **IW24** | **IW25** | **IW28** | **IW29** | **IW43** | **IW44** | **IW49** | **IS 10500** |
| BF/GW EC | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | |
| *Pathogens* | | | | | | | | | | | | | | | | | | | | | | | |
| TC$^{a,b,c,d}$ (MPN/ 100 mL) | < 2–120 | < 2–240 | 30–110 | < 2–170 | < 2–93 | < 2–240 | < 2–93 | < 2–1,600 | < 2–93 | < 2–23 | < 3–93 | < 2–93 | < 2–30 | < 2–65 | < 2–150 | < 2–93 | < 2–9 | < 2–60 | < 2–50 | < 2–30 | <2–11 | 2–460 | 0 |
| TTC$^{a,b,c,d}$ (MPN/ 100 mL) | < 2–43 | < 2–93 | < 2 | 0–90 | 0–9 | < 2–93 | < 2–15 | < 2–93 | < 2–9 | < 2– < 3 | < 2–9 | 0–23 | 0–9 | < 2–9 | 0–93 | 0–15 | 0– < 3 | 0– < 3 | 0– < 3 | 0– < 3 | <2– < 3 | <2–23 | 0 |
| *Inorganic chemicals* | | | | | | | | | | | | | | | | | | | | | | | |
| TH (mg/L $CaCO_3$) | 295 | 297 | 279 | 261 | 261 | 243 | 226 | 218 | 217 | 189 | 219 | 223 | 128 | 120 | 113 | 128 | 137 | 123 | 116 | 133 | 110 | 141 | 300 |
| Alkalinity (mg/L $CaCO_3$) | 300 | 289 | 281 | 266 | 255 | 236 | 218 | 210 | 209 | 184 | 203 | 225 | 118 | 107 | 106 | 107 | 121 | 115 | 105 | 114 | 97 | 126 | 200 |
| $Ca^{2+}$ (mg/L) | 73 | 74 | 66 | 66 | 68 | 58 | 53 | 63 | 56 | 48 | 55 | 54 | 35 | 33 | 31 | 35 | 37 | 34 | 33 | 34 | 30 | 38 | 75 |
| $Mg^{2+}$ (mg/L) | 27 | 27 | 28 | 25 | 22 | 24 | 23 | 19 | 19 | 17 | 19 | 21 | 9.7 | 9.5 | 8.6 | 9.6 | 11 | 9.1 | 8.4 | 12 | 8.8 | 11 | 30 |
| $K^+$ (mg/L) | 5.7 | 4.1 | 6 | 5.7 | 3.5 | 4.8 | 4.9 | 5 | 7.2 | 5.3 | 5.5 | 3.6 | 3.8 | 3.6 | 3.5 | 3.8 | 4.1 | 4.4 | 3.8 | 3.5 | 3.3 | 3.9 | |
| $SO_4^{2-}$ (mg/L) | 30 | 29 | 25 | 24 | 22 | 23 | 30 | 24 | 24 | 24 | 24 | 15 | 21 | 19 | 19 | 22 | 22 | 19 | 19 | 22 | 19 | 19 | 200 |
| *Salinity and sodicity* | | | | | | | | | | | | | | | | | | | | | | | |
| EC (μS/cm) | 699 | 704 | 646 | 610 | 610 | 531 | 521 | 503 | 457 | 433 | 456 | 508 | 294 | 271 | 255 | 281 | 303 | 282 | 251 | 300 | 237 | 304 | |
| TDS (mg/L) | 415 | 443 | 413 | 377 | 379 | 318 | 326 | 296 | 289 | 274 | 296 | 318 | 186 | 169 | 157 | 176 | 192 | 179 | 157 | 188 | 150 | 194 | 500 |
| $Na^+$ (mg/L) | 22 | 25 | 33 | 22 | 21 | 17 | 19 | 16 | 12 | 16 | 12 | 18 | 8.4 | 7.7 | 6.6 | 7.0 | 9.2 | 7.4 | 6.9 | 7.0 | 7.5 | 7.9 | |
| $Cl^-$ (mg/L) | 21 | 24 | 19 | 19 | 17 | 16 | 16 | 15 | 12 | 15 | 12 | 13 | 9.3 | 10 | 8.1 | 8.3 | 10 | 9.4 | 7.4 | 9.5 | 8.0 | 10 | 250 |
| Nutrients | | | | | | | | | | | | | | | | | | | | | | | |
| TOC (mg/L) | 1.1 | 1.8 | n.d. | 1.4 | 1.3 | 1.8 | 1.5 | 1.3 | 2.2 | 1.5 | 1.2 | 1.2 | 0.6 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 0.4 | n.d. | |
| $NO_3^-$ (mg/L) | 13 | 13 | 9 | 9.8 | 16.3 | 7.3 | 9.4 | 5.8 | 9.7 | 5.5 | 9.3 | 10 | 8.4 | 9.0 | 6.4 | 8.0 | 10.1 | 6.7 | 6.2 | 8.7 | 7.9 | 11 | 45 |
| $NH_4^+$ (mg/L) | < 0.1 | < 0.1 | n.d. | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | 0.1 | < 0.1 | < 0.1 | < 0.1 | 0.1 | < 0.1 | < 0.1 | < 0.1 | <0.1 | <0.1 | n.d. | |
| *Turbidity and particulates* | | | | | | | | | | | | | | | | | | | | | | | |
| Turbidity(NTU)$^{b,c}$ | 1.5 | 3.8 | 3.2 | 2.0 | 1.2 | 1.4 | 3.9 | 1.2 | 1.6 | 0.8 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 3.4 | 1.5 | 0.9 | 2.0 | 1.3 | 1.5 | 5 |

BF/GW, bank filtrate to groundwater ratio = $(X_{RBF}-X_{GW})/(X_{SW}-X_{GW})$, n.d.: not determined, data from 2005–2006.

[a] Dash (2011).

[b] Sandhu (2014); Sandhu *et al*. (2011).

[c] Saini (2011) and 2012–2013 (NIH).

[d] NIH: 06/2013–10/2013.

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*E. coli* O157:H7 to account for chlorination disinfection performance (WHO 2011).

RBF and chlorine disinfection reduced the average pathogenic risk associated with *E. coli* O157:H7 by 2 $\log_{10}$ units from 0.115 (no treatment) to 0.00165 DALYs per person per year. Risk was reduced to 0.100 and 0.0064 DALYs when only disinfection or RBF is applied, respectively. Monsoon-risk was calculated to 0.00131 DALYs and was 1 $\log_{10}$ unit above the non-monsoon risk (0.00034 DALYs). Mean number of TTC calculated in the bank filtrate for non-monsoon during the Monte Carlo analysis was 2.5 TTC/100 mL and was in good agreement with numbers measured in the field. The final public health burden of disease risk of 0.00165 DALYs is >1 $\log_{10}$ unit below the national diarrhoeal incidence of 0.022 DALYs (NCMH 2005) for India and meets the adopted health target in this study of 0.005 DALYs per person per year.

No data were available for numbers of *Cryptosporidium* and rotavirus in the Ganga at Haridwar. In order to estimate the required log removal for rotavirus, numbers in the Ganga were calculated from discharge data for raw and treated sewage available for major cities upstream from Haridwar (JNNURM 2006). Numbers for rotavirus in sewage were taken from the Netherlands ($2 \times 10^4$ PDU/L, Lodder & de Roda Husman 2005). The average hospitalization of children aged <5 associated with rotavirus in India (Tate *et al.* 2009) is 5.3 times higher than in the Netherlands (van Pelt *et al.* 2008). Thus, numbers for rotavirus in sewage in the Netherlands were multiplied by a factor of 5.3 to account for a higher prevalence in India. Sewage treatment was considered by a 0.2 $\log_{10}$-unit removal (Lodder & de Roda Husman 2005). Finally, rotavirus numbers in the Ganga River were estimated at 720 per litre for a base flow of 200 $m^3/s$. The RBF log removal required to meet the health target of 0.005 DALYs for rotavirus was calculated as 4.8 $\log_{10}$ units based on a disinfection efficiency of 2 $\log_{10}$ units. Rotavirus removal has been reported in the order of >4 $\log_{10}$ after 2 to 10 weeks' travel time or 25 to 30 m travel distance in the Netherlands (Havelaar *et al.* 1995). Somatic bacteriophages, a surrogate for viruses, were removed easily by 3 $\log_{10}$ units at an RBF site in Delhi after 1 m travel distance (Sprenger *et al.* 2008). Hijnen *et al.* (2005) reported that *Cryptosporidium* was removed more effectively than *E. coli* and MS2 phages, a surrogate for viruses, respectively, in column tests with sandy and gravelly media from a RBF site. Hence, the likely removal in the Haridwar RBF system may be >3.5–4.4 $\log_{10}$ (Dash *et al.* 2010) units as observed for TTC. Therefore, the RBF system in Haridwar may meet the health target for rotavirus and *Cryptosporidium* but absence of data only allows the risks to be declared uncertain.

### Inorganic chemicals

Total iron and manganese concentration of up to 0.02 mg/L and 0.08 mg/L are below the Indian guideline values of 0.3 and 0.1 mg/L for drinking water (IS 10500). Although alkalinity (101–375 mg $CaCO_3$/L) exceeds the desirable limit of 300 mg/L, according to WHO (2011) and analogous to IS 10500, alkalinity is of low risk unless it exceeds the palatability of drinking water in terms of TDS of 1,200 mg/L. Heavy metals such as copper, nickel, lead, chromium, cadmium and titanium are below detection limit. Arsenic, barium and zinc are below drinking water guideline limits and thus are of low risk.

### Salinity and sodicity

Salinity ranging from 150 to 443 mg/L is below the guideline value of 500 mg/L (IS 10500) and risk is rated low.

### Nutrients

Ammonia and nitrate concentrations of <0.1 mg/L and 16 mg/L are below levels of concern for drinking water (nitrate = 45 mg/L). Phosphate concentration was <0.1 mg/L in two wells and TOC ranges from <1 mg/L to 2.2 mg/L. Hence, nutrients pose a low risk for bio-stability and clogging. However, based on a Ganga TOC concentration of <1.3 mg/L, TOC concentrations of up to 2.2 mg/L in wells that are assumed to receive a higher portion of groundwater may indicate contamination with sewage. As can be seen from Table 3, the lowest TOC concentration of <1.0 mg/L was measured in wells with >80% bank filtrate.

### Organic chemicals

The risk from organic chemicals is rated as low. These results from 2005 (see Stage 2 semi-quantitative 'maximum

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risk assessment') were confirmed during monsoon in 2013 when triazines such as atrazine including its metabolites deethylatrazine and deisopropylatrazine, terbutryn, simazine and ametryn were not found above the detection limit of 10 ng/L by LC-MS analysis (Sandhu 2014).

### Turbidity and particulates

The Indian drinking water guideline (IS 10500) sets a guideline value of 5 NTU and values measured in the RBF wells range from 0.8 to 3.9 NTU. Turbidity itself does not pose a risk to human health but may be an indicator of contamination generally and can interfere with disinfection.

### Radionuclides

This risk could not be assessed and was rated uncertain (see Stage 2 semi-quantitative 'maximum risk assessment').

### Pressure, flow rates, volumes and groundwater levels

This risk is rated as low (see Stage 2 semi-quantitative 'maximum risk assessment'). Very high flows in the monsoon season and canal bed dredging in November/December (post-monsoon) regularly restore hydraulic conductivity of the canal/river bed. If clogging persisted, abstraction could draw more groundwater from the unconfined aquifer beneath the city or mobilize iron or manganese, both resulting in water quality deterioration.

### Contaminant migration in fractured rock or karstic aquifers

This risk does not apply for the Haridwar case study as the aquifer is alluvial.

### Aquifer matrix dissolution and stability of well and aquitard

The unconfined alluvial sand and gravel aquifer has low risk of dissolution or well stability issues. However, wells need to be maintained (regular repair of cracks, fissures in well-caisson and covers) to prevent contamination in the event of inundation from an extreme flood.

### Aquifer and groundwater-dependent ecosystem

This risk is rated low (see Stage 2 semi-quantitative 'maximum risk assessment').

### Energy and greenhouse gas considerations

This risk is rated as low (see Stage 2 semi-quantitative 'maximum risk assessment').

## Stage 4: Refine risk management plan

Additional measures in the formation of a WHO WSP can be implemented prior to more engineered post-treatment options. These measures 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 (Tables 4 and 5). Wells that are assumed to receive only a small portion of groundwater have evidence to deliver better quality water in terms of pathogens, TOC and inorganic chemicals compared with wells that mainly receive groundwater. Hence, it is recommended to operate wells with a high portion of bank filtrate preferentially. Furthermore, optimized (monsoon) well operation such as increasing abstraction rate of wells with longer travel distance and reduction of abstraction rates at wells with short travel times or the well operation in descending order starting with wells that have the highest travel time or a travel time >50 days is also a potential operation philosophy to minimize risks. Regular and necessary well maintenance, well head sealing and rehabilitation may be performed during non-monsoon while different wells are operated to meet water demand. The operational procedures corresponding to the preventative measures and critical control points are detailed in Table 6 and should be made accessible to all staff and employees. These procedures and supporting documentation have been developed to undertake operational and maintenance activities and are required to be undertaken weekly and monthly by staff in order to address the operating plan and to demonstrate that the risk management plan is fully implemented.

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**Table 4** | Preventive measures to control general pathogen-related risks in the catchment

| No. | Measure | Hazard arising from | Identified specific improvement plan | Time frame |
|---|---|---|---|---|
| 1.1 | Well sanitation | • Leakage from pipe joints and valves, insufficient sanitation, well head housing and use as public washing place | • Clean well heads (house) (WHO/WEDC 2011)<br>• Waterproof the floors and base around the vertical line shaft pumps in the well house to prevent ingress of foreign matter into the well-caisson<br>• Prohibit defecation, housing, public washing and cattle | Immediately |
| 1.2 | Well protection I | • Unrestricted accessibility | • Restrict access to wells (house)<br>• Liaise with landholder about security of premises<br>• Fence off buffer zone around well head | Immediately – short |
| 1.3 | Well protection II | • Wet season and flooding<br>• Ingress | • Install water-tight covers on entrance hatches on top of well-caisson and their regular maintenance<br>• Improve well head seal (e.g. WHO/WEDC 2011; Saph Pani 2013) | Short-medium |
| 1.4 | Groundwater protection | • Unsanitary defecation in well catchment zone<br>• Use of unsealed pit latrines | • Liaise with municipalities to improve design of existing pit latrines or design and implement alternative solutions | Medium |
| 1.5 | Source water protection | • Partially treated sewage discharge<br>• Untreated stormwater run-off | • Liaise with municipalities<br>• Reduce discharge of partially treated wastewater and treat storm water run-off | Long |

**Table 5** | Preventive measures to control general pathogen-related risks in the treatment process

| No. | Measure | Hazard arising from | Identified specific improvement plan | Time frame |
|---|---|---|---|---|
| 2.1 | Improve disinfection | • Requirements for residual-free chlorine >0.2 mg/L not met within the distribution system<br>• Insufficient disinfection | • Improve disinfection (residual chlorine >0.2 and <1.5 mg/L)<br>• Increase chlorine contact time<br>• Add additional chlorine injection points within the network | Medium |
| 2.2 | Well management | • Not existing | • Investigate well performance<br>• Rehabilitate wells<br>• Implement well operation philosophy | Medium<br>Medium |
| 2.3 | Improve distribution network | • Unrestricted tapping, insufficient pressure head<br>• Wastewater ingress | • Liaise with municipalities<br>• Increase pressure, resolve leakages, restrict tapping<br>• Increase public awareness to minimize water wastage (open and dripping taps) | Long |

## Verification of WSP

The verification monitoring programme ought to confirm compliance if the water quality management plan is achieved, and also determine where modifications to the preventive management plan are needed. For operational and regulatory requirements, it is also recommended to monitor the drinking water quality inside the distribution network.

## Management and communications

Data from the Haridwar RBF scheme should be compiled and reviewed regularly after each monsoon season.

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### Emergency operation procedures

Responses to incidents or emergencies can compromise the operation of an RBF system. The development of preventive measures appropriate to the risks should be documented as part of the WSP. Management of incidents and emergencies for the Haridwar RBF system need to include responses to risks from floods to wells and facilities (Saph Pani 2013) and well recommissioning, risks from the spill of hazardous substances in the catchment and high *E. coli* and turbidity values (Tables 4–6).

## DISCUSSION

In several years of operation, various studies have improved the understanding of the risks for RBF in Haridwar. However, variability and uncertainties concerning groundwater

**Table 6** | Monitoring requirements and corrective actions

| Control measure | Critical limit | What | Where | When | How | Who | Corrective actions |
|---|---|---|---|---|---|---|---|
| Treatment control for pathogen-related risks at point of abstraction | • Chlorine concentration must be >0.2 | • Free chlorine residual | • Within the distribution system | • Weekly | • On-site sampling | • Water chemist | • Increase chlorine dosage<br>• Add additional chlorine injection points<br>• Report to water quality officer engineer/ stakeholder |
| Treatment control at point of abstraction | • Turbidity <5 NTU | • Turbidity | | | | | • Report to water quality officer engineer/ stakeholder<br>• Pipe flushing programme |
| Control of pathogen development at point of abstraction | • No fecal contamination | • Animal or human fecal matter lingering in or around well<br>• Odor, flies | • Site inspection:<br>✓ Well head<br>✓ Well house<br>✓ Well casing | • Monthly | • On-site visit | • Service personnel (well in charge/ supervisor/ engineers) | • Clean well<br>• Remove fecal matter, cattle or inhabitants<br>• Document incidence |
| | • No unrestricted accessibility and housing/ encroachment in/to well heads | • Inhabitants<br>• Broken/open gate/fence/ door/ windows | | | | | • Meet with encroachers and inform of eviction/ alternative housing programme<br>• Document incident |
| | • No cattle in or around well head (house) | • Cattle grazing around well heads | | | | | • Meet with landowner in breach and discuss incentive programme<br>• Document incidence |
| | • No leakage from joints and valves | • Visible water leakage on pipes, valves and ground | | | | | • Report to engineer<br>• Document incidence<br>• Resolve leakage |

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quality (mixing), capture zones for RBF well (contaminant migration) and pathogen capabilities (pathogenic risk) remain. Overall, the quality of the source water improved after RBF and existing operational data indicate sufficient removal of turbidity (88%). Risks from inorganic chemicals such as TDS, alkalinity and TH associated with groundwater mixing are below drinking water guideline values. Mean thermotolerant coliform numbers in RBF wells were reduced by >3.5 $\log_{10}$ units to 18 TTC/100 and 1 TTC/100 mL during monsoon and non-monsoon, respectively.

Pathogen data are available but the effectiveness of the disinfection is questionable at a residual-free chlorine concentration of 0.11 (±0.12) mg/L. Risks from ingress of surface water into the distribution system itself are likely but have not been quantified. Pipes are laid under and above the ground and sometimes alongside sewer canals, water pipe pressure is low and at times negative, and illegal pipe tapping is common so that surface water ingress into the network remains an important consideration (JNNURM 2006). Risks from contaminant migration from human defecation, on-site facilities, public washing in close vicinity to the RBF wells and the risks associated with floods such as direct ingress of surface water remain high.

Uncertainty of monitoring data was associated with unknown groundwater contamination, on-site pollution and also microbial sample quality management. Hence, the budget for monitoring data could have a higher value if it was instead invested in improved well head sanitation and protection if not in place yet.

Monsoon season was identified as a major contributor to the calculated burden of diarrhoeal disease associated with *E. coli* O157:H7 (0.00165 DALYs). Hence, monitoring has the highest value when performed in the monsoon season. The highest impact on final DALYs was correlated to RBF pathogen removal capabilities ($r^2 = -0.39$) and disinfection efficiency ($r^2 = -0.37$). During non-monsoon, disinfection efficiency had a slightly higher impact ($r^2 = -0.09$) on final DALYs compared with RBF removal ($r^2 = -0.08$).

## CONCLUSION

The RBF risk management framework presented in this paper is consistent with the WHO WSP and is the first reported internationally to provide a staged approach to managing risks associated with RBF systems. This case study evaluated whether Ganga water after RBF treatment meets the standards for potable quality and if a staged risk assessment is useful for RBF sites in India. It also provides WSP measures to manage risks associated with RBF sites in India.

The RBF staged risk assessment demonstrated that the risks from inorganic chemicals, salinity, nutrients and turbidity were acceptable. The QMRA indicated that the risks to human health from bacterial pathogens are below the reference risk used in this study. This QMRA was limited by inadequate characterization of viral and protozoan pathogen numbers in source water. However, pathogen capabilities for RBF reported in the literature indicate high removal capabilities even for viral and protozoan pathogens. In a longer-term assessment, these risks need be to better characterized.

The QMRA approach was not found to be useful for data-scarce RBF sites in India. However, general recommendations taken from this specific case study such as the need for well head protection, characterization of both source and groundwater quality, and management of monsoon effects as part of a WSP can be applied to all Indian RBF sites including poor data sites. It is thus useful for all new RBF projects to reveal the information gaps that need to be filled in order to assess the risk and the prospective measures required.

In India, intense rainfall events or temporarily high nutrient loading in surface water during the monsoon are common and frequently cease operations of conventional surface water treatment plants because of insufficient turbidity removal and siltation of supply pipes. Furthermore, surface water intake structures are prone to extreme floods and can be damaged resulting in prolonged water supply interruptions. Operational experiences of RBF sites in Uttarakhand have demonstrated that as long as the wells are not submerged, back-up electricity supply via on-site generators is available and supply-pipes are not damaged, the RBF wells are more robust against monsoon effects compared with surface water intakes and thus ensure a constant water supply.

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