Training Course on
Bank Filtration for Sustainable Drinking Water Supply in India

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Course Module

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1 Introduction

Throughout the world governments have failed in the attempt to protect rivers from pollutions. As a consequence water supply for drinking as well as irrigation directly from the river has become a rather hazardous and dangerous affair.

Groundwater appeared to be the obvious alternative together with intensive treatment. Costs can be enormous and furthermore, the depletion of groundwater resources is a common feature where water is most urgently needed.

By contrast, bank filtration wells located close to the river (or a lake) are generally shallow and therefore cheaper to build. During filtration the natural treatment process significantly improves the water quality, in some cases to an extent that very little post treatment other than chlorination is required.

The technology is not a new invention but has been successfully applied across the world for over 100 years. As the demand for drinking water in particular in developing countries is soaring up, the technology has seen rising interest in recent years.

This course material is meant to help the interested reader to gain an understanding of the bank filtration process (Section 2) and some of the more technical aspects such as the investigation of potential sites for BF wells (Section 3). The understanding of the principles is supported by the introduction into modelling techniques and the analysis and interpretation of model results (Section 4). Water quality aspects in particular pathogens are discussed in Section 5. The BF sites of Srinagar (Alaknanda River, India), Haridwar (Ganga River, India) and Düsseldorf (Rhine River, Germany), on which parts of this course material are based, are described in Section 6.

Where possible the material presented makes intensive use of data, investigations and results from existing sites. Details of the individual sites are given in Section 6 which should be consulted to enable a better understanding of the examples used.

The majority of the material used for this course has been developed during the work on various research projects including ‘Saph Pani – Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India’. Other material has been added as appropriate.

Where material from other sources has been used this is clearly stated and the sources and respective references are given.

2 Bank filtration – Overview

2.1 Process

Riverbank filtration (RBF) or simply bank filtration (BF, a unified term for river and lake bank / bed filtration) can occur under natural conditions or be induced by lowering the groundwater table below the surface water level by abstraction from adjacent boreholes. Figure 2-1 shows the typical flow conditions. For the quantitative and qualitative management of bank filtration systems, the catchment zones, infiltration zones, mixing proportions in the pumped raw water, flow paths and flow velocities of the bank filtrate need to be known. Flow conditions during bank filtration are commonly described using interpretations of water level measurements and hydrogeological modelling.

The success of RBF schemes is dependent on the microbial activity and chemical transformations that are commonly enhanced in the clogging layer within the river bed compared to those that take place in surface or ground waters. The actual biogeochemical interactions that sustain the quality of the pumped bank filtrate depend on numerous factors including aquifer mineralogy, shape of the aquifer, oxygen and nitrate concentrations in the surface water, types of organic matter in the surface and ground water environments and land use in the local catchment area.

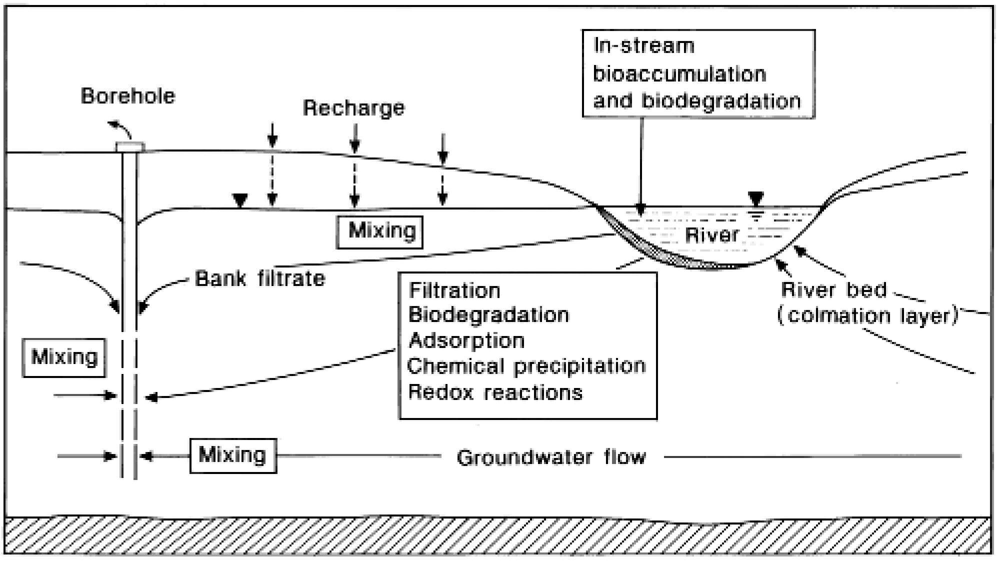


Figure 2-1 Schematic diagram of processes affecting water quality during bank filtration (Hiscock & Grischek, 2002)

2.2 Applications

In many countries of the world, alluvial aquifers hydraulically connected to a water course are preferred sites for drinking water production given the relative ease of shallow groundwater exploitation, the generally high production capacity and the proximity to demand areas. Although proximity to a river can ensure significantly higher recharge and pumping rates, water quality problems may be encountered during exploitation of river bank well-fields. Even with these problems, groundwater derived from infiltrating river water provides 50% of potable supplies in the Slovak Republic, 45% in Hungary, 16% in Germany and 5% in The Netherlands. In Germany, the City of Berlin depends to 75% on bank filtration while Düsseldorf, situated on the Rhine, has been using river bank filtration since 1870; with bank filtration as the most important source for public water supply in this densely populated and industrialised region.

In the United States, the water supply industry has adopted the broadly-defined regulatory concept of "*groundwater under the direct influence of surface water".* Increased exploitation of water from alluvial aquifers along river banks is expected in the US in the future, given the rise in demand for drinking water, the ease of abstraction and the positive effects of bank filtration on the quality of the infiltrating surface water.

2.3 Advantages and Disadvantages

Generally bank filtration is a natural, sustainable and low cost technology. Pathogens and organics can be effectively removed and there is the potential to compensate shock loads. In many cases disinfection is sufficient to ensure a safe drinking water supply.

Figure 2-1 shows schematically the attenuation processes that are known from various bank filtration sites. Compared with surface water abstraction, bank filtration with its effective natural attenuation processes has the following advantages:

- Elimination of suspended solids, particles, biodegradable compounds, bacteria, viruses and parasites;
- Partial elimination of adsorbable compounds and
- Equilibration of temperature changes and concentrations of dissolved constituents.

Undesirable effects of bank filtration on water quality can include

- increases in hardness, ammonium and dissolved iron and manganese concentrations and
- the formation of hydrogen sulphide and other malodorous sulphur compounds as a result of changing redox conditions.

2.4 Riverbank filtration examples from Dresden, Germany

Grischek et al. (2011) describe the development and current application of RBF in the German city of Dresden.

Dresden, the capital of the federal state of Saxony, Germany, has half a million inhabitants. The city is situated in a rift valley along the Elbe River, which is mainly filled with glacial deposits consisting of gravels and coarse sands with a thickness of about 15 m and a hydraulic conductivity ranging from 0.6 - 2×10^{-3} m/s. The Quaternary aquifer is in direct hydraulic contact with the Elbe River. In Dresden, the flow of the Elbe River ranges from 100 - 4,500 m^3/s with a mean of about 300 m^3/s. In general groundwater exfiltrates from both sides of the valley into the river.

Groundwater resources around the city were not sufficient for drinking water supply for the growing city during the 19th century. The river water quality was not sufficient for drinking because pathogens in river water had caused waterborne diseases. Two options were identified to increase the amount of water available for the city. The first option was the installation of wells along the river to use RBF to remove pathogens. The second option was to construct large reservoirs in the mountains and to transport the water to the city.

After good experience with the first RBF waterworks Dresden-Saloppe, production wells and a siphon pipe were constructed for the waterworks Dresden-Tolkewitz in 1896. The system was extended in 1901 and 1919 by two more siphon pipes to cover the continuously increasing water demand. Figure 2-2 shows the final system of pipes with a total of 72 wells. During intensive reconstruction works after 1989, only four wells had to be replaced.

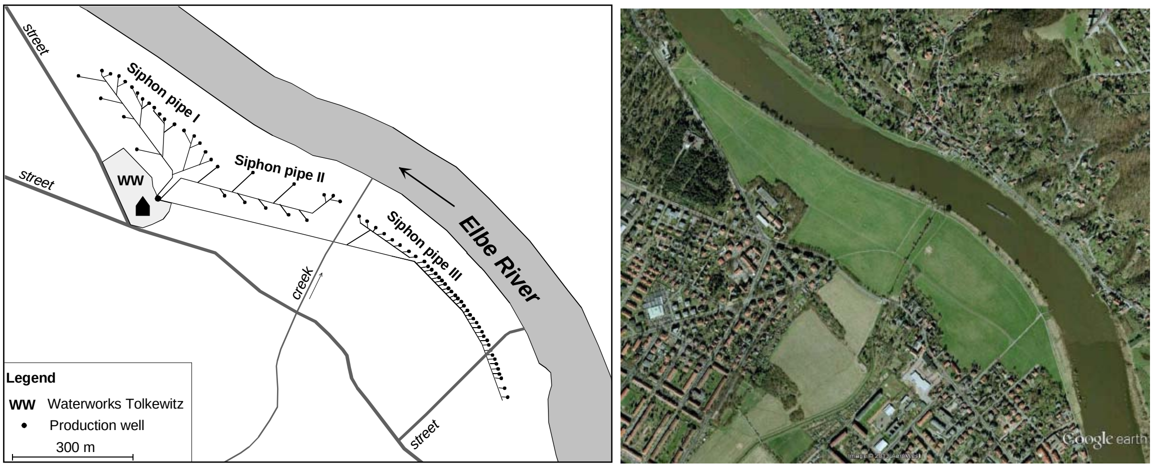


Figure 2-2 Location map of the bank filtration scheme of waterworks Dresden-Tolkewitz (Grischek et al., 2011) and satellite view on location (Source: Google earth)

Today, the waterworks is still abstracting raw water from 72 wells using the original siphon pipe system. The three pipes connect one collector well (with a pump) with the vacuum well galleries. No further pumps are installed in the wells. The maximum capacity is now 35,000 m^3/d. Later a third RBF waterworks was constructed in Dresden-Hosterwitz. The raw water quality and treatment at waterworks Dresden-Tolkewitz can be optimized by various variables, e. g. by managing specific mixing ratios of bank filtrate and land-side groundwater. Pumping rates were reduced to get longer retention times in the aquifer and higher attenuation rates of organic compounds. No indication of a decrease in attenuation capacity of the aquifer with time has been observed for a >20 years long monitoring period.

In contrast to other countries, the water demand in Germany is decreasing now demanding optimisation of management of RBF sites. The water demand in Dresden has been decreasing since 1991 as the result of a new price system and water saving measures and the close-down of some industries. Nowadays, a certain volume of water is continuously pumped to enhance stable redox conditions in the aquifer between the river and the wells. This also ensures stable mixing ratios of bank filtrate, having low nitrate and sulphate concentrations, and land-side groundwater, which has high nitrate and sulphate concentrations.

Even during periods of lower water demand, RBF waterworks are operated in Dresden to have two independent sources for water supply: RBF and reservoir water. At present, public water supply in Dresden is based upon 72 % surface water from reservoirs, 20% bank filtrate from Elbe River and artificial recharge and 8 % groundwater abstraction. Long-term experiences and results of the evaluation of historic and recent data and of investigations using modern modelling tools prove that riverbank filtration is a sustainable water resource for water supply in Dresden.

3 Bank filtration - site investigation, assessment & well operation

3.1 Site investigation

3.1.1 Geological analyses

The investigation of the underground forms the basis for assessing the suitability of a particular site for riverbank filtration:

- The clogging layer plays an important role in eliminating pathogens on the one hand but leads to the reduction of water abstraction (due to lower infiltration rates) on the other hand. An appropriate balance has to be found meeting both demands.
- Percolating contamination from the surface through seepage of wastewater has to be avoided in any case. Areas with shallow groundwater table have to be treated with caution and source protection areas should be defined in the hinterland (restricted land use, sewer pipelines, etc.).
- As sufficient travel time is crucial for allowing effective purification, minimum set back distances have to be guaranteed and preferential (fast) transport paths (fractures and coarse material) should be limited.

3.1.2 Surface water quality data review

The microbiological surface water quality can vary due to variances in socio-economic conditions (i.e. population, infrastructure, land use) and environmental factors (e.g. terrain, climate). The higher the quantities of untreated or insufficiently treated wastewater discarded into a river, the higher is the resulting organic and microbial load of the surface water.

Warmer climates lead to increased microbial activity whereby the natural self-purification of the river is enhanced. Additionally, natural mortality increases with increasing temperature.

However, adsorption of pathogens as an important removal process during riverbank filtration is not favoured by higher temperatures and elevated DOC levels. Organic substances compete with the pathogens for attachment sites.

Hence, the water quality (components and temperature) at potential RBF sites has to be individually evaluated and analysed in the context of the other site characteristics, in particular the geology.

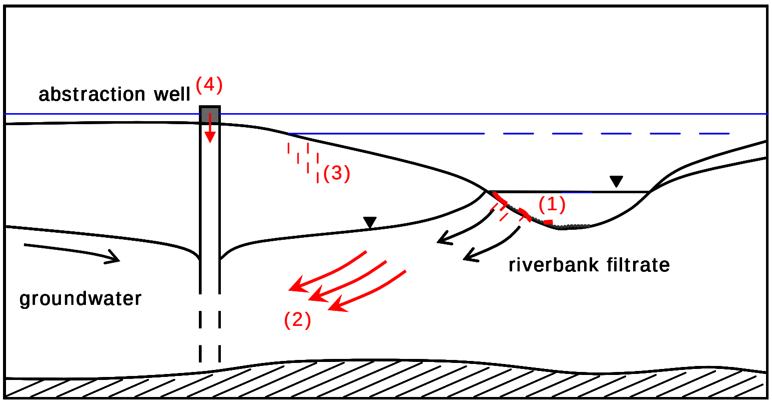
3.1.3 Hydrologic assessment

The hydrological regime of the river and its fluctuations has a major impact on the RBF performance in terms of scouring of the riverbed, travel time of the bank filtrate and removal efficiencies of contaminants and pathogens, as well as risk to wells from eventual floods. The range of river flow and the frequency of low as well as high flow conditions have to be assessed when identifying potential RBF sites and developing the site design.

A flood risk assessment should be carried out in order to ensure the abstracted water is safe during such extreme conditions. This is particularly the case as during floods the water quality can deteriorate e.g. due to wastewater treatment plant overload and/or failure, flooded urban area, overflowing sewers and rain-caused run-off from agricultural lands and any contamination of the drinking water needs to be avoided. At the same time, the performance of RBF might undergo deteriorations.

Figure 3-1 shows the main changes that might occur under flood conditions. The clogging layer which plays a key role in retaining pathogens might be damaged due to the shear forces (1, Figure 3-1). The elevated water level leads to an increased pressure gradient affecting travel times and removal processes, e.g. adsorption (2, Figure 3-1). Enlarged river outreaches and possibly even a changed river course might cause additional vertical percolation into previously unsaturated sediments which lack the removal capacities of adapted areas (3, Figure 3-1). The direct intrusion of surface water into the well has in any case to be prevented by a proper installation (4, Figure 3-1).

As flooding in connection with deteriorating river water quality is a major risk to the water supply from RBF sites, the topic has been treated in more detail in Section 3.3 where an example is also discussed and some practical solutions are given.



(1) Clogging layer

(2) Pressure gradient

(3) Unsaturated regions

(4) Flooding of the well

Figure 3-1 Changed RBF processes under flood conditions (Syhre et al., 2009)

3.1.4 Groundwater flow and transport modelling

Modelling can be employed to help understand the site conditions and groundwater dynamics and allow conclusions as to the suitability of a particular site.

Modelling, however, requires input information and the quality and reliability of the results heavily depends on the input information.

More details are given in Section 4.

3.1.5 Key characteristics of BF sites

Grischek et al. (2007) give a summary of the key characteristics of a potentially successful RBF site based on the review of numerous RBF operations and site characteristics. From their review they concluded that:

- the site is typically located at the mid-reaches of the river,

- the location at an inner bend of a meander is an advantage,
- flow velocity of >1 m/s and a shear stress of <5 N/m^2 helps avoid clogging of the river bed,
- the thickness of the aquifer is typically >10 m,
- the aquifer conductivity ranges between 10^{-2} and 10^{-4} m/s and
- infiltration rates <0.2 $m^3/m^2/d$ are to be preferred.

These parameters should be used as indicative parameters as RBF can be used for a wide variety of conditions. On the other hand there might be conditions such as insufficient oxygen concentration available in the river water which could limit the application of the BF technique at a particular location.

3.2 Assessment

3.2.1 Pumping test

Once the construction of the well has been completed, the well must be developed. This includes a pumping test to further assess the characteristics of the well and ensure it will meet the estimated production and to establish the optimum dimensions of the pump.

As with any other pumping test, the pumping tests at RBF sites are carried out to estimate hydraulic properties of the aquifer system also. The following parameters can be established:

- Transmissivity,
- Hydraulic conductivity and
- Storativity (storage coefficient).

Pumping tests can also identify and locate recharge and no-flow boundaries that may limit the lateral extent of aquifers.

During the test the well is pumped at a controlled rate that is frequently monitored. The water level response (drawdown) in one or more surrounding observation wells and optionally in the pumped well (control well) itself is measured.

3.2.2 Monitoring

Post construction monitoring at each RBF site should be carried out on a regular basis to ensure quantity and quality of the abstracted water meet the targets and to identify problems.

3.2.3 Example - pumping test at Srinagar, India

In November 2011 a pumping test at one of the RBF wells at Srinagar was carried out to assess the actual productivity of the well and the efficiency of the pump and also to more accurately establish the hydraulic parameters (HTWD and UJS, 2012a).

Details of the RBF site at Srinagar, India are given in Section 6.1. A location map is shown in Figure 3-2 below. The three wells (DST, Monitoring Well (MW) and Central Ground water Board (CGWB)) where the test was carried out are enclosed in a red rectangle. MW and CGWB were used for monitoring; pumping took place in the DST well.

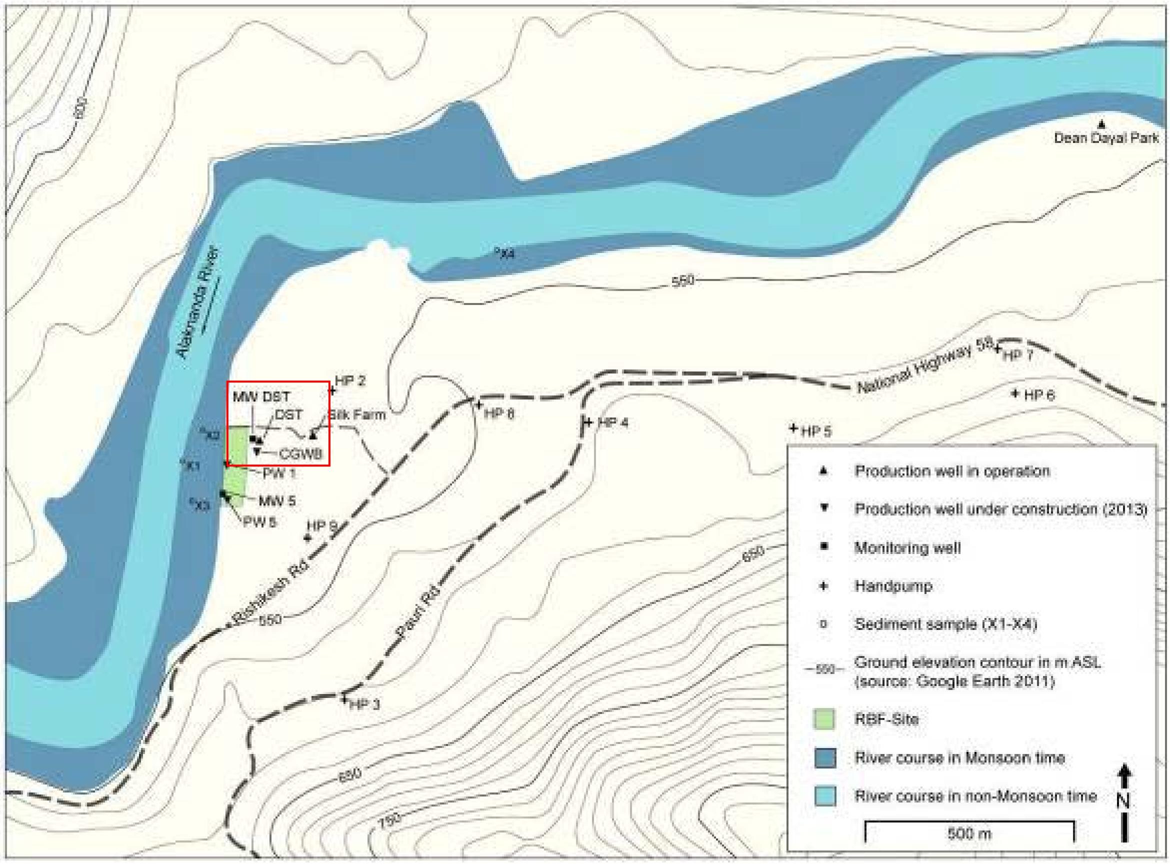


Figure 3-2 Location of pumping test wells at Srinagar (Saph Pani, 2013)

The pumping test was carried out with a constant discharge of 710 l/min. A pressure transducer (Diver) was used to measure the water level in the well. The air pressure was measured in parallel (Baro-Diver) to allow the corrections of levels considering that a nonvented transducer was used.

Water levels and air pressure were measured every 10 seconds. Prior to the test, pumping was suspended for eight hours to allow establish the groundwater level at rest. After the test had been finished it was noted that the levels had risen higher than the assumed rest water level and consequently this level was used as reference level.

The continuous pumping took place for a period of 24 hours. After 24 hours the pump was switched-off and the resulting rising of the water levels (residual drawdown) was recorded.

Figure 3-3 shows the development of the water level in the two monitoring wells.

The maximum observed draw down was 1.72 m at MW und 1.59 m at CGWB located further away from DST.

After approximately 10 hours there is no further draw down and the water level remains constant until the pump was switched off (note: the sudden drop in level at 7 hours and 22 hours is due to an uncontrolled increase in the pumping rate probably as a result of a change in pressure in the water supply pipes or voltage surge in the electricity supply to the pumps).

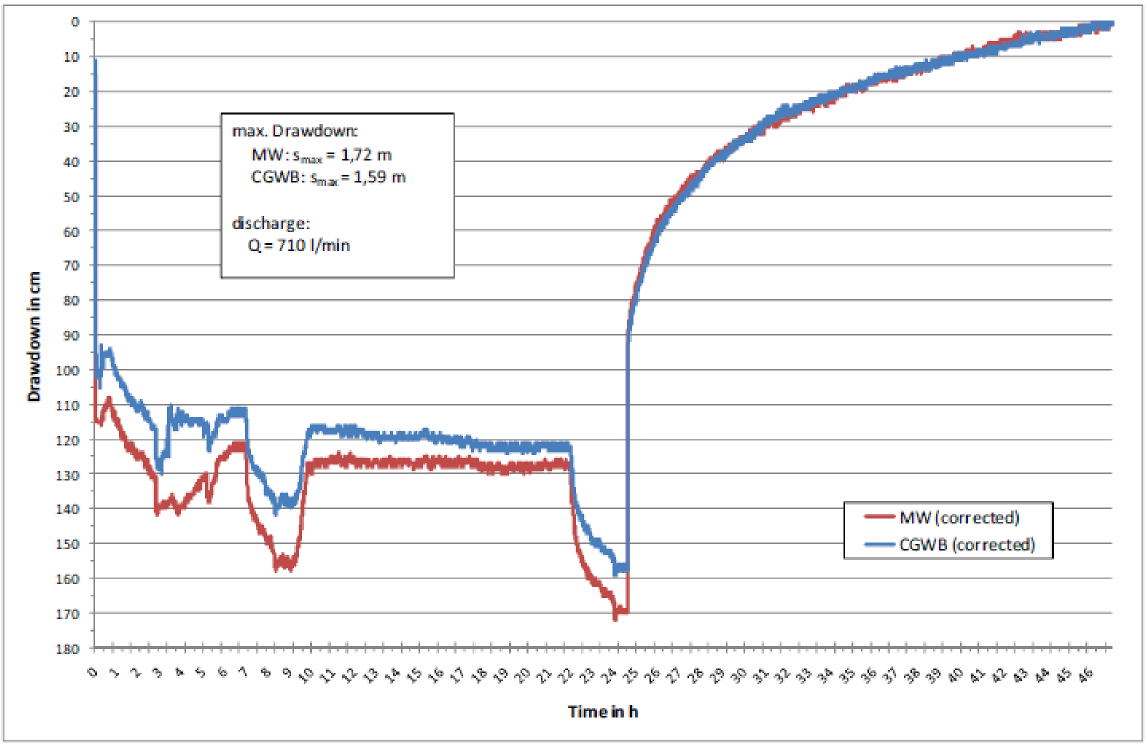


Figure 3-3 Location of pumping test wells at Srinagar (HTWD and UJS, 2012a)

In order to calculate the hydraulic conductivity k, the measured water levels and pumping conditions were processed using the software AQTESOLV. Certain key assumptions such as to the ratio of horizontal and vertical conductivity had to be made. The subsurface lithology was interpreted from borehole logs. The lithology and corresponding groundwater levels indicated unconfined conditions. The underlying bedrock was taken as the aquifer base.

The processed results are shown in Figure 3-4. The transmissivity was calculated using the Neumann method that takes into account boundary conditions such as rivers and no-flow boundaries e.g. presence of impermeable barriers such as rock-massifs of mountains. The calculated transmissivity of 0.045 m²/s was then divided by the saturated thickness of the aquifer resulting in a hydraulic conductivity k of 4×10^{-3} m/s.

Based on the results the specific discharge q (discharge Q per unit cross-sectional area A of saturated porous material), also called darcy velocity or darcy flux and average groundwater velocity v_a were calculated:

$$v_a = \frac{q}{n_e}$$

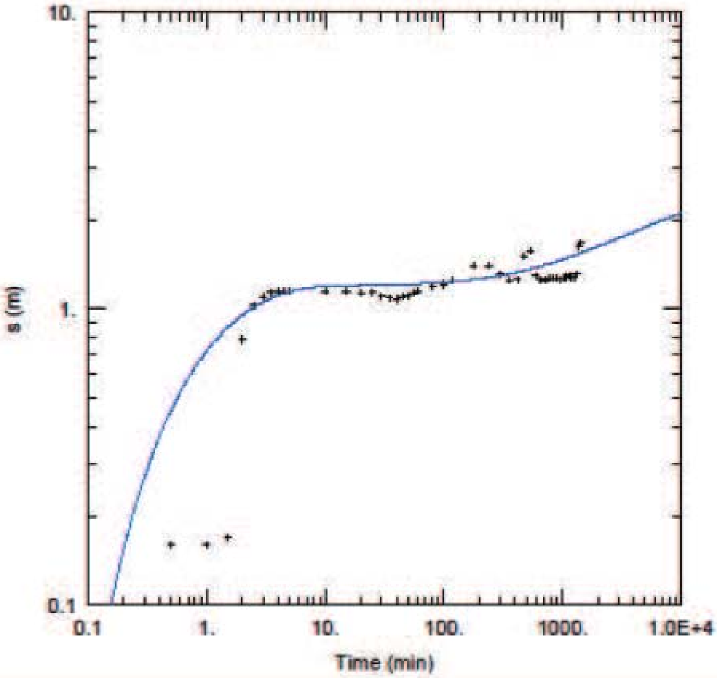
$$q = \frac{Q}{A} = k \cdot \frac{h}{l}$$

where n_e is the effective porosity (%), h is the difference in still water level between the monitoring wells (m) and l is the distance between the monitoring wells (m).

Assuming a porosity of 30% (for compressed medium to coarse sand), the estimated average groundwater velocity v_a is 0.46 m/d. Dividing v_a by the distance between the river bank and the well gives information on the travel time of the bank filtrate.

The travel time for the water abstracted at the RBF well DST at Srinagar varies between 150 and 370 days and depends on the season (shorter travel time during monsoon and longer travel time during pre- and post-monsoon). During the monsoon when water levels are high and the river extends onto the floodplain, the travel time is significantly shorter.

As a result, short travel time and deteriorating surface water quality coincide during the monsoon.



WELL TEST ANALYSIS

Data Set: C:\Users\Wasserwesen\Desktop\Srinagar neumann.aqt
Date: 01/27/12 Time: 11:03:40

PROJECT INFORMATION

Location: Srinagar
Test Well: PW
Test Date: 04.11.11

AQUIFER DATA

Saturated Thickness: 11.18 m

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
DST	0	0

Observation Wells

Well Name	X (m)	Y (m)
+ MW	0	-9.9

SOLUTION

Aquifer Model: Unconfined
Solution Method: Neuman

T = 0.04507 m^2/sec
Sy = 0.2165
S = 0.00135
Kz/Kr = 0.1275

Figure 3-4 AQTESOLV processing results of pumping test at Srinagar (HTWD and UJS, 2012a)

3.3 Flood Risk

3.3.1 Introduction

In Europe, floods are a common natural hazard with an expected increase in frequency and severity and consequent rise in damages. Wells used for the production of drinking water are at risk of microbial contamination and interruption of power supply leads to disruptions in drinking water supply. In other countries such as India, floods are an annual occurrence regularly causing widespread damage.

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

In the context of RBF wells used for the supply of drinking water, the main risk is the breakthrough of pathogens as consequence of floods (Saph Pani, 2013). While the disruption of the supply can be bridged by external emergency supply, pathogens in drinking water are a severe risk to the health and can cause fatal diseases (see Chapter 5).

It is therefore important to consider the site specific risk of each site and to adapt the design accordingly in order to minimise the risk.

Table 3-1 summarises various aspects to be considered when identifying the site specific risk of an existing well or designing a new well.

Table 3-1 Risks to RBF wells from floods in relation to various aspects of the location and design of wells (Saph Pani, 2013)

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

3.3.2 Mitigation Measures

Generally protection measures should be considered on a catchment scale thereby establishing long-term protection of the drinking water supply. Measures should include the reduction of sewer overflow and limiting discharge of untreated wastewater or human excreta into the River thereby reducing the pathogen numbers.

However, immediate mitigation measures are required to address the actual risks. They focus on the protection of the wells considering the following:

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

In response to the requirements listed above, a number of designs have been recently developed during the work of the Saph Pani project (Saph Pani, 2013) at RBF sites in India. Details are described below.

<u>Sanitary sealing</u>

It is absolutely necessary to seal all wells around their base to prevent the vertical seepage of water in the immediate vicinity of the well and particularly along the casing pipe as a precaution against short-circuiting of seepage water with groundwater. It is suggested to excavate an area of at least 1 m^2 (with the well at the centre) to a depth of 1 m and fill (seal) the excavation with a material of high plasticity, such as clay or concrete. Thereafter the sealing should be compacted thoroughly. The sanitary sealing is illustrated in Figure 3-5, and has already been executed at the wells PW5, MW5 and PW-DST at the RBF site in Srinagar in November 2011 by UJS.

Figure 3-5 Sanitary sealing of production wells PW-DST (left) and PW5 and MW5 (right) at Srinagar RBF sites implemented by UJS (photos: Heinze and Lesch, 2012)

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

This design (1) consists of a well-head chamber made of cement-concrete, built into the top of an elevated mound (Figure 3-6). The upper 1 m below ground level, where the abstraction pipe emerges, is first sealed with a 0.5 m thick clay layer above which a 0.5 m thick concrete layer is placed in order to prevent vertical seepage of flood water into the well casing (similar to sanitary sealing shown in Figure 3-5). The well chamber is constructed of reinforced concrete, with a base located approximately 2.25 m above ground level. The chamber has a fully-waterproof cover. All the important armatures such as the bypass, valve, flow meter, backflow flap (non-return valve), the lid of the water level gauge pipe as well as the electricity supply are placed in the 2.8 m long and 1.3 m high well chamber. The entire well chamber is surrounded by an inclined earth mound that extends from the top of the well chamber to the ground level. During a monsoon flood, the flood water will flow around the mound and thus not come in direct contact with abstraction pipe, armatures and electricity supply system. This will provide sufficient protection against the hydro-dynamic effects of the flood, other mechanical forces and trespassing by unauthorised persons.

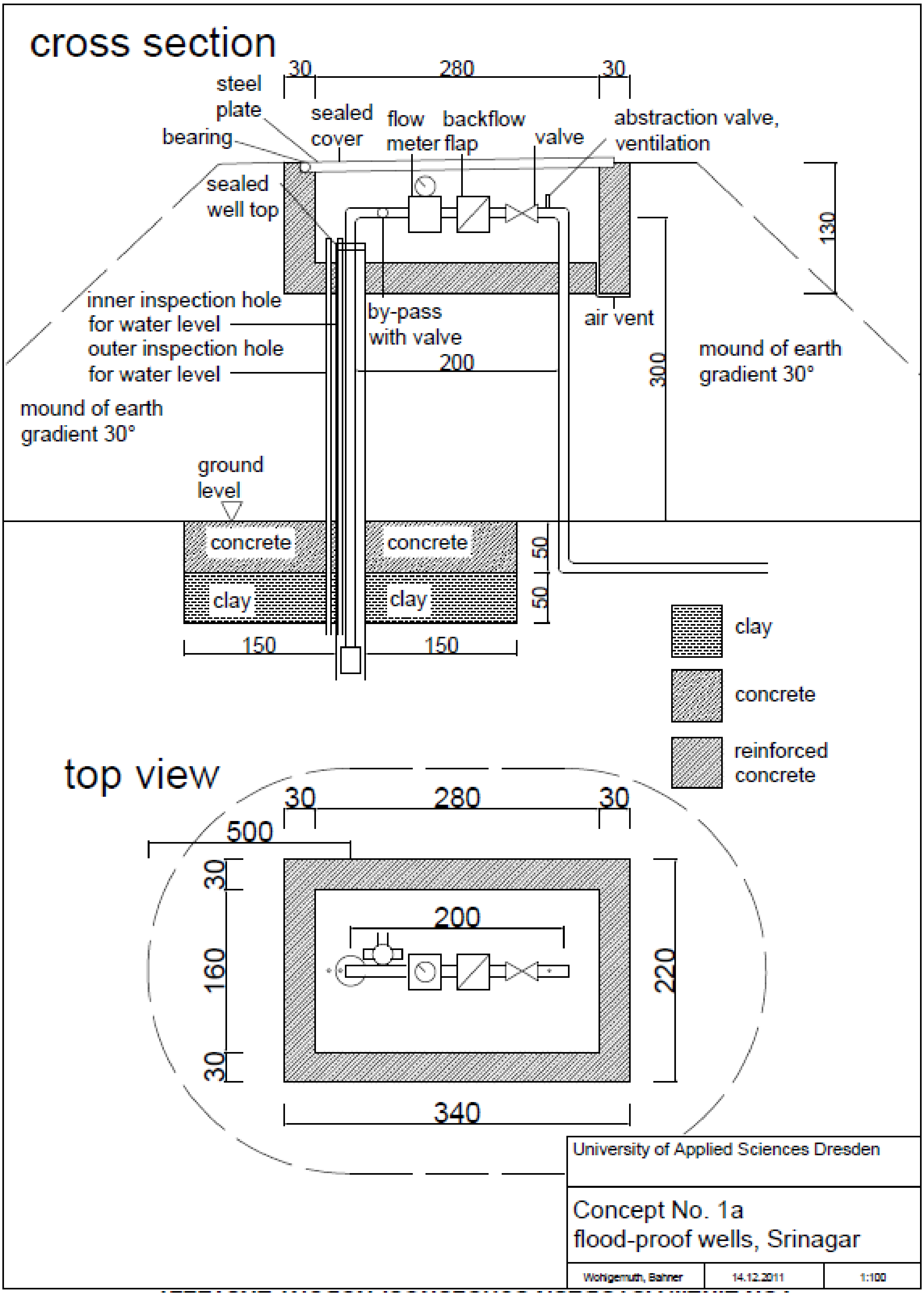


Figure 3-6 Design 1 - Cement-concrete well-head chamber built on elevated mound (Saph Pani, 2013)

Design 2 - Elevated platform

In this design (2), the abstraction and the casing pipe are elevated on a platform located at a level that remains unaffected by the flood water. The armatures, valves and electrical installations are placed on this platform (Figure 3-7). Similar to the conceptual design 1 the upper 1 m below ground level, where the abstraction pipe and casing pipe emerge, is first sealed with a 0.5 m thick clay layer above which a 0.5 m thick concrete layer is placed in order to prevent vertical seepage of flood water into the well casing. The well top is welded onto the casing pipe to prevent water entering. The abstraction pipe rises vertically up to 3 m above ground level and is then laid horizontally for 2 m. Thereafter the abstraction pipe returns vertically to the ground and leads away from the RBF site below ground level. In the horizontal 2 m pipe section, the bypass, valve, flow meter and backflow flap (non-return valve) are installed. At an elevation of around 2 m above ground, an approximately 5 m^2 steel platform is placed to enable a person to stand to operate, inspect and maintain the armatures. While the two vertically placed water abstraction and supply pipes will be exposed directly to flood water, all other sensitive equipment will be placed on the platform. Although the two vertical pipes are at risk of being damaged by floating debris, this would be a low risk as the area lies in the spill-over region (of the full channel under extreme floods) and does not lie directly in the path of the main flood water. Therefore the velocities are relatively low compared to the main channel. Furthermore the site is protected towards the river by a railing which will eventually provide some resistance against floating debris flowing towards the wells.

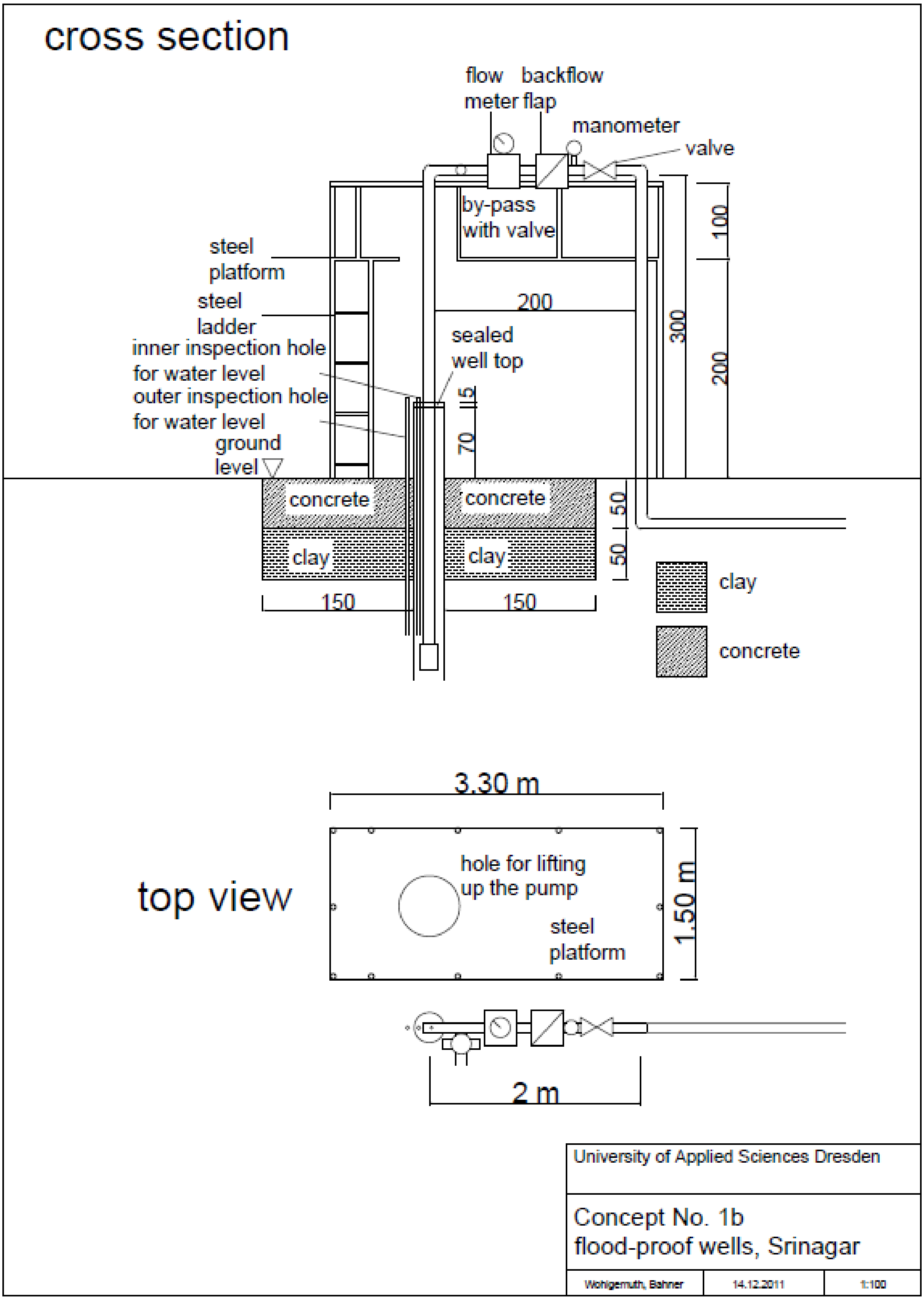


Figure 3-7 Design 2 – Elevated platform (Saph Pani, 2013)

Design 3 – Subsurface reinforced concrete well chamber

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

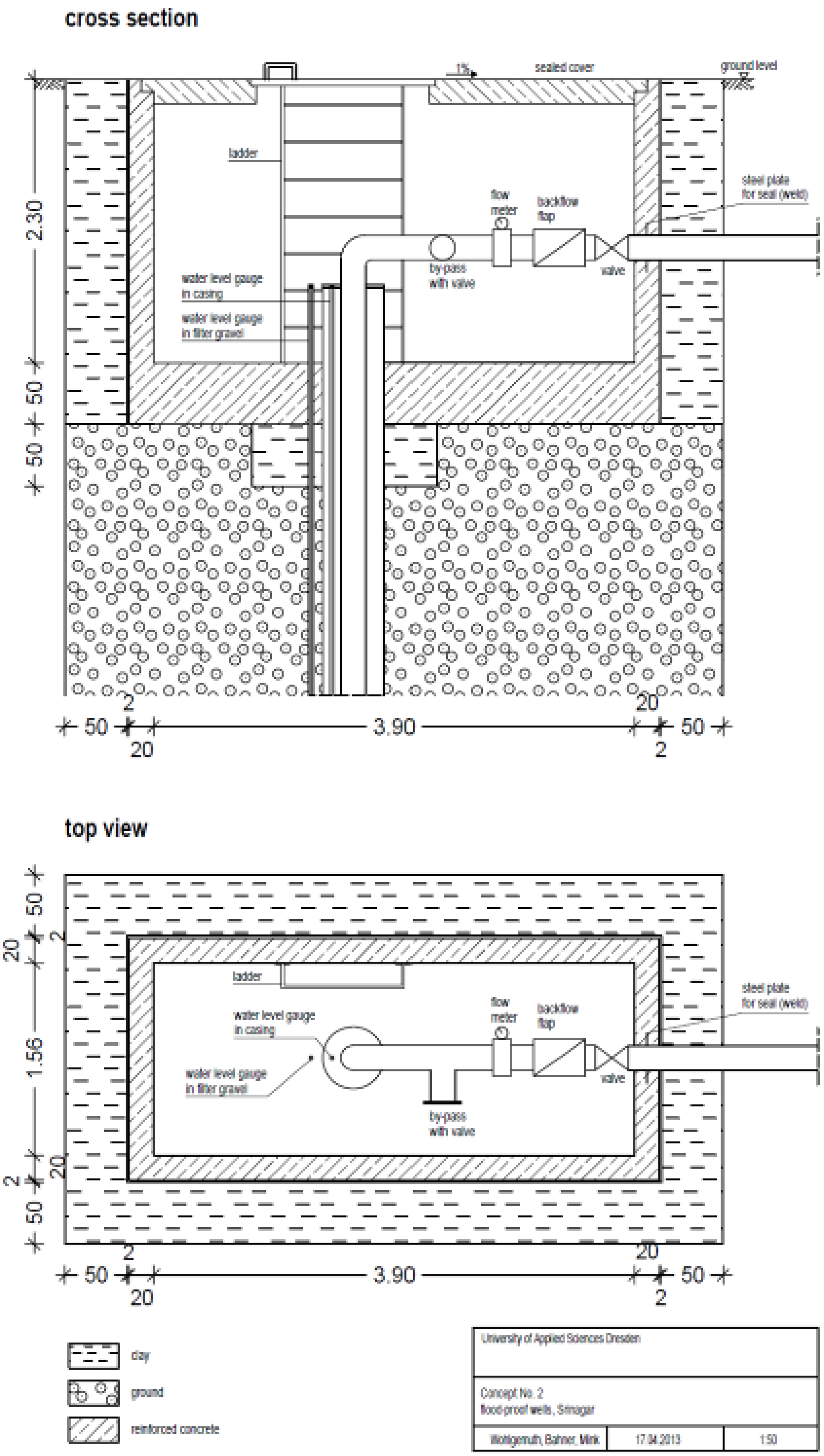


Figure 3-8 Design 3 – Subsurface reinforced concrete well chamber (Saph Pani, 2013)

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

3.3.3 Example – Flood Risk Identification at RBF sites at Srinagar and Haridwar, India

A number of RBF schemes have been successfully developed in northern India. During the monsoon (July, August and September) river levels are generally high causing a regular risk to the water supply from the RBF schemes.

<u>Overview of identifiable risks</u>

Based on the highest ever recorded flood of 2010 in Haridwar and 2011 in Srinagar, the risks to the RBF sites are summarised in Table 3-2, using Table 3-1 as a reference. It is evident that most risks associated with the location of the RBF wells and their design are applicable as presented in Table 3-2. However, for the design below ground level, there is no apparent shortcoming.

Table 3-2 Summary of risks to RBF sites in Haridwar and Srinagar (Saph Pani, 2013)

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

Existing flood protection measures

Generally, as a rule in many parts of India, the banks of rivers that experience, or are at risk of serious flooding, are fortified by flood-protection measures. Such measures include stone and boulder filled galleries reinforced with wire-mesh, concrete blocks and permanently constructed stone and concrete embankments as well as dykes. As such, along the Ganga River's west bank in Haridwar, there is a flood protection embankment (red line in Figure 3-9).

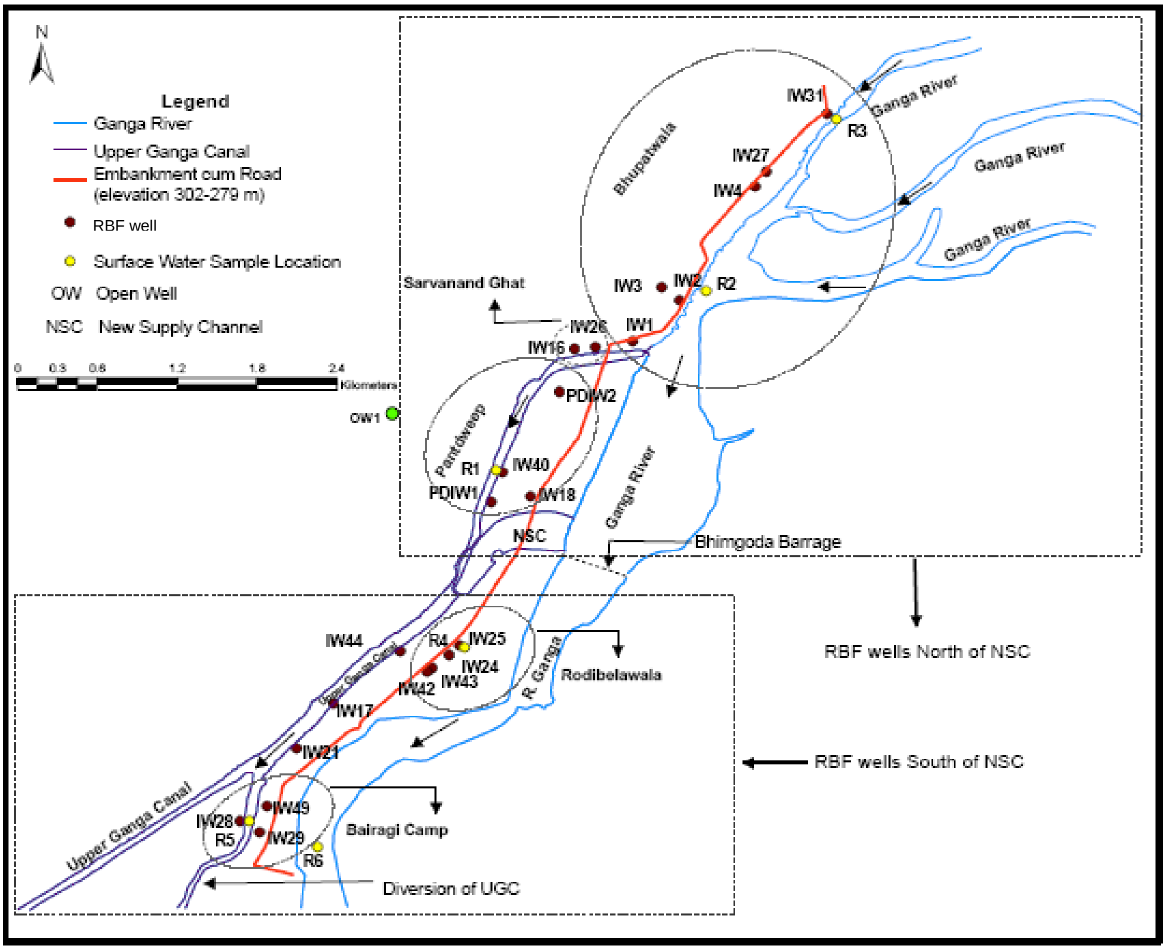


Figure 3-9 Flood protection embankment cum road (red line) (Saph Pani, 2013)

The river-side boundary of the park in Srinagar where the RBF wells are located has a permanent stone and cement retaining wall. To protect the retaining wall (and the park) from flooding, a flood-wall exists towards the river a few metres away from the retaining wall (Figure 3-10 and Figure 3-11). During normal monsoons, the river water level reaches the flood wall. However, during the monsoon in August 2011, the flood damaged downstream end of the flood wall and the retaining wall as a consequence of which a portion of the land around well PW5 subsided (Figure 3-12).

Figure 3-10 View of flood-wall (left) and retaining wall (right) of the lower level of the park where the RBF site in Srinagar is located (Photo: M. Ronghang, IITR, 2011)

Figure 3-11 Intact retaining wall at the downstream-end of the RBF site in Srinagar at the onset of the monsoon flood in August 2011 (Photo: J. Ebermann, HTWD, 2011)

Figure 3-12 Damaged retaining wall of the RBF site in Srinagar after the monsoon flood of August 2011 (facing upstream) (Photo: T. J. Voltz, HTWD, 2012)

<u>Design of wells and direct contamination</u>

Furthermore there is a significant difference in the design of the RBF wells in Haridwar and Srinagar. The caisson well design of the wells in Haridwar implies that the well head or the ceiling of the caisson on top of which the vertical turbine pumps and associated armatures, valves and electrical installations are installed is at a sufficient elevation above ground level so that the entry of flood water from directly above is not possible (Figure 3-13). However, if cracks / fissures are present in the caisson wall around or below ground level, then these provide a pathway for direct entry of flood water into the well. In case of some of the RBF wells in Haridwar, the area around the caisson at ground level is not sufficiently sealed with a concrete base or clay layer to prevent flood water (or water from an intense precipitation event) seeping down along the outer wall of the caisson to the groundwater table.

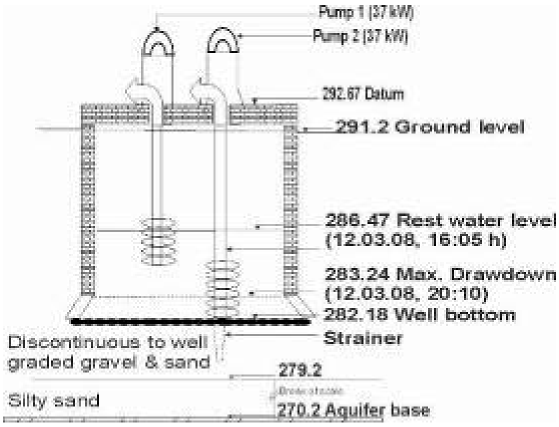


Figure 3-13 Cross-section of a typical large-diameter caisson RBF well (IW18) in Haridwar (Sandhu, 2013)

Figure 3-14 A RBF well in Kharagpur (Kang-sabati River, West Bengal) at risk of contamination by floods (Photo: C. Sandhu)

In comparison, the wells PW5 and MW5 in Srinagar that were affected by the flood in August 2011 underwent a sanitary sealing after the flood. The sanitary sealing includes the construction of a concrete and / or clay seal in the immediate vicinity of the well base. Its purpose is to prevent the seepage of water into the ground and along the annulus between the well casing and the aquifer material to the groundwater table ("short-circuiting"). In the event that a sanitary sealing is constructed, and as long as the casing pipe and well head remain above the flood level, the risk of direct entry of flood water through the well head or short circuiting along the well casing is lessened but not eliminated. Even if a sanitary seal may exist, the flood-water nevertheless comes in direct contact with the casing and thus potential contamination by damage from floating debris or entry of flood-water through impervious seals cannot be excluded (Figure 3-14).

3.4 Isotope analyses

3.4.1 Isotopic characteristics of water

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

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

3.4.2 Methodology

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

$$m_r = m_1 + m_2 \qquad (3.1)$$

$$m_r C_r = m_1 C_1 + m_2 C_2 \qquad (3.2)$$

where m is the quantity of components expressed in fraction, C is the tracer concentration, the subscript r denote admixture at the point of interest, and the subscripts 1 and 2 denote the two components that contribute to the water. In the absence of volumetric data, m_r could be assumed to be equal to one and the m_o and m_n could be expressed as ratio to the total water at a particular time. Rewriting equation (3.1), we get:

$$m_1 = 1 - m_2 \qquad (3.3)$$

Substituting equation (3.3) in (3.2) and rearranging, we get:

$$m_2 = \frac{C_1 - C_r}{C_1 - C_2} \qquad (3.4)$$

Equations (3.1) and (3.4) could be used to compute the fraction of the two components of the stream flow at a given point in space and time.

3.4.3 Sampling locations and frequency

A total of 28 sampling locations which include 25 sites for subsurface water samples, 2 sites for the river Ganga water samples, and 1 for Upper Ganga canal water had been identified for isotopic analysis (Figure 3-9).

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

3.4.4 Results of isotope analyses

Isotopic composition of the rivers in the snow free catchments reflects the isotopic composition of the rainfall. But in a glaciated catchment, the isotopic composition of the river water in summers reflects the isotopic composition of the snow and ice (Rai et al, 2009). But in the catchments with large water storages, small events of rain and snow and ice melting are mixed with stored water and are lost. Variation in isotopic composition of the Ganga River is shown in Figure 3-15.

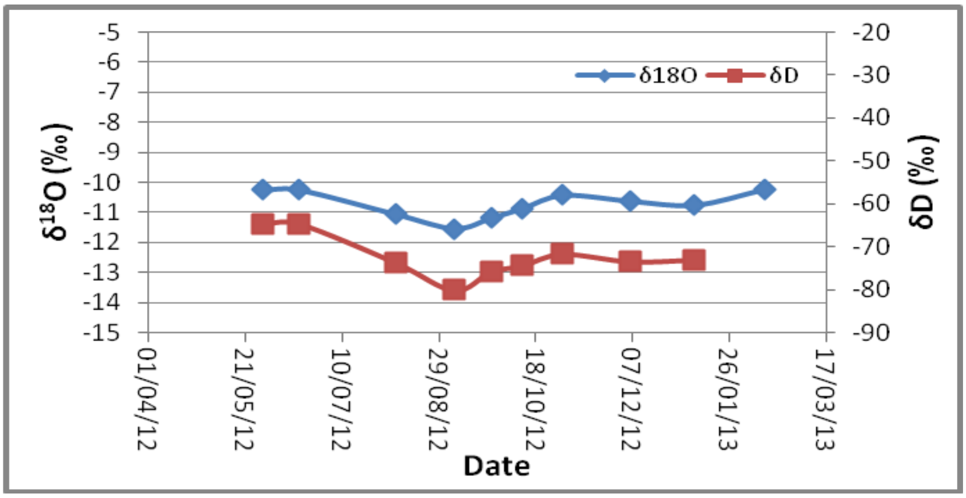


Figure 3-15 Isotopic characteristics of Ganga River water at Haridwar (Saph Pani, 2013)

Figure 3-15 indicates that during the period of investigations, the isotopic values varied from -64.8 to -80.1‰ and -10.19 to -11.68 ‰ for δD and $\delta^{18}O$, respectively. With the advancement of the monsoon, the isotopic values get depleted due to enhanced melting of snow and ice (Rai et al., 2009). After the monsoon, it again gets enriched, with relatively higher contribution of groundwater generated due to monsoon rains.

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

For determining the component of river water in the IWs and the open wells, the groundwater isotopic indices and the isotopic indices of river water have been used. For determining the groundwater indices, the maximum isotopic value of the month has been considered, whereas for determining the isotopic indices of the river water the average of the river isotopic value has been considered. As the Ganga River is very wide and not very deep in the area, the isotopic composition of the near surface water or slow flowing water may get enriched due to evaporation. Considering this fact, the minimum of the isotopic value observed in the wells has been taken as the river water index for that month. The indices for the different sampling dates are given in Table 3-3.

Table 3-3 Isotopic indices (δ18O) of groundwater and river water (Saph Pani, 2013)

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

Based on these indices, the proportion of the river water in groundwater wells can be computed and is given in Table 3-4.

Table 3-4 Relative proportion of river water in well water in Haridwar site (Saph Pani, 2013)

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

		2012								2013	
Lo-cation	Well No.	30.05.	18.06.	07.08.	06.09.	25.09.	11.10.	01.11.	06.12.	08.01.	13.02.
Bhupat wala											
Jhanda Chowk Jawala pur	OW2		25	24		40	33		51	54	56
Firahe diyan Jawala pur	OW3		42	39	26	36	31		33	38	30
Colour code	Dark green	>75%	Light green	50-75%	Light blue	25-50%	Pink	<25%			

4 Modelling and analysis of travel-time and flow-path during bank filtration

4.1 Introduction

Groundwater flow modelling in the context of RBF is a supporting tool that should complement but not replace comprehensive site investigations. Modelling a particular area of interest potentially helps to:

- Improve the understanding of the site specific bank filtration processes,
- Evaluate the performance of a RBF well in terms of the quantity and quality of the abstracted water either compared to the targets or prior to construction as part of the site investigations.

Groundwater modelling as any other modelling requires input data and the quality of the model results heavily depends on the reliability of the input data. Utmost care should be taken when determining or estimating these parameters. The key inputs generally required for groundwater modelling are listed below:

- Hydrological inputs (recharge or its determining components such as rainfall, evaporation, runoff etc.),
- Boundary and initial conditions (such as head and flow conditions),
- Parameters (including the geometry and distances of the domain modelled and the characteristics of the aquifer including conductivity, transmissivity, porosity etc.) and
- Operational information (e.g. pumping rates).

There are two broad categories of modeling methods (or ways of resolving the ground water flow equation):

- Analytical modelling which exactly solve the groundwater flow equation under a simplified set of conditions. It is a simplified method primarily used to deal with simple problems.
- Numerical methods which solve the groundwater flow equation under more general conditions to an approximation. It is a complex method applied to address complex real life problems.

4.2 Modelling using MODFLOW and its application PROCESSING MODFLOW

4.2.1 Overview

MODFLOW is a modular three-dimensional finite-difference groundwater model developed by the U. S. Geological Survey, to the description and prediction of the behaviour of groundwater systems have increased significantly over the last few years. The “original” version of MODFLOW-88 (McDonald and Harbaugh, 1988) or MODFLOW-96 (Harbaugh and McDonald, 1996a, 1996b) can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration.

Since the publication of MODFLOW various codes have been developed by numerous investigators. These codes are called packages, models or sometimes simply programs.

The software PROCESSING MODFLOW for Windows (PMWIN) offers a totally integrated simulation system for modelling groundwater flow and transport processes with MODFLOW-88, MODFLOW-96, PMPATH, MT3D, MT3DMS, MOC3D, PEST and UCODE. PMWIN comes with a professional graphical user-interface, the supported models and programs and several other useful modelling tools. The graphical user-interface allows you to create and simulate models with ease and fun. It can import DXF- and raster graphics and handle models with up to 1,000 stress periods, 80 layers and 250,000 cells in each model layer. The modelling tools include a *Presentation tool*, a *Result Extractor*, a *Field Interpolator*, a *Field Generator*, a *Water Budget Calculator* and a *Graph Viewer*.

The *Result Extractor* allows the user to extract simulation results from any period to a spread sheet. You can then view the results or save them in ASCII or SURFER-compatible data files. Simulation results include hydraulic heads, drawdowns, cell-by-cell flow terms, compaction, subsidence, Darcy velocities, concentrations and mass terms.

The *Field Interpolator* takes measurement data and interpolates the data to each model cell. The model grid can be irregularly spaced.

The *Water Budget Calculator* not only calculates the budget of user-specified zones but also the exchange of flows between such zones. This facility is very useful in many practical cases. It allows the user to determine the flow through a particular boundary.

The *Field Generator* generates fields with heterogeneously distributed transmissivity or hydraulic conductivity values. It allows the user to statistically simulate effects and influences of unknown small-scale heterogeneities.

The *Graph Viewer* displays temporal development curves of simulation results including hydraulic heads, drawdowns, subsidence, compaction and concentrations.

Using the *Presentation tool*, you can create labelled contour maps of input data and simulation results. You can fill colours to model cells containing different values and report quality graphics may be saved to a wide variety of file formats, including SURFER, DXF, HPGL and BMP (Windows Bitmap). The Presentation tool can even create and display two dimensional animation sequences using the simulation results (calculated heads, drawdowns or concentration).

More recently Visual MODFOW followed by Visual MODFLOW Flex has been developed with a more GIS based interface and visually more attractive presentation options although the basic algorithms remain the same.

4.2.2 Example - modelling of RBF site at Srinagar, India

A model of a small RBF site in northern India has been developed to help analyse the contribution of bank filtrate and groundwater to the discharge of a number of wells.

The study area is shown in Figure 4-1. The figure shows the location of the Alaknanda River and its flood extent during monsoon, the contour lines of the terrain, the location of the wells together with some hand pumps used to facilitate the set-up of the model.

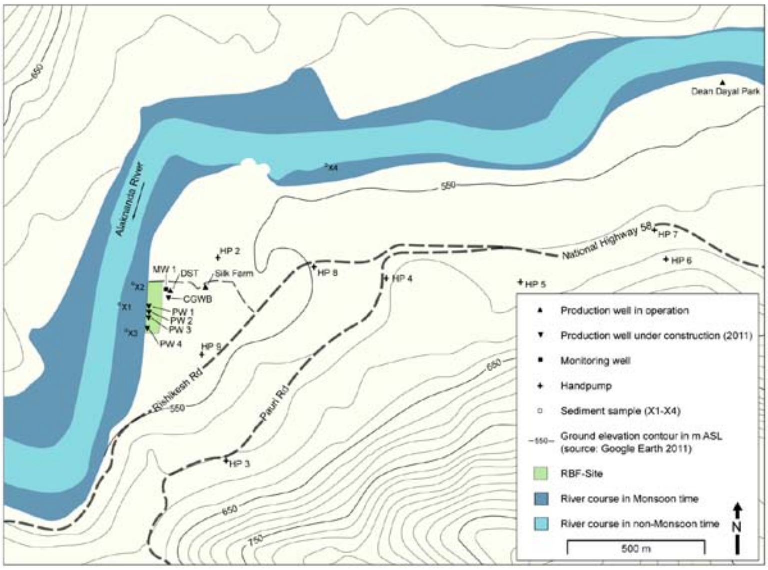


Figure 4-1 Modelling Area at Srinagar (Saph Pani, 2012)

Model construction and run

In order to model the groundwater conditions and resulting travel time, a groundwater model was developed using the software Processing MODFLOW (Version 8.03).

The model requires a number of input parameters and specifications which have to be defined either by the user (e.g. the mesh grid size etc.), determined from observations (such as the river level) or estimated from literature where observations are not available.

Table 4-1 summarises the main input parameters which are discussed in more detail in the sections after the table.

Table 4-1 Summary of MODFLOW parameters (Saph Pani, 2012)

Item	Parameter	Characterisation
1	Model area	1500 m × 1600 m
2	Grid size	Variable 0.34 m × 0.34 m to 100 m ×100 m
3	Ground surface	Elevation from point survey
4	Thickness of layer	21 m (taken from cross section based on borehole logs)
5	Boundary conditions	
	River levels	Water level gauged on 10.12.2011 (low flow conditions)
	Groundwater levels	All levels gauged on reference day measurement 10.12.2011
	Abstraction Scenario 1	Total abstraction: 0.06 m^3/s
	Abstraction Scenario 2	Total abstraction: 0.3 m^3/s
	Groundwater recharge	3.96×10^{-8} m^3/s
6	Hydraulic conductivity (K)	River cells: $k_x = k_y = 1 \times 10^{-3}$ m/s, $k_z = 1 \times 10^{-4}$ m/s
		Floodplain cells (RBF well field): $k_x = k_y = 3 \times 10^{-3}$ m/s, $k_z = 3 \times 10^{-4}$ m/s
		Bank: $k_x = k_y = 6 \times 10^{-6}$ m/s, $k_z = 6 \times 10^{-7}$ m/s
		Effective porosity: 0.3
7	Simulation type	Unconfined conditions, steady state

1 The area has been determined based on the map shown in Figure 4-1. A groundwater triangulation (see Figure 4-2) using the observed well water levels has been carried out to facilitate the definition of the model coverage.

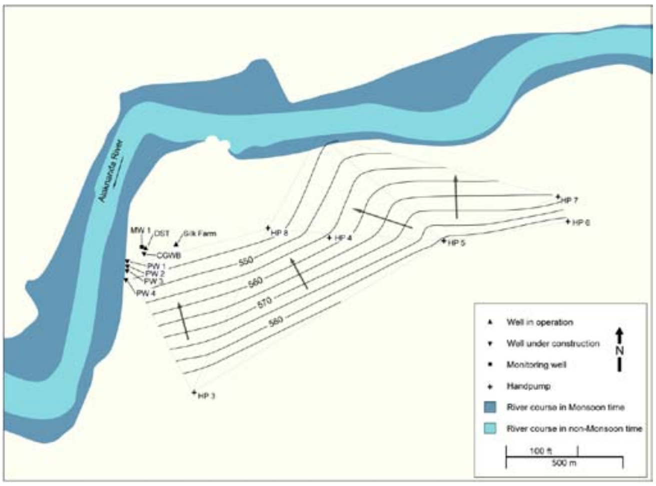


Figure 4-2 Groundwater triangulation to initially assess the groundwater flow regime at Srinagar prior to modelling (HTWD and UJS, 2012b)

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2 The grid size has been established starting from an initial 100 m × 100 m grid which has been refined in the vicinity of the production and observation wells. The final mesh is shown on Figure 4-3 together with the results. The grid has been built using the function *Mesh Size*.

3 Boundary conditions are required along the river for each cell covering the river together with initial groundwater levels for each cell. The observed levels have been entered using the *Digitiser* function and then interpolated using the *Field Interpolator* function.

The abstraction figures are based on the known discharge and operation time of the well pumps. Estimates have been made for the wells under construction.

4 The Groundwater recharge was estimated using monthly rainfall data available from 1965 to 1985.

5 In order to determine the aquifer parameter such as the hydraulic conductivity field investigations have been carried out.

The hydraulic conductivity of the river bed has been calculated empirically after Beyer (1964) based on four sieve analyses which allowed a good estimate of the horizontal hydraulic conductivity.

The horizontal hydraulic conductivity of the floodplain has been taken forward from pumping tests carried out at an earlier stage.

The vertical conductivity has been estimated to be 10 % of the horizontal value.

The respective values have been entered using the function *Horizontal Hydraulic Conductivity and Vertical Hydraulic Conductivity*.

As there is little information regarding the conductivity across the modelling area, the values have been adjusted during the calibration of the model where observed and modelled water levels have been compared.

The effective porosity has been estimated to be 0.3.

6 The ground surface has been derived using the same methodology applied to establish the groundwater table. A point survey was undertaken and the established elevations have then been entered using the *Digitiser* function and then interpolated using the *Field Interpolator* function.

7 The depth of the groundwater layer has been established using a cross section derived from an existing drilling profile in the model area. The established depth of 21 m has been subtracted from the ground surface to establish the bottom of the groundwater layer using the function *Bottom of Layers*.

8 Prior to the start of the model run the status of the cells needs to be defined. There are active, inactive and constant cells. The river has been defined as “constant head”. Cells which are not relevant for the computation or cells without any groundwater exchange (q=0) have been set “inactive”. For all other cells defined as “active” and groundwater levels have been calculated.

Once the model has been established and all parameters and boundary conditions have been entered, a steady state simulation for the unconfined conditions has been carried out.

Model runs for two different scenarios have been carried out. Scenario 1 assumes at total abstraction of 0.06 m^3/s at all wells; Scenario 2 tested a 5 fold increase in discharge.

<u>Interpretation of Results</u>

The results have been processed in the MODFLOW environment. The two left hand pictures in Figure 4-3 and Figure 4-4 show the groundwater contour lines for the Scenario 1 and Scenario 2, respectively. The pictures on the right hand side show the flow path for each scenario.

Figure 4-3 indicates that during low flow conditions and with the assumed abstractions (Scenario 1 assumes at total abstraction of 0.06 m^3/s), there is no bank filtration from the river to the west closest to the wells. The feeding process is dominated by bank filtrate infiltrating from the north east further away upstream from the sites and groundwater from the landward side. The bank filtrate is characterised by long travel times of approximately 650 days.

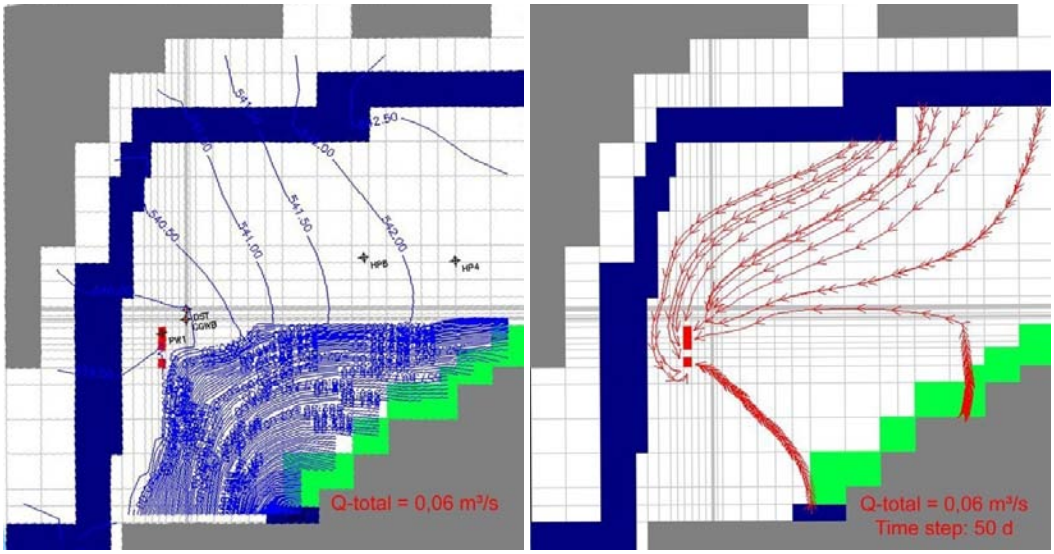


Figure 4-3 Simulated groundwater contours (left) and flow paths (right) at Srinagar - Scenario 1 (Saph Pani, 2012)

Figure 4-4 indicates that increased abstractions (Scenario 2 tested a 5 fold increase in discharge at each well) will lead to an increase in the proportion of bank filtrate from the river immediately to the west of the wells which is characterised by shorter travel times.

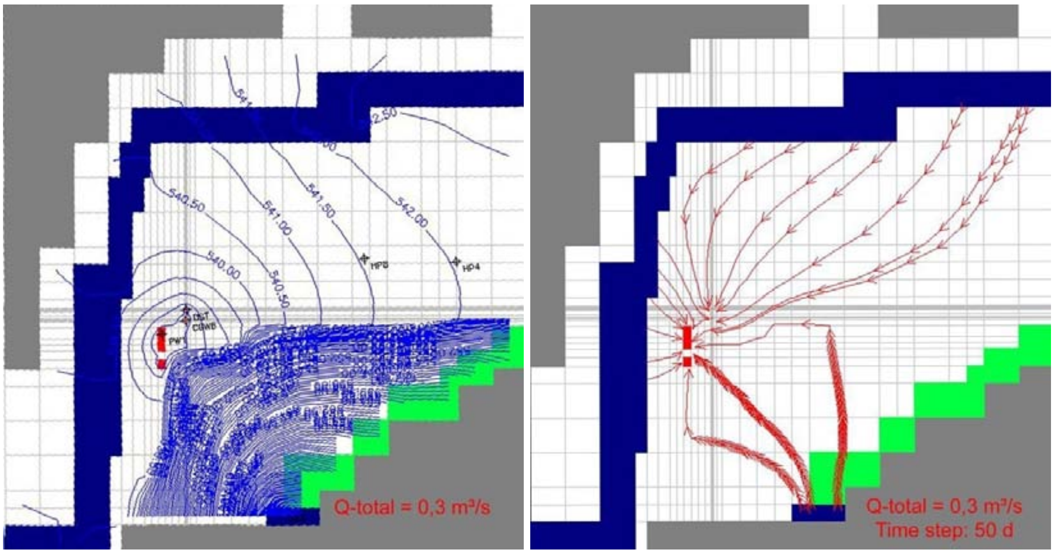


Figure 4-4 Simulated groundwater contours (left) and flow paths (right) at Srinagar – Scenario 2 (Saph Pani, 2012)

During high flow conditions (monsoon) the flow dynamics are likely to change due to an increase in the hydraulic gradient. To model high flow conditions, measurements of river levels and well levels would be required which represent these conditions which will then be used to set up a model.

5 Water quality aspects during bank filtration

5.1 Overview

The natural removal of pathogens from river water during the process of BF is a major advantage of this technology. Equally, if the removal process fails due to adverse conditions such as flooding, the consequences can be life threatening. Details are given in Section 5.2.

However, there are other water quality issues to be considered:

- Physical (turbidity, colour, odour)
- Organic (which include pathogens but also dissolved organics such as pesticides etc.)
- Inorganic (including Iron, Arsenic, Manganese, Magnesium, Sodium)

Some quality issues are known to be efficiently resolved by the BF technique, including turbidity.

5.2 Removal of Pathogens

5.2.1 History

The disposal of untreated sewage into rivers is still commonly found. Additionally, animal faeces – containing pathogens – from agricultural lands and roaming animals are introduced into water bodies. If rivers are directly and without sufficient treatment used as the source of drinking water, there is no barrier to the transmission of waterborne diseases.

Clean water has been recognised as the source of health for more than 4000 years. While the medieval ages marked a dark period in terms of hygiene, the awareness that many diseases are waterborne revived in Europe around the 17th century. Efforts to disconnect drinking water from wastewater, i.e. the faecal-oral route, were intensified in the 19th century. At this time slow sand filtration was first used for treating water, and finally confirmed as an effective means to fight disease outbreaks in 1893. The milestones up to 1893 are summarised in Table 5-1.

Table 5-1 Certain milestones related to pathogens in drinking water and natural treatment by bank filtration (Syhre et al., 2009)

Period	Event
2000 BC	A Sanskrit manuscript states that “It is good to keep water in copper vessels, to expose it to sunlight and filter it through charcoal”.
500 BC	The Greek scientist Hippocrates invents the first cloth bag filter aiming to improve the taste and smell of drinking water – the two parameters which were believed to represent the health of water. The existence of microbes had been unknown for another 2000 years.
1676	The scientist Antonie van Leeuwenhoek creates the prototype of a microscope and becomes the first person to see and describe tiny living forms, i.e. micro-organisms in water.
1804	The first municipal water works using slow sand filtration is installed in Paisley, Scotland.
1854	The physician John Snow links the accumulation of Cholera cases in a London district to a particular well which is contaminated by percolating sewage – known as the Broad Street Pump Affair.
1865	Civil engineer Joseph Bazalgette enforces the construction of large inter¬cepting sewers for collecting the London wastewater and releasing it with sufficient distance downstream of the

Period	Event
	city into the Thames River, and in this way disconnecting wastewater and drinking water.
1870	The Duesseldorf Water Works implements riverbank filtration for public drinking water supply in the densely populated Rhine region.
1893	By investigating the 1892 Cholera outbreak in Hamburg on the River Elbe with 16956 inhabitants being infected of which 8605 died (Schindler, 2004), the physician and microbiologist Robert Koch correlates the very low number of Cholera cases in Altona, the adjacent city downstream, to the town's practice of purifying its drinking water using sand filtration.

5.2.2 Disease causing pathogens

Table 5-2 summarises some of the most dangerous pathogens together with the respective disease they are known to cause. Some diseases such as Cholera, Haemolytic-Uraemic Syndrome (HUS), Cryptosporidiosis are potentially life threatening while others can significantly weaken the body or be fatal to vulnerable people including young children.

Table 5-2 Variety of disease-causing pathogens found in water (Syhre et al., 2009)

Pathogens		Disease
Salmonella ssp. Shigella ssp. Vibrio cholerae Leptospira interrogans Yersinia enterocolitica Campylobacter jejuni Enterotoxygenic E. coli	Bacteria	Typhoid Dysentery Cholera Leptospirosis Gastroenteritis Gastroenteritis Haemolytic-Uraemic Syndrome
Poliovirus *Rotaviruses* *Hepatitus A virus* *Norwalk virus*	Viruses	Poliomyelitis Gastroenteritis Jaundice Gastroenteritis
Giardia lamblia *Cryptosporidium parvum* *Entamoeba histolytica*	Protozoa	Giardiasis Cryptosporidiosis Amoebic dysentery

5.2.3 Microbial indicators

Due to the large variety of pathogens, it is not possible to test water (regularly) for all individual disease-causing micro-organisms. Microbial indicators – such as the bacterium Escherichia coli – are used to assess water quality in terms of hygiene. Although indicator micro-organisms are not necessarily pathogenic, i.e. disease-causing, they are found in the intestines and hence, in human and animal faeces. For this reason, their presence in water signals faecal contamination and thus, the likeliness of other micro-organisms which do spread diseases via the faecal-oral route. Furthermore, faecal indicator bacteria also seem to be able to penetrate into an aquifer as far as viruses, and may therefore be useful indicators of faecal contamination (Schijven, 2002).

The commonly used microbial indicators applied in the EU are summarised in Table 5-3.

Table 5-3 Established microbial indicators and EU drinking water requirements

Indicator	EU drinking water standard (1998)
Coliform bacteria	0/100 ml
E. coli	0/250 ml
Enterococci	0/250 ml
Pseudomonas aeruginosa	0/250 ml
Clostridium perfringens	0/100 ml
Colony count 22°C	100/ml
Colony count 37°C	20/ml

While *Escherichia coli* has been established as a reliable faecal indicator in temperate climates, possible abundance and regrowth in subtropical soils have been reported and therefore the applicability of E. coli in such countries should be treated with caution.

Beside E. coli, the entire group of coliform bacteria (to which also E. coli belongs to) is commonly used as a microbial indicator.

Enterococci are currently intensively discussed as alternative indicator organisms as they might provide a higher correlation with human pathogens in faeces than the coliform group.

Pseudomonas aeruginosa are bacteria which are, once introduced into the drinking water system, able to survive for a long time and even multiply given favourable nutrient levels and regions with stagnant water. The bacteria are transmitted to humans if they breathe them in above sinks, potted plants or humidifiers or if patients in intensive care receive artificial ventilation. In people with a weak immune system (which is especially the case for hospital patients) a respiratory infection with severe complications can develop.

Clostridium perfringens is a spore-forming bacterium. Its spores are able to endure even under extreme conditions in the environment for a long time. At the same time, the spores exhibit a high resistance against conventional disinfection (chlorine). Clostridium perfringens is therefore especially proposed as indicator for parasites (Cryptosporidium parvum, Giardia lamblia) which are similarly resistant. An investigation for Clostridium perfringens is usually only necessary if the water derives from surface water or a surface water influenced source.

An additional method to assess drinking water quality is counting the culturable micro-organisms, i.e. the colony forming units (CFU) which grow at a set temperature within a specific incubation time.

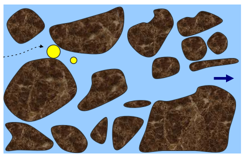
The colony count at 22°C or 20°C represents the number of colonies which can either be detected without a magnifying glass after incubating 1 ml drinking water at 22°C for 72 hours on a nutrient-poor culture medium, or with a magnifying glass after incubating 1 ml drinking water at 20°C for 44 hours on a nutrient-rich agar plate.

The colony count at 36°C represents the number of detectable colonies which can either be detected without a magnifying glass after incubating 1 ml drinking water at 36°C for 72 hours on a nutrient-poor culture medium, or with a magnifying glass after incubating 1 ml drinking water at 36°C for 44 hours on a nutrient-rich agar plate.

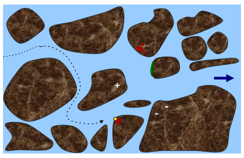
5.2.4 Removing Processing

During underground passage pathogens are removed due to the interaction of various processes: physical filtration, attachment to biofilms and aquifer material, grazing by other micro-organisms, being trapped in immobile pore water and natural decay.

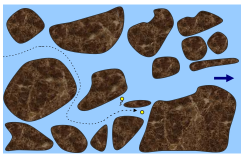
Various environmental factors as well as microbial properties influence the transport and removal processes such as straining, adsorptions, stagnation, grazing and natural decay. Further details are given below.



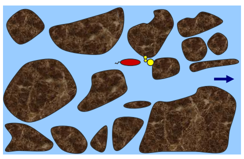
The efficiency of *straining*, i.e. physical filtration depends on the size and shape of the individual microbial pathogen in relation to the particular grain and pore size distribution.



Adsorption processes, i.e. the removal of pathogens due to attachment to the aquifer material are influenced by manifold factors: surface charges of the sediment as well as of the pathogen's surface, the micro-organism's hydrophobicity and exopolymeric structures, the occurrence of metal oxide coatings and biofilms (facilitating adsorption), water chemistry (DOC, pH, concentration of ions) and the flow regime (a high pressure gradient and a high flow velocity supporting desorption).

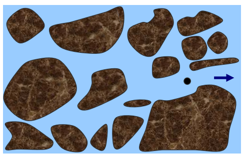


Stagnation In dependence of pore size distribution, flow regime, microbial size and mobility, pathogens can (temporarily) *stagnate* when reaching dead end pores.



Grazing by other micro-organisms (e.g. nanoflagellates) poses a fourth removal mechanism.

In view of these processes, the clogging (colmation) layer in a river bed or sand filter plays an important role for the removal of pathogens due to fine structure of the grains in the first centimetres, the high abundance of microbes (predators and competitors) and the generally elevated heterogeneity.



As final removal mechanisms, the *natural decay* of pathogens in the environment, i.e. outside the host, leads to a decline of their concentration.

As both pathogens and environmental factors vary considerably, the interactions are complex:

- Pathogenic protozoan cysts or oocysts which pose a high risk due to their high infectivity and resistance to chlorination can be effectively removed by straining during sediment passage due to their comparably large size.

- Viruses on the other hand are a concern in view of their small size and persistence. However, they can easily diffuse to sediment grains and adsorb on positive surfaces such as metal oxide coatings.

5.2.5 Efficiency of pathogens removal at bank filtration sites

Microbial analyses of riverbank filtrate from abstraction wells on the River Rhine (Germany) demonstrated a 99.9 % (3 log) removal of coliform bacteria and the complete elimination of Giardia and Cryptosporidium oocysts. At RBF sites in North America, removal rates of coliform bacteria and E. coli are reported to be >2 log and >1.9 log respectively (Table 5-4), reaching as high as ≥5 log and >3.5 log respectively. Investigations conducted at RBF sites in The Netherlands (Havelaar et al., 1995; Medema et al., 2000) determined a removal of Enteroviruses of >1.7 log.

RBF also provides sufficient water quality for irrigation even if the surface water is polluted by pathogens. Investigations at the Zarqa River, Jordan, demonstrated that fecal indicator bacteria and bacteriophages were removed from river water by RBF by 3.4–4.2 log and 2.7–3.3 log, respectively (Saadoun et al., 2008). In a well used for irrigation in Muzaffar Nagar, by the Kali River in the state of Uttar Pradesh in North India, total and fecal coliforms were removed by 1.7–1.9 log and > 1.5 log respectively (Thakur et al., 2009).

However, log removal rates for fecal coliforms reported for specific sites cannot simply be transferred or assumed for other pathogens and other sites. For example, a recent study by Metge et al. (2011) suggests that in evaluating the efficacy of RBF operations to remove the protozoan pathogen Cryptosporidium parvum oocysts, it may be necessary to consider not only the geochemical nature and size distribution of the sediment grains, but also the degrees of sediment sorting and the concentration, reactivity, and aquifer penetration of the source water DOC as in the case of E. coli described above (Sandhu and Grischek, 2012).

Table 5-4 Reported RBF log removal rates (compiled by Syhre et al., 2009)

Micro-organism	Log removal	RBF location	Reference
Coliform bacteria	≥ 5.0 ≥ 4.8 2 - 3.5 2.15 - 2.35	River Rhine (Remmerden, NL) Missouri River (Parkville, USA) River Rhine (Flehe, Germany) North Platte River (Casper, USA)	Havelaar et al., 1995 Weiss et al., 2005 Rohns et al., 2006 Gollnitz et al., 2005
Escherichia coli	> 3.5 1.9 - 2.05	Missouri River (Parkville, USA) North Platte River (Casper, USA)	Weiss et al., 2005 Gollnitz et al., 2005
Enteroviruses	≥ 2.6 1.7	River Rhine (Remmerden, NL) River Meuse (Roosteren, NL)	Havelaar et al., 1995 Medema et al., 2000
Clostridium perfringens spores	3.3 - 5.0 > 4.8 3.1	River Meuse (Roosteren, NL) Missouri River (Parkville, USA) River Rhine (Remmerden, NL)	Medema et al., 2000 Weiss et al., 2005 Havelaar et al., 1995
particles in the size of protozoa	3.0 - 4.0	Great Miami River (Cincinnati, USA)	Gollnitz et al., 2004

At most sites in India where directly abstracted surface water is used for drinking, the removal of pathogens has the highest priority (Sandhu et al., 2011a). Examples of bank filtration schemes in India have been illustrated by Sandhu and Grischek (2012) to highlight the ecosystem service of bank filtration for providing drinking water for improved human health (Table 5-5). Accordingly, bank filtrate from a few sites monitored in recent years has shown a significantly higher quality when compared to directly abstracted surface water.

Table 5-5 Coliform counts in surface water at selected RBF sites in India, and coliform removal during RBF (Sandhu and Grischek, 2012)

Sea-son	Parameter (coliform counts in MPN/100 ml)	RBF site					
		Haridwar (b, own data)	Nainital (a)	Patna (d)	Mathura (c)	Satpuli	Delhi, Palla well field (e)
Non-monsoon	TCC in SW	4,300–15,000	46,000–240,000	24,000–160,000	2,300–1,500,000	240	1200 CFU/100 ml
	TCC in RBF well	<2–93	<2	8–170	43–75,000	<2	<1 CFU/100 ml
	Log removal of TC	2.5	>5.2	2.3–4.2	1.3–1.7	>2.1	>3.1
	FCC in SW	2,100–15,000	5,000–24,000	n. d.	150–230,00	n. d.	500–40,000
	FCC in RBF well	<2–93	<2	n. d.	43–9,300	<2	<1
	Log removal of FC	3.5	>4.2	n. d.	2.3–3.2	n. d.	2.7–4.6
Monsoon	TCC in SW	9,300–230,000	50–500,000	90,000–160,000	n. d.	920	similar to non-monsoon
	TCC in RBF well	<2	<2	8–300	n. d.	49	as above
	Log removal of TC	4.7	>5.4	2.6–4.4	n. d.	1.3	n. d.
	FCC in SW	1,500–93,000	50–50,000	n. d.	n. d.	8	1000–3000
	FCC in RBF well	0–17	<2	n. d.	n. d.	<2	<1
	Log removal of FC	4.4	>4.4	n. d.	n. d.	>0.6	3.0–3.5

TCC: Total coliform counts in abstracted water (before disinfection); FCC: Fecal coliform counts in abstracted water (before disinfection); SW: surface water; n. d.: not determined. a: Dash et al., 2008; b: Dash et al., 2010; c: Singh et al., 2010; d: Sandhu et al., 2011b; e: Sprenger et al., 2008

5.3 Organic miropollutants

5.3.1 Claimer

This section is primarily based on a presentation given by C. Sprenger and G. Grützmacher at the Saph Pani Training Course on ‘Bank Filtration for Sustainable Drinking Water Supply in India’ in New Delhi in 2012. It is compiled from two previous literature reviews, by Huelshoff et al. (2009) and Sprenger et al. (2011), carried out within the EU funded project TECHNEAU (Contract Number: 018320).

5.3.2 Introduction

Organic micropollutants comprise a large group of chemical substances of different origin like agrochemicals (e.g. pesticides), industrial chemicals (e.g. plasticizers, mineral oils) or municipal sewage (e.g. pharmaceutical residues).

Many of these substances are toxic, carcinogenic or suspected to be endocrine disruptors and therefore considered not only hazardous to the ecosystem but also a threat to water supply systems. Some have been observed to be readily degradable while others are persistent. The same is true for the degradation products and sometimes the toxicity of a metabolite is even higher that of the parent compound (e.g. vinyl chloride is more toxic than 1.2-dichloroethene). The increasing contamination of the hydrosphere with thousands of micropollutants is a key environmental problem (Schwarzenbach et al., 2006). In groundwater systems, loads of organic micropollutants may be attenuated by dissolution, advection, dispersion, diffusion, sorption, volatisation and degradation processes.

The following sections cover organic chemicals of major concern to groundwater abstracted drinking water including pesticides, hydrocarbons as well as emerging substances such as pharmaceuticals and endocrine disruptors for which to date the health implications are not fully understood. The list of micropollutants discussed is not exhaustive and the classification of substances may sometimes overlap. Several organochlorine pesticides, for instance, have been recognised to be potent endocrine disrupting compounds.

5.3.3 Pesticides

Pesticides are a heterogeneous group with varying degradation and sorption properties and many pesticides are toxic and long-term persistent in the environment (Tuxen et al., 2000; Verstraeten et al., 2003). Surface water can become polluted with pesticides by diffuse sources such as agricultural run-off or point sources such as wastewater effluent (Gerecke et al., 2002; Neumann et al., 2002).

Developed countries still account for three-quarters of all pesticides used worldwide; but the use of pesticides is on the rise in developing countries (Miller, 2004). Since the 1950’s, the overall pesticide use has increased 50-fold and was about 2.3 million tonnes per annum in 2002 (Miller, 2004). China has meanwhile emerged as the world’s second largest producer and consumer of pesticides. Surveys carried out in Brazil, Central America and Nigeria revealed that mishandling and overuse have put humans at risk for direct pesticide poisoning.

The fate and transport of pesticides during underground passage depends on redox conditions, temperature, sorption processes as well as organic and water content in the soil (Verstraeten et al., 2003). The importance of sufficient travel time and necessity for microbial adaptation was shown in aerobic, aquifer material filled columns that were fed with 25 µg/l of selected pesticides. Isoproturone and 4,6-Dinitro-o-cresol (DNOC) were significantly retarded by sorption while retardation for bentazone, MCPP, dichlorprop and 2,4-D was low. Only after a lag time of 16-33 days for MCPP, 2,4-D and dichlorprop and 80 days for DNOC, the substances were degraded (1.3-2.6 µg/l per day) (Tuxen et al., 2000). Soils with moderate to high organic matter and clay content will adsorb pesticides onto soil particles. The observed reductions for several pesticides during bank filtration are summarised in In Table 5-6 .

Generally, an improvement of surface water quality is to be expected after bank filtration because many pesticides are either partially or fully removed during subsurface passage (Ray et al., 2002; Verstraeten et al., 2003). But due to large uncertainties of the fate and transport of pesticides during BF it is difficult to predict the likely effects on BF systems.

Table 5-6 Degradation of relevant pesticides and metabolites during subsurface passage

Pesticide	Reduction	Conditions	Reference
2,4-D	86 - >97%		Schmidt et al., 2003
Bentazone	0 – 60%	20 to >360 d	Schmidt et al., 2003
Bromoxynil	78 – 99%		Schmidt et al., 2003
Dichlorprop-P (2,4-DP)	30 – 50%		Schmidt et al., 2003
Flufenacet	63%	suboxic BF, 6 d	Schmidt et al., 2003
Glyphosate	17 - >30%	anoxic BF, 30-300 d	Schmidt et al., 2003
Isoproturone	10 - >75%		Schmidt et al., 2003
MCPA	74%		Schmidt et al., 2003
Mecoprop-P	0 – 80%		Schmidt et al., 2003
Metazachlor	40 - >99%		Schmidt et al., 2003
S-Metolachlor	0 - >70%		Schmidt et al., 2003
Metalaxyl-M	>75%		Schmidt et al., 2003
Terbuthylazin	10 - >70%		Schmidt et al., 2003
p,p'-DDA (DDT metabolite)	no removal	Lake Wannsee	Heberer et al., 2004
o,p'-DDA (DDT metabolite)	no removal	Lake Wannsee	Heberer et al., 2004

5.3.4 Hydrocarbons

Microbial degradation of aromatic hydrocarbons (Toluene, Pseudocumene, Hemellitene and Ethylbenzene) at the first meters of underground passage during BF was observed by several authors (Jüttner, 1999; Schwarzenbach et al., 1983). Volatile aromatic hydrocarbons are generally removed effectively only after a few meters during bank filtration (Schwarzenbach et al., 1983).

The authors observed large seasonal differences in the degradation of halogenated benzenes, at a bank filtration sites during summer and during winter. It was suggested, for instance, that anoxic conditions in summer prevent the biodegradation of l.4-dichlorobenzen. Moreover, a group of organic chemicals (chloroform, 1,1,1-trichloro-ethane, trichloroethylene and tetrachloroethylene) were found to be persistent and thus ineffectively removed by bank filtration (Schwarzenbach et al., 1983). This is in line with findings by (Kühn and Brauch, 1988) reporting less than 10% reduction for TCE and PCE during bank filtration at the river Rhine. However, in the same study THM and 1,4-DCB were removed between 40 to 60% and 1,2-DCB even between 60 to 90%. The effect of redox conditions was studied at a remediation site, the authors found half-lives for DCE at groundwater temperatures (10°C) to be 39 days under aerobic and 4.060 days under anaerobic conditions illustrating that long travel times may be required under unfavourable conditions (Noble and Morgan, 2002). Bradley and Chapelle (1998) observed for the breakdown of DCE via VC to CO2 a two times higher degradation rate under oxic conditions. The efficiency decreased from conditions of Fe (III) reduction to SO42-reduction to methanogenesis, however, degradation was still evidenced under anaerobic conditions. Lower chlorinated hydrocarbons are predominantly biodegraded under oxic conditions whilst higher substituted hydrocarbons (e.g. TCE, PCE) are rather biodegraded in the absence of oxygen (Hülshoff et al., 2009).

Bank filtration holds potential to remove micropollutants and mitigate shock loads that are present in surface water. The time required for degradation can be several months to years (especially under anaerobic conditions) and complete degradation of the toxic substances is uncertain. Due to the diversity of hydrocarbons and the complexity of degradation processes, a general prediction for their removal during BF is difficult. Low soluble compounds tend to sorb and degradation depends on redox conditions as well as the availability of co-metabolites as primary substrates. The persistence or extremely slow degradation has been observed for several chlorinated hydrocarbons (e.g. TCE, PCE) and in some cases the metabolite (e.g. vinylchloride) exhibits a higher toxicity than its parent compound. Bank filtration may mitigate shock loads but is overall less suited to remove the chlorinated hydrocarbons discussed due to their persistence, long retention times and strongly diverging redox requirements.

It seems likely that newly-industrialised countries are considerably affected by chlorinated hydrocarbons as earlier suggested for pesticides; however, monitoring is yet scarce.

5.3.5 Endocrine disruptors

Endocrine disrupting chemicals (EDC) are exogenous, either natural or synthetic, substances that mimic hormones and hence interfere with the endocrine system. Endocrine disruptors can be cleaners, pesticides, food additives, cosmetics, contraceptive drugs or even inorganics such as heavy metals. Although the risk posed to human health is little understood, concerns have been expressed regarding their cumulative and synergistic effects (e.g. infertility). In the aquatic ecosystem which serves as an early warning system for environmental toxins, the feminisation in male fish has been observed (CEH, 2002; Jobling and Tyler, 2006). Endocrine disrupting chemicals are omnipresent in industrial and domestic wastewater and often incompletely removed by sewage treatment. Thus, it is important to know for BF operation whether EDCs present in surface waters can be removed by subsurface passage. EDC´s have been detected in effluents of wastewater treatment plants around the world (Kumar et al., 2008; Ying et al., 2002; Ying et al., 2008), but only few studies focused on EDC occurrence in groundwater systems (Sonzogni, 2006).

In lab-scale experiments conducted by Ying et al. (2008) efficient degradation was observed for E2, EE2, BPA, 4-t-OP and 4-n-NP in aquifer materials under oxic conditions while under anoxic conditions, E2 was the only substance degraded. Half-lives were in oxic aquifer material between 0.2 and 4.1 days. The data compiled in Table 5-7 suggests that an efficient removal is achievable during BF under aerobic conditions depending on the length of the oxic passage.

Table 5-7 Degradation of endocrine disruptors during underground passage

Substance	Reduction	Days (d) or distance (m)	Conditions	Reference
BPA	1) 100% 2) $t_{1/2}$ 3) 100% 4) >95%	1) n.a. 2) 0.2 to 4.1 d 3) 4) 60 to 100 d	1) BF, c_o = 50 ng/l 2) oxic aquifer material columns 3) oxic (BF) 4) oxic	1) Sacher et al. (2000) 2) Ying et al. (2008) 3) Schmidt et al. (2003) 4) Schmidt (2003)
E2 and EE2	1) 100% 2) t1/2	1) first meters of BF 2) 26 d for E2, 0.2 to 4.1 d for EE2	1) oxic 2) oxic aquifer material columns	1) Zühlke (2004) 2) Ying et al. (2008)
NP	1) $t_{1/2}$ 2) 70% 3) 93% 4) $t_{1/2}$ 5) 100%	1) 14 to 99 d 2) 14 m 3) 5-14 m 4) 0.2 to 4.1 d	1) oxic 2) co = 1 µg/l oxic 3) co = 2.7 µg/l suboxic 4) oxic aquifer material columns 5) oxic (BF)	1) Yuan et al. (2004) 2) Schaffner (1987) 3) Ahel et al. (1996) 4) Ying et al. (2008) 5) Schmidt et al. (2003)
NP M	1) $t_{1/2}$ 2) 98-99%	1) 69 to 116 d 2) 1-14 d	1) oxic 2) suboxic BF	1) Yuan et al. (2004) 2) Ahel (1996)
OP	$t_{1/2}$	0.2 to 4.1 d	oxic	Ying et al. (2008)
BPA = bisphenol A, E2 = 17ß-estradiole, EE2 = 17α- ethinylestradiole, NP = nonylphenol, OP = octylphenol, NPM = nonylphenol monoethoxylate				

Concerns have been raised that developing and newly-industrialised countries are particularly exposed to endocrine disrupting chemicals due to excessive use of pesticides and rapid industrial growth. Several organochlorine pesticides which are banned in industrialised countries because of their toxic properties are still used in low-income countries. Exponential industrial growth and in particular, the production of plastics contribute to the release of endocrine-disrupting chemicals into the environment. According to the Society of the Plastics Industry (1997), the sector of plastics industry has grown in the US at the rate of 6-12% per year in the 1990s while in developing countries, the annual growth rate was already 40% often without any precautions taken to protect the environment.

Although there is currently scarce evidence that endocrine disrupting chemicals can cause health problems to humans at the low levels found in drinking water, the cumulative and synergistic effects of endocrine disruptors remain a concern. Adverse effects have been observed in aquatic organisms which function as an early warning system for environmental toxins. Bank filtration is suitable to remove several endocrine disrupting chemicals by sorption and degradation under oxic conditions. However, some (especially organochlorine) pesticides can be persistent.

5.3.6 Pharmaceuticals

Several pharmaceutically active compounds (PhACs) were detected in the aquatic environment but the fate during BF was found to be inconsistent (Halling-Sørensen et al., 1998; Heberer, 2002; Heberer et al., 2004). Some PhACs were partially removed (e.g. diclofenac) or completely removed (e.g. bezafibrate, indomethacine) but several other PhACs were found to be very persistent (e.g. carbamazepine, primidone, AMDOPH) during BF passage (Heberer et al., 2004; Massmann et al., 2008; Reddersen et al., 2002). Massmann et al. (2008) investigated elimination efficiency of a groundwater recharge site in Berlin (Germany) regarding carbamazepine, phenazone and phenazone-like pharmaceuticals. The authors found that removal during infiltration was not observed for carbamazepine, independent of the redox state of the aquifer, therefore its degradation rate was assumed to be insensitive to temperature (Greskowiak et al., 2006; Massmann et al., 2008). On the other hand low temperatures and oxic state of the aquifer was shown to enhance elimination potential of phenazone-type pharmaceuticals in winter, while post oxic conditions in summer (T>14°C) caused a breakthrough of phenazone type pharmaceuticals (Massmann et al., 2008; Massmann et al., 2006b).

Pharmaceuticals that have repeatedly been reported to be redox-dependent and degradable best under oxic conditions are dimethylaminophenazone (DMAA), phenazone and phenazone-type analgesics (Heberer et al., 2004; Massmann et al., 2006a; Zühlke, 2004), as well as the estrogenic steroids 17ß-estradiole, estrone and 17α-ethinylestradiole (Zühlke, 2004). Pharmaceutical substances that have been reported to be redox-dependent and degradable best under anoxic/anaerobic conditions are sulfamethoxazole (Jekel and Grünheid, 2007) and amidotrizoic acid (Schmidt et al., 2003; Schmidt, 2003).

A redox-independent and readily degradable pharmaceutical is the X-ray contrast agent iopromide (Jekel & Grünheid, 2007). Substances that have repeatedly been reported to be difficult to break down during bank filtration irrespective of the redox conditions include the analgesic-metabolite AMDOPH (Zühlke, 2004; Heberer et al., 2004) and the two anti-convulsants primidone (Heberer et al., 2004) and carbamazepine (Heberer et al., 2004, Schmidt et al., 2003; Sacher et al., 2000).

In Table 5-8, substances are classified into groups for which low removal efficiency (0-40%), medium removal efficiency (40-90%) and high removal efficiency (>90%) has been observed during bank filtration. The column “conditions” provides explanatory information for the respective study on redox conditions (oxic, suboxic, anoxic), retention time (d) and well depth where this information was available.

Table 5-8 Overview of substance degradability during subsurface passage

Pharmaceutical	Removal	Conditions	Reference
Low removal (0-40%)			
AMDOPH (A)	1a) 0% 1b) 0%-70% 2) 0%	1a) oxic BF3-50 d 1b) anoxic BF, 80-240 d 2) shallow monitoring well	1) Schmidt (2003) 2) Heberer et al. (2004)
Amidotrizoic acid (X)	1) 95% 2) 65-95%	1) oxic BF 2) anoxic BF, 80-240 d	1) Schmidt et al. (2003) 2) Schmidt (2003)
Carbamazepine (V)	1) 0% 2) <10% 3) 0% 4a) 0-40% 4b) 0-40%	1) shallow monitoring well 2) (sub)oxic: >365 d ($t_{1/2}$) 3) oxic BF 4a) oxic BF, 7-100 d 4b) anoxic BF, 20-120 d	1) Heberer et al. (2004) 2) Stuyfzand et al. (2007) 3) Schmidt et al. (2003) 4) Schmidt (2003)
Primidone (V)	0%	shallow monitoring well	Heberer et al. (2004)
Medium removal (40-90%)			
Clofibric acid (M)	1) 40-90% 2) 59-75%	1) oxic BF, 20-65 d	1) Schmidt (2003) 2) Heberer et al. (2004)
Iopamidol (X)	1) 0-90% 2) 52%	1) (sub)oxic: 25-85 d ($t_{1/2}$) 2) oxic BF	1) Stuyfzand et al. (2007) 2) Schmidt et al. (2003)
Propyphenazone (A)	1) 20-90% 2) 52-69%	1) anoxic BF, 20-120 d 2) shallow monitoring well	1) Schmidt (2003) 2) Heberer et al. (2004)
Sulfamethoxazole (B)	1) 0-70% 2) 78% 3) 70-90%	1) (sub)oxic: > 365 d ($t_{1/2}$), anoxic: 25-55d ($t_{1/2}$) 2) oxic BF 3) anoxic BF	1) Stuyfzand et al. (2007) 2) Schmidt et al. (2003) 3) Schmidt (2003)
High removal (>90%)			
Bezafibrate (M)	1) 100% 2) 100% 3) 75-99%	1) oxic BF 2) oxic BF 3) anoxic BF, 20-120 d	1) Kühn & Müller, 2000 2) Schmidt et al. (2003) 3) Schmidt (2003)
Diclofenac (A)	1) >94% 2) 98% 3a) 80->95% 3b) 30-99%	1) oxic 2) oxic BF 3a) oxic BF, 7-100 d 3b) anoxic BF, 20-120 d	1) Kühn & Müller, 2000 2) Schmidt et al. (2003) 3) Schmidt (2003)
Iomeprol (X)	1) >90% 2) 100%	1) (sub)oxic:<0.5 - <6 ($t_{1/2}$) 2) oxic BF	1) Stuyfzand et al. (2007) 2) Schmidt et al. (2003)
Iopromide (X)	1) >90% 2) 100% 3) 82->99%	1) (sub)oxic: <7 d ($t_{1/2}$), anoxic: 140 - >365 d ($t_{1/2}$) 2) oxic BF 3) anoxic BF, 80-240 d	1) Stuyfzand et al. (2007) 2) Schmidt et al. (2003) 3) Schmidt (2003)
Metoprolol (M)	97%	oxic BF	Schmidt et al. (2003)
Phenazone (A)	100%	(sub)oxic: <2 d ($t_{1/2}$)	Stuyfzand et al. (2007)
A = Analgesics, B = Antibiotics, M = Miscellaneous, V = Anticonvulsants, X = X-ray contrast agent			

In developing countries it is expected that types of medicinal products such as anti-tuberculotics (e.g. isoniazide, pyrazinamide) or anti-malaria drugs (e.g. chloroquine, mefloquine) are more likely to be present in developing countries than for example, blood-lipid regulating agent like clofibric acid. In newly-industrialised countries, the consumption and discharge of pharmaceuticals is likely to increase and the drugs used will reflect the level of sanitation and development. Since little is known on the adverse effect of pharmaceuticals in drinking water, they are at present not in the focus of concern in developing and newly-industrialised countries.

5.3.7 Summary

The downside of industrialisation is often environmental pollution. Organic micropollutants of anthropogenic origin are nowadays ubiquitously found in the environment of which many show adverse effects on humans, animals and the aquatic microflora.

Rapid industrial growth, lack of emission controls and indiscriminate waste disposal have led to the distribution of organic micropollutants such as aromatic and chlorinated hydrocarbons in newly-industrialised countries. China and India account already for one third of the global crude oil demand. Studies from an industrial area in China reported concentrations of aromatic hydrocarbons (typical by-products from fossil fuels) in 10 rivers to range between 45.8 and 1.276 ng/l (Shi, 2003). In case of aromatic hydrocarbons (BTEX and PAHs), bank filtration holds potential to remove micropollutants by sorption and degradation. It may also mitigate shock loads in surface waters as caused by spills. However, the time required for degradation may take months to years. Under anaerobic conditions, substances can be either persistent or degradation rates are frequently found to be slower than under aerobic conditions.

The organochlorine pesticides (e.g. DDT, lindane) are much more persistent and accumulate in the food chain. Pesticides do not only exhibit an endocrine disrupting effect but some are considered carcinogenic. Although developed countries still account for three-quarters of all pesticides used worldwide; the use of pesticides in developing countries is on the rise (Miller, 2004). China has meanwhile emerged as the world's second largest producer and consumer of pesticides. Surveys carried out in Brazil, Central America and Nigeria revealed that mishandling and overuse have put humans at risk for direct pesticide poisoning. The pesticide levels in water bodies of developing and newly-industrialised countries are estimated to be high but there is often no monitoring (Schwarzenbach et al., 2006). The removal of pesticides during subsurface passage is influenced by sorption and degradation depending on clay content and redox conditions. Bank filtration may improve surface water quality by complete or partial degradation (and peak load mitigation) but in some cases a subsequent post-treatment (e.g. GAC filtration) may become necessary.

As mentioned for organochlorine pesticides, chlorinated hydrocarbons are often toxic and persistent micropollutants that tend to sorb or bioaccumulate. They seem likely to be a problem wherever industrialisation is on the rise; however, the monitoring in newly-industrialised countries is yet scarce. Tetrachloroethane, dichloromethane, trichloroethene and cis-1.2-dichloroethene were the most common micropollutants found in German and US groundwaters in proximity to industrial sites suggesting their poor degradability. Degradation is influenced by the number of chlorine substituents, redox conditions and the presence of co-metabolites as primary substrate. Bank filtration is less suited for the removal of chlorinated hydrocarbons since very long retention times may be required but it can effectively mitigate shockloads.

For developing and newly industrialised countries, the issues of endocrine disruptors and pesticides are closely linked. Organochlorine pesticides are potent endrocrine disrupting chemicals, which are banned in industrialised countries because of their toxic properties but are still used in low-income countries. Moreover, the exponential industrial growth and the production of plastics in particular, contribute to the release of endocrine-disrupting chemicals into the environment. The plastics industry has grown in the US at the rate of 6-12% per year in the 1990s while in developing countries the annual growth rate was already 40% often lacking precautions to protect the environment. Several industrial by-products and pharmaceuticals of endocrine-disrupting potential (Bisphenol A, nonylphenols, estradiols) are removed by BF. They tend to sorb due to their hydrophobic character and were reported to be biodegraded under oxic conditions.

Disinfection of pre-treated water is generally recommended for developing, newly-industrialised and industrialised countries alike to ensure safe drinking water. The disinfection with oxidants is known since the 1970's to generate harmful disinfection by-products when reacting with organic matter. Bank filtration is an ideal pre-treatment by considerably reducing pathogen loads, removing organic matter that may act as DBP precursor and actual disinfection by-products, if they are present in source water.

Pharmaceuticals are not seen as critical water quality parameter in developing countries, since the use of pharmaceuticals and the operation of sewage treatment facilities as major point sources are both characteristic for industrialised countries and developed infrastructures. In newly-industrialised countries, the consumption and discharge of pharmaceuticals is likely to increase and also the type of drugs used will reflect the level of sanitation and development. Overall, little is yet known on the cumulative and synergistic adverse effect of pharmaceuticals on humans.

While pharmaceuticals are likely insignificant in developing countries, they are in the focus of concern in developed countries as emerging pollutants and not yet in the focus of interest of newly-industrialised countries. This illustrates the different emphasis placed on water contaminants based on the level of industrialisation.

5.4 Example – removal of pathogens at Srinagar, India

At the RBF site at Srinagar, India which has been discussed in some of the previous sections, intensive measurements of the water quality of the river and at the RBF wells was carried out from September to December 2012. The period includes the high water levels resulting from the monsoon and the subsequent falling limb of the annual hydrograph. Figure 5-1 shows the gradual retreat of the water away from the bank.

Samples from the production well PW5, monitoring well MW5 and the Alaknanda River (see Figure 5-1) were taken regularly and analysed for Total Coliforms, E. Coli and on one occasion Enterococci.

Figure 5-1 Retreat of the Alaknanda River's water line from September to November 2012 (Saph Pani, 2013)

The samples were directly collected from the sampling point in 100 ml sterile containers and stored in a thermo box at 4 – 7°C. After all samples were collected, they were transported to the UJS laboratory in Srinagar where they were analysed. Samples were introduced into IDEXX colilert trays and incubated overnight (18 to 19 hours) at

35°C±0.5°C. Cell numbers in the samples were determined using IDEXX's *51-Well Quanti-Tray MPN Table* or *Quanti-Tray®/2000 MPN Table*. The most probable number (MPN) method is a probabilistic test that assumes cultivable bacteria meet certain growth and biochemical criteria. The procedure for the preparation of the samples for Enterococci is similar. However, the reagent used was Enterolert-DW and the samples for incubated for 24 hours.

Table 5-9 provides a summary of the range and mean values for Total Coliform, E. coli and Enterococci counts in the Alaknanda River and the production and monitoring wells of the RBF site in Srinagar from samples taken from 27 September to 7 November 2012.

Table 5-9 Range and mean Total Coliform and E. Coli counts, and snap-shot analyses of an Enterococci count, in the Alaknanda River and RBF site in Srinagar (Saph Pani, 2013)

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

It is observed that while the total coliform counts in the Alaknanda River can attain a maximum of nearly 21,000 MPN/100 ml, it is yet considerably lower compared to total coliform counts reported for RBF sites (e.g. Haridwar, Patna and Mathura) along the Ganga River and its tributaries (Table 5-5). The same applies also for E. coli counts. This is due to the considerably low impact of the population upstream of Srinagar accompanied with enhanced biodegradation due to the relatively high dissolved oxygen content in the river and high gradient allowing for enhanced dilution. However, the mean total coliform and maximum E. Coli counts of >7500 MPN / 100 ml and >6500 MPN / 100 ml, respectively in the Alaknanda River are higher than the environmental limit of <5000 MPN / 100 ml determined (by the CPCB - Central Pollution Control Board of India) for drinking water sources requiring conventional treatment and disinfection.

The total coliform and E. Coli counts found in the production wells at the RBF site (PW5 and PW-DST) are significantly lower although not completely absent (Table 5-9).

It is observed that the production well PW5 that is located only 5.4 m from the normal monsoon water line (park boundary) of the Alaknanda, has a significantly lower mean total coliform and E. Coli count of only 45 MPN / 100 ml and 2.2 MPN / 100 ml, respectively compared to the Alaknanda River. These mean values, as also those for the production well PW-DST located around 170 m from the normal monsoon water line and with even lower coliform counts, lie within the environmental limit of <50 MPN / 100 ml determined by the CPCB for drinking water sources not requiring conventional treatment but disinfection.

Figure 5-2 shows the E. coli count in the samples taken from the Alaknanda River and the production wells. There is a significant reduction in the number of E. coli from the river to the wells.

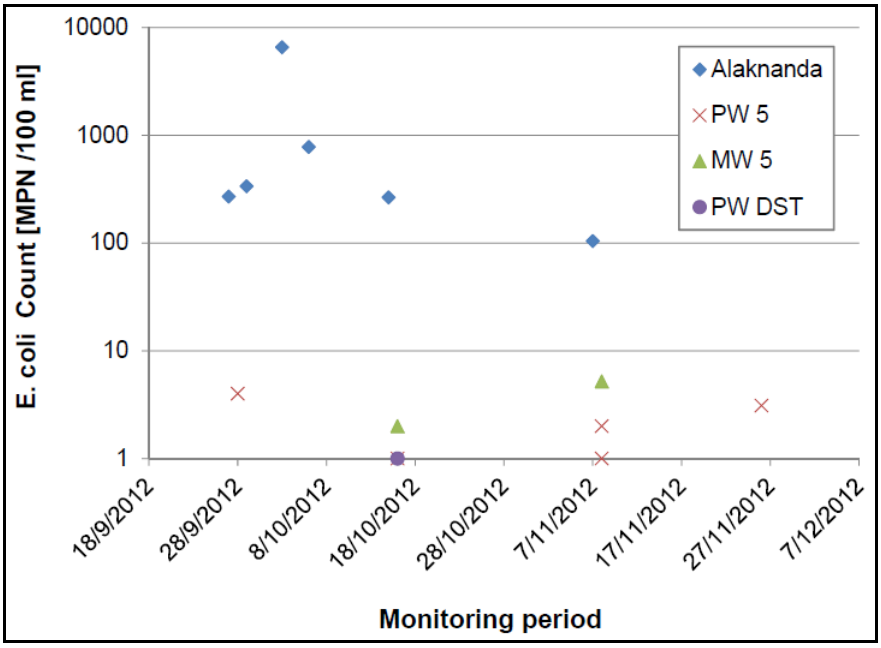


Figure 5-2 E. Coli counts in the Alakanda river and wells at the RBF site in Srinagar during the period September – November 2012 (Saph Pani, 2013)

5.5 Example – Purification of drinking water at RBF site Düsseldorf, Germany

The information given in this section is based on an article by Richters (2011) from the Stadtwerke Düsseldorf published in 'Drinking Water – Source, Treatment and Distributions' (Dehradun, 2011) which summarises the contributions to a workshop dedicated to RBF.

More details of the RBF site are given in section 0.

Removal of particles and turbidity

The concentration of suspended solids in the river water depends on the discharge. Highest values appear in the phase of increasing water levels during flood waves. The concentration of suspended solids in the Rhine Rver varies between 10 g/m³ and about 400 g/m³; the mean value is less than 40 g/m³.

The raw water in the wells however is always clear; the turbidity measured in the raw water is 0.05 FNU. The particle counts in the raw water of the Flehe waterworks were investigated in 1996 and 1998. The total count is between 70 and 250 particles per millilitre.

As a consequence of the removal of particles and turbidity, clogging of parts of the riverbed during the operation of riverbank filtration wells is unavoidable. The flow in the infiltration area is permanently directed from the river to the aquifer. Suspended silt cannot pass the aquifer and is removed and deposited in the upper layer of the aquifer. Clogged areas tend to expand from the well side bank to the middle of the riverbed. This will be limited especially by bed load transport in the river, which whirls up and removes the deposits in regions with sufficient shear forces.

Equilibration of fluctuating concentrations in the river water

Comprehensive field studies were carried out to get time-series of hydraulic, chemical and physical parameters of bank filtration. The subsoil region between the riverbed and the wells works as an almost perfect mixer to compensate fluctuating concentrations of substances in the river water. One effect of this is, that fluctuating concentrations, for instance of chloride (Figure 5-3), are balanced out to their mean values.

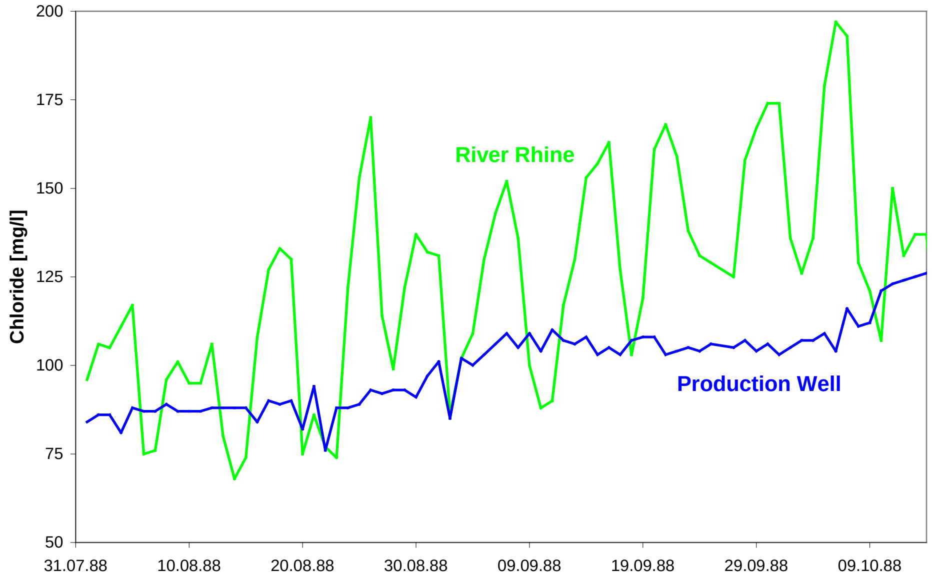


Figure 5-3 Equilibration of chloride fluctuation during bank filtration

A second effect is that accidental pollution, which causes peak concentrations in the river water, will be damped down to about 3 - 5% in the well water due to dilution.

Removal of biodegradable compounds

The assumption that biodegradation in bank filtration is very similar to slow sand filtration and will happen just below the infiltration areas was investigated with samples taken from a diving cabin 0.6 m below the riverbed and from boreholes between the river and the wells (Figure 5-4).

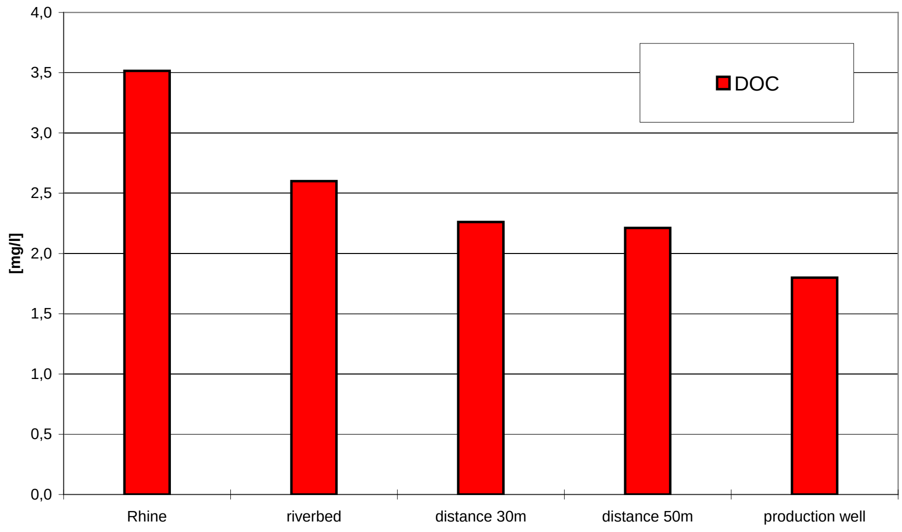


Figure 5-4 Removal of DOC under aerobic conditions

6 Details of case study sites used as examples

6.1 Riverbank filtration site in Srinagar, India

6.1.1 General geography

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

6.1.2 Drinking water production

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

6.1.3 Riverbank filtration scheme

In May 2010, one production and one monitoring well (PW-DST & MW1) were constructed in the South-West part of the town (Figure 6-1) as part of a separate project by UJS (Ronghang et al., 2011; Kimothi et al., 2012). These wells are located 170 m from the riverbank and were drilled up to a depth of 20 m BGL. With the objective to cater for current and future increases in demand, two additional boreholes were drilled for the construction of production wells PW1 and PW5 on the lower level of a public park (administered by the Municipal Corporation of Srinagar) located in between the existing PW-DST and the river in August 2011 (Figure 6-1). Currently only PW5 has a temporary submersible pump for testing purposes within the Saph Pani project. Another monitoring well (MW5) was constructed by AJD between PW5 and the Alaknanda River in May 2012 (Figure 6-1).

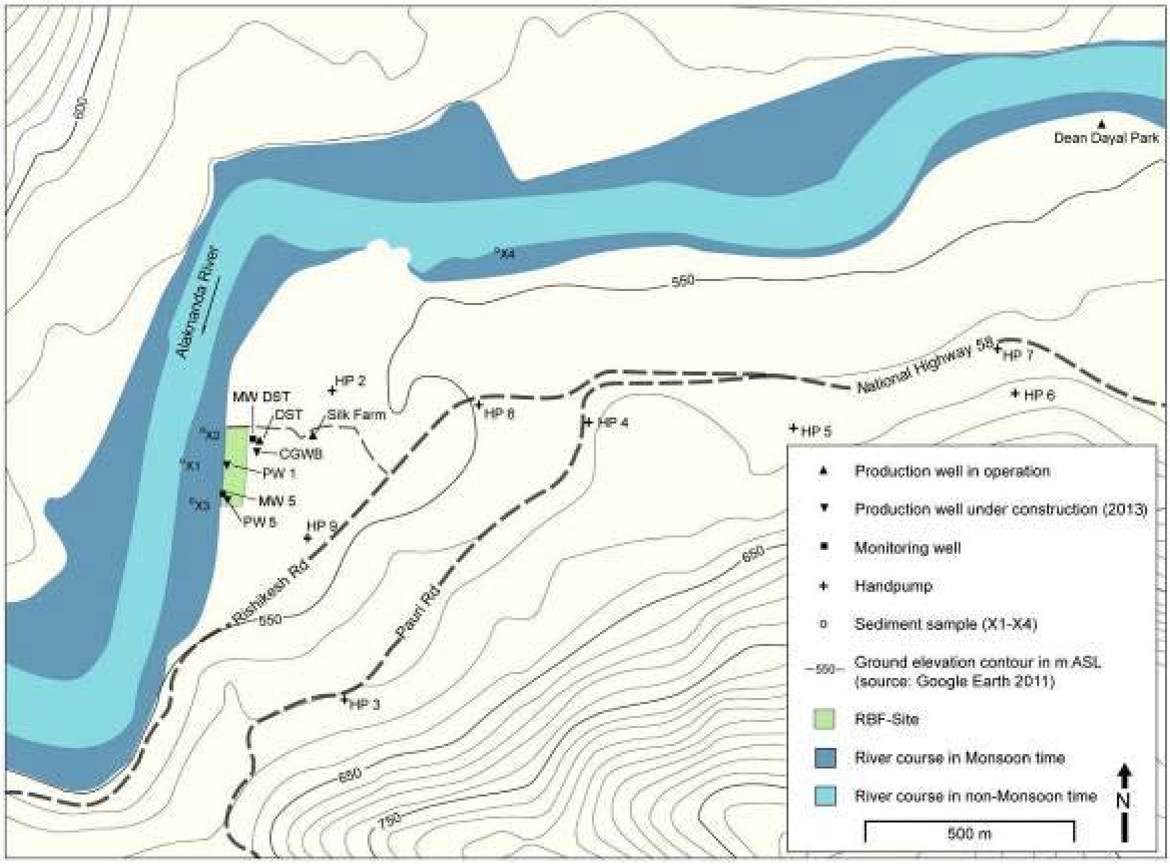


Figure 6-1 RBF well field in Srinagar under development since May 2010 (Saph Pani, 2013)

The interpretation of the borehole material showed that the aquifer comprises medium to coarse sand. Interpretation of pumping test data from PW-DST showed the hydraulic conductivity of the aquifer to be in the range of 1.3×10^{-3} – 4.0×10^{-3} m/s (HTWD and UJS, 2012a). The PW-DST currently operates for 20 – 22 hours/day with a production of 852 - 937 m^3/day. After abstraction and on-site disinfection by chlorination, the water is pumped into a storage reservoir and then supplied into the distribution network by gravity. The production from the PW-DST accounts for 18 – 22 % of the combined drinking water production of Srinagar and Pauri (Kimothi et al., 2012).

6.1.4 Hydrogeology

Srinagar lies in a localised flood plain of the Alaknanda River, after the river emerges from a relatively narrow valley. Fluvial terraces on either side of the river indicate the presence of mainly matrix supported gravels of debris flow origin, clayey silt and fine sand (Jha, 1992). This alluvium is constituted of relict lake sediments (Sundriyal et al., 2007). The thickness of the aquifer at the RBF site was determined to be 21 m as interpreted from borehole logs of the production wells PW-DST, silk farm, PW1 and PW5 (Figure 6-2).

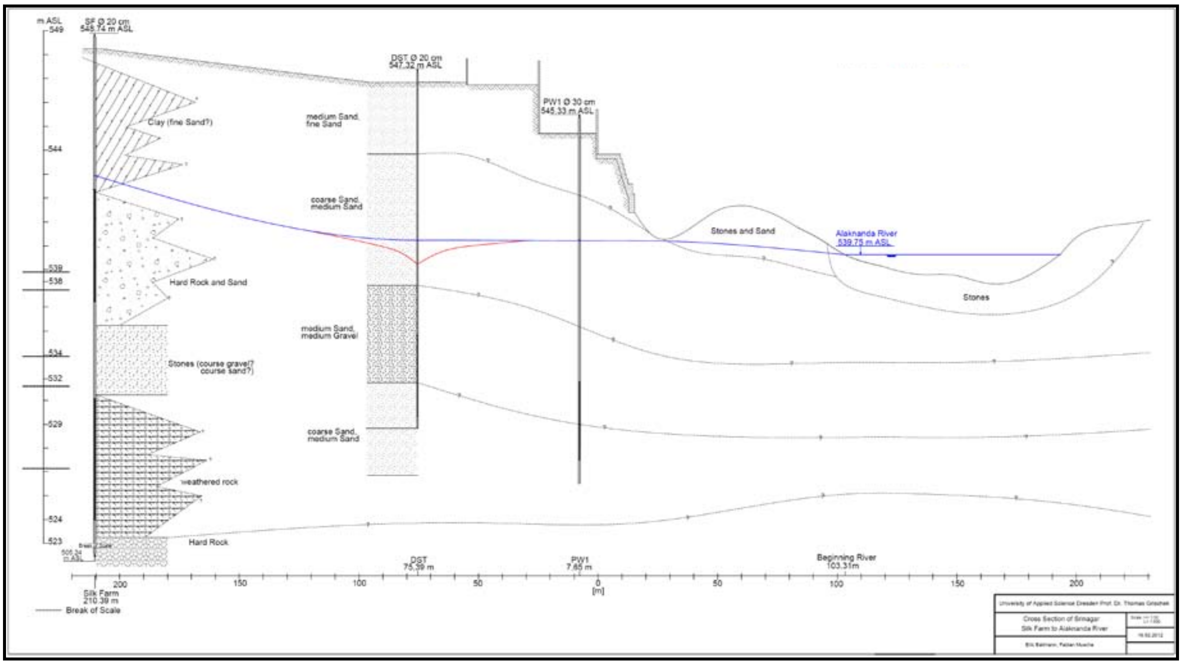


Figure 6-2 Subsurface cross section of RBF site in Srinagar (Saph Pani, 2013)

The top soil and upper unsaturated subsurface is mainly made of fine to medium sand. The post-monsoon depth to the groundwater table in the monitoring well MW DST, based on a reference day measurement in December 2011, was around 7 m BGL. The saturated aquifer material has a medium to coarse sand layer followed by medium sand to medium gravel beneath which a medium to coarse sand layer is again found. The base of the aquifer is made up of consolidated and unconsolidated rock. The mean hydraulic conductivity of 4.5×10^{-2} m/s for the riverbed material was obtained after *Beyer* from sieve analyses of sediment taken from four different locations along the river (Figure 6-1, sediment sample locations X1…X4, Saph Pani 2013). Information obtained from a report of the construction of a dam a short distance upstream of Srinagar, indicates that a thin layer of topsoil covers a predominantly hard rock layer mostly in areas with a steep topography further upstream of the RBF site.

6.1.5 Historic flood event in Srinagar

The RBF site in Srinagar where the drilling of the boreholes for the production wells PW1 and PW5 commenced in the beginning of August 2011 was flooded on 12 August 2011 (Figure 6-3 and Figure 6-4).

Figure 6-3 Potential RBF site under development in Srinagar inundated by the monsoon flood of the Alaknanda (facing upstream) in August 2011
(Photo: J. Ebermann, HTWD, 2011)

Figure 6-4 Production well PW5 (under construction) in the background (encircled) inundated by the monsoon flood of the Alaknanda (facing downstream) in August 2011 (Photo: J. Ebermann, HTWD, 2011)

The flood water rose to around 0.7 m above the ground level at the site. At the time of the flood, the RBF site was under construction with only the casing pipe and filter section for the production well PW5 having been installed. However the flood water did not enter the borehole of PW5 because the top of the casing pipe remained above the flood level (Figure 6-4). Due to the sudden onset of the flood, more enhanced measures other than temporarily covering the top of the casing of PW5 were not possible as the site had become inaccessible, especially for equipment required for enhanced sealing of wells (e.g. welding a cover onto the casing). The boreholes for PW1 and PW5) were drilled after the flood receded. The reoccurrence of the flood was witnessed again during the monsoon in 2012, with the flood water attaining a level below 0.7 m (above ground level of the RBF site). As the area in the vicinity around the site is sparsely populated, no previous eye-witness accounts of the highest flood level attained by the Alaknanda in this particular location were available before the site-selection and construction of the wells.

6.2 Riverbank filtration site in Haridwar, India

6.2.1 General geography

The Census of India (2011) defines Haridwar as an urban agglomeration having a permanent population of 310,582 persons. The urban agglomeration (UA) of Haridwar is spread over the elongated topographically level flood-plain area (> 11 km) on the West bank of the Ganga River, where the Ganga exits from the Siwalik hill range (Lesser Himalayas) and enters the Northern fringe of the Indo-Gangetic alluvial plain and thereby transitioning from its upper into its middle course (Figure 6-5). The Haridwar UA comprises the main or “core” part of the city (that is administered by the municipal corporation – “*Nagar Palika Parishad*, NPP”) and the suburban areas that include the industrial areas. The main city administered by the NPP has a permanent population of 225,235 persons.

6.2.2 Religious significance and impact on population numbers

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

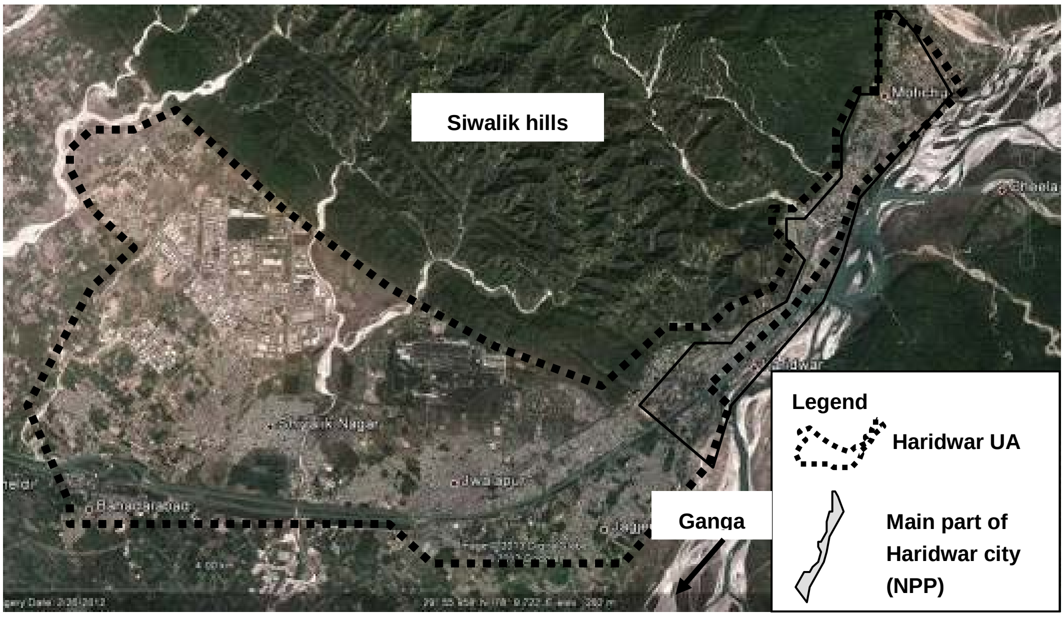


Figure 6-5 Overview of Haridwar (adapted from Google earth © Google, 2013)

6.2.3 Riverbank filtration scheme

Twenty two RBF wells (Figure 6-6) abstract a mixture of bank filtrate and groundwater from the upper unconfined aquifer, which accounts for nearly 68 % (> 43,000 m^3/day) of the total drinking water production of the entire population within the main city of Haridwar (Sandhu and Grischek, 2012). Groundwater abstraction through vertical production wells (colloquially called "tube" wells) from the deeper confined aquifer covers the remainder of the drinking water production in the main city. The 22 large-diameter (10 m) bottom-entry caisson RBF wells of 7 – 10 m depth are located in an area from 29°54'44" to 30°0'10" N and from 78°8'33" to 78° 12' 33" E.

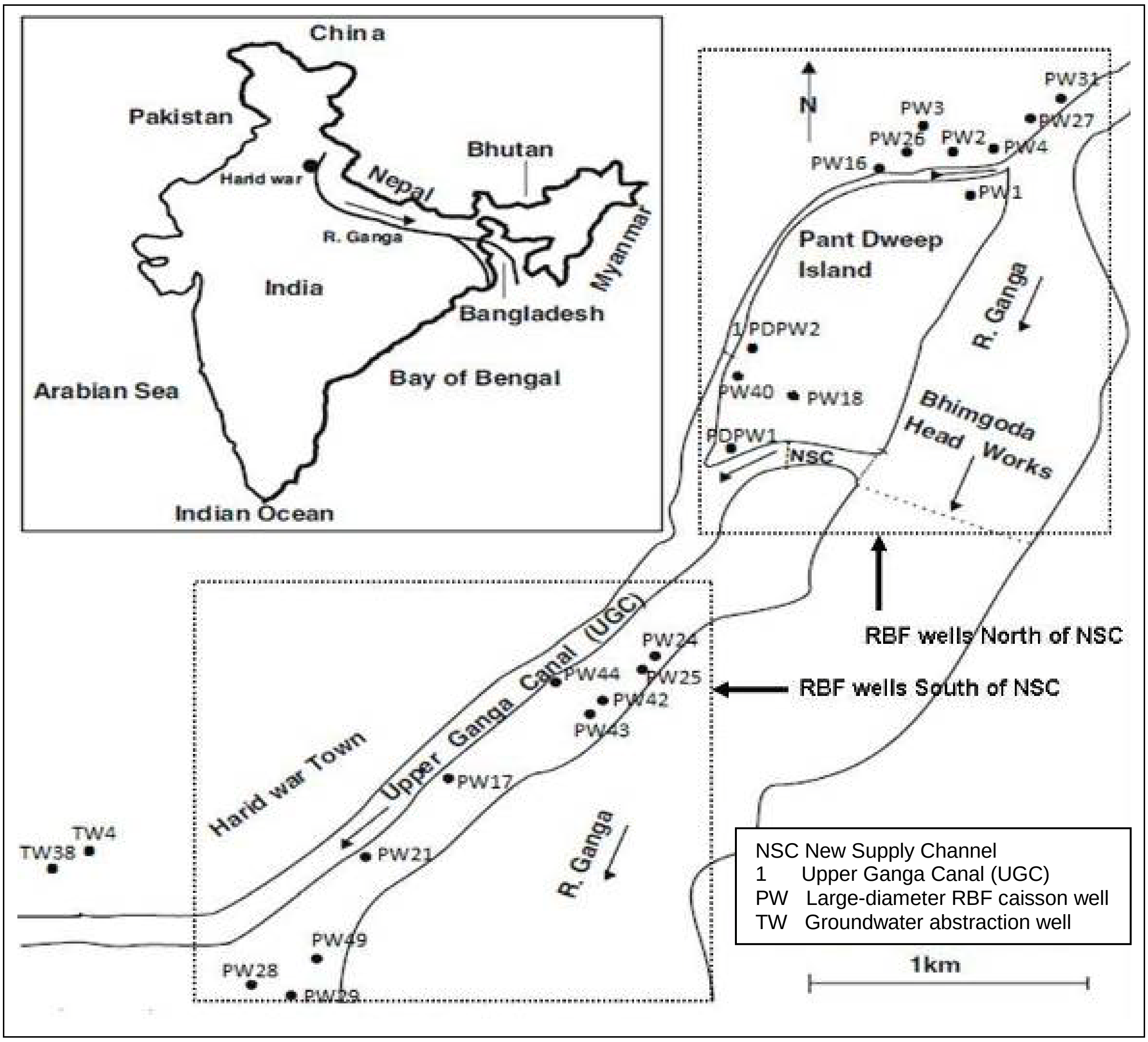


Figure 6-6 Location of large-diameter RBF wells in Haridwar (after Saini 2011)

The 22 RBF wells can be distinctly divided into two groups based mainly on the proportion of bank filtrate to groundwater abstracted. Those RBF wells located to the North of the New Supply Canal (NSC) on Pant Dweep island and in Bhupatwala abstract a comparatively lower portion of bank filtrate than those located to the South of NSC and in between the Upper Ganga Canal (UGC) and Ganga River (Figure 6-6). The NSC additionally diverts flow of the Ganga from the Bhimgoda barrage reservoir in a regulated manner into the UGC. The shortest distance from the RBF wells to the Ganga or the UGC varies between 50 m and 490 m from the centre of the respective water course (Figure 6-6). Normally, 12 – 13 wells are operated continuously (24 hours) with the remaining wells operating 9 – 19 hours per day using fixed-speed vertical line shaft pumps through 150 mm diameter impeller. The abstracted water is only chlorinated at the well using Sodium hypochlorite (NaClO).

Figure 6-7 Example of large-diameter RBF well adjacent to Ganga River, Haridwar (Photo: L. Rossoff, HTWD, 2011)

6.2.4 Hydrogeology

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

The hydrogeological formation of the study area is interpreted from the borehole data of three exploratory wells (data source UJS) located along a NE-SW transect and extending almost across the entire length of the study area (Figure 6-8). The cross-sectional view of the sub-surface formations (Figure 6-9, X-X') showed that the uppermost layer of around 2 m comprises surface soil, which is underlain by fluvial deposits of fine to coarse sand mixed with pebbles and boulders. Furthermore, hydrogeological investigations conducted on Pant Dweep island concluded that the aquifer is hydraulically connected to the Ganga River and the UGC system under unconfined conditions (Dash et al., 2010). These fluvial deposits are underlain by sequences of relatively thick clay layers mixed with pebbles or boulders, which act as impervious strata with no sign of vertical and horizontal connectivity to the river, canal and the underlying confined aquifer. The depth to groundwater level varies from location to location as the area has a varying topography.

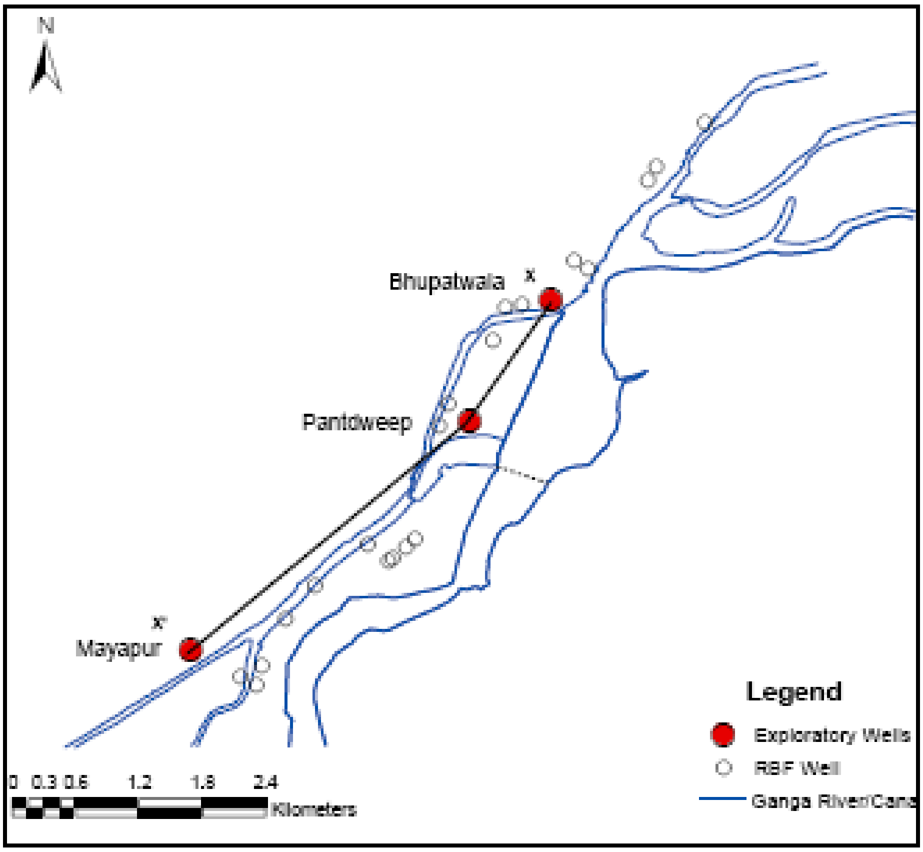


Figure 6-8 Transect X-X' connecting the exploratory wells used for aquifer characterisation (Saph Pani, 2013)

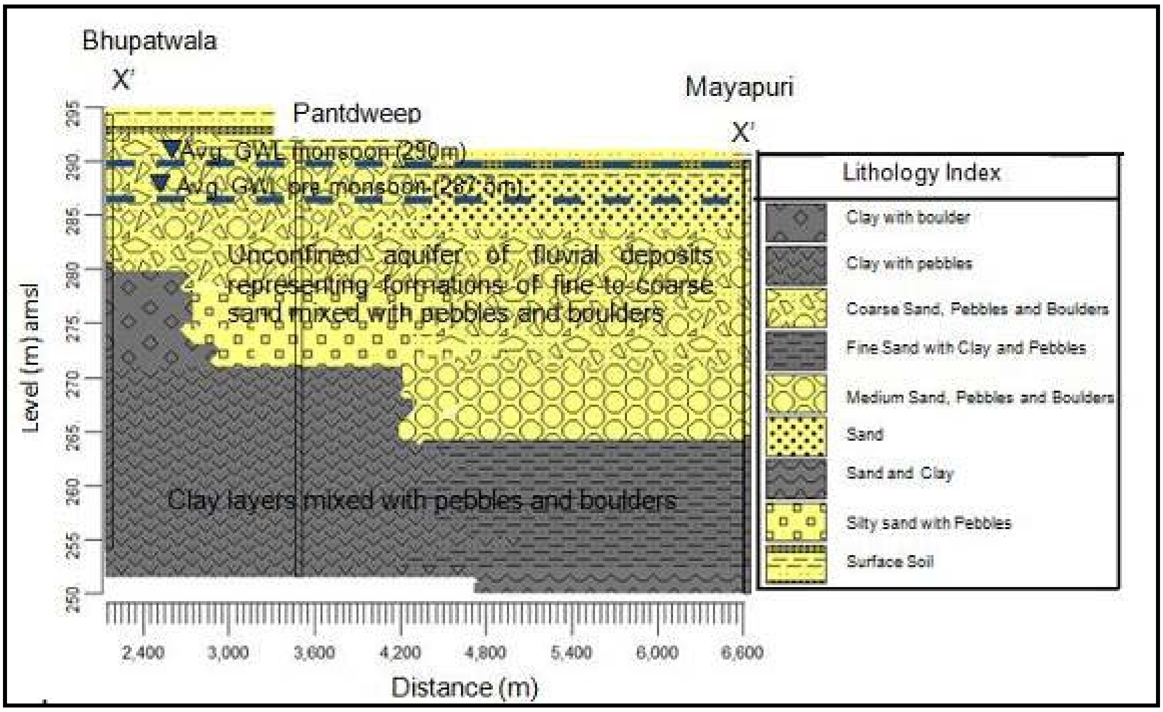


Figure 6-9 Cross-section of the study area along the X-X' transect in Figure 6-8 (Saph Pani, 2013)

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

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

In the Northern part of the study area, the Ganga River and UGC form a natural boundary to the East and South-East respectively for the RBF wells in the Bhupatwala area (IW31, IW27, IW4, IW3, IW2, IW 26, IW16). For all other RBF wells located further downstream on Pant Dweep Island and to the island's South, the UGC and the Ganga River form hydraulic boundaries to the West and East respectively. Consequently, these boundaries cause a natural groundwater flow direction from West to East and also affect the portion of bank filtrate abstracted, as indicated from water quality (Saini, 2011) isotope and groundwater flow modelling investigations. In this context, Saini (2011) observed a different water quality pattern by analysing the electrical conductivity, alkalinity, total organic carbon (TOC) and major ions for the RBF wells in 2011. The water abstracted from the RBF wells to the North of the NSC exhibited higher mean values of electrical conductivity and concentrations of TOC, Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-} compared to the wells to the South of the NSC. Furthermore the abstracted water from the RBF wells to the South of the NSC had a comparable electrical conductivity to the surface water (UGC and Ganga River). This indicates that the production wells to the North of the NSC abstract a lower portion of bank filtrate compared to the South.

6.2.5 Historic flood event in Haridwar

The highest extreme monsoon flood-event (in terms of surface water discharge and level of the Ganga and corresponding wide-spread inundation of river-side land) that was ever recorded occurred on 19 September 2010 (CWC 2010). Water levels recorded at the gauging station of the Central Water Commission (CWC) located approximately 1 – 2 km upstream of Pant Dweep Island in Haridwar reached 296 mASL. During that monsoon (August – September 2010), most of the abstraction structures that pump-out water directly from rivers in the North Indian mountainous state of Uttarakhand, were also submerged. Around the period 18 – 21 September 2010, the area around some of the RBF wells in Haridwar (from North to South: IW 31, 27, 42, 43, 25, 24) was inundated by the flood-waters of the Ganga (Figure 6-10).

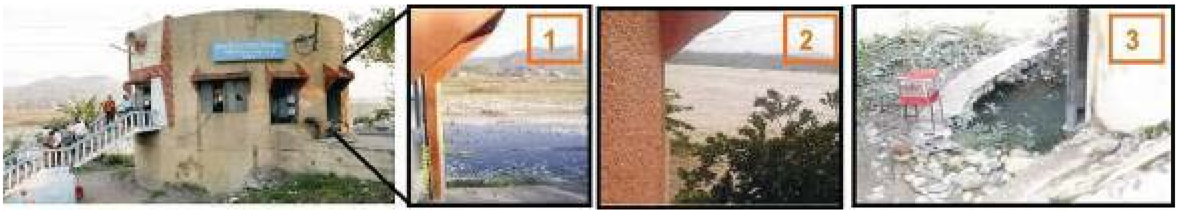


Figure 6-10 RBF well IW 24 in Haridwar (left photo), (1) view of the Ganga River in the background in April 2005 (pre-monsoon), (2) flood-water of Ganga inundates the base of well on 19/09/2010 and (3) damage by scouring to base of well no. 24 (photos from L to R: Schoenheinz and Grischek (2005), Subodh & Kumar (2010))

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

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