Saph Pani

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

Project supported by the European Commission within the Seventh Framework Programme Grant agreement No. 282911

Deliverable D1.4

Report on bank filtration economics and cost-estimates

Work package	WP1 Bank filtration in urban areas under varying pollutant loads and flood situations
Deliverable number	D1.4
Deliverable name	Report on BF economics in India and cost-estimates or options of additional treatment measures
Due date	Month 36
Actual submission date	Month 38
Start date of project	01.10.2011
Participants (Partner short names)	HTWD, UJS, IHE
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Dissemination level: (**PU**blic, Restricted to other **P**rogrammes **P**articipants, **RE**stricted to a group specified by the consortium, **CO**nfidential- only for members of the consortium)	PU
Deliverable Status:	Revision 1.0

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1 Introduction

1.1 Objectives and structure

The objective of this deliverable (Deliverable D1.4) is to:

- present economic and cost aspects of bank filtration (BF) systems for the Saph Pani case study sites of Haridwar and Srinagar in India. This task was mainly conducted in work package (WP) 1 on bank filtration, but also in conjunction with WP4 (post-treatment) and WP6 (integrated sustainability assessment).
- discuss the benefits of BF in terms of improved quantity and quality of water relative to other water abstraction and treatment options at some existing and potential BF sites, but as of 2014 only documented as part of the Saph Pani project (2011-2014), in the states of Bihar, Jharkhand, Andhra Pradesh, Madhya Pradesh, Gujarat and the city of Jammu in the state of Jammu and Kashmir.

In this context, a brief description of economic and cost benefit analysis components of bank filtration systems for drinking water production in India is presented in chapter 2. Chapters 3 and 4 describe the capital and operating expenditures (capex and opex) for the BF sites of Haridwar by the Ganga River and Srinagar by the Alaknanda River (state of Uttarakhand in northern India) and are compared to the capex of existing groundwater abstraction in Haridwar and capex and opex of direct surface water abstraction followed by conventional treatment in Srinagar. The various technical, health, environmental and socio-economic benefits of the Haridwar and Srinagar BF systems are also discussed. Chapter 5 provides an overview of water quality at various BF sites in India in context to direct surface water abstraction and subsequent conventional treatment. Chapter 6 provides a summary and conclusion.

1.2 Cost and benefit aspects of bank filtration for water supply in India

Presently, in India there is scarce baseline information available on the economic aspects of using BF (i.e. economic analysis), especially in comparison to using alternative drinking water treatment technologies (i.e. cost benefit analysis or CBA). While the CBA of a water supply project has almost become mandatory for budget approval by various funding agencies, lack of baseline data has been identified as one of the constraints for conducting such analysis in an Indian context (Roy et al., 2010).

Nevertheless, past experience has shown that there is significant demand for information on the cost of a BF system, especially by various water utility groups and organisations engaged in water resources management in India.

Scientific studies in India from 2005 onwards, as summarised by Sandhu et al. (2014) to sites of drinking water supply organisations in the states of Uttarakhand, Bihar, Jharkhand, Andhra Pradesh, Gujarat and West Bengal have revealed the presence of various BF systems operating in areas of varied hydro-climatic, geological and surface water quality conditions. It is observed that while there generally is an emphasis on abstracting large volumes of water, the BF system design and subsequent water treatment system design also vary accordingly. The surface water quality, while observed to be very poor (highly polluted) for the Yamuna River between Delhi and Agra, is especially favourable for BF at the Saph Pani project case study sites of Haridwar, Srinagar and Nainital such that only disinfection (and mixing in case of Srinagar) after BF is required as the final drinking water treatment process. Data-collection field surveys on water quality and system design to potential BF water supply schemes, as part of the Saph Pani project, in monsoon (June-July 2013) and pre-monsoon (May-June 2014) to the states of Bihar, Jharkhand, Andhra Pradesh, Madhya Pradesh, Gujarat and the city of Jammu in the state of Jammu and Kashmir also generally revealed suitable water quality conditions for BF. However at BF sites in the states of Andhra Pradesh and Jharkhand, where in some areas the existing BF systems are the only viable means of obtaining water compared to direct surface water or even groundwater, the travel time of the bank filtrate is very short due to the radial collector design of the BF wells located within the riverbed, resulting in a breakthrough of bacteriological indicators and turbidity, especially in monsoon, such that the bank filtrate is post-treated by aeration, flocculation, rapid sand filtration and finally disinfection (Sandhu et al., 2014). Consequently, while conducting an economic analysis of BF systems, it is necessary to not only examine the financial costs of such systems but also to discuss the benefits in terms of improved quantity and quality of water relative to other water abstraction and treatment options.

2 Economic and cost benefit analysis components of bank filtration systems for drinking water production in India

2.1 Overview of concepts

An economic analysis or assessment generally aims to improve the social wellbeing of society in terms of income or consumption by encouraging the efficient use of resources and is carried out in conjunction with social, technical, institutional and environmental analyses, as reported by the Asian Development Bank (ADB, 1999). In this context the ADB (1999) recognises that an important objective of a water supply project is the improvement of health due to the reduction and ultimate elimination of waterborne diseases. The significance of economic assessments is that they permit drinking water interventions to be compared with a wide range of health and non-health interventions aimed at improving human wellbeing though creating opportunities for more productive livelihoods (WHO, 2012).

A cost benefit analysis (CBA) is an economic tool for evaluating all relevant costs and benefits of an investment, reflecting the total impact of a project on society as a whole and entails the systematic estimation of all benefits and all costs of a contemplated course of action in comparison with alternative courses of action (Baffoe-Bonnie et al., 2008). In industrialised countries, formal CBAs are used for the evaluation of water supply projects and to justify investment needs, improvements of water quality and other serviceability parameters in industrialized countries and consequently best management practices have been developed to standardise CBA (Baffoe-Bonnie et al., 2008; Roy et al., 2010), in India such standards do not exist (Roy et al., 2010).

2.2 Costs

2.2.1 Cost categories

Capital, operation, maintenance, environmental and social costs should be taken into consideration for a CBA (Baffoe-Bonnie et al., 2008). But due to the complexity in quantifying environmental and social costs, only capital, operation and maintenance costs have been taken into consideration in this study. However, reference is made to relevant health, environmental, social, institutional and economic aspects for BF, that have been analysed within the Saph Pani project (Saph Pani D1.1, 2012; D1.2, 2013; D6.1, 2012; Essl et al., 2014; Bartak et al., 2014).

The main cost categories used by public or state-owned water utility organisations in India, such as the Saph Pani project partner Uttarakhand Sate Water Supply and Sewerage Organisation – Uttarakhand Jal Santhan (UJS), can be divided into two broad categories, (1) capital costs and (2) operation and maintenance costs.

2.2.2 Capital costs

Capital costs or capital expenditures (capex) are fixed, one-time expenses incurred on the purchase of land and equipment and purchase / construction of buildings for the production of goods or in the rendering of services. In other words it is essentially the total cost needed to bring a project to a commercially operable status. They include expenses for tangible goods and intangibles assets (trademarks, copyrights, software development).

On one hand, BF is commonly used when groundwater resources are insufficient, the cost of treating direct intake of surface water is higher than for treating pumped bank filtrate with improved quality and water quality fluctuations require increased treatment efforts to reach the desired quality (Grischek et al., 2002). On the other hand, suitable hydrogeological conditions are paramount for the success of a BF system (Ray et al., 2002). Consequently, the cost of a BF system primarily depends on various site-specific technical (hydrogeological and water quality) factors in order to obtain a desired quantity of water that can be (pre-)treated to a desired quality by bank filtration.

Concentrating only on the water abstraction and treatment infrastructure and assuming comparable costs (to alternative surface water abstraction and conventional treatment systems) for the distribution of the water, the capital costs for a BF system typically include, but are not limited to:

- comprehensive hydrogeological investigation for the site-selection of a BF system,
- purchase of land to construct the BF well(s) and pump houses as well as placing ancillary equipment and installation of pipelines and electricity connections,
- construction of flood-proof well infrastructure (Saph Pani D1.2, 2013; Sandhu et al., 2014) comprising drilling of the borehole and flood-proof well construction (including pump house, well-head) and purchase of respective materials, followed by the development of the well,
- purchase and installation of pumps and ancillary electrical components (pump control panel),
- redundancy measures for back-up electricity supply e.g. generators,
- robust disinfection equipment (if BF is the final treatment step before disinfection and distribution to the consumer),
- and measures to implement well-head and source protection zones (construction of boundary walls, fences).

These capital costs would also be applicable to a drinking water production system solely based on groundwater (GW) abstraction wells, whereby if the site of the GW abstraction wells is not threatened by floods, then an adequate sanitary sealing is sufficient instead of more elaborate flood-proofing measures.

2.2.3 Operation and maintenance costs

Operation and maintenance (O&M) costs or operating expenditures (opex) are the expenses which are related to the operation of a business, or to the operation of a device, component, piece of equipment or facility. They are the cost of resources used by an organization just to maintain its existence. The operation and maintenance costs for a BF system typically include, but are not limited to:

- purchase of electricity, fuel (for diesel-electric generators) and lubricants,
- salary of personnel involved in operating the BF system,
- annual repair and maintenance of equipment and permanent infrastructure,
- regular monitoring and analysis of hydrogeological (well discharge, water level) and water quality parameters,
- chemicals for post-treatment (disinfection, removal of hardness),
- and the electronic transfer of data from the pump control panel to a supervisory control and data acquisition (SCADA) system.

These operation and maintenance costs would also be applicable to a drinking water production system solely based on groundwater (GW) abstraction wells.

2.3 Benefits

Water supply companies and communities in Europe and North America have recognised the immediate benefits of BF as (Ray et al., 2002):

- the minimised need for adding chemicals like disinfectants and coagulants to surface water to control pathogens,
- and decreased cost to the community without increased risk to human health.

Furthermore, when considering the need for barriers to prevent contamination of drinking water, BF offers the first important barrier between the source of the water and point of abstraction in terms of a significant removal of pathogens and turbidity in India (SaphPani D1.2, 2013). Thus, the removal of contaminants and use of BF provides various socio-economic values as listed in Table 2. In this context, in the state of Uttarakhand in India, BF has increased the per-capita availability of water at four BF sites that were constructed in 2010 (Kimothi et al., 2012).

Table 2-1 Socio-economic value of bank filtration (Ray et al., 2002)

Services and benefits	Value
Contaminant removal (pathogens / chemicals)	Reduced medical costs, longer life span, improved productivity, capital cost reduction, cancer risk reduction & enhanced environment
Reduced maintenance	Capital cost reduction
Improved reliability (as source-water)	Drought protection
Removal of nutrients	Reduced post-treatment costs, lower regulatory scrutiny & lower monitoring costs
Enhanced community supply	Increase in per capita-availability & less time spent to access / collect water

3 Case study site Haridwar

3.1 Drinking water supply system

On account of Haridwar being one of the most important Hindu pilgrimage sites in the world, around 50,000 pilgrims come to the city daily with up to 8.2 million for religious ritual bathing in the Ganga River and Upper Ganga Canal (UGC) during specific days such as the Kumbh Mela (Gangwar & Joshi, 2004). Hence the city's drinking water supply, managed by the Uttarakhand State Water Supply and Sewerage Organisation – Uttarakhand Jal Sansthan (UJS), is crucial. Qualitatively safe drinking water has to be supplied by UJS to meet highly variable water demands. This especially occurs at times of peak demand during religious occasions (Kumbh, Ardh-Kumbh and Kanwar Melas) and during the monsoon. In addition, ~225,235 permanent residents of the city (Census of India, 2011) also have to be supplied with water. As of 2013, around 59,000 m^3/day (in non-monsoon) to 67,000 m^3/day (in monsoon) of pre-treated water is abstracted in total from 22 RBF wells, with a year-round total average abstraction of around 61,000 m^3/day (Sandhu, 2015; Annex 1). After abstraction, the water is disinfected at the well and distributed directly to the consumer and to the storage reservoirs. The 24/7 supply from the BF wells is limited to areas close to the Ganga River and UGC due to the importance given to this area on account of the religious activities occurring there and due to sufficient pressure in the distribution pipes. In addition, around 52 deep groundwater abstraction wells (as of 2012-2013) supplement the water production. The abstracted groundwater is supplied to areas located further away from the river and canal. In these areas the pressure is reported to be insufficient leading to an intermittent supply (UDD, 2007).

3.2 Capital and operating costs

3.2.1 Bank filtration system

A summary of the unit capex for one large diameter (~10 m) and shallow (7-10 m) BF well in Haridwar is presented in Table 3-1 based on the construction costs given in Saph Pani Deliverable D6.1 (2013). Consequently the capital cost of constructing one large diameter and relatively shallow BF well, excluding the cost for constructing the distribution pipeline, is around INR 6 million or 90,910 €. The average operating cost (opex) for one BF well is presented in Table 3-2, and is around INR 4,503,409 or 68,233 €.

Table 3-1 Average capital cost of a large diameter and shallow BF caisson well in Haridwar

Capex component	Total cost for 22 BF wells [1]	Unit cost for one BF well [1]	
	Indian Rupees (INR)	Indian Rupees (INR)	Euro[2] (€)
Average cost of civil engineering works for excavation, and construction of well caisson (large diameter ~10 m and 7-10 m deep) and pump house	110,000,000	5,000,000	75,758
Average cost of electrical engineering works for pumps, automation and control panels	22,000,000	1,000,000	15,152
Average cost of diesel-electric generator, construction of foundation, earthing and electrical connection to pump [3]	16,280,000	740,000	11,212
Average cost of connection of pump and control panel to main electricity supply [3]	17,600,000	800,000	12,121
Installation and testing of valves, flow meters and disinfection equipment [3]	9,020,000	410,000	6,212
Total	174,900,000	7,950,000	120,455

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014); [3] common for GW abstraction well

Table 3-2 Average O&M cost of a large diameter and shallow BF caisson well in Haridwar

Opex component	Total cost for 22 BF wells in 2011-2012 (Essl et al., 2014)	Unit cost for one BF well[1]	
	Indian Rupees (INR/a)	Indian Rupees (INR/a)	Euro[2] (€/a)
Personnel	29,814,000	1,355,182	20,533
Annual repair and maintenance including consumables (for disinfection / post-treatment)	15,824,000	719,273	10,898
Electricity	53,437,000	2,428,955	36,802
Total	99,075,000	4,503,409	68,233

a: annum; [1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

The electricity and salary of staff account for the largest expenditures, with electricity being the single highest opex cost component accounting for nearly 54% of total opex. This proportion, as well as those for personnel and annual repair and maintenance including consumables such as chemicals (in this case sodium hypochlorite as a disinfectant) match the average proportions of 30 – 50% for electricity, up to 36% for personnel and 13 – 19 % for chemicals, repair and maintenance reported by the CPHEEO and WHO (2005).

Based on the year-round average total abstraction of around 61,000 m^3/day from the 22 BF wells in Haridwar (section 3.1; Annex 1), then the average operating cost of drinking water production is calculated at 4.45 INR/m^3 or 0.07 €/m^3 (Table 3-3) by dividing the O&M costs (in Table 3-2) by the average total daily drinking water production.

Table 3-3 Unit-cost of drinking water for bank filtration system in Haridwar

Opex component	Total O&M cost for 22 BF wells in 2011-2012 [1] (Essl et al., 2014)	Cost [2] of drinking water for a 22 well BF system with a total average production of ~61,000 m^3/day	
	Indian Rupees (INR/a)	(INR/m^3)	(€/m^3)
Personnel	29,814,000	1.34	0.02
Annual repair and maintenance including consumables (for disinfection / post-treatment)	15,824,000	0.71	0.01
Electricity	53,437,000	2.40	0.04
Total	99,075,000	4.45	0.07

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

If a debt service of 20% and depreciation of 2% (CPHEEO and WHO, 2005) on the total capital cost (Table 3-1) for a BF well in Haridwar is included in the operating cost, which would amount to 1.57 INR/m^3 and 0.16 INR/m^3 respectively, then the average total operating cost for drinking water production would be 6.18 INR/m^3 (0.09 €/m^3). In most of the cities in India, the water tariffs for the consumer are so low that they do not even cover the annual operation and maintenance cost (CPHEEO and WHO, 2005). However it is important to include debt service and capital costs in water tariffs for the consumer to ensure an economically sustainable water supply service (OECD, 2006).

3.2.2 Groundwater abstraction system

According to data provided by UJS, 52 vertical wells abstracted groundwater from the lower (deeper) confined aquifer in Haridwar to supplement the drinking water production in 2013. The estimated discharge per well is estimated (by UJS) to vary between approx. 84 and 100 m^3/hour and on an average each well operates for around 16 hours per day. A summary of the unit capex for one comparatively deep (to a BF well) groundwater well in Haridwar is presented in Table 3-4.

Table 3-4 Average capital cost of a deep groundwater abstraction well in Haridwar

Capex component	Total cost for 52 GW wells[1]	Average unit cost for one GW well[1]	
	Indian Rupees (INR)	Indian Rupees (INR)	Euro[2] (€)
Average cost of civil engineering works for drilling of borehole, construction of well and pump house and subsequent well development	208,000,000	4,000,000	60,606
Average cost of electrical engineering works for pumps, automation, control panels and disinfection equipment	30,940,000	595,000	9,015
Average cost of diesel-electric generator, construction of foundation, earthing and electrical connection to pump	38,480,000	740,000	11,212
Average cost of connection of pump and control panel to main electricity supply	41,600,000	800,000	12,121
Installation and testing of valves, flow meters and disinfection equipment	21,320,000	410,000	6,212
Total	340,340,000	6,545,000	99,166

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

In comparison to the average unit capital cost to construct one large diameter caisson BF well, the cost to construct a deeper vertical production well (200 – 300 mm internal diameter) is cheaper by around 1.4 million INR. Due to the complexity in separating opex costs for GW and BF abstraction wells and in the absence of a separate monitoring system, it is beyond the scope of this report to uniquely identify the opex for GW abstraction wells.

3.3 Summary of benefits

The existing BF system in Haridwar has been found to be beneficial from human health and technical perspectives such as the existence of suitable hydrogeological conditions for BF, the concentration of organic and inorganic chemicals, nutrients and turbidity of the water from the BF wells are below the limits of the Indian Standard (IS 10500, 2012) and because of a significant removal of bacteriological indicators and turbidity such that the risks to human health from bacterial pathogens is low (Dash et al., 2010; Sandhu et al., 2011; Sandhu & Grischek, 2012; Bartak et al., 2014). On one hand UJS fulfils social aspects such as meeting its obligation to provide high quality drinking water to the residents and pilgrims in Haridwar for very low tariffs, thereby ensuring their fundamental constitutional right to water, but on the other hand the revenues are insufficient to cover the operational cost for the production of drinking water (Essl et al., 2014).

The quantity of groundwater abstracted by the 52 deep vertical wells to supply the urban area mainly to the West of the UGC is comparable to that of the BF wells. Apart from the Haridwar city's urban area, groundwater is also the main source for drinking and irrigation in the Haridwar district. Consequently, with up to 225 groundwater abstraction wells owned by the government and 32,930 private wells in the district as reported in 2009, the groundwater level is reported to be decreasing steadily as a result of which it has attained a critical status (CGWB, 2009). In contrast, the BF wells have an environmental benefit in that they are located in an area where a natural flow between surface water bodies occurs, such that the aquifer is also naturally recharged, sustainable abstraction by the BF wells is ensured and no long-term lowering of the groundwater table in the area of the BF wells occur (Sandhu et al., 2010; Saph Pani D5.3, 2014).

Although the capital cost to construct a large-diameter caisson BF well in Haridwar is higher than to construct a deeper vertical groundwater abstraction well, the operating costs in terms of electricity consumption of BF wells are lower. In 2013 preliminary energy efficiency measurements were performed on the vertical turbine pump sets of the BF wells, which indicated that there is substantial room for improving the energy efficiency of the pumps. However, in comparison, the submersible pumps typically installed in deep vertical groundwater abstraction wells tend to be operated at a lower energy efficiency. Thus as electricity consumption by the pumps is one of the major opex factors involved, the operation of BF wells in this perspective tends to be more economical. Additionally, the large diameter of the caisson BF wells allow for a high water storage capacity, such that high abstraction rates can be obtained until the storage capacity of the wells is exhausted. This in turn permits the high water demand, in areas where the religious activities occur, to be met.

The BF system in Haridwar currently serves as both a sustainable alternative to surface water abstraction followed by conventional treatment and supplements the groundwater supply (Sandhu & Grischek, 2012). A surface water abstraction system followed by conventional treatment has never been considered for the city due to recognition of the fact that large quantities of pre-treated water can be, and have been, obtained by BF for around 50 years. On one hand cost of building a conventional water treatment plant based on surface water abstraction would have incurred an extremely high capital cost. On the other hand, planners and engineers already recognised around 50 years ago that large quantities of naturally pre-treated water can be obtained by BF. Furthermore, instances have been compiled where the failure of surface water based conventional treatment plants has resulted in the outbreak of water borne diseases (Saph Pani D1.2, 2013).

The presence of perennial surface water bodies in hydraulic contact with a sufficiently thick alluvial aquifer provides potential for the expansion of the existing BF system. In this context, locations with surface water boundaries on two or more sides (e.g. on Pant Dweep Island or between the Ganga and UGC), which are influenced by the existing naturally occurring surface water – groundwater gradient, are potential sites for new BF wells. However, sufficient travel time of the bank filtrate, well head protection zones, source protection zones based on the flowpath of bank filtrate and ambient groundwater and robust disinfection will have to be taken into account when constructing new BF wells and for maintaining the high quality of the abstracted water.

4 Case study site Srinagar

4.1 Drinking water supply system

The town of Srinagar is located by the Alaknanda River along the road to the important religious shrines of Badrinath and Hemkund and is the main commercial and administrative centre of the district of Pauri in Uttarakhand. However the production of drinking water has not been able to match the growing demand of permanent residents and the temporary "floating" population of pilgrims. Around 80% of the drinking water is produced from directly abstracted Alaknanda River water followed by conventional treatment (flocculation – sedimentation – rapid sand filtration – disinfection), with the remainder supplied by a BF and 2 – 3 groundwater wells. During the severe monsoons of 2010, 2011 and 2013 the surface water supply had to be discontinued for several days due to excessive turbidity and damage to the surface water intake structures. To determine whether RBF could serve as an alternative to surface water treatment for the year-round production of drinking water and to address the deficit between demand and supply of the existing conventional surface water treatment system, UJS constructed a RBF well in 2010 (Kimothi et al., 2012). Depending upon the duration of operation of the well, it abstracts around 900 m^3/day (852-937 m^3/day; Kimothi et al., 2012). After abstraction the water is disinfected by NaClO at the well. Due to the concentration of nitrate in the abstracted water from the BF well exceeding the Indian Standard guideline value of 45 mg/L (IS 10500, 2012), the abstracted water is mixed with conventionally treated surface water.

4.2 Capital and operating costs

4.2.1 Bank filtration system

Unlike the shallow large diameter caisson BF wells in Haridwar, the BF well in Srinagar is of the vertical filter design and is around 18 m deep. A summary of the capex for this production well is presented in Table 4-1. Consequently the capital cost of constructing one 200 mm diameter vertical well, excluding the cost for constructing the distribution pipeline, is around INR 1.6 million or 24,250 €. The capex to only drill a larger diameter borehole of 550 mm to a depth of 18 m by the rotary drilling technique in Srinagar and subsequently construct a 300 mm diameter well assembly (excluding other items as listed in Table 4-1) is around INR 1 million, or nearly four times that of a 200 mm diameter well. Depending on the pump selected, the other capex would vary accordingly but be slightly higher as the well would have a higher yield and thus more water (compared to 200 mm diameter well) could be abstracted with a higher capacity pump.

Table 4-1 Capital cost of a vertical 200 mm diameter production well in Srinagar

Capex component	Unit cost for one BF well[1]	
	Indian Rupees (INR)	Euro[2] (€)
Civil engineering works for drilling of 18 m deep borehole by ODEX method, and construction of well assembly	250,800	3,800
Pump, related items, installation and testing	234,400	3,552
SCADA motor-starter control panel	94,000	1,424
Diesel-electric generator, construction of foundation, earthing and electrical connection to pump[3]	851,300	12,898
Connection of pump to control panel[3]	50,000	758
Installation and testing of valves, flow meters and disinfection equipment[3]	120,000	1,818
Total	1,600,100	24,250

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014); [3] common for GW abstraction well

The average operating cost (opex) for one BF well is presented in Table 4-2, and is around INR 901,000 or 13,646 €.

Table 4-2 Average O&M cost of a 200 mm diameter vertical production well in Srinagar

Opex component	Unit cost for one BF well[1]	
	Indian Rupees (INR/a)	Euro[2] (€/a)
Personnel	237,000	3,591
Annual repair and maintenance including consumables (for disinfection / post-treatment)	158,000	2,394
Electricity	506,000	7,661
Total	901,000	13,646

a: annum; [1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

Based on an average daily abstraction of around 900 m^3 from the BF well, then the average operating cost of drinking water production, is calculated at 2.74 INR/m^3 or 0.04 €/m^3 by dividing the total O&M costs by the average daily drinking water production (Table 4-3). Furthermore, if a debt service of 20% and depreciation of 2% (CPHEEO and WHO, 2005) on the total capital cost (Table 4-1) for the BF well in Srinagar is included in the operating cost, which would amount to 0.97 INR/m^3 and 0.10 INR/m^3 respectively, then the average total operating cost for water production from this particular BF well would be 3.81 INR/m^3 (0.06 €/m^3).

Table 4-3 Unit-cost of water from a 200 mm diameter vertical production well in Srinagar

Opex component	O&M cost for one 200 mm diameter and 18 m deep BF well in 2011-2012[1]	Cost[2] of water for a BF system with an average production of ~900 m^3/day	
	Indian Rupees (INR/a)	(INR/m^3)	(€/m^3)
Personnel	237,000	0.72	0.01
Consumables, mainly chemicals (for disinfection / post-treatment)	158,000	0.48	0.01
Electricity	506,000	1.54	0.02
Total	901,000	2.74	0.04

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

4.2.2 Surface water abstraction and conventional treatment system

Comparable data for a surface water abstraction (SWA) system followed by conventional treatment of a similar production capacity to the BF system in Srinagar are difficult to obtain. Nevertheless a comparison has been made for a system with a production capacity of 2,000 m^3/day in Srinagar, that was constructed from 1997 – 2000 for a total capital cost of INR 28.9 million (~438,000 €).

Based on an average daily surface water abstraction and subsequent conventional treatment capacity of around 2,000 m^3, then the average operating cost of drinking water production, is calculated at 12.73 INR/m^3 or 0.19 €/m^3 in a similar manner to a BF system (Table 4-4).

Table 4-4 Unit-cost of water from a 2,000 m^3/day surface water based conventional treatment system in Srinagar

Opex component	O&M cost for 2,000 m^3/day SWA & conventional water treatment plant in Srinagar[1]	Cost[2] of water for 2,000 m^3/day SWA & conventional water treatment plant	
	Indian Rupees (INR/a)	(INR/m^3)	(€/m^3)
Personnel	1,133,700	1.55	0.02
Consumables, mainly chemicals for conventional water treatment	2,914,250	3.99	0.06
Annual repair and maintenance including consumables (for disinfection / post-treatment)	1,412,000	1.93	0.03
Electricity	3,834,250	5.25	0.08
Total	9,294,200	12.73	0.19

[1] Reference financial year in India: 1st April 2011 – 31st March 2012; [2] Mean currency exchange rate from 1st April 2011 to 31st March 2012: 1 € = INR 66,00 (European Commission, 2014)

Furthermore, if a debt service of 20% and depreciation of 2% (CPHEEO and WHO, 2005) on the total capital cost of INR 28.9 million (~438,000 €) for the SWA and conventional treatment system in Srinagar is included in the operating cost, which would amount to 7.92 INR/m^3 and 0.79 INR/m^3 respectively, then the average total operating cost for water production would be 21.44 INR/m^3 (0.33 €/m^3).

4.3 Summary of benefits

The main techno-economic advantages of using BF in the drinking water production systems in the hilly parts of the north Indian state of Uttarakhand, but also in other hilly regions of India in comparison to SWA followed by conventional treatment, is the significant year-round removal of pathogens and turbidity at a comparatively lower cost of up to 50% depending on production capacity and required post-treatment (organic compounds are normally found on an average in very low concentrations so are not critical).

The present surface water abstraction systems in Uttarakhand face two major recurring problems with respect to quantity and quality for drinking water production that typically lead to interruptions in water production lasting from a few days to weeks, and due to which BF is advantageous (Sandhu et al., 2014):

- 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 subsurface flow in the riverbeds, e.g. 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 SWA and treatment plants are rendered inoperable with consequent interruptions in water supply. 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 and D1.2, 2013).

It is evident that irrespective of the drinking water treatment technology in use, the cost of electricity accounts for the highest individual opex component. According to a recent study (Voltz et al., 2014), the expenditure incurred by UJS on electricity is around 1 million €/a for pumping drinking water at various stages and locations from Srinagar to Pauri towns, starting from pumping surface water out of the Alaknanda River in Srinagar, to conventionally treating the surface water and finally lifting the drinking water up to the town of Pauri (altitude difference 1700 m). As individual pump-motor sets have real power demands as high as 200 kW, pumping is very energy intensive and comprises >90% of the electricity demand (Voltz et al. 2014). Furthermore, Voltz et al. (2014) state that the pumps have to be over-dimensioned in order to account for the intensive wear-and-tear of the internal pump components due to the high turbidity in surface water in monsoon. Although the present BF system abstracts on an average less than half of the SWA system, the cost of electricity for a pump in a BF system is 1.54 INR/m^3 compared to 5.25 INR/m^3. While the expansion of a BF system will lead to higher capex and opex, the economies of scale will result in the general decrease of the cost per unit of drinking water produced with increasing total production because the fixed costs will be spread out over more units of water produced. Furthermore, the wear and tear on pump components used in a BF system will be considerably less compared to SWA because of the high natural removal of turbidity and suspended solids by BF prior to abstraction.

The comparatively less time required to construct and operationalise a new BF system compared to a surface water system, leads to an increase in the per capita availability of drinking water within a short time (Kimothi et al., 2012).

5 Overview of water quality at potential bank filtration sites in India

5.1 Motivation, objective and methodology

5.1.1 Motivation and objective

According to the Indian standard on drinking water (IS 10500, 2012), which was last revised for the second time in 2012 taking into consideration relevant international benchmarks (European Council, 1980, 1998; CPHEEO, 1999; USEPA, 2002; WHO, 2008), the eleventh five year plan document of India (2007-12) states that there are around 2.17 hundred thousand water quality affected habitations in the country with more than half affected with excess iron, followed by fluoride, salinity, nitrate and arsenic. Furthermore it states that approximately 10 million cases of diarrhoea, >7.2 hundred thousand typhoid cases and 1.5 hundred thousand viral hepatitis cases occur annually with the majority attributed to unclean water supply and poor sanitation (IS 10500, 2012). Consequently, the Government of India has recognized the provision of safe drinking water as a major challenge and aims at addressing water quality problems in all affected habitations by prioritising water quality surveillance and monitoring.

As of 2014, a compilation of system design and capacity of at least 24 known small to large urban and rural BF systems in different hydro-climatic conditions across India has indicated a total production capacity of all of these systems summed together to be around 384,000 – 410,000 m^3/day of water (Sandhu et al., 2014). However, apart from various BF case study sites in Uttarakhand whose water quality has been monitored for long durations exceeding at least one year, very limited water quality information is available for BF sites in other locations in India (except Delhi and Mathura). The main quality parameters that are usually routinely determined by water supply utilities are physical field parameters, total hardness and total alkalinity, major anions and often only the presence and absence of bacteriological coliform indicators, and only occasionally as counts per 100 mL of sample (permissible limits of all parameters in accordance with IS 10500, 1991 and 2012). This limited set of parameters is insufficient to describe the efficiency of a BF system. Furthermore, with only around 31 – 51% of the total domestic sewage generated by major towns and cities in India being treated as of 2009 (CPCB, 2009), and the un- to partially-treated wastewater disposed directly into surface water bodies (Kumar et al., 2014), the various types of pollutants in the source water, their concentrations and distribution are an important aspect for determining the natural attenuation efficiency of the BF system and the post-treatment requirements.

Furthermore, the importance of ascertaining the water quality with regard to organic micropollutants (OMPs), especially in industrially developing and agrarian based countries accompanied with insufficient wastewater treatment capacities such as in India and the resultant escalating potential risk to drinking water production has been elucidated by Schnitzler et al. (2014).

Consequently, a snap-shot screening of various water quality parameters, which included instant physical field parameters, major ions, total coliforms at a few select sites, inorganic elements, dissolved organic carbon (DOC) and 54 OMPs (those of environmental relevance in Europe) in surface water, BF well water and in some case ambient groundwater was conducted for various existing and potential BF sites in India as part of the Saph Pani project.

5.1.2 Methodology

Water samples were collected by the Division of Water Sciences at the HTW Dresden (HTWD) with support from the Saph Pani project partners NIH Roorkee and its regional centres, IIT Roorkee, UJS and UNESCO-IHE, from 28 different locations across India that included the BF case study sites of the Saph Pani project and some other existing and potential BF sites in the states of Bihar, Jharkhand, Andhra Pradesh, Madhya Pradesh, Gujarat and the city of Jammu in the dry pre-monsoon season in May-June 2014 and in the monsoon in June-July 2013.

The temperature, pH, dissolved oxygen and electrical conductivity of the water samples were determined on-site using a WTW multi 3430 instrument. Two 100 mL water samples were collected from each sampling location, one each for DOC and for ions (and inorganic trace elements). All samples were filtered with a 0.45 µm Whatman syringe filter. Subsequently the samples for the determination of DOC were conserved with nitric acid. The samples for ions and other inorganic trace elements were analysed by an ion chromatograph at the Division of General and Inorganic Chemistry at the Faculty of Mechanical Engineering / Process Engineering in the HTWD (HTWD, 2014).

Samples for the analysis of total coliforms (TC) in monsoon (late June 2013) were collected from one BF radial collector well constructed within the riverbed each at three different locations (1 in Andhra Pradesh and 2 in Jharkhand) and were analysed on-site by HTWD using the Colilert-18 method from the company IDEXX.

Samples from two different RBF systems with subsequent conventional treatment were taken in Jharkhand in the pre-monsoon (early June 2014). The samples were analysed for TC, fecal coliforms and E. coli by an accredited environmental engineering laboratory in Ranchi using the multiple tube fermentation technique.

The samples for the OMPs were extracted from 0.5 – 1 L water samples. In total, >120 water samples were collected from locations (in 2013 and 2014) on-site using a mobile solid phase extraction unit with an enrichment by a factor of 1000 (Ullmann, 2013). Subsequently, a target screening analysis of 54 compounds (pharmaceuticals, pesticides and transformation products, antibiotics, medical contrast media, corrosion inhibitors and stimulants such as caffeine), relevant in waters in Europe and North America, with RP-HPLC and ESI-MS/MS (QTRAP) was conducted. The analysis for the OMPs and DOC were analysed in cooperation with the Institute for Water Chemistry at the Dresden University of Technology (Schnitzler et al., 2014; TUD and HTWD, 2014).

5.2 Water quality

5.2.1 Physical parameters and major ions

The instant field parameters and major ions are compiled for 13 selected sites (Table 5-1). These parameters have been discussed in detail for the Saph Pani project case study sites of Haridwar, Srinagar (Uttarakhand), Nainital and Delhi in other Saph Pani work package 1 deliverables in detail and are hence not presented here again. At the sites presented in Table 5-1, the common drinking water treatment technologies are the direct surface water abstraction followed by conventional treatment or BF followed by post-treatment as well as in some cases an alternative source, usually at a private consumer level such as a private groundwater abstraction well or a reverse osmosis filter fitted to the tap receiving water directly from the water works abstracting surface water directly or production well.

Generally at all sampled locations except Mathura and Agra, most of these parameters for surface water that is used as a source for the production of drinking water, lie within the required acceptable limit prescribed by the Indian Standard (IS10500, 2012), and nearly in all cases meet the permissible limit in the absence of an alternate source. Although the pH marginally exceeds the upper limit of 8.5 for some surface waters, this is not critical as the subsequent treatment either conventionally or naturally by BF lowers the pH within the permissible range of 6.5 to 8.5. This also applies to the other physical parameters and major ions.

However the Yamuna River water in Mathura and Agra is characterised by an extremely high salinity (high electrical conductivity - EC) giving the drinking water brackish taste. The stretch of the Yamuna between Delhi and Agra is infamous for its pollution (CSE, 2007) and 85% of the total pollution of the Yamuna is attributed to the discharge of partially-to-untreated domestic sewage (CPCB, 2006). The relatively high EC for surface water at the locations can be attributed the high salinity and sodicity (Table 5-1). In Mathura, the EC of the BF water is slightly lower compared to the Yamuna water, indicating a considerably high portion of bank filtrate in the abstracted water. A household reverse osmosis (RO) apparatus further treats the water for local use by a few persons at the RBF well in Mathura, thereby substantially removing most ions such that the EC is lowered by a factor of 10 (Table 5-1).

In Agra, the groundwater in the city is also characterised by a very high EC (Table 5-1). The high EC is widespread across the city and gives the groundwater a brackish taste. Magnesium and nitrate also exceed the permissible limits for drinking water (Table 5-1). Many households in Agra that rely both on public water supply (originating from groundwater and surface water) and on groundwater abstracted from private production wells, use an RO apparatus if affordable, in order to lower the ionic concentration and as a safeguard against pathogens.

Table 5-1 Field parameters and major ions of source water (surface or groundwater), bank filtrate and drinking water at various locations in India sampled in 2013 and 2014

Location (state), season	Source of water sample	Name of SW body	T_W	pH	DO	EC	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	NO_3^-	SO_4^{2-}
		Treatment	°C	-	mg/L	μS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dehradun (UK), pre-mon. 2014	SW	various rivers	25.0	7.8	n.d.	n.d.	92	38	3.0	1.4	3.4	4.9	301
	DW	SWA	26.0	7.7	n.d.	n.d.	96	40	3.4	1.5	5.2	2.7	343
Jammu (JK), mon. 2013	SW	Tawi	27.0	8.5	n.d.	539	26	5.2	3.9	1.9	<5	<1	<10
	BF	Tawi	21.9	8.3	4.0	591	25	6.7	2.7	0.8	n.d.	<5	<10
Mathura (UP), pre-mon. 2014	SW	Yamuna	30.8	7.9	6.3	**1700**	76	34	199	21	280	14	97
	BF	Yamuna	34.7	7.3	0.1	**1455**	69	29	161	17	215	4.4	69
	DW (BF - small RO)		38.2	**6.4**	1.1	150	2	0.6	17	1.7	15	<1	<5
Agra (UP), pre-mon. 2014	SW	Yamuna	29.6	**8.8**	18.5	**1665**	77	35	206	21	290	22	92
	DW	SWA	30	7.5	0.1	**1645**	73	33	199	20	279	13	97
	GW (private well)		28.5	6.8	3.3	**3400**	121	**116**	372	5.1	661	**74**	353
Bhopal (MP), pre-mon. 2014	SW	Bhopal L.	29.6	8.1	7.1	337	19	7.6	11	2.8	0.2	n.b.	<5
	DW	SWA	30.4	8.1	7.2	257	22	8.2	12	2.5	12	<1	7.2
Daltonganj (JH), pre-mon. 2014	SW	N. Koel	27.7	7.6	5.0	251	22	6.7	17	2.2	5.3	<1	6.8
	BF	N. Koel	31.2	7.6	5.2	272	22	5.9	15	2.0	5.9	<1	8.0
	DW	BF-CT	30.3	7.9	6.9	255	23	6.9	18	2.5	7.1	<1	9.1
Japla (JH), pre-mon. 2014	SW	Son	32.8	**8.6**	8.1	172	16	5.1	9.0	2.1	5.9	<1	11
	BF	Son	32.0	8.5	7.5	177	17	5.2	9.7	7.2	9.5	<1	13
	DW	BF-CT	30.6	8.3	7.0	193	17	4.9	9.3	2.1	5.3	<1	10
Ray Bazaar (JH), pre-mon. 2014	SW	Saphi	37.6	**8.6**	8.8	253	23	6.9	17	2.4	8.8	<1	14
	BF	Saphi	26.8	7.2	4.4	313	29	8.1	19	3.4	11	1.2	14
	DW	BF-CT	29.2	7.9	7.1	325	30	7.8	19	3.8	12	1.1	17
Gumla (JH), pre-mon. 2014	SW	Nagpheri	31.0	8.2	8.1	131	12	3.0	9.5	1.8	5.5	<1	<5
	BF	Nagpheri	30.5	7.5	5.6	135	12	3.0	9.6	2.0	5.5	<1	<5
	DW	BF-CT	30.3	7.3	6.9	141	14	2.7	8.5	2.3	5.2	1.3	8.4
Dhanbad / Jamadoba (JH), pre-mon. 2014	SW	Damodar	34.6	**8.9**	11.8	347	27	12	20	6.3	15	2.1	60
	DW	SWA	34.6	8.1	7.9	371	26	13	20	6.3	15	3.0	61
Gaya (B), mon. 2013	SW	Falgu	36.0	**9.2**	8.1	185	18	5.3	7.8	2.9	6.2	<1	<10
	BF	Falgu	32.0	7.9	n.d.	155	62	17	11	1.9	<5	<1	<10
Anakapalli (AP), mon. 2013	SW	Sarada	31.5	**9.0**	12.5	398	20	18	35	4.5	35	<1	17
	BF	Sarada	30.7	8.1	7.1	540	25	17	29	5.6	33	<1	17
Ahmedabad (GJ), mon. 2013	SW	Sabarmati	30.1	**9.2**	9.6	558	20	8	6.5	1	6.1	<1	<10
	DW	CT-BF/DIS	29.8	**9.1**	12.7	611	21	7.6	6.2	1	6.4	< 1	< 10

Note: Values highlighted in **bold font**: values exceeding the permissible limit in the absence of an alternate source (Indian Standard; IS 10500, 2012) or exceptionally high values for EC resulting in a noticeable saline taste; **Abbreviations:** BF: bank filtration well water; DW: drinking water (after post-treatment / disinfection); GW: groundwater; SW: surface water; SWA: Surface water abstraction followed by conventional treatment; BF-CT: Bank filtration followed by conventional Treatment; DIS: Only disinfection by Chlorination as post-treatment; RO: reverse osmosis; **States:** UP: Uttar Pradesh; UK: Uttarakhand; JH: Jharkhand; B: Bihar; AP: Andhra Pradesh; GJ: Gujarat; **Seasons:** pre-mon. 2014: pre-monsoon (May-June 2014); mon. 2013: monsoon (June-July 2013); n. d.: not determined

5.2.2 Bacteriological indicators

Considering the predominantly hard-rock geology of Jharkhand and parts of Andhra Pradesh and Odisha, with limited horizontal and vertical extent of alluvium confined to the riverbed, near-river areas and in the plains, the existing RBF schemes comprising radial collector wells (RCWs) are thus constructed within the riverbed (Sandhu et al., 2014). According to Sandhu et al. (2014), as the riverbeds consist of medium to coarse sand and gravel and thereby exhibit a suitable hydraulic conductivity for RBF, most of these rivers have a substantial subsurface 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 usually with lower discharges and reduced operating hours. While these RBF systems are one of the only suitable means (in these regions) for the abstraction of water in significant quantities compared to direct surface water or even groundwater abstraction, one disadvantage is the very short travel time of the bank filtrate to the well on account of locating the RCWs within the shallow riverbed alluvium. Consequently, these RBF systems primarily serve to buffer the quantity of water required through bank- / bed-storage, rather than remove pathogens.

In this context, very short travel times result in an insufficient removal of pathogens, especially during monsoon, as was observed in 2013 when the entire channel width of the rivers was inundated by the monsoon flow with a high turbidity. The results of the total coliform (TC) analysis of the RBF RCWs in Andhra Pradesh and Jharkhand confirmed a substantial breakthrough of total coliforms (TC) of >2,400 MPN/100 mL in three RBF RCWs.

However, during the pre-monsoon (2014), the surface water (source water for BF) quality improves substantially in terms of a very low turbidity and much lower bacteriological indicator counts compared to the monsoon. Nevertheless, a breakthrough of bacteriological indicators occurs, albeit in relatively low numbers, not only in the BF RCWs but also in the post treated drinking water (Table 5-2).

Table 5-2 Bacteriological indicator counts for drinking water production systems based on RBF followed by conventional treatment in Jharkhand, June 2014 (pre-monsoon)

Parameter	Bacteriological indicator counts [MPN/100 mL]					
	Site 1			Site 2		
	Surface source water	RBF well water	Drinking water[1]	Surface source water	RBF well water	Drinking water[1]
Total coliform	70	13	27	120	170	11
Fecal coliform	41	8	21	70	94	5
E.coli	17	6	8	21	25	4

1: RBF water is subsequently post-treated by conventional treatment involving aeration, flocculation, rapid sand filtration and lastly disinfection using calcium hypochlorite [$Ca(ClO)_2$] or sodium hypochlorite (NaClO) and then supplied as drinking water

From Table 5-2 it is evident that while at site 1, there is a slight increase in bacteriological indicators in drinking water, on the other hand at site 2 the RBF well exhibits a greater bacteriological indicator count than the river water. At site 1, the water from the RBF well is piped to the conventional water treatment plant at a distance of around 10 km from the well. At the water treatment plant, the RBF water is exposed to the elements as the aeration cascade and flocculators are not covered. Furthermore, there are no designated water sampling points for quality control. Similarly at site 2, there are no adequate sampling points for taking microbiological samples. Thus, the implementation of adequate sanitary and hygienic measures at the water works and RBF well should prevent any potential contamination after abstraction by the RBF well because bacteriological indicator counts in small number of similar magnitude as shown in Table 5-2 can even arise due to a person's contact with water (e.g. by an operator, technician) during routine operation and maintenance procedures at the water treatment plant.

5.2.3 Inorganic elements

In addition to the physical parameters and major ions, a spectrum of 18 inorganic (trace) elements, including trace metals and radionuclides were determined (HTWD, 2014), which comprised iron (Fe), manganese (Mn), strontium (Sr), barium (Ba), zinc (Zn), silicon (Si), chromium (Cr), cobalt (Co), nickel (Ni), copper (Cu), aluminium (Al), selenium (Se), lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), silver (Ag) and nickel (Ni). The objective was to determine if the concentrations of these elements exceeded the drinking water limit and or if the concentrations were unusually high, thereby indicating a possible contamination for instance from industries.

The concentrations of **mainly Fe, Mn and As** exceed the Indian drinking water guideline requirement (acceptable limit; IS 10500, 2012) only in some source waters and occasionally in drinking water, and in some case the permissible limit in the absence of an alternate source (Table 5-3).

Table 5-3 Summary of inorganic elements exceeding acceptable limits (IS 10500, 2012)

Element	Source water	Concentration	Location and remarks
Fe	GW	0.7 - 11 mg/L	**Delhi (central)**, handpumps on East bank of Yamuna R. (Nizamuddin Bridge)
	BF	2 mg/L	**Mathura**, BF RCW within Yamuna R. bed, only in mon. 2013
	SW	0.3 - 1.4 mg/L	**Agra**, Keetham Lake surface water scheme intake & Yamuna R. (d/s city)
Mn	SW, BF & GW	0.2 - 0.6 mg/L	**Delhi** (central), Yamuna R. at Nizamuddin and ITO bridges, handpumps on East bank of Yamuna R. (Nizamuddin Bridge) & 5 BF RCW
	BF	0.6 - 1 mg/L	**Mathura**, BF RCW within Yamuna R. bed, in mon. 2013 & pre-mon. 2014
	GW	0.3 mg/L	**Mathura**, handpump on West bank of Yamuna R. near BF well, in mon. 2013
	GW	1.3 mg/L	**Gaya**, mixed sample from various vertical wells within Falgu riverbed downstream of city (Panchayati Akhara), near main railway bridge, possibly also receiving wastewater, in mon. 2013
	BF & DW	0.4 - 0.9 mg/L	**Ray Bazaar**, BF RCW (0.9 mg/l) within riverbed and subsequently conventionally treated DW (0.4 mg/l), in pre-mon. 2014
	SW	0.2 mg/L	**Chas (Bokaro, Jharkhand)**, Garga River at confluence with Damodar R., receiving substantial amount of wastewater from Bokaro Steel City
	BF	0.2 - 0.3 mg/L	**Nainital,** BF vertical wells number 2 & 4
As	SW	30 µg/L	**Koelwar,** Son River water near sand mining site within river bed
	GW	44 - 66 µg/L	**Delhi,** handpumps on East bank of Yamuna R. (Nizamuddin Bridge)
	GW	20 µg/L	**Mathura**, handpump on West bank of Yamuna R. near BF well, in mon. 2013
	BF	32 µg/L	**Mathura,** BF RCW within Yamuna R. bed, in pre-mon. 2014 only
Al	SW	30 - 40 µg/L	**Coastal Andhra Pradesh,** Godavari, Sarada and Thatpudi rivers
	DW	278 µg/L	**Bhopal,** conventionally treated drinking water from PHED water treatment plant
Zn	GW	6.2 - 7.7 mg/L	**Dehradun,** handpump in Selaqui Industrial Area

Elements: Fe: iron; Mn: manganese; As: arsenic; Al: aluminium; Zn: zinc;
Abbreviations: BF: bank filtrate/filtration; DW: drinking water; GW: groundwater; SW surface water; BF RCW: bank filtration radial collector well; PHED: Public Health and Engineering Department

Fe and Mn are of widespread significance because of their effects on acceptability, but are not a concern to human health. According to the WHO (2011), at concentrations >0.3 mg/L, Fe stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations <0.3 mg/L, although turbidity and colour may develop.

At concentrations >0.1 mg/L, Mn in water supplies causes an undesirable taste in beverages and stains sanitary ware and laundry. The presence of manganese in drinking water, like that of iron, may lead to the accumulation of deposits in the distribution system and at a concentration of 0.2 mg/L, manganese will often form a coating on pipes, which may slough off as a black precipitate (WHO, 2011). Furthermore, Mn is naturally occurring in many surface water and groundwater sources, particularly in anaerobic or low oxidation conditions (WHO, 2011). This could explain its comparatively high concentration especially in the Yamuna River in Delhi (Table 5-3) because of the very high input of wastewater (industrial and domestic) and correspondingly very low dissolved oxygen concentrations of 0.1 – 0.3 mg/L in the river water and groundwater (handpumps). The Indian standard for drinking water (IS 10500, 2012) requires an acceptable limit of 0.1 mg/L and a permissible limit in the absence of an alternate source of 0.3 mg/L. Although for some source waters, the Mn concentration is considerably higher (Table 5-3), according to the WHO (2011) it can be removed by chlorination followed by filtration.

For most BF systems in Jharkhand, the abstracted water from BF RCW in the riverbed subsequently undergoes conventional post-treatment involving rapid sand filtration followed by disinfection using a chlorine-based compound. In this context, the concentration of Mn at the water works in Ray Bazaar (Jharkhand) is lowered from 0.9 mg/L at the BF well to 0.4 mg/L after subsequent conventional post-treatment involving filtration and chlorination. Similarly, the water from the BF RCW in Mathura also undergoes conventional post-treatment.

Arsenic exceeded the required acceptable limit of 10 µg/L for drinking water (IS 10500, 2012; WHO, 2011) in handpumps in Delhi and Mathura (Table 5-3). In the BF RCW in Mathura, arsenic exceeded the Indian guideline acceptable requirement of up to 10 µg/L only in the pre-monsoon 2014, but not in monsoon 2013. The concentration was <50 µg/L limit in the absence of an alternate source. For all other samples, the arsenic concentration was <10 µg/L detectable limit.

Aluminium was found above the detectable limit of 10 µg/L mainly in surface waters, and substantially exceeded (up to 278 µg/L) the acceptable required drinking water guideline value of 30 µg/L (IS 10500, 2012) only in one drinking water sample from the PHED water treatment plant in Bhopal that conventionally treats surface water (from Bhopal Upper Lake), using aluminium-based coagulants (Table 5-3). While the IS 10500 (2012) permissible limit in the absence of an alternate source is 200 µg/L, the WHO (2011) advocates a practicable concentration of ≤100 µg/L for large water treatment facilities using aluminium-based coagulation processes. Otherwise, Al concentrations ≥30 µg/L were mainly found in the sampled rivers of Andhra Pradesh in monsoon 2013 (Table 5-3). The detectable naturally occurring Al in surface water in Andhra Pradesh is probably due to the surface runoff from the substantial bauxite (an aluminium ore) deposits found in the Eastern Ghats (hills) through which these rivers flow. Al concentrations were below the detectable limit of 10 µg/L in most other samples from BF and groundwater production wells and drinking water.

High zinc concentrations (6 - 8 mg/L) were only found in a handpump abstracting groundwater in an industrial area in Dehradun (Table 5-3). Zinc is normally not of a concern to human health at concentrations found in drinking water (≤100 µg/L), but it imparts an undesirable astringent taste to water at a taste threshold concentration of around 4 mg/L (WHO, 2011). However, the Indian standard has prescribed an accepted required limit of 5 mg/L, with a permissible limit of 15 mg/L in the absence of an alternate source (IS 10500, 2012). For other samples, the Zn concentration ranged from mostly below the detectable limit (BDL) of 4 µg/L, up to a maximum of 714 µg/L for a groundwater handpump in Delhi. The Zn concentration in all RBF (except central Delhi) and drinking water samples was <100 µg/L.

Cr, Ni, Cu and Cd were mostly in all samples below their detectable limits of 2, 20, 1 (except 10 µg/L in the production well in Srinagar, 41 and 22 µg/L in the Yamuna R. in Delhi and Mathura respectively, and 10 µg/L in Ranchi Lake) and <3 µg/L respectively and thus did not exceed the IS 10500 (2012) guideline value and as such are not critical to human health. The concentrations of **Se and Pb** were mostly <10 µg/L (or 10 µg/L in a few cases) and <4 µg/L respectively, and thereby also met the Indian guideline value of 10 µg/L for both (IS 10500, 2012). **Hg, Ag and Co** were consistently not detected in any sample.

5.2.4 Dissolved organic carbon

Of all the surface waters sampled, it was found that the stretch of the Yamuna River starting in Central Delhi (ITO Bridge) up to ~200 km downstream in Agra, had the highest concentration of dissolved organic carbon (DOC; Figure 5.1, Figure 5.2) of around 12 mg/L.

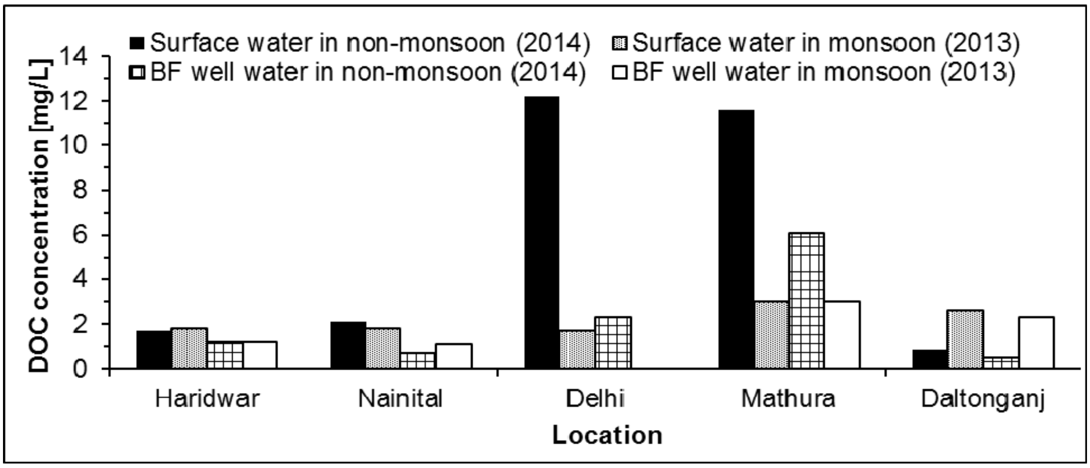

Figure 5.1 Dissolved organic carbon (DOC) concentrations in surface water and water from bank filtration (BF) wells at selected sites in the pre-monsoon and monsoon

In Figure 5.1 it can be observed that the DOC concentrations in the Yamuna R. at Delhi and Mathura are significantly lower during the monsoon in 2013 compared to the pre-monsoon in 2014. The annual monsoon thus has a positive effect on highly polluted surface waters in terms of lowering the DOC concentration by dilution. On the other hand, for surface waters already having a relatively low ambient or background DOC concentration such as observed in Uttarakhand, Jharkhand and Andhra Pradesh, it may even increase during monsoon due to surface runoff.

The DOC concentration in directly abstracted surface water and drinking water derived therefrom by conventional treatment in pre-monsoon 2014 is compared for the cities of Agra, Bhopal (PHED water treatment plant abstracting water from Bhopal Upper Lake) and Dhanbad (Figure 5.2). It is observed that the removal of DOC is comparatively lower to BF systems that are at a completely different location but have similar surface water DOC concentrations (as shown in Figure 5.1). Ranchi Lake water, with a DOC concentration of 13 mg/L (in June 2013), is used for the production of drinking water by direct abstraction and conventional treatment.

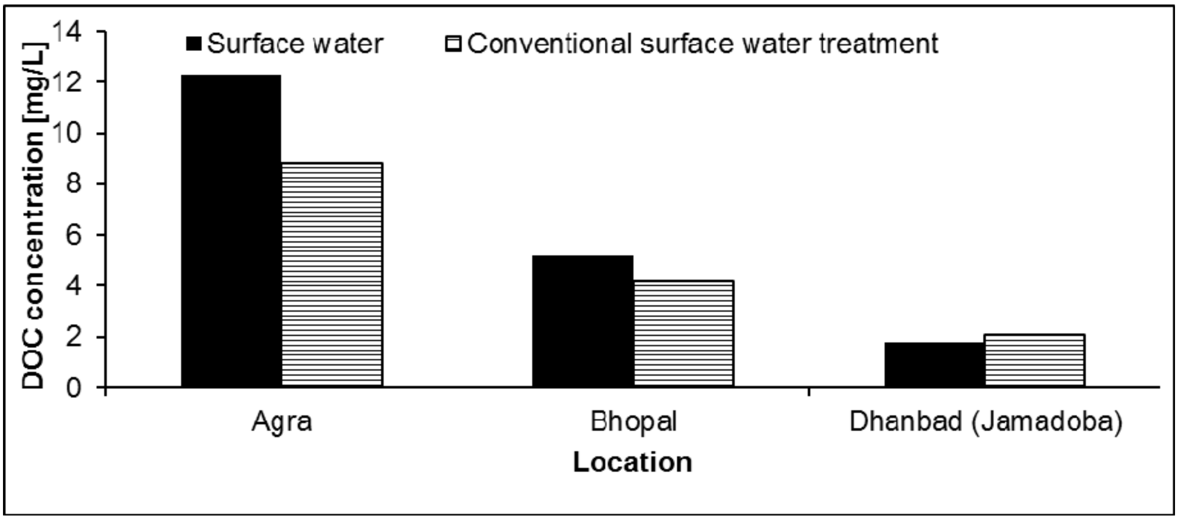

Figure 5.2 **Dissolved organic carbon (DOC) concentrations in surface water and conventionally produced drinking water derived from direct surface water abstraction at select sites**

The DOC concentration in surface water at the BF sites of Haridwar (Ganga R. and Upper Ganga Canal), Srinagar (Alaknanda R.) and Nainital (Nainital Lake) in Uttarakhand, and in the Asan R. that flows past the industrial area in Dehradun city was relatively low at 1.1 to 2.4 mg/L with no significant variation between the pre-monsoon and monsoon seasons. In the corresponding BF wells, the DOC concentrations were 0.4 to 2.3 mg/L and generally lower than the respective surface water, except for one BF well in Haridwar and Srinagar that had slightly higher DOC concentrations (compared to their surface water sources) of 2.5 and 2.7 mg/L respectively. The higher DOC concentration in the BF well in Haridwar can be attributed to human activities, such as washing and bathing, that take place at the well.

At the BF sites of Daltonganj (North Koel R.), Gumla (Nagpheri R.), Ray Bazaar (Saphi Nadi R.) and Japla (Son R.) in Jharkhand, the surface water and water from the BF wells contained DOC in the range of 0.9 to 3 mg/L and mostly 0.5 to 1.7 mg/L respectively, with higher DOC observed in monsoon (Figure 5.1). The water from two wells showed exceptionally higher DOC of 2.7 and 3 mg/L. However, while these BF sites are generally affected by low surface water pollution on account of them being located mostly in the upstream areas of the towns and the impact of anthropogenic activities (large-scale agricultural and industrial activities) is low, the observed DOC removal is generally low due to the very short travel time of the bank filtrate to the wells (section 5.2.2).

In the rivers Sarada, Tandava and Godavari in coastal Andhra Pradesh between Visakhapatnam and Rajahmundry, surface water DOC in monsoon (June 2013) was higher at 3 to 4.6 mg/L. At the BF system in Anakapalli, DOC was 3 mg/L.

In monsoon 2013 at other locations in India, the DOC in surface water in Gaya (Falgu R.), Patna (Ganga R.), Koelwar (Son R.) and Ahmedabad (Sabarmati R.) was 1.9 to 2.3 mg/L and 3.2 to 3.8 mg/L upstream and downstream respectively of the Tawi R. in Jammu, with lower concentrations of 0.9 to 1.5 mg/L in the BF and groundwater abstraction wells. In these towns, the BF systems are also located in the upstream areas and consequently the lower anthropogenic impact is noticeable.

However, two different BF site examples to those discussed previously, are in Daltonganj and Gaya, where the BF wells have been inappropriately sited within the riverbed and downstream of the towns such that they are directly impacted by wastewater discharged locally or upstream. Consequently, not only is the DOC concentration in the surface water higher, but due to the discharge and accumulation of domestic wastewater directly at and around the wells, which can also be potentially contaminated by flood water, the DOC concentration in the abstracted well-water is nearly 4 mg/L.

5.2.5 Organic micropollutants

Similar to the highest DOC concentrations found in the Yamuna R. water between Delhi and Agra, the highest occurrence and nearly also highest concentrations of organic micropollutants (OMPs) comprising pharmaceutical, medical contrast media, personal care products, corrosion inhibitor, insecticide and herbicide compounds is also found along this stretch in the river water and also partly in the BF RCW in Mathura and handpumps located near the river (groundwater).

The removal efficiency of OMPs by BF can be demonstrated by taking the Mathura BF site as an example where the Yamuna River has comparably (to Delhi and Agra) high concentrations of OMPs (Figure 5.3). Consequently, the concentrations of some OMPs in the BF well water were 13 – 99% lower than river water (RCW design, fast travel time), whereas others were not present in well water. On the other hand, most of the 54 OMPs were either not present or only detectable in very low concentrations for very few OMPs in the surface water in Haridwar, Srinagar and Nainital in Uttarakhand and in Gumla, Ray

Bazaar and Daltonganj in Jharkhand (Chapter 2, Table 2.1; Sandhu et al., 2014), whereas none were detectable in the BF wells at these sites.

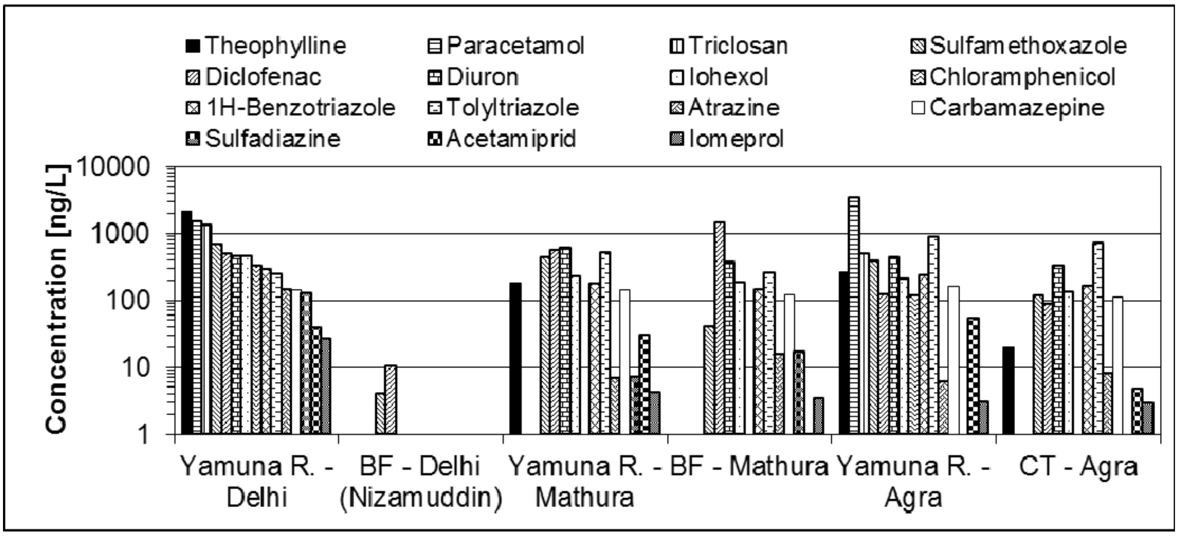

Figure 5.3 **Median concentrations of OMPs in surface water, bank filtrate (BF) and conventionally treated (CT) drinking water**

Amongst the herbicides, atrazine was found in the Yamuna region in relatively higher concentrations of up to 153 ng/L in the river water, but was significantly removed by BF to a concentration of 16 ng/L in Mathura and not found in the investigated RCW in Delhi. In comparison, at the BF site of the town of Japla (surrounded by predominantly agricultural areas) in Jharkhand, atrazine was found in surface, bank filtrate (RCW) and subsequently conventionally treated water with a concentration of 13 – 14 ng/L indicating no substantial removal most likely on account of the very short travel time of the bank filtrate due to the shallow RCW design of the wells.

Further to the East, in the more industrialised and densely populated area of Jharkhand, mainly a wide range of pharmaceutical compounds (paracetamol, sulfamethoxazole, phenazone, diclofenac, theophylline, tolyltrizole and carbamazepine), contrast media (iohexol) and the herbicide diuron were found in concentrations ranging from 40 to 146 ng/L in the Garga R. near the town of Chas (where it joins the Damodar R.) that predominantly contains wastewater from the industrial city of Bokaro. A few kilometres downstream, in the Damodar R. water where it is abstracted directly for the production of drinking water for the city of Dhanbad, only iohexol, tolyltrizole, sulfamethoxazole and paracetamol could still be found in the surface water in concentrations of 10 – 77 ng/L. In the treated drinking water derived thereof, only sulfamethoxazole and iohexol (7 – 10 ng/L) and tolyltrizole (67 ng/L) were still found but in relatively similar concentrations to surface water thereby indicating on one hand no significant removal by conventional treatment but on the other hand indicating a natural removal of the other compounds within the river water by degradation and/or dilution.

Although at considerably lower concentrations to the Yamuna R. water, diuron was also found in Nainital Lake water in concentrations ranging from 70 – 112 ng/L, but not found in the water abstracted by the BF wells. Out of the pharmaceuticals paracetamol, sulfamethoxazole and theophylline found in the lake water in concentrations of 5 – 105 ng/L, only sulfamethoxazole could be determined in the BF well water in very low concentrations of 5 – 9 ng/L, similar to those found in lake water.

No OMPs, or if at all then mainly pharmaceuticals (carbamazepine, theophylline, triclosan, paracetamol) in insignificantly low concentrations, were found in the BF wells in Haridwar, drinking water from the conventional treatment plant in Dehradun, water from BF wells in Gumla, Ray Bazaar and Daltonganj and conventionally treated surface water from the Bharaka R. in Dhanbad in Jharkhand, most BF wells and drinking water in Nainital in Uttarakhand and one RCW in Delhi.

6 Summary and conclusions

Studies on the economic aspects of BF systems in India, especially in relation to their environmental and human health benefits in comparison to other existing abstraction and treatment methods for drinking water production for the same urban area (town or city), are rare. Past experience has shown that there is a significant demand for a comparison of the costs and benefits of BF systems in comparison to typical surface water abstraction and conventional treatment systems in India. In this context, the objective was to collect information on costs available for at least two bank filtration (BF) case study sites of the Saph Pani project, for which information was also available for at least one existing alternative method for the production of drinking water. Furthermore, it was necessary to supplement this information with water quality and system design information of BF systems operating under diverse hydro-climatic conditions at various existing and potential locations in India. The objective of the latter is to obtain a broader overview, and simultaneously to extend the database of relevant pollutants in urban areas and their attenuation at BF sites (Deliverable D1.1) and on the present post-treatment conducted and future post-treatment requirements at BF sites in India (work package 4).

With these objectives, information on the capital and operating expenditures (capex and opex) were collected for the BF sites of Haridwar by the Ganga River and Srinagar by the Alaknanda River (state of Uttarakhand in northern India) and compared to the capex of existing groundwater abstraction in Haridwar and capex and opex of direct surface water abstraction followed by conventional treatment in Srinagar. Subsequently, the indicative cost per cubic meter of water is calculated for the different methods used to produce drinking water. The environmental and human health benefits of improved water quality and sustainable quantity relative to direct surface water and even groundwater abstraction are discussed. Furthermore, a snap-shot screening of various water quality parameters, including instant physical field parameters, major ions, total coliforms at a few select sites, inorganic elements, dissolved organic carbon (DOC) and 54 organic micropollutants (OMPs) in surface water, BF well water and in some case ambient groundwater was conducted for various existing and potential BF sites in India as part of the Saph Pani project.

The indicative production cost of drinking water in Haridwar and Srinagar was calculated at 0.09 and 0.06 €/m^3 respectively, although for different types of BF systems, these costs are still considerably lower compared to the indicative cost of direct abstraction of surface water followed by conventional treatment at 0.32 €/m^3 (Table 6-1), and lies within the range of 0.03 – 0.17 €/m^3 as reported by Sharma et al. (2012) for a feasibility study on BF for five locations in Africa. The main health benefit of BF in Srinagar and Haridwar is the removal of total thermotolerant coliforms of 2.1 to 4.4 log$_{10}$ that is attributed to relatively superior surface water quality and suitable hydrogeological conditions (Sandhu et al., 2014). The main environmental benefit lies in the year-round uninterrupted abstraction by the BF wells on account of their siting between surface water boundaries (Ganga R. and Upper Ganga Canal) that ensures a sustainable recharge of water to the wells (Saph Pani

D5.3, 2014). In general, when the source water quality and local hydrogeological conditions are favourable, BF is the cheapest and most effective method of water treatment for developing countries requiring no or minimal post-treatment (Sharma et al., 2014).

Table 6-1 Comparative and indicative per cubic meter production cost of drinking water

Opex component	Unit-cost of drinking water production [€/m^3]		
	BF system in Haridwar[1]	BF system in Srinagar[2]	SWA-CT system in Srinagar[3]
Personnel	0.02	0.01	0.02
Annual repair and maintenance including consumables (for disinfection / post-treatment)	0.01	0.01	0.09
Electricity	0.04	0.02	0.08
Debt service and depreciation[4]	0.02	0.02	0.13
Total	0.09	0.06	0.32

[1] 22 large-diameter wells BF system in Haridwar with a total average drinking water production of ~61,000 m^3/day; [2] 200 mm diameter single vertical well BF system with an average drinking water production of ~900 m^3/day; [3] direct surface water abstraction followed by conventional treatment system with an average drinking water production of 2,000 m^3/day; [4] debt service and depreciation at 20% and 2% respectively of total capital cost

The Yamuna R. water quality between Delhi and Agra was observed to have the highest organic pollution (concentration of dissolved organic carbon and organic micropollutants) and the surface as well as groundwater is characterised by an extremely high salinity (high electrical conductivity - EC) giving the drinking water derived thereof brackish taste. However, the concentrations of some OMPs in the BF well water were 13 – 99% and DOC was 50% lower than in river water. The removal of DOC and some OMPs by BF is considerably greater compared to direct surface water abstraction and subsequent conventional treatment (e.g. in Agra). Nevertheless for the BF system in Mathura, the main benefit of BF lies in the cost-effective removal of organic contaminants, colour, UV-absorbance and TTC are removed by around 50% and is thus a vital pre-treatment step to the necessary post-treatment by aeration, filtration and disinfection (Kumar et al., 2012). Furthermore, 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 byproducts do not build up in the treated water.

At most BF locations in Uttarakhand, Jharkhand, Andhra Pradesh, Bihar and Jammu, surface water quality is generally good with respect to all inorganic parameters, although bacteriological indicators are present in highly variable numbers. The BF sites in Uttarakhand are mainly advantageous due to the very high removal of bacteriological indicators and turbidity especially in monsoon. The design and location of the radial collector wells (RCWs) in Jharkhand and Andhra Pradesh within the riverbed ensures the year-round abstraction of water, even during the pre-monsoon when very low to negligible surface water flow is observed (Sandhu et al., 2014). Accordingly, as a result they are less prone to the shifting river courses compared to surface water abstraction structures.

However, the travel time of bank filtrate for such riverbed RCW systems is too short and thus breakthroughs of pathogens and turbidity occur in high numbers especially in monsoon and the removal of organics is also lower. One advantage at these locations is that the surface water itself has relatively low concentrations of DOC and OMPs. Iron and manganese can also occur in the abstracted water from such systems. Thus the bank filtrate subsequently undergoes post-treatment comprising aeration, flocculation, rapid sand filtration and disinfection. According to Sandhu et al. (2014), in some coastal and peninsular (hard rock) areas of India (Jharkhand, Odisha, Andhra Pradesh and Tamil Nadu), BF is the only viable means of obtaining water compared to direct surface water or even groundwater, and 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.

Acknowledgements

All information and data contained within this deliverable (D1.4) was collected and analysed within the project “Saph Pani - Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India” (www.saphpani.eu), co-funded by the European Commission (grant agreement no. 282911). The authors are especially grateful to Dr. N. C. Ghosh of the Saph Pani project partner National Institute of Hydrology (NIH) Roorkee and Mr. B. Chakraborty, Mr. M. Nema, Dr. Y.R.S. Rao and Mr. T. Thomas of the NIH regional centres in Patna (Bihar), Jammu, Kakinada (Andhra Pradesh) and Bhopal (Madhya Pradesh) respectively, and Prof. P. Kumar, Mr. M. Ronghang, Ms. S. Kumari and Dr. A. Gupta of the Saph Pani project partner Indian Institute of Technology Roorkee (Environmental Engineering Section at the Department of Civil Engineering), as well as Dr. Prashant Singh and Mr. Manindra Mohan of D.A.V. (P.G.) College Dehradun for making arrangements for site visits and assisting with the sample collection. Furthermore the help of Prof. Anupam K. Singh from JK Lakshmipat University in Jaipur, formerly at the Pandit Deendayal Petroleum University in Gandhinagar (Gujarat), for conducting sampling in Ahmedabad and the Uttarakhand State Water Supply and Sewerage Organisation in Haridwar and Srinagar and Drinking Water and Sanitation Department (DWSD) of Jharkhand, especially Mr. D. K. Singh, Mr. R. K. Rohila, Mr. P. K. Saini, Mr. S. Prasad, Mr. P. K. Singh and Mr. S. K. Dawn, is gratefully appreciated. The assistance of Mr. A. Gulati of the Saph Pani project partner Akshay Jaldhara for providing information on the cost of construction of wells is also kindly acknowledged.

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Annexes

Annex 1 Mean discharge of bank filtration wells in Haridwar (Sandhu, 2014)

Well No.	Location	Mean discharge [m^3/hour]	Monsoon (July – September)		Pre- & post-monsoon (October – June)	
			Mean duration of operation [hours/day]	Mean daily discharge [m^3/day]	Mean duration of operation [hours/day]	Mean daily discharge [m^3/day]
31	Bhopatwala	229.9 [b]	20	4598	10	2299
27	Bhopatwala	118.8 [b]	20	2375	14	1663
4	Bhopatwala	100.8 [b]	20	2016	20	2016
2	Bhopatwala	213.0 [c]	20	4259	10	2130
3	Bhopatwala	170.1 [c]	20	3401	20	3401
1	Bhopatwala	176.3 [c]	20	3526	20	3526
26	Bhopatwala	102.0 [a]	16	1632	16	1632
16	Bhopatwala	108.0 [d]	12	1296	12	1296
18	Pantdweep	134.3 [c]	10	1343	10	1343
PD2	Pantdweep	120.0 [d]	10	1200	10	1200
PD1	Pantdweep	65.7 [c]	12	789	12	789
40	Pantdweep	109.6 [c]	22	2412	22	2412
25	R. Belwala	177.9 [c]	22	3913	15	2668
24	R. Belwala	202.6 [c]	23	4660	15	3039
43	R. Belwala	132.9 [c]	22	2924	22	2924
42	R. Belwala	110.7 [b]	22	2435	22	2435
44	Vishnu Ghat	127.0 [c]	24	3049	24	3049
17	Lalta Rao	327.2 [c]	23	7526	23	7526
21	Alaknanda	108.0 [c]	16	3344	16	3344
49	B. Camp	108.0 [a]	23	2484	23	2484
29	B. Camp	149.7 [c]	23	3443	23	3443
28	M. Milan	209.4 [c]	23	4815	23	4815
			Mean total daily discharge	**67,440 m^3**		**59,434 m^3**
Weighted mean year-round total daily discharge = ((67440 m^3/day×92 days) + (59434 m^3/day×273 days)) ÷ 365				**61,452 m^3**	(~61,000 m^3)	
a: discharge provided by UJS in 2006; b, c: discharge measured using an ultrasonic flowmeter in 12/2012 and 10/2013 respectively; d: adapted from UJS (2006)						