

**RIVERBANK FILTRATION MODELING FOR THE
HARIDWAR CASE STUDY**



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PREFACE

Riverbank Filtration as a natural low cost pre-treatment technique is gaining popularity in India for drinking water supply particularly in rural and sub-urban areas. India has a lot of potential to apply this technique particularly in the alluvium and coastal areas. Implementation of this technique in feasible areas would require an in-depth study a-priori on the hydraulic properties of the river and the hydrogeological characteristics of the aquifer including water quality of both the domains.

As background knowledge, some fundamental principles of riverbank filtration processes have been presented in this report together with an overview of the RBF technique and its limitations.

To demonstrate the performance of the technique, the case study site at Haridwar representing the scheme of 22 RBF wells located in the vicinity of the Ganga River and the Upper Ganga Canal network and being used for drinking water supply in the Haridwar city has been studied in details and modelled using the visual MODFLOW, The study entitled “Riverbank Filtration Modeling for Haridwar case study” has been carried out by Ms. Shashi Poonam Indwar, Scientist-B, as the Principal Investigator along with , Dr. Anupma Sharma, Scientist-D, Mr. Rajan Vatsa Scientist B, Mr Sanjay Mittal SRA all from GWHD with the support from Dr C.K.Jain Scientist G EHD and Dr Sudhir Kumar Scientist G, HID under the guidance of Dr. N.C.Ghosh Scientist G and Head GWHD. The study has been carried out under the work programme for the year 2011-2015 and partly based on the financial support of the “Saph Pani” project sponsored by European Union (Grant Agreement no.”282911”). I put on record my appreciation for the work carried out in the study and the content presented in this report.

(Raj Deva Singh)
Director, NIH

Abstract

Riverbank Filtration (RBF) or simply, Bank Filtration (BF)-as a unified term, is emerging as a potential natural pre-treatment technique for sustainable drinking water supply in many rural and peri-urban areas in India. The successful performance of the technique mainly in the context of removing suspended particles, pathogenic compounds, trace organics and microorganisms present in the source water, in many European Countries and USA since more than a century has established its credibility for wide application.

In this report, the fundamental principles of riverbank filtration processes have been presented and described. Parameters, which affect and control the processes of bank filtration, have also been highlighted and an overview of the factors as well as attributes, limitations has been described in detail.

To evaluate the performance of the technique, the case study site at Haridwar representing the scheme of 22 RBF wells which are located in the vicinity of the Ganga River and the Upper Ganga Canal network and are being used for drinking water supply to the Haridwar city, has been studied and modelled using visual MODFLOW.

The report also deals with analysis of the performance of riverbank filtration process in Haridwar using the numerical groundwater flow simulation tool visual MODFLOW (version 9.1). The flow modelling refers simulation of the aquifer responses due to pumping of the RBF wells under changing hydrologic and hydraulic conditions (stress-periods). The Modflow simulation has been carried out by considering the steady state condition of the model inputs. From the modelling, the travel times, flow-paths and source of the extracted water, which affects the quality of riverbank filtrate, have been investigated. Water quality analyses of 19 parameters namely; EC, HCO_3^- , TDS, pH, Temperature, Turbidity, Alkalinity, Total Hardness, Cl^- , NO_3^- , SO_4^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} and the bacteriological parameters include; Total Coliform and Faecal Coliform have been carried out on monthly basis for one year during monsoon and non-monsoon period to assess the RBF performance and to evaluate the removal efficiency of the biological parameters such as Total coliform and Faecal coliform. An isotope analysis of water samples of river, canal and groundwater has been carried out to quantify the source of water in the extracted bank filtrate and to validate the model output in the context of riverbank filtration process taking place in Haridwar site.

The results of analysed water quality parameters showed that all physiochemical parameters except Turbidity of the extracted water, which constitutes mixing water of

riverbank filtrate and groundwater, have concentration much below the acceptable limit prescribed in the BIS, 2012 for both non-monsoon and monsoon periods. The turbidity in the extracted water although removed about 98% during the monsoon and 76% during the non-monsoon period in comparison to the river/canal water, it's concentration in some of the production wells were higher than the acceptable limit of 1 NTU. The percent removal of coliform varied between 78% and 83% for Total coliform and between 65% and 85% for Feacal coliform in comparison to the quality of groundwater for both the non-monsoon and the monsoon periods. To remove biological contents in the extracted water Uttarakhand Jal Sansthan who is responsible for operation and management of RBF wells at Haridwar is using *Sodium Hypochloride* (NaClO) solution as disinfectant for post treatment of the supplied water.

| S.No | Content | Page No. |
|-------------|---|-----------------|
| 1 | Introduction | 1 |
| 2 | Bank Filtration and its processes | 2 |
| 2.1 | <i>Processes involved in Bank Filtration</i> | 3 |
| 2.2 | <i>Factors affecting Bank Filtration</i> | 4 |
| 2.3 | <i>Factors to be considered for Bank Filtration in India</i> | 4 |
| 2.4 | <i>Attributes and limitations of Bank Filtration</i> | 5 |
| 3 | Domestic Water Demand in India | 6 |
| 4 | Riverbank Filtration Modeling for Haridwar case study | 10 |
| 4.1 | <i>Study Area Description</i> | 10 |
| 4.1.1 | <i>General Description</i> | 10 |
| 4.1.2 | <i>Climatology</i> | 10 |
| 4.1.3 | <i>Hydrogeological evaluation of Haridwar and Geomorphology</i> | 11 |
| 5 | Groundwater Quality Trends in Study Area | 18 |
| 5.1.1 | <i>Water quality sample collection</i> | 18 |
| 5.1.2 | <i>Water Quality Analysis</i> | 22 |
| 5.1.3 | <i>Result of Water Quality Analysis</i> | 25 |
| 5.1.4 | <i>Hydrochemistry</i> | 26 |
| 5.1.5 | <i>Results and Discussion</i> | 29 |
| 5.2 | Isotope analysis for Haridwar site | 31 |
| 5.2.1 | <i>Isotopic Characterises of water</i> | 31 |
| 5.2.2 | <i>Methodology</i> | 33 |
| 5.2.3 | <i>Result of Isotope Analysis</i> | 34 |
| 5.2.4 | <i>Concluding remarks</i> | 40 |
| 6 | Modelling of Bank Filtration | 41 |
| 6.1 | <i>Simulation Software Visual MODFLOW</i> | 41 |
| 6.2 | <i>Setup of MODFLOW(a numerical model)</i> | 45 |
| 6.3 | <i>Modelling with respect to RBF</i> | 46 |
| 6.4 | <i>MODPATH</i> | 49 |
| 6.5 | <i>Data Collection</i> | 50 |
| 6.6 | <i>Water levels</i> | 50 |
| 6.7 | MODFLOW Model Development | 52 |
| 6.7.1 | <i>Model Configuration: Model Domain</i> | 52 |
| 6.7.2 | <i>Model properties and boundary conditions</i> | 55 |
| 6.7.3 | <i>Steady-state model calibration and validation</i> | 57 |
| 6.7.4 | <i>Particle tracking and zone budgeting</i> | 63 |
| 6.1.5 | Result and Discussion | 63 |
| 6.7.5(a) | <i>Particle tracking</i> | 63 |
| 6.7.5(b) | <i>Zone budgeting</i> | 65 |
| 6.8 | Correlation of model output with Isotope result | 67 |
| 7 | Conclusion | 67 |
| | References | 70 |
| | Appendix-I | 72 |

| S.No | Content | Page No. |
|-------------|----------------|-----------------|
| | Appendix-II | 78 |
| | Appendix-III | 79 |
| | Appendix-IV | 80 |
| | Appendix-V | 80 |
| | Appendix-VI | 81 |
| | Appendix-VII | 81 |
| | Appendix-VIII | 82 |
| | Appendix-IX | 83 |
| | Appendix-X | 83 |
| | Appendix-XI | 84 |

| S.No. | List of Figures | Page No. |
|--------------|--|-----------------|
| Figure 1 | Schematic diagram of a bank filtration well | 2 |
| Figure 2 | Schematic diagram of processes affecting water quality during bank filtration | 4 |
| Figure 2a | Figure2a. Water consumption in India and Per Capita Domestic Consumption for India in the Year 2000 and 2050E | 8 |
| Figure 2b | Figure 2b. Location of potential riverbank filtration sites(Source: Sandhu et al,2011) | 9 |
| Figure 3 | Study area representing setting of 22 Riverbank Filtration Wells in the vicinity of the river Ganga and Upper Ganga Canal (UGC) at Haridwar. | 13 |
| Figure 4 | Geological map of the Haridwar district highlighting the study area (Source: CGWB-UR, 2009) | 15 |
| Figure 5 | The exploratory borelogs' wells in the study area used for characterizing hydrogeological setups. | 16 |
| Figure 6 | Hydrogeological setup of the study area, section along X-X'. | 17 |
| Figure 7 | Concentration Plot of major ions present in Pumping wells and River Ganga | 22 |
| Figure 8 | Concentration Plot of Ferrous and manganese present in Pumping wells and river Ganga | 23 |
| Figure 9 | Turbidity (NTU) in river Ganga and Pumping wells. | 24 |
| Figure10 | River water quality and water quality of Pumping wells regarding electrical conductivity (EC), total dissolved solids (TDS) and bicarbonate (HCO ₃ ⁻) | 25 |
| Figure 11 | Box Whisker's Plot of Turbidity, TDS, Total Hardness, Bicarbonate, Nitrate, Sodium, Total Coliform and Feecal Coliform in River ,Open well and 22 RBF wells at Haridwar site | 28 |
| Figure 12 | Isotopic characteristics of Ganga River water at Haridwar | 34 |
| Figure 13 | Isotopic ($\delta^{18}\text{O}$) variation in Bhupatwala area. | 35 |
| Figure 14 | Isotopic ($\delta^{18}\text{O}$) variation in Bhupatwala area. | 36 |
| Figure 15 | Variation of $\delta^{18}\text{O}$ with time in Pantdeep area. | 38 |
| Figure 16 | Variation of $\delta^{18}\text{O}$ with time in Rodibelawala area. | 38 |
| Figure 17 | Variation of $\delta^{18}\text{O}$ with time in Alaknanda Hotel area. | 39 |
| Figure 18 | Variation of $\delta^{18}\text{O}$ with time in area near Bairagi Camp. | 40 |
| Figure 19 | Example of Boundary Conditions | 43 |
| Figure 20 | Schematic of River boundary (modified from VM, 2003) | 47 |

| S.No. | List of Figures | Page No. |
|--------------|--|-----------------|
| Figure 21 | Modelling of an additional riverbank layer | 48 |
| Figure 22 | Study area of the riverbank filtration site with 22 production wells in Haridwar, India | 53 |
| Figure 23 | Discretized model domain of Haridwar showing 22 RBF wells and River Ganga | 54 |
| Figure 24 | DEM (ASTER data) generated for Haridwar study area and interpolated in model domain using inverse distance technique of Visual MODFLOW. | 54 |
| Figure 25 | Conceptualized model domain area of the 22 RBF wells in Haridwar | 55 |
| Figure 26 | Flow Chart of the methods involved in calibration of the groundwater flow model, path lines and portion of extracted bank filtrate from each well. | 59 |
| Figure 27 | Cross-section schemes to estimate the steady state (undisturbed) groundwater level for an RBF-well using the interpolation method | 61 |
| Figure 28 | Summary of the modelled maximum travel times from each source to each well | 65 |
| Figure 29 | Proportion of the extracted water for each well under pre-monsoon (upper) and monsoon (lower) conditions | 66 |

| S.No | List of Tables | Page No. |
|-------------|--|-----------------|
| Table 1 | Existing and projected water-use patterns of India | 6 |
| Table 2 | Climatological data of Roorkee Observatory | 11 |
| Table 3 | Distance of the wells from the centre of the river Ganga and the Upper Ganga Canal (PW: Pumping well). | 13 |
| Table 4 | Min, Max and Standard Deviation of Water Quality data in Non Monsoon and Monsoon period. | 27 |
| Table 5 | Location of sampling stations for isotopic analysis. | 31 |
| Table 6 | Isotopic indices ($\delta^{18}\text{O}$) of groundwater and river water | 35 |
| Table 7 | Relative proportion of river water in well water at Haridwar site | 37 |
| Table 8 | Data used to prepare the groundwater flow model for Haridwar | 50 |
| Table 9 | Rated discharge, operating hours and the daily discharge of water (Q_{ex}) abstracted during monsoon and non-monsoon season for each RBF well (listed from north to south) | 56 |
| Table 10 | Calibrated Hydraulic conductivities for the hydrogeological set-up of the model. | 60 |
| Table 11 | Statistical Evaluation of the calibrated model | 60 |
| Table 12 | Validation result for the measured and interpolated water levels in pre-monsoon (08.01.2013) | 62 |

1. Introduction

Riverbank Filtration (RBF) or simply Bank Filtration (BF) as a unified term is a natural pre-treatment technique, which enables the utilisation of surface water sources such as lakes or rivers water to pass through the natural porous sub-surface (aquifer) formation to the production well. The porous media serves as a natural filter and reduces the suspended solids and pathogens. (BF) applied to a river or lake, is a reliable, natural and multi-objective treatment process which removes particles, biodegradable organic compounds, trace organics, microorganisms as well as ammonia and nitrate to some extent. Furthermore, it also dampens temperature peaks and concentration peaks associated with spills. BF could replace or support other treatment process, thus could provide a robust barrier within a multi-barrier system and also decreases the costs of water treatment. BF is a traditional, efficient and well accepted method of surface water treatment in Europe. For more than 100 years, river bank filtration has been used in Europe for public and industrial water supply along Rhine, Elbe, and Danube rivers (Griseck et al., 2002). Bank filtrate monitored in recent years has shown a significantly higher quality compared to water abstracted directly from surface or groundwater sources. For conventional treatment, high concentrations of organic contaminants requires high doses of chlorine (40-60mg/L) prior to flocculation thus it has created a greater risk for formation of carcinogenic disinfection by-products, as reported in Mathura (Singh et al. 2010) . BF in such situation has been reported advantageous as a pre-treatment in order to reduce the necessary doses of chlorine prior to flocculation. Additional advantages of BF may also be seen during the monsoon season principally in the removal of turbidity and pathogens, as well as in the removal of colour and dissolved organic carbon (DOC), UV absorbance, turbidity, total and thermo tolerant coliform counts (Dash et al. 2008 ; Sandhu et al. 2010 ; Thakur et al. 2009a, 2009b ; Dash et al. 2010). Bank filtration, however, does not present an absolute barrier to other substances of concern (e.g. ammonium) and some inorganic trace elements may even be mobilized. In Delhi, which has poor surface water quality, extensive post-treatment has been reported to be a potential solution to remove high levels of ammonium (Sprenger et al. 2008). Similar aquifer contamination has also been observed in Europe (e.g. Berlin) downstream of sewage irrigation fields. Detailed investigations (Hamann 2009) have shown that even after source water improvement, ammonium continued to leach from the soil for decades.

India has a lot of potential for employing BF technique, particularly in the Indo-Gangetic-Brahmaputra alluvium areas, coastal alluvium tracks and scattered inland pockets in different states where surface water bodies are hydraulically connected to the adjoining aquifer, and aquifers have good soil pores.

To have better understanding about the technique and its performance in the Indian context, a detailed investigation covering the physical processes of RBF technique, its scope, limitations, and performance evaluation including modelling has been envisaged in the present study.

Bank Filtration and its processes

The bank filtration technique takes advantage of existing geologic formations adjacent to water bodies to filter drinking water. Wells are dug in fine, sandy sediments next to water bodies and water is extracted from these wells. Water in the water bodies filters through the sediments removing contaminants. The water obtained is often of much higher quality than the raw surface water. The removal of contaminants in surface water is important because when the water is chlorinated these contaminants can be converted to harmful chemicals referred to as disinfection by-products (DBPs). Chlorine must be added to most drinking water supplies to kill pathogens. The emphasis on controlling DBPs began when research showed that trihalomethanes (THMs) were produced by the reaction of chlorine with aquatic humic substances during the chlorination of drinking water. THMs include some known and suspected carcinogens (chloroform and dichloroacetic acid). National surveys by USEPA indicated the presence of THMs in virtually every chlorinated water supply tested. Research was initiated in the 1970's, and continues today, into identification of significant DBPs and methods to avoid their formation in the drinking water. Bank filtration wells can either be horizontal or vertical depending upon the hydrogeologic setting, required production rate, and the utility's preference. Shallow alluvial deposits and a higher rate of pumping from a given location often favour horizontal wells, sometimes called Ranney wells or laterals. The laterals of the collector wells can all be directed towards the river or distributed in all directions.

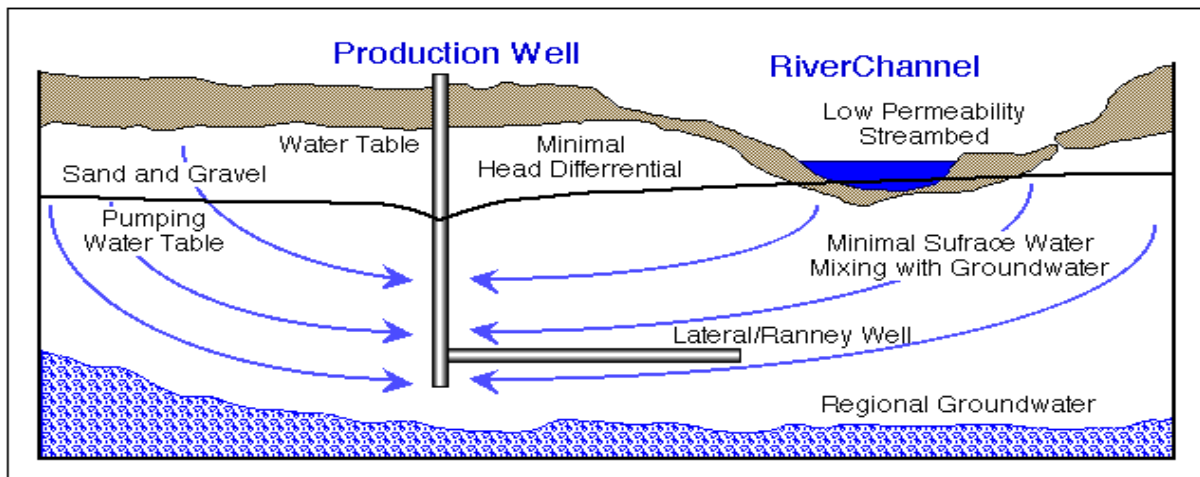


Figure 1. Schematic diagram of a bank filtration well

In Europe, particularly in Germany, bank filtration as a water treatment process has been applied since the 1870's and the first research project on bank filtration started in 1898. In the United States there have been bank filtration wells operating for nearly half a century. Since Sandoz Pharmaceutical's accidental spill of herbicides into the Rhine River in 1986, a rigorous 3-year study involving 6 water works, five research institutes, and several universities was conducted by Prof. Heinrich Sontheimer at the University of Karlsruhe, Germany. The study focused on hydrology, removal of organic compounds that included natural organic matter (NOM) and DBP pre-cursors, removal of particles, and the simulation of ground water passing through test filters. (Dr. Ray 2008).

2.1 Processes involved in Bank Filtration

Three filtration mechanisms are possible. Physical filtration or straining takes place when suspended particulates are too large to pass through interstitial spaces between alluvial soils particles. Biological filtration occurs when soil microorganisms remove and digest dissolved or suspended organic material and chemical nutrients. Chemical filtration or ion exchange may take place when aquifer soils react with soluble chemicals in the water (Metcalf & Eddy (1972). Most 'normal' contaminants (microbial organisms and inorganic or organic pollutants) will be removed by bank filtration, either because they get filtered out by the sand/earth of the bank, or because the passage/travel time (which may be days or potentially weeks) is sufficient to render them inactive.(Ray et al, 2008).The research has shown that the removal efficiency depends not only on the contaminant, but also on the "hydraulic and chemical characteristics of the bottom sediment and the aquifer, the local recharge-discharge conditions, and biochemical processes". (Heberer, Thomas et al. 2001).Several mechanisms are responsible for improvement of water quality during BF.

During Pumping and travel through the soil and aquifer sediments, surface water is subjected to a combination of physical, chemical and biological processes such as (i) filtration, (ii) solution-precipitation. (iii) ion-exchange, (iv) sorption-desorption, (v) complexation, (vi) redox reactions. (vii) Microbial biodegradation and (viii) dilution that significantly improve water quality. A schematic diagram of processes affecting water quality during bank filtration is presented in Figure 2.

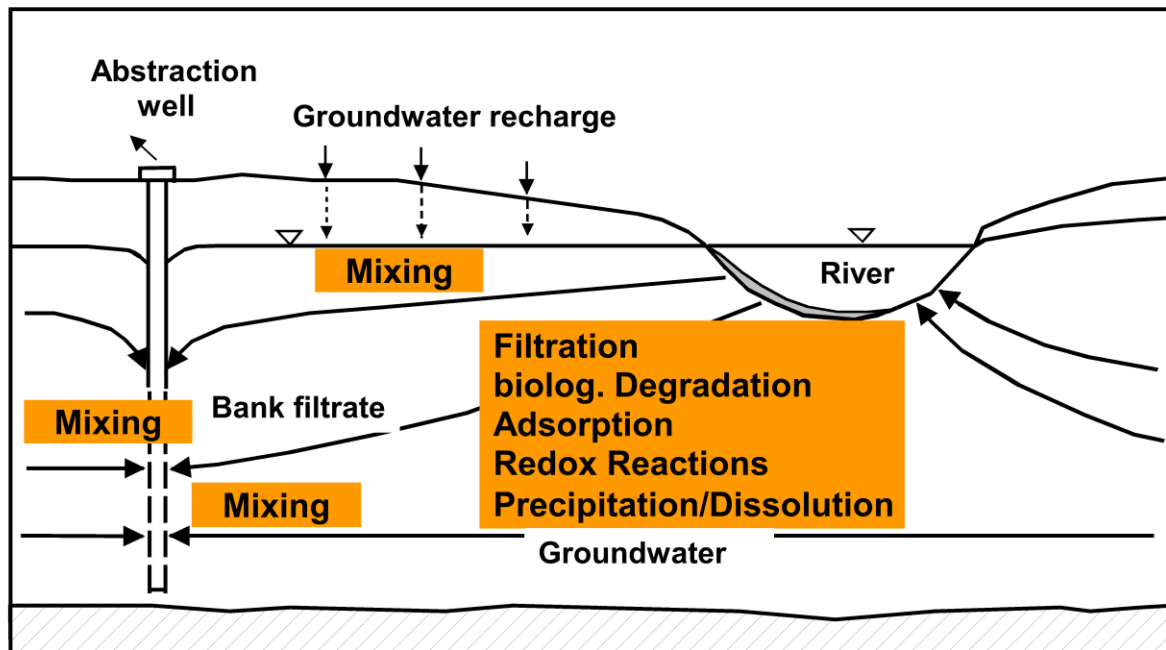


Figure 2. Schematic diagram of processes affecting water quality during bank filtration

Source: Hiscock and Grischek (2002)

2.2 Factors affecting Bank Filtrations

The performance of BF with respect to water quality improvements depends on a number of variables; (i) hydrogeological conditions including characteristics and composition of alluvial aquifer materials, (ii) river/lake water quality, (iii) groundwater dilution, (iv) filtration velocity and distance of the well(s) from river/lake, (v) temperature of the water, (vii) pumping rate, and (viii) soil/sediment characteristics at the river/lake-aquifer interface (ix) Hydraulic connection between river and aquifer (x) Unconfined or confined aquifer (xi) Aquifer thickness and hydraulic conductivity (xii) Continuous river flow, stable river banks (xiii) Sand and gravel river bed, bed erosion (xiv) Average Pumping rates $< 0.2 \text{ m}^3/(\text{m}^2 \times \text{day})$ (xv) Sand and gravel aquifers with a hydraulic conductivity $> 1 \times 10^{-4} \text{ m/s}$ (about 10 m/d) (xvi) Aquifer thickness $> 10 \text{ m}$.

2.3 Factors to be considered for BF in India

- Naturally occurring factors affecting BF:

(i) Dynamic river discharge: scouring of riverbed, flooding of wells, travel time of bank filtrate (ii) High sediment transport in monsoon: clogging of the riverbed (iii) Shifting river courses: travel time & flow path of bank filtrate (iv) Arsenic, nitrate and other harmful substances in groundwater (v) Discharge of untreated sewage: pathogens

- Institutional factors concerning BF site selection:

(i) Access to data: documentation, not in public domain (ii) Availability of high-cost riverside land for constructing wells (conflicting interests)

2.4 Attributes and Limitations of BF

The main attributes and limitations of bank filtration systems are listed below (Ray et al. 2002; IAH and IHP, 2005):

Attributes:

- BF is a natural treatment process, avoids or reduces the use of chemicals and produces biologically stable water.
- BF improves water quality by removing particles (suspended solids), organic pollutants, microorganisms, heavy metals and nitrogen.
- BF dampens concentration peaks associated with spills (in river/lake) and dampens temperature peaks.
- BF replaces or supports other treatment processes by providing a robust barrier and reduces the overall cost of water treatment.

Limitations:

- BF is site specific, and is feasible only when the local hydrogeological conditions are favourable.
- There can be leaching of the aquifer materials under reducing conditions, sometimes leading to increased concentration of iron and manganese in extracted water.
- One of the main problems is clogging of the aquifer due to accumulation of suspended matter that is filtered out when river/lake water enters the aquifer, especially when the system is not properly designed.
- BF and groundwater recharge may be only a limited barrier for certain contaminants.
- Influences of surface water and operation on quality are poorly known.

2. Domestic Water Demand in India

Domestic water consumption in India in the year 2000 was 93 billion litres per day as per the estimation given by(Note: 1All projected figures indicate water demand Source: 'Water for People Water for Life', United Nations World Water Development Report, 2003; 'The Global Water Crisis: A Question of Governance', Policy Research Division, Department of Foreign Affairs and International Trade Canada; 'Statistical Yearbook for Asia and the Pacific 2007', United Nations Economic and Social Commission for Asia and the Pacific; 'India's Water Future to 2025 –2050: Business as Usual Scenario and Deviations', International Water Management Institute; OS-Connect Database; US Geological Survey -Water Resources; Aquastat Database)and is expected to grow 277 billion litres/day by 2050(Figure 2a). The per capita domestic water consumption for India in the year 2000 was 88.9 litres/day whereas by 2050 it is expected to grow 167 litres/day. Hence a demand for domestic consumption of water is projected to increase by 78.1 litres/day by 2050(Figure 2a). Therefore, the country may face exponential decline in per capita availability of water (for drinking as well as domestic purposes).

According to the census reports of Indian Census 2011, the population of India is 1,210,193,422. As the India's population has crossed 1.2 billion marks it faces daunting challenges in the growing water supply needs of an increasing population. From 2001 to 2011 population increased by 17.64 %(COI 2011) with net addition of 91 million to the Urban population. (Source: Census 2011-Provisional population totals-India).The problem of water is acute for the urban population- about 31.16 % of the total population (COI 2011).Given the current demographic trends India's population is projected to be nearly 1.4 billion by 2025 (COI 2011).

Table 1. Existing and projected water-use patterns of India

| | India (Government of India 1999) | | | | | | | |
|-------------------------|---|------|--------------------------------------|------|--------------------------------------|------|--------------------------------------|------|
| | 1990 | | 2010 | | 2025 | | 2050 | |
| Category | 10 ⁹ m ³ /year | % | 10 ⁹ m ³ /year | % | 10 ⁹ m ³ /year | % | 10 ⁹ m ³ /year | % |
| Irrigation | 460 | 88.6 | 536 | 77.3 | 688 | 73 | 1008 | 70.9 |
| Industries ^a | 34 | 6.6 | 41.4 | 6 | 80 | 8.5 | 121 | 8.5 |
| Domestic and others | 25 | 4.8 | 115.6 | 16.7 | 174 | 18.5 | 293 | 20.6 |
| Total | 519 | 100 | 693 | 100 | 942 | 100 | 1422 | 100 |

^aIncluding power generation

Domestic water demand in India (excluding agricultural and industrial use) amounted to only 4.8% of the total demand in 1990 and is projected to increase to 20.6% of total water use by 2050 (Table 1). This is projected to show an increasing trend from 25×10^9 m³/year in 1990 to 116×10^9 m³/year in 2010 and reach 174×10^9 m³/year by 2025. The country is thus expected to face an exponential decline in per capita availability of water (for drinking and other domestic purposes). (Sandhu et al, 2011).

Considering the current domestic water supply scenario, India can benefit from the wider use of riverbank filtration (RBF) by many communities where favourable hydrogeological conditions exist. Even if only used as a pre-treatment step for conventional water treatment plants, RBF could provide a long-term solution saving or reducing large infrastructure investments. The overall water usage and per capita domestic consumption of water is expected to increase due to various factors by 2050 hence there is necessity of better water management measures and reduction in per capita water consumption in India to meet the water demand of the day to day increasing population through sustainable supply of water and better pre and post treatment techniques which are cost effective, hence RBF can serve as one of the alternatives and efficient technique to fulfil the above goal.

As a preliminary task, some of the potential sites where RBF schemes either in place or can be developed have been identified. These places are Allahabad (Yamuna River), Bhubaneswar(Mahanadi River), Guwahati (Brahmaputra River), Kota (Chambal River) Lucknow (Gomti River), Vijayawada (Krishna River), Sahebganj(Ganga River) and some of the in place RBF sites identified are Mathura (Yamuna River), Patna(Ganga River), Ahmedabad (Sabarmati River), Vadodara (Mahi River), Medinipur (Kangsabati River), Dehradun(Bandal River),Srinagar (Alaknanda River), Nainital (Nainital Lake), Rishikesh (Ganga River), Haridwar (Ganga River) (Figure 2b).

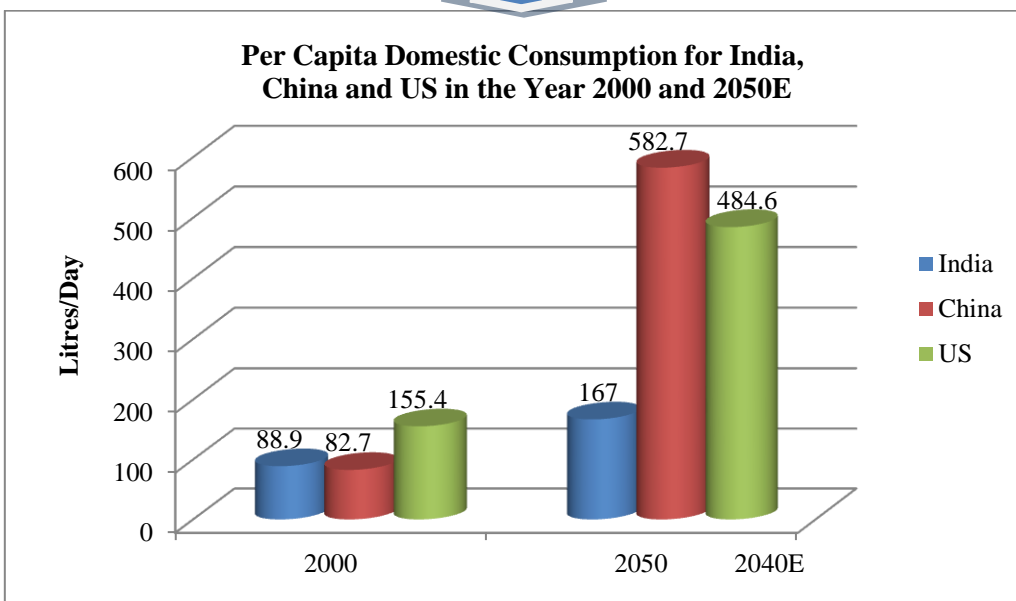
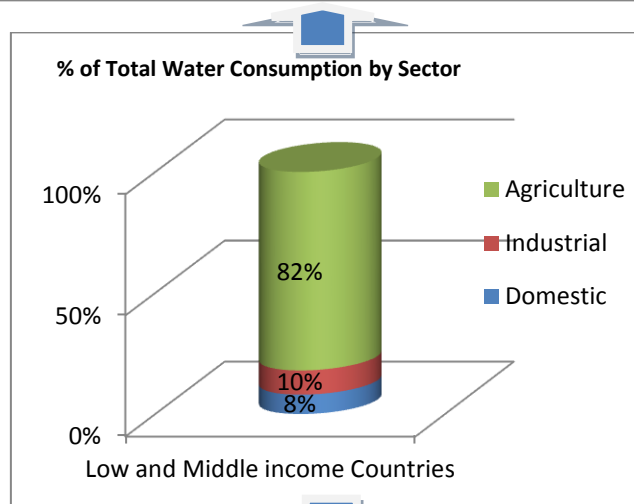
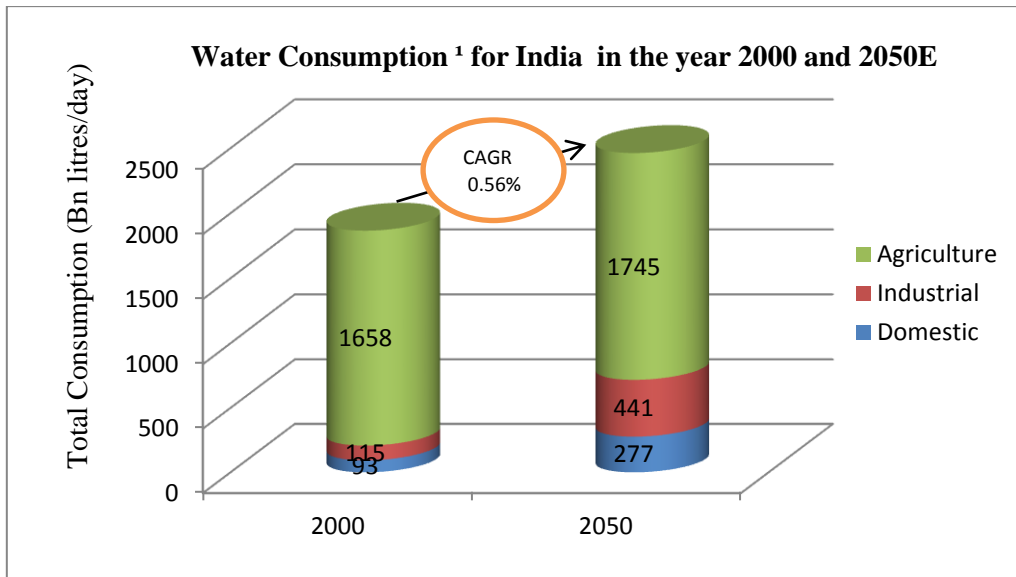


Figure2a. Water consumption in India and Per Capita Domestic Consumption for India in the Year 2000 and 2050E

[Note: 1 All projected figures indicate water demand
 Source: 'Water for People Water for Life', United Nations World Water Development Report, 2003; 'The Global Water Crisis: A Question of Governance', Policy Research Division, Department of Foreign Affairs and International Trade Canada; 'Statistical Yearbook for Asia and the Pacific 2007', United Nations Economic and Social Commission for Asia and the Pacific; 'India's Water Future to 2025 –2050: Business as Usual Scenario and Deviations', International Water Management Institute; OS-Connect Database; US Geological Survey -Water Resources; Aquastat Database]

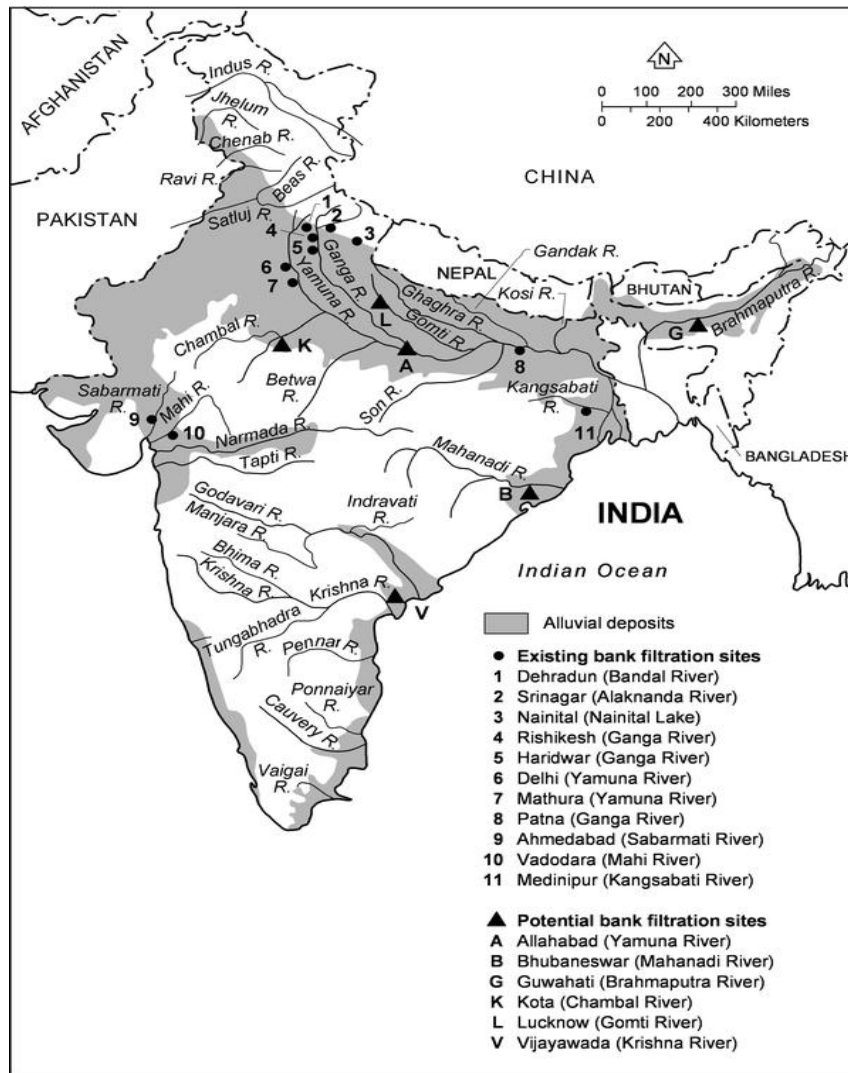


Figure 2b. Location of potential riverbank filtration sites (Source: Sandhu et al, 2011)

3. Riverbank Filtration Modelling for Haridwar case study:

4.1. Study Area Description

4.1.1 General Description

The bank filtration scheme at Haridwar is comprised of 22 large diameter (10 m) bottom-entry caisson of 7 to 10 m deep wells located along the right bank of the river Ganga at varying distances (10 m - 295 m) from the river/canal within a stretch of about 6.5 km (Fig. 4). These RBF wells, locally called 'Pumping Well (PW)', are situated in the vicinity of the river Ganga and Upper Ganga Canal (UGC) network. The UGC receives diverted flow from the river and meets the agricultural and drinking water requirements downstream.

Haridwar is one of the very important Hindu pilgrimage sites of the world. The city, situated along the right bank of the river Ganga, has population of approximately 225,235 (Census of India 2011). More than 50% ($> 64,000 \text{ m}^3/\text{day}$) of drinking water requirement of the city is supplied by 22 RBF wells. Each RBF well is equipped with a pump set above the ground surface and extracts water by a suction pipe of 15 cm diameter. Some have been constructed as a tube well in the caisson well. The tube wells have an aquifer penetration depth of about 5-6 m below the bottom of the caisson well. The discharge of the pumps ranges from 72 to 170 m^3/hr and the operating hours of these wells vary from one season to another between 10 and 24 hours continuously in a day. A schematic diagram of a RBF well in Haridwar is shown in Fig. 5. The wells tap the unconfined aquifer of average thickness about 21 m hydraulically connected with the river/canal. Being located in the vicinity of the canal and river network, the wells when pumped induce water from both river and canal at varying rates depending upon the distance of the wells from them.

4.1.2 Climatology

District Haridwar experiences moderate subtropical to humid climate with three distinct seasons viz. summer followed by rainy and winter seasons. The hydrometeorological observations for Roorkee observatory are given in Table 2. Temperature begins to rise from March (29.1°C) and reaches to its maximum in May (39.2°C), with the commencement of monsoon season by mid-June, the temperature begins to fall. During the winter season in the month of November to February the

temperature ranges between 10.5⁰ C and 6.1⁰ C. The relative humidity is highest in monsoon season (85% in the morning and 79% in the evening). The lowest humidity is observed during the month of April and May i.e. 24% (in evening) and 40% in May (in morning).

The mean monthly wind speed is highest in the summer season when it goes up to 7.4 and 7.2 km/hour in the month of May and June and the minimum wind speed is observed during winter when it is 2.6 km/hour in the month of October. The potential evapotranspiration is maximum in the month of May 198.9 mm and minimum 38.5 mm in the month of December.

Table 2. Climatological data of Roorkee Observatory

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Mean/ Total | |
|----------------------|------|------|-------|-------|-------|-------|-------|-------|-------|------|------|----------------|--------|
| Temp °C | | | | | | | | | | | | | |
| Maximum | 20.4 | 23.5 | 29.1 | 35.7 | 39.2 | 38.1 | 33.5 | 32.4 | 22.7 | 31.4 | 27.1 | 22.3 | 38.5 |
| Minimum | 6.1 | 8.2 | 12.8 | 16.3 | 22.1 | 24.9 | 24.5 | 24.5 | 22.9 | 17.2 | 10.5 | 6.7 | 18.8 |
| Humidity | | | | | | | | | | | | | |
| Morning | 85 | 78 | 53 | 44 | 40 | 59 | 82 | 85 | 82 | 74 | 79 | 82 | 71 |
| Evening | 53 | 43 | 34 | 24 | 24 | 42 | 68 | 79 | 65 | 58 | 49 | 54 | 48 |
| Rainfall (mm) | 36.5 | 33.0 | 34.5 | 8.4 | 19.2 | 128.7 | 342.6 | 336.8 | 157.8 | 39.4 | 5.5 | 14.3 | 1156.4 |
| No. of rainy days | 3.2 | 1.8 | 2.3 | 0.9 | 1.9 | 5.8 | 12.3 | 13.1 | 6.0 | 1.7 | 0.5 | 1.0 | 50.5 |
| Wind Speed (kmph) | 3.9 | 4.9 | 5.6 | 6.4 | 7.4 | 7.2 | 5.8 | 4.7 | 4.1 | 3.1 | 2.6 | 3.0 | 4.9 |
| PET (mm) | 42.8 | 62.4 | 110.4 | 152.7 | 198.9 | 192.0 | 135.3 | 123.8 | 121.6 | 99.4 | 55.5 | 38.5 | 1333.8 |

4.1.3 Hydrogeological evaluation of bank filtration case study site Haridwar

The bank filtrate of the Haridwar site comprises production of nearly 50% (>43,000 m³/day) of the total drinking water demand in the city from network of 22 large-diameter (10 m) bottom-entry caisson wells of 7-10 m deep located within area captured by the latitude from 29° 54' 44.14" N to 30° 0' 10.25" N and longitude from 78° 8' 33.03" E to 78° 12' 32.95" E. These 22 RBF wells are situated along the right bank of the river Ganga at varying distances from it (Figure 3). A number of wells are embraced between the river Ganga and the Upper Ganga Canal (UGC) –a diversion channel that carries regulated flow from the Ganga. Along the river, there is a flood protection embankment constructed by the government to protect entry of flood water from the Ganga to the Haridwar city (Figure 3). The wells are located on both sides of this embankment. The top surface elevation of this flood protection embankment that ranges between 279 and 302 m above msl is largely above the normal ground surface elevations where these 22 RBF wells are located. The setup of the 22 RBF wells can distinguishably be recognized by two groups: one group is located in the

north of new supply canal (NSC) and the other group is in the south of the NSC (Figure 3). The significance of the NSC is that, it is the location where entry of the Ganga water flow to the UGC is regulated by the Bhimgoda barrage headwork. The shortest distance of the 22 wells (Table-3) from the Ganga or the UGC varies between 50 m and 490 m from the centre of the respective water course. These RBF wells in the field are recognized as 'Pumping Well (PW)' with a specific number assigned by the promoter of the well, i.e., Uttarakhand Jal Santhan (UJS). To maintain conformity with the field, the same nomenclature and the number are also followed in this study.

Elaborating more precisely the positional details of the 22 RBF wells (Figure 3) in the network of the Ganga, UGC and the flood protection embankment; 3 wells (ID # : PW31, PW27, PW4) located in the Bhupatwala area exclusively along the right bank of the river Ganga are in the embrace of the river Ganga and the embankment, 2 wells (ID#: PW3, PW2) also in the Bhupatwala area along the right side of the river Ganga are located in the outer side of the embankment, 3 wells (ID# : PW1, PW 26,PW16) in the Sarvanand Ghat area along the right bank of the Upper Ganga Canal (UGC) are located in the outer side of the embankment, 4 wells (ID # : PDPW2, PW40, PDPW1, PW18) in the Pantdweep area, which have the river Ganga at the left and the UGC at the right, are located in the embrace of the UGC and the embankment, 4 wells (ID# : PW25, PW24, PW43, PW42) in the Rodibelawala area embrace between the Ganga river and the embankment, have the river Ganga at the left and the UGC at the right, and the remaining wells at the southern part (ID#: PW44, PW17, PW21, PW49, PW29, PW28) located between the embankment and the UGC have the river Ganga at the left and the UGC at the right except well# PW 28 that has the UGC on both sides .

Normally, 12-13 wells are operated continuously (24 hours) with the remaining wells operating 9-19 hours per day by fixed-speed vertical line shaft pumps connected to the vertical production wells ("tube" wells) through 15 cm dia pipe . The abstracted water is only chlorinated using Sodium hypochlorite (NaClO) at the well particularly, during monsoon season when the river/canal water normally has high turbidity.

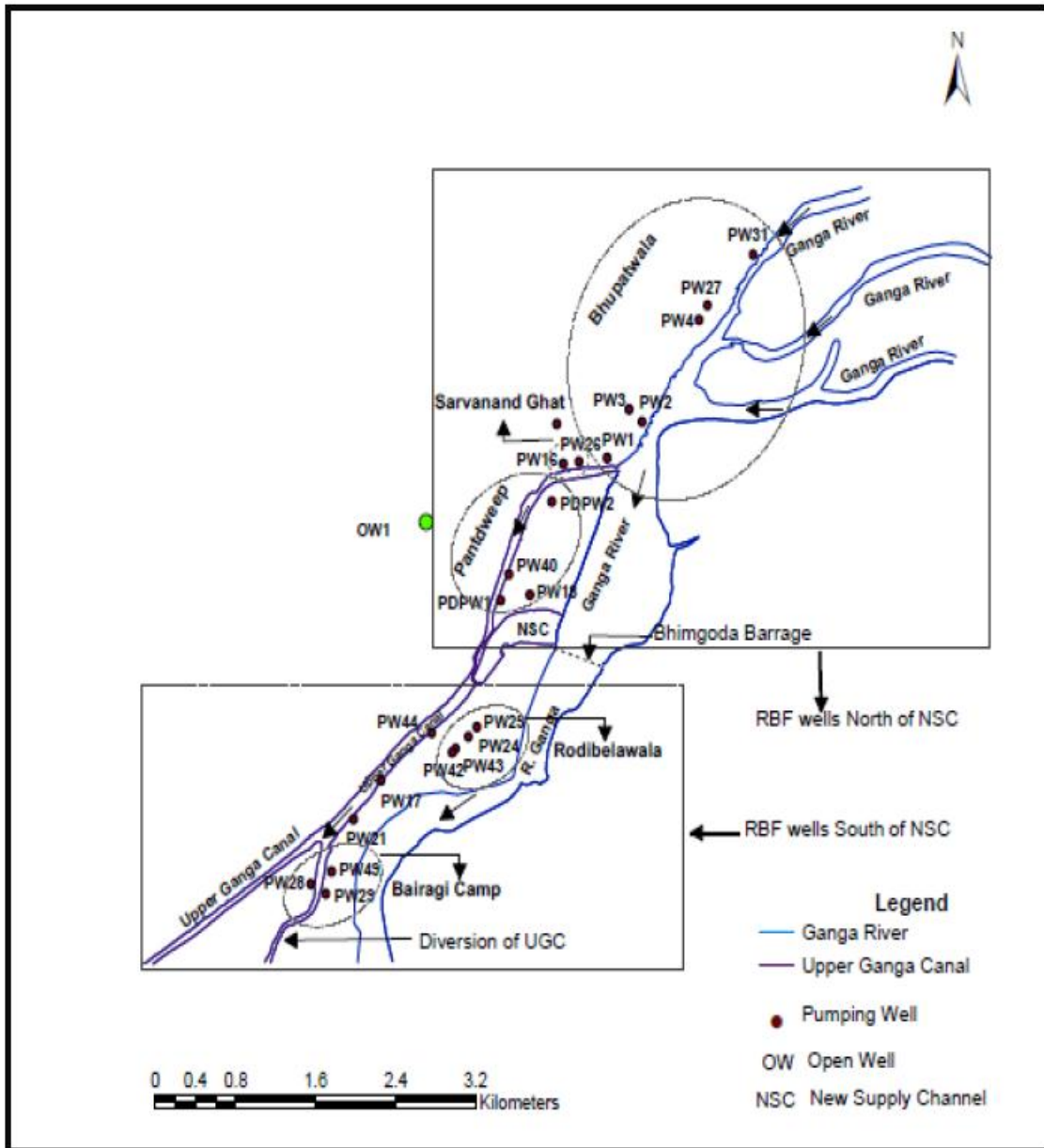


Figure 3: Study area representing setting of 22 Riverbank Filtration Wells in the vicinity of the river Ganga and Upper Ganga Canal (UGC) at Haridwar.

Table 3: Distance of the wells from the centre of the river Ganga and the Upper Ganga Canal (PW: Pumping well).

| Well ID # | Distance from river (m) | Distance from canal (m) | Width(m) GR-Ganga River; UGC- Upper Ganga Canal | River/canal boundary |
|---------------------------------------|-------------------------|-------------------------|---|-------------------------|
| North of New Supply Canal(NSC) | | | | |
| PW31 | 102 | - | GR : 107.4 | Ganga river (Left side) |
| PW27 | 238 | - | GR: 67 | Ganga river (Left side) |

| | | | | |
|---------------------------------------|------|-------------|--------------------|--|
| PW4 | 239 | - | GR : 102 | Ganga river (Left side) |
| PW3 | 333 | - | GR: 311 | Ganga river (Left side) |
| PW2 | 139 | - | GR : 239 | Ganga river (Left side) |
| PW1 | 315 | 102 | GR: 266, UGC : 49 | Ganga river and UGC (left side) |
| PW26 | - | 95 | UGC:80 | UGC (Left side) |
| PW16 | - | 95 | UGC: 75.4 | UGC (Left side) |
| PDPW2 | 693 | 195 | GR:459, UGC:103 | UGC (right side) and Ganga river (left side) |
| PW40 | 985 | 50 | GR:796 UGC : 59 | UGC (right side) and Ganga river (left side) |
| PDPW1 | 982 | 51 | GR:837, UGC : 54 | UGC (right side) and Ganga river (left side) |
| PW18 | 743 | 288 | GR:868, LC : 67 | UGC (right side), Link canal (left side) and Ganga river (left side) |
| South of New Supply Canal(NSC) | | | | |
| PW25 | 533 | 421 | GR: 263, UGC: 147 | UGC (right side) and Ganga river (left side) |
| PW24 | 586 | 491 | GR:255, UGC:155 | UGC (right side) and Ganga river (left side) |
| PW43 | 683 | 461 | GR:258, UGC: 150 | UGC (right side) and Ganga river (left side) |
| PW42 | 672 | 464 | GR: 264, UGC:150 | UGC (right side) and Ganga river (left side) |
| PW44 | 910 | 107 | GR:295, UGC:137 | UGC (right side) and Ganga river (left side) |
| PW17 | 1210 | 72 | GR:657, UGC:133 | UGC (right side) and Ganga river (left side) |
| PW21 | 545 | 110 | GR:257, UGC:161 | UGC (right side) and Ganga river (left side) |
| PW49 | 368 | 96 | GR:330, UGC:70 | UGC (right side) and Ganga river (left side) |
| PW29 | 371 | 83 | GR:241, UGC:44 | UGC (right side) and Ganga river (left side) |
| PW28 | - | 61, and 475 | UGC1: 44, UGC2:241 | UGC both sides. |

Geological and Hydro-geological setups

The geological formations as depicted by the map developed by CGWB-UR (2009) (Figure 4) showed that most part of the study area particularly along the N-W, N-E, and S-E directions has geological setups of Shiwalik group having sedimentary formations with conglomeration of sandstone and clay stone sequences. In the S-W part around Haridwar city area, it has newer alluvium group having Fan alluvium and channel alluvium formation with sequence of brown to grey clay, silt, sand with pebbles and boulders.

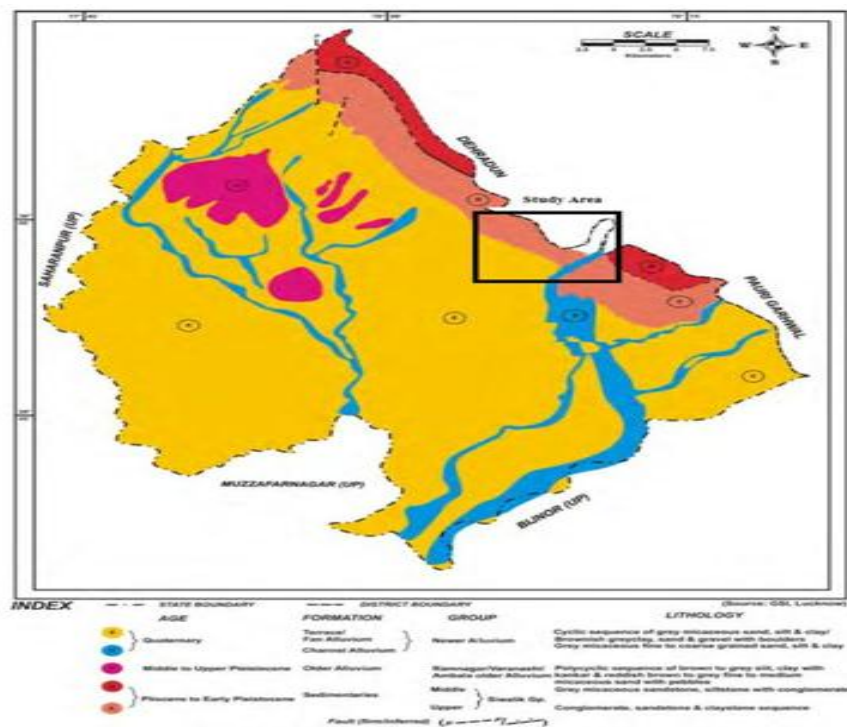


Figure 4: Geological map of the Haridwar district highlighting the study area (Source: CGWB-UR, 2009)

The detailed hydrogeological formations of the study area are delineated from the borelogs data of three exploratory wells (data source UJS) located along NE-SW direction extending almost the entire length of the study area (Figure 3). The sectional view of the sub-surface formations along X-X' (Figure 5) showed that the uppermost layer comprising thickness of about 2 m has surface soil, which is underlain by the formations represented by fluvial deposits of fine to coarse sand mixed with pebbles and boulders that represent the aquifer hydraulically connected to the Ganga River and the canal system under the unconfined condition. The thickness of these formations increases from NE to SW direction between depth ranges from about 12 m to 36 m below the overburden surface soil. These fluvial deposits are underlain by sequences of large depth of clay layers mixed with either pebbles or

boulders, which act as impervious strata with no sign of vertical and horizontal connectivity to the river, canal and the underneath aquifer. The hydrogeological setup of all the 22 RBF wells represents an unconfined aquifer of depth varies between 14 m at the upper reaches and about 38 m at the lower reaches below the ground surface. The depth to groundwater level varies from location to location as the area has a varying topography; during non-monsoon months groundwater level occurs at a depth below 2.8 m from the lowest ground level (near to Bhupatwala PW3) and 9.35 m below from the highest ground level (near to Bhupatwala PW27) that gives an average depth of 6.25m below the normal ground surface level. In terms of elevation, the groundwater table during non-monsoon months occurs at 288.75m above msl. During monsoon months, the groundwater level goes up by an average height of 1.25 m and reaches to the average level of 290 m. The normal groundwater flow direction along the right bank of the river Ganga is from the north-westerly towards the south-easterly, i.e., from the nearby foothills around the right hand side towards the river Ganga.

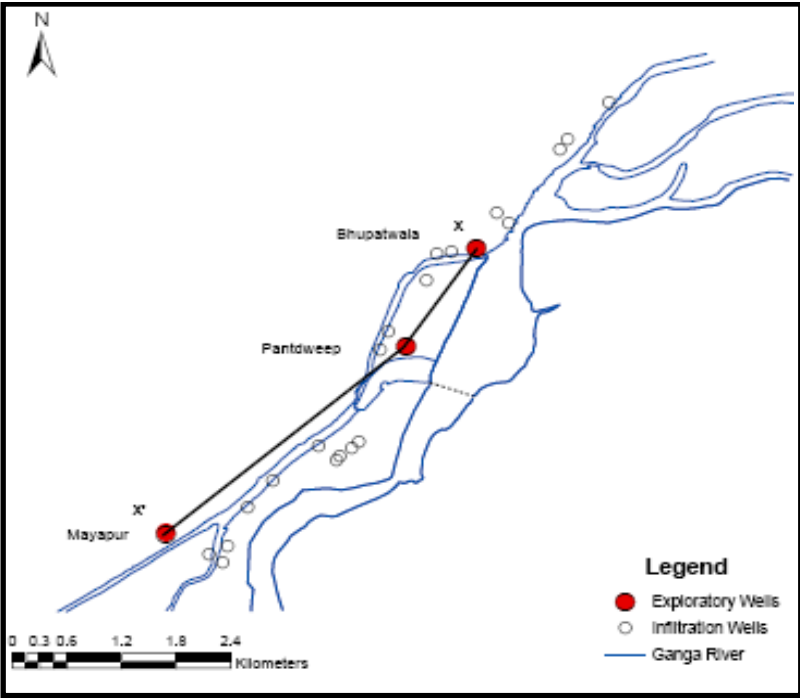


Figure 5.The exploratory borelogs’ wells in the study area used for characterizing hydrogeological setups.

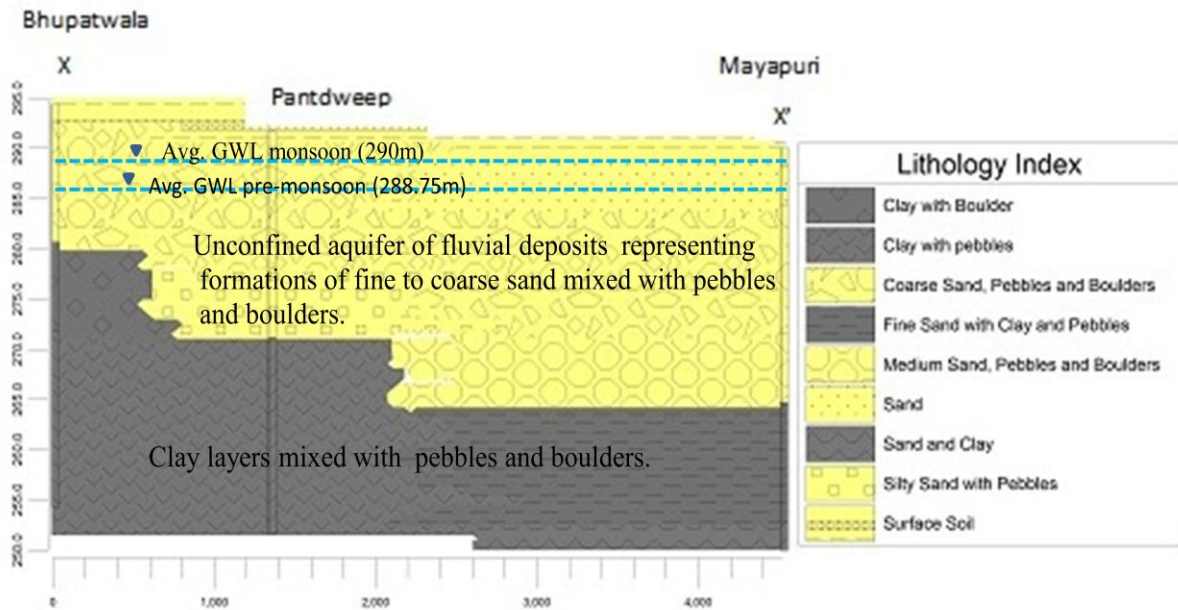


Figure 6.Hydrogeological setup of the study area, section along X-X’.

The tapping zone of all the 22 RBF wells lies within the unconfined aquifer between depth of 8 m and 14 m below the ground surface. Most of the wells have penetrated the aquifer partially, and maintain a considerable gap between the well-bottom and the underneath impervious strata. The hydrogeological formations represented by this unconfined aquifer have a very good hydraulic properties representing hydraulic conductivity (K) value range of 16 -50 m/day (Dash et al., 2010).

Except the wells (PW31, PW27, PW4, PW3, PW2) in the Bhupatwala area which have natural hydraulic boundary at one side with the Ganga river, all other wells have natural hydraulic boundary at both sides either with the Ganga and the UGC or the UGC explicitly. Therefore, the wells influenced by the both sides hydraulic boundary will draw proportionate quantity of water from the respective sources depending on their distances from the well and travel time of water; those wells are expected to have more bank filtrate water for the long duration pumping. The wells influenced by the one side hydraulic boundary will draw proportionate quantity of groundwater and bank filtrate water from the natural boundary source in the initial period, but as the pumping continued for a long duration, the proportion of bank filtrate water from the natural boundary source will increase to its fullest extent.

4. Groundwater Quality Trends in Study Area

5.1.1 Water quality sample collection

To determine the water quality improvement of riverbank filtrate, samples of the surface, ground and the production well water have been collected once a month. Comparing different water quality parameters for surface ground and well water samples enables the assessment of the natural treatment process of riverbank filtrate, when passing the subsurface. The isotopes within the samples have been analyzed to gain an insight of the actual mass transport of the water. This approach gives a rough estimation whether the extracted well-water is mainly containing groundwater or riverbank filtrate. The isotopic signature is used to evaluate the model performance regarding the flow patterns of the extracted water. As per the physical process of bank filtration, during pumping, the induced bank filtrate from river water after mixing with the groundwater gets withdrawn, which leads to modification of quality of bank filtrate water by the quality of groundwater. Thus, the quality of extracted water depends on mixing proportion of groundwater with the bank filtrate water.



Plate1. Water quality sample collection and discharge control of Old Supply Channel

In the field, five samples for each extraction well and at particular river locations (also partly at groundwater locations) were collected. The first sample was unpreserved to analyse physico-chemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, as well as the major ions sodium (Na^+), calcium (Ca^{2+}), potassium (K^+) and magnesium (Mg^{2+}) and sulphate (SO_4^{2-}). The EC is directly related to the ionized substance in the water. Solutions of most inorganic acids, bases and salts are relatively good conductors, which is why a high value of EC indicates a high rate of dissolved ions. A high concentration of dissolved solids generally characterizes water of inferior palatability and may induce an

unfavourable physiologically reaction in the consumer. For this reason, an upper limit of 500 mg dissolved solids per litre is given for drinking waters (Chandra, 1987). Suspended particles or colloidal matter, such as clay, silt as well as finely divided organic and inorganic compounds are causing a high degree of turbidity within waters. Thus, the turbidity is an indicator for the clarity and optical quality of water. Compared to groundwater, the turbidity within rivers is mostly higher due to higher flow velocities, which causes erosion of bed-material. Microorganisms are typically attached to particulates and removal of turbidity by riverbank filtration will significantly reduce microbial contamination within water. Turbidity also affects the selection and efficiency of treatment processes, particularly the efficiency of disinfection with chlorine since it exerts a chlorine demand and protects microorganisms and may also stimulate the growth of bacteria (WHO 2011). Analysing the ions enables to assess the mineralization process of the water during the subsurface-passage. The mineralization depends on the rate of water flow, the duration for which water is held up in the aquifer, the composition of the aquifer material and the quality of infiltrating water (Dash et al. 2010). Na^+ , Ca^{2+} , K^+ and Mg^{2+} are essential elements, which are occurring widely in the environment and are commonly found in water. Referring to WHO (2011) these elements are not considered necessary to establish a health based guideline value in drinking water. Sulphates occur naturally in numerous minerals and are principally used in the chemical industry. There is no health-based guideline proposed for sulphate, but a maximum concentration of 500 mg/L is recommended after WHO (2011).

A second sample was preserved with nitric acid (HNO_3) to determine the metal ions ferrous-iron (Fe^{2+}) and manganese (Mn^{2+}). Ferrous-iron and manganese are essential dietary elements and are one of the most abundant metals in the crust of the earth. Nevertheless, the amount of those metals is affecting the taste and appearance of drinking water. The presence of iron and manganese can cause economic problems in the supply of water, since it tends to deposit in water pipes. According to WHO (2011), the recommended health based limit values for Fe^{2+} and Mn^{2+} are 2 mg/L and 0.4 mg/L, respectively. However, at iron concentrations above 0.3 mg/L, a noticeable taste is present in the drinking water (WHO, 2011).

To analyse the concentration of nitrate (NO_3^-) and the chemical oxygen demand (COD) another sample, preserved with sulphuric acid (H_2SO_4) is collected. Nitrate is found naturally in the environment and is an important plant nutrient (nitrogen cycle). It is mostly associated with agricultural activities and sewage, which can affect surface waters and shallow unconfined aquifers. The microbial reduction of nitrate to nitrite can cause injuries of health.

Methaemoglobinaemia is a consequence of the reaction of nitrite with haemoglobin in the red blood cells, which prevents the oxygen transport. As a preventive protection against methaemoglobinaemia, the guideline values for nitrate and nitrite in drinking water are 50 mg/L and 3 mg/L, respectively (WHO 2011)]. To estimate the amount of organic matter in water, the chemical oxygen demand is used. COD characterizes the oxygen equivalent of the oxidizable materials present in the water.

A fourth sample was used for the evaluation of the bacteriological parameters total coliforms and faecal coliforms. The sample should be stored in an icebox to avoid a further growing of the bacteria. The presence of coliforms in water (i.e. *Escherichia coli*, *Citrobacter*, *Klebsiella* and *Enterobacter*) provide evidence of recent faecal contamination and can cause gastrointestinal illness in the consumer (WHO 2011). Referring to WHO (2011), health based guideline values are not mentioned, the EU Drinking Water Standard (1998) intends a limit value of 0 MPN / 100 ml drinking water. For this report the coliforms are not evaluated due to inadequate storage and transportation of the samples and inconsistent laboratory results.

The last sample is not related to the water-quality parameters and is used for the identification of the isotopic signature of oxygen 18 and deuterium, which are affected by global weather patterns, topography and moisture transport. The isotopic method enables the assessment of the mass transport of water. River systems are transporting the surface runoff caused by precipitation falling at higher altitudes. However, the sources of groundwater recharge are the Pumping of local precipitation and the Pumping of river water. To analyse the potential sources of groundwater recharge, stable isotope indices can be used. The value-range of analysed isotopes depends upon the altitude of the precipitation. Therefore isotope samples have been collected at predominantly groundwater abstraction wells which are uninfluenced by river water (distance to river approx. 700 m), directly at the river and at the 22 production wells. The value-range of isotopic indices for the groundwater samples should show a significant distinction compared to the river samples. Analysing the well samples, a categorization to the respective isotopic value-range gives an insight of the source of recharged water.

A plausibility analysis was realised for all water quality samples applying the ionic balance method according to DVWK (1992). The ionic balance is calculated considering the ions Ca^{2+} , Mg^{2+} , K^{+} , NH_4^{+} , Fe^{2+} , Mn^{2+} , HCO_3^{-} , Cl^{-} , NO_3^{-} and SO_4^{2-} . For ferrous iron or manganese concentrations greater 0.2 mg/L, NO_3^{-} was not considered in the balance under the condition that its concentration is greater than 2 mg/L. If the error of equation (1) is below 10 %, the

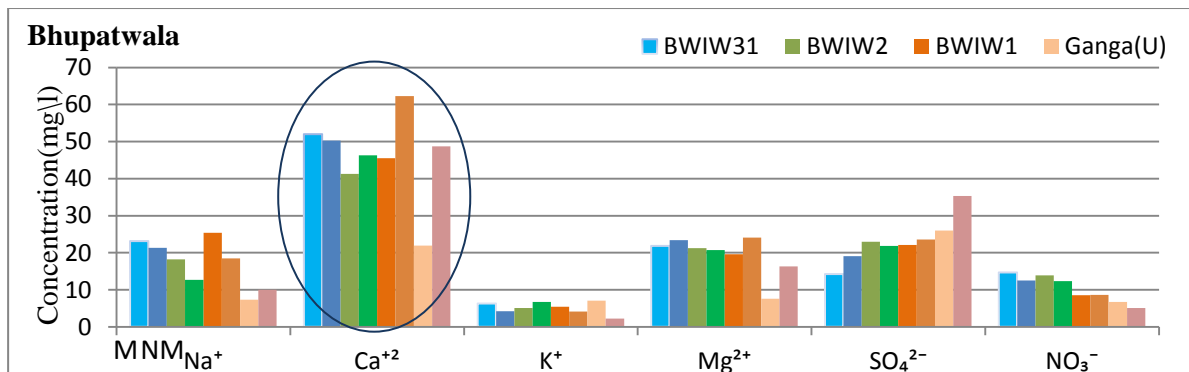
sample was detected as plausible. Additionally, the electrical conductivity of each sample, according to a temperature of 25 °C ($EC_{25^{\circ}C}$) was used to verify the water quality results (2). This method is applicable for samples with an electrical conductivity up to 2000 $\mu\text{S}/\text{cm}$. For the case, that $EC_{25^{\circ}C}/100$ was unequal to both, the sum of all cation equivalents and the sum of all anion equivalents, the sample was classified as implausible. For the final analysis of the water quality parameters all implausible samples were not considered.

$$err = \frac{\sum cationequivalents - \sum anionequivalents}{\sum cationequivalents + \sum anionequivalents} \cdot 100 \quad (1)$$

$$\sum cationequivalents = \sum anionequivalents = \frac{EC_{25^{\circ}C}}{100} \quad (2)$$

5.1.2 Water Quality Analysis

To assess the improvement in water quality of riverbank filtrate, samples of groundwater, surface water and RBF wells' water were collected once a month continuously for two years. Compared results of water quality parameters for surface and groundwater, and pumping well showed considerable improvement in the quality of riverbank filtrate water as it moves through the subsurface. Analyses of major ions such as, Na^{2+} , K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , and NO_3^- enabled to understand the mineralization process of water during the subsurface passage. Concentration graph showing the major ions present in surface, groundwater and Pumping well has been plotted to depict the same for Bhupatwala, Pantdweep and Beragi Camp area. Ca^{2+} concentration is high in Bhupatwala and Pantdweep as influenced by already mineralized groundwater whereas Bairagi camp has low Ca^{2+} concentration due to its near proximity to canal or surface water. (Figure 7)



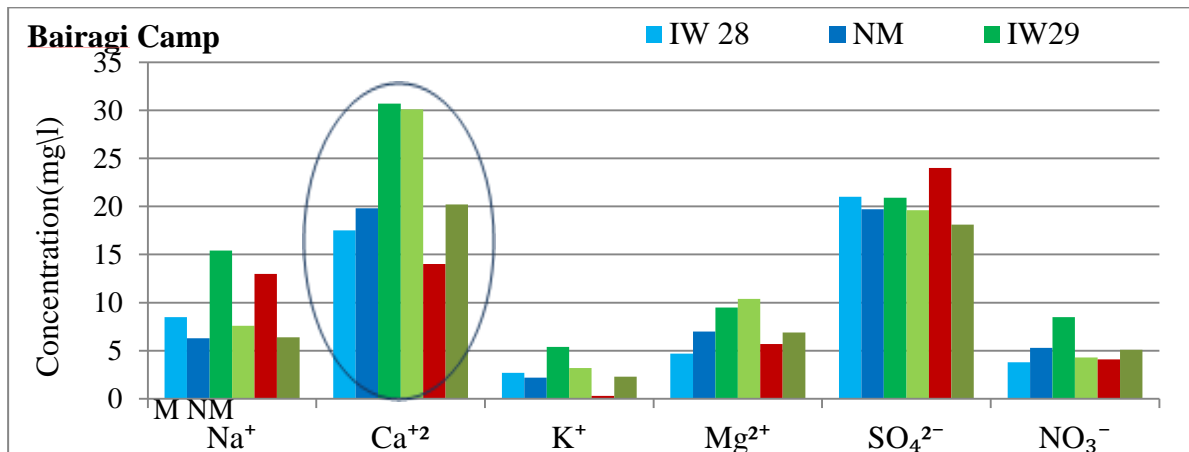
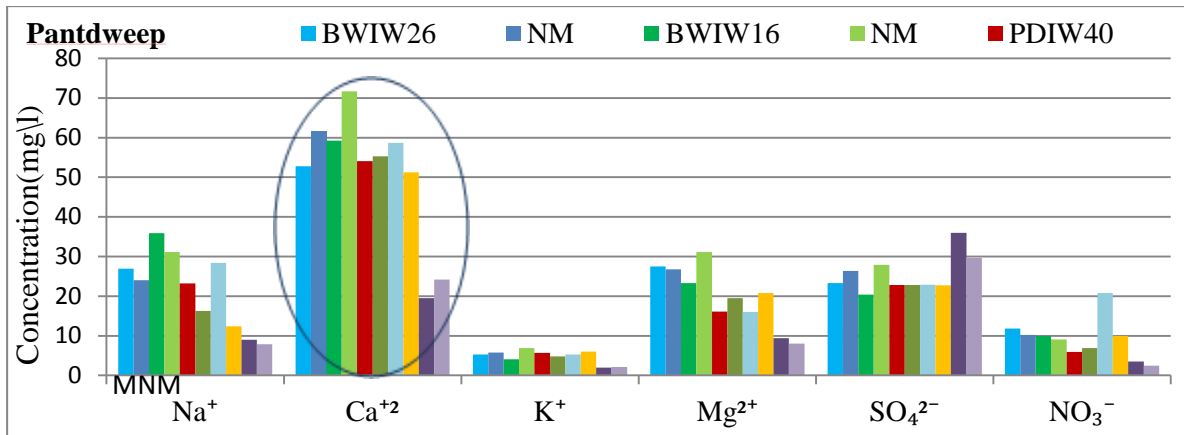


Figure 7. Concentration Plot of major ions present in Pumping wells and River Ganga

Ferrous and Manganese are essential dietary element present in water and according to WHO(2011) the recommended health based limit values for Fe^{2+} and Mn^{2+} are 2 mg/L and 0.4 mg/L, respectively. Concentration plot for Ferrous and Manganese present in River and nearby RBF wells for Bhupatwala, Pantdweep and Bairagi camp depict that surface water is having higher concentration of Ferrous and Manganese ranging from 2.1 to 5.5 mg/L and from 1.9 to 6.7 mg/L, respectively, during monsoon as higher discharge and flow velocities cause erosion of Fe^{2+} and Mn^{2+} which is accumulated in riverbed during low flow in river (Figure 8).

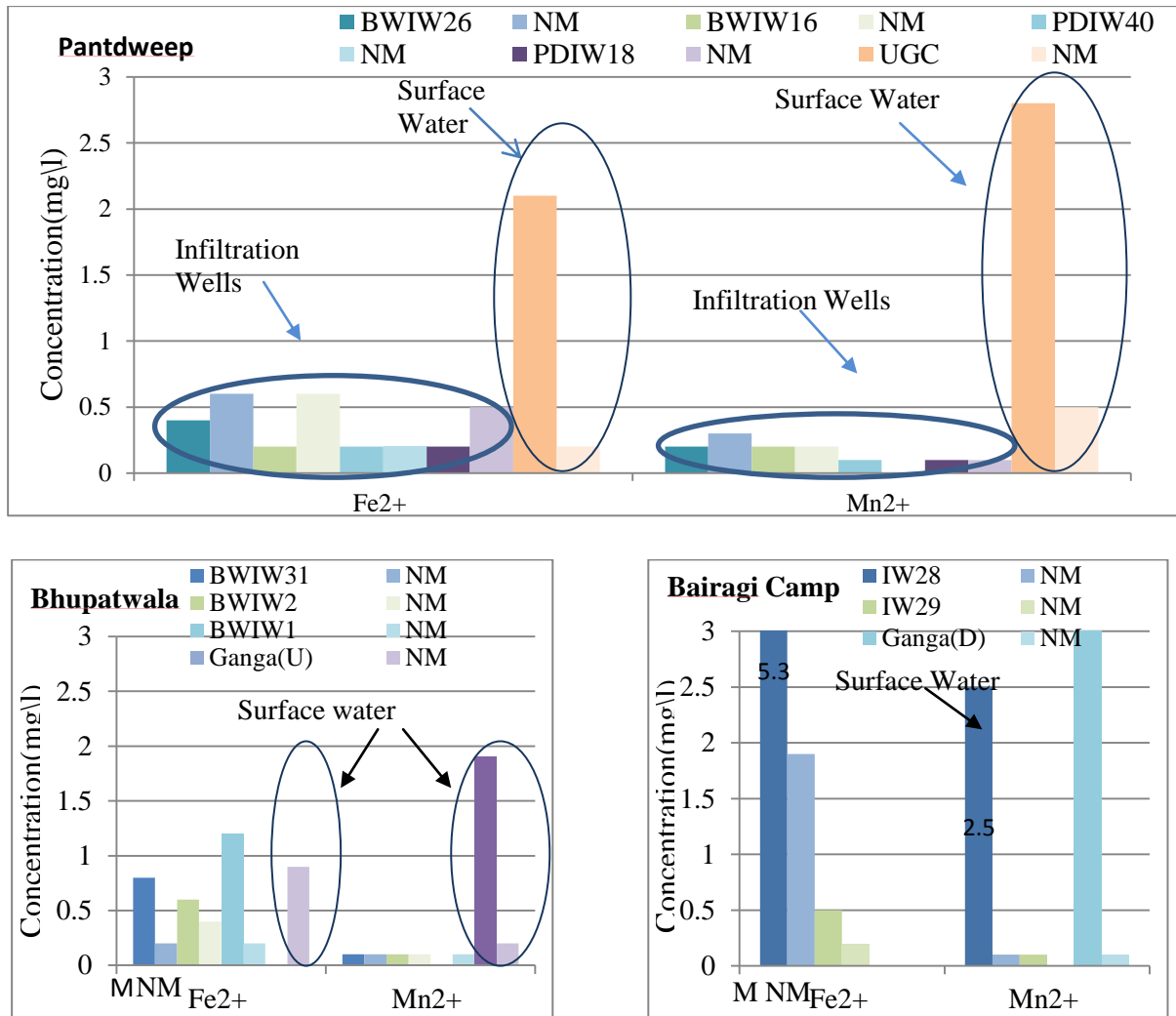


Figure 8. Concentration Plot of Ferrous and manganese present in Pumping wells and river Ganga

Turbidity is the measure of relative clarity of a liquid. Material that causes water to be turbid includes clay, silt, finely divided inorganic and organic matter, algae, soluble colour organic compounds, and plankton and other microscopic organisms. The most important health-related function of turbidity is its use as an indicator of the effectiveness of drinking water treatment processes, particularly filtration, in the removal of potential microbial pathogens. There is no precise relationship between the magnitude of turbidity reduction and the removal of pathogens. Turbidity result is visualized in Figure 9 which shows that the turbidity of Ganga River (upstream and downstream of Bhimgoda barrage) is 2 to 15 times more turbid in monsoon season due to high flow velocities, high runoff and erosion of soil and riverbed materials respectively. The turbidity of the abstracted water from RBF wells is below the Indian Standard limit of 5 NTU (IS 10500, 1993) during monsoon and non-monsoon.

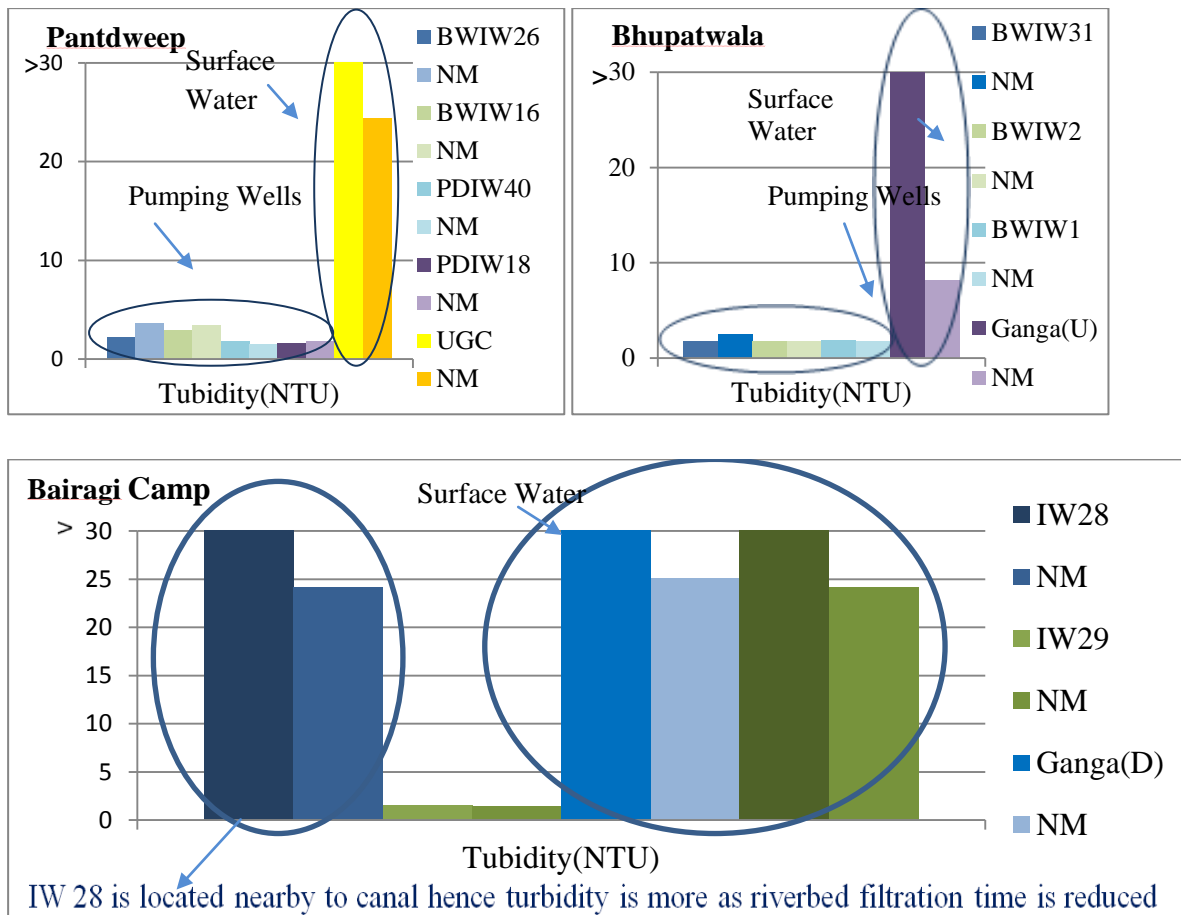


Figure 9. Turbidity (NTU) in river Ganga and Pumping wells.

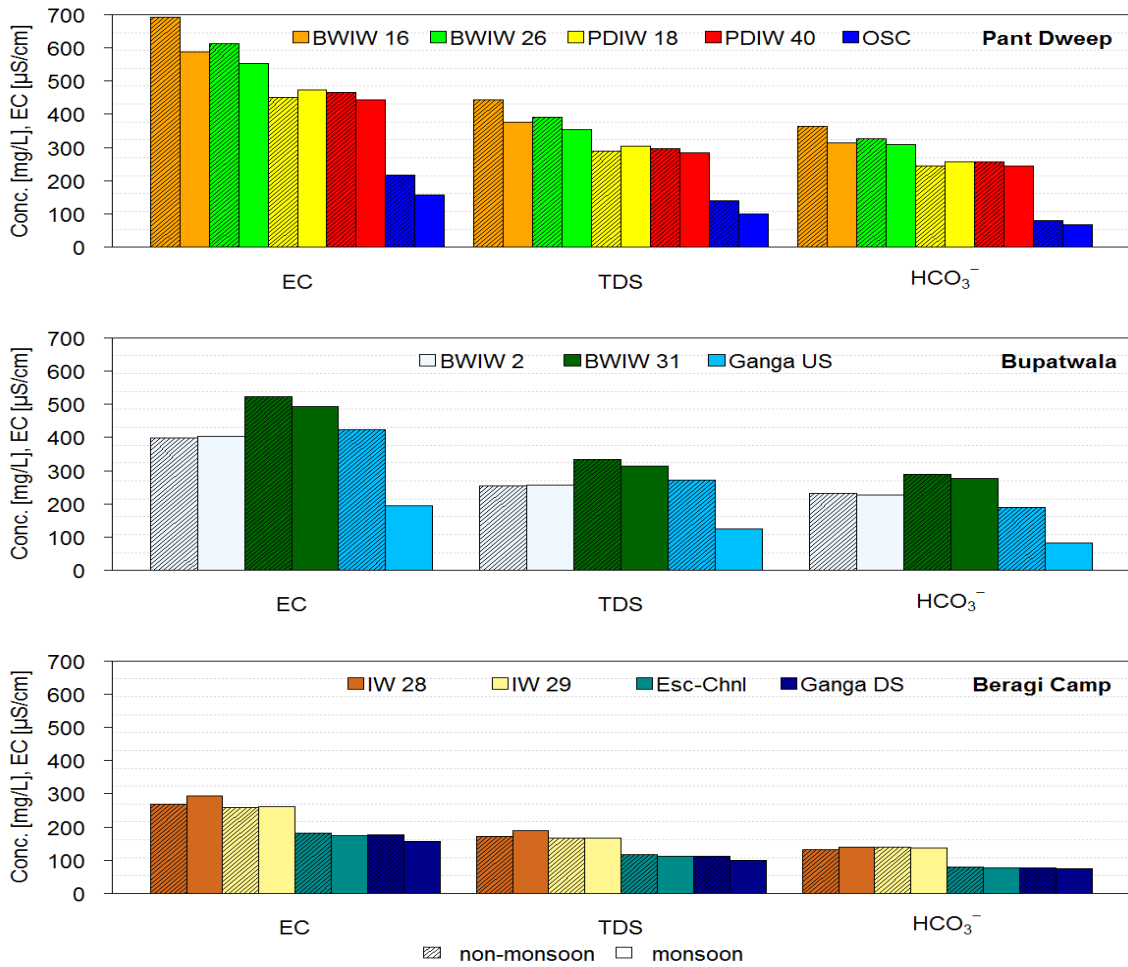


Figure 10. River water quality and water quality of Pumping wells regarding electrical conductivity (EC), total dissolved solids (TDS) and bicarbonate (HCO₃⁻)

5.1.3 Result of Water Quality Analysis

- During non-monsoon and monsoon season the extracted water gets mineralized during the sub-surface passage through the aquifer, as illustrated by the increasing concentrations of major ions within each well sample.
- The longer the water is held up in the aquifer the more the concentration of Na⁺, Ca²⁺, K⁺ and Mg²⁺ increases.
- Ca²⁺ concentration is high in Bhupatwala and Pantdweep as influenced by already mineralized groundwater whereas Bairagi camp has low Ca²⁺ concentration due to its near proximity to canal or surface water.
- The nitrate and sulphate concentration for each well is below the recommended guideline value of 50 mg/L and 500 mg/L, respectively.

Ferrous and Manganese are essential dietary element present in water and according to WHO(2011) the recommended health based limit values for Fe²⁺ and Mn²⁺ are 2 mg/L

and 0.4 mg/L, respectively. All Pumping wells except PW28 shows Fe^{2+} and Mn^{2+} concentration below recommended health limit.

- Turbidity of Ganga River (upstream and downstream of Bhimgoda barrage) is 2 to 15 times more turbid in monsoon season due to high flow velocities, high runoff and erosion of soil and riverbed materials respectively.
- Turbidity of the abstracted water is below the Indian Standard limit of 5 NTU (IS 10500, 1993) during monsoon and non-monsoon.
- Electrical conductivity (EC), total dissolved solids (TDS) and bicarbonate (HCO_3^-) of all Pumping wells is under the allowable limits.

5.1.4 Hydrochemistry

Water samples from the river Ganga, UGC, groundwater and 22 RBF wells were collected monthly from May 2012 to October 2013 for the non- monsoon and monsoon seasons. Each sampling campaign, comprising of 25 samples was analysed in the laboratory as per the guidelines prescribed by the American Public Health Association (APHA, 2006) to determine physicochemical and biological parameters. The analysis of physicochemical parameters include; pH, Temperature, Turbidity, Alkalinity, Total Hardness, Cl^- , NO_3^- , SO_4^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} and the bacteriological parameters include; Total Coliform and Faecal Coliform. Analysed results of physicochemical and biological parameters (total sample size: 10 for non-monsoon, and 8 for monsoon) are summarised in Table 4. Spatial variation of concentrations of few physicochemical and biological parameters measured in the extracted water from 22-RBF wells is shown in Fig. 11.

Table 4. Min, Max and Standard Deviation of Water Quality data in Non Monsoon and Monsoon period.

| | River and Canal water | | | | Extracted water (RBF wells) | | | | Groundwater (Open well) | | | | Acceptable limit (IS:10500) |
|--------------------------------------|-----------------------|-----------------------|--------------|----------------------|-----------------------------|---------------------|--------------|---------------------|-------------------------|--------------------|---------------|----------------------|-----------------------------|
| | Non- monsoon | | Monsoon | | Non- monsoon | | Monsoon | | Non- monsoon | | Monsoon | | |
| | (Min.- Max.) | Mean \pm std. | (Min.- Max.) | Mean \pm std. | (Min.- Max.) | Mean \pm std. | (Min.- Max.) | Mean \pm std. | (Min.- Max.) | Mean \pm std. | (Min.- Max.) | Mean \pm std. | |
| Turbidity(NTU) | 2.25-19.10 | 8.49 \pm 6.33 | 3.20-346 | 104.66 \pm 109.74 | 1.09-5.67 | 2.08 \pm 1.05 | 1.24-7.62 | 2.2 \pm 1.48 | 0.73-5.02 | 1.99 \pm 1.41 | 0.70-48.10 | 6.54 \pm 14.65 | 1 |
| TDS (mg/L) | 141.44-329.60 | 233.92 \pm 74.03 | 93.44-286.08 | 160.45 \pm 160.45 | 136.88-459.52 | 256.6 \pm 104.36 | 161.88-442 | 272.94 \pm 88.62 | 660.48-760.96 | 712.05 \pm 35.77 | 684.16-884.48 | 769.22 \pm 63.77 | 500 |
| Ca ²⁺ (mg/L) | 23.30-71 | 44.08 \pm 17.30 | 17.60-58.47 | 31.63 \pm 13.27 | 29.36-71.35 | 45.39 \pm 13.35 | 28.29-72.45 | 47.25 \pm 14.35 | 94.64-133.13 | 120.21 \pm 12.72 | 68.97-159 | 113.2 \pm 26.25 | 75 |
| Mg ²⁺ (mg/L) | 7.78-25 | 15.61 \pm 7.05 | 4-20.41 | 10.17 \pm 5.11 | 7.16-30 | 17 \pm 8.42 | 8.52-28 | 16.72 \pm 6.44 | 9.23-60.75 | 34.24 \pm 17.64 | 31.98-64 | 48.47 \pm 11.71 | 30 |
| Na ⁺ (mg/L) | 3.63-11.60 | 7.25 \pm 2.68 | 0.82-10 | 4.46 \pm 2.60 | 4.62-24.18 | 11.85 \pm 6.93 | 7.62-34.92 | 14.7 \pm 6.93 | 40-78 | 51.48 \pm 12.15 | 24.29-95 | 49.03 \pm 26.75 | - |
| K ⁺ (mg/L) | 1.61-2.90 | 2.16 \pm 0.43 | 0.31-16.31 | 5.24 \pm 5.36 | 2.70-7.07 | 4.27 \pm 1.29 | 3.88-6.73 | 4.61 \pm 0.70 | 6.94-8.60 | 8.08 \pm 0.58 | 1.14-9.80 | 6.4 \pm 2.30 | - |
| HCO ₃ ⁻ (mg/L) | 97.60-280.60 | 180.87 \pm 67.72 | 75.64-225.70 | 116.17 \pm 49.95 | 113.16-367.74 | 216.83 \pm 89.24 | 117.96-324 | 212.23 \pm 74.35 | 434.32-566.08 | 531.92 \pm 45.21 | 499.96-688.08 | 558.39 \pm 62.76 | - |
| Cl ⁻ (mg/L) | 0-14 | 10.5 \pm 4.68 | 1--16 | 8.4 \pm 5.52 | 8.50-28.57 | 15.35 \pm 5.85 | 8.04-22.41 | 12.26 \pm 3.84 | 46-60 | 53.71 \pm 5.09 | 42.40-61 | 50.88 \pm 5.53 | 250 |
| SO ₄ ⁻ (mg/L) | 20-46 | 31.69 \pm 10.55 | 18.14-41.80 | 28.55 \pm 7.92 | 15.79-30.63 | 22.49 \pm 3.50 | 13.85-28.96 | 21.09 \pm 3.40 | 26-52.50 | 42.2 \pm 8.64 | 29.30-58.80 | 46.89 \pm 8.97 | 200 |
| NO ₃ ⁻ (mg/L) | 1.32-11 | 4.89 \pm 3.22 | 3.90-32.12 | 11.92 \pm 9.10 | 4.36-18.68 | 8.22 \pm 3.82 | 5.08-14.28 | 9.32 \pm 2.65 | 0.40-63 | 27.68 \pm 23.84 | 8.80-137 | 38.29 \pm 44.31 | 45 |
| TC (MPN/100 mL) | 28-2400 | 897.625 \pm 1045.27 | 1000-2400 | 1614.29 \pm 735.82 | 64-1305 | 374.27 \pm 284.84 | 9.20-2400 | 416.7 \pm 524.66 | 1100-2400 | 2140 \pm 581.38 | 1100-2400 | 1966.67 \pm 750.56 | Must not be detectable |
| FC (MPN/100 mL) | 43-2400 | 686 \pm 1004.17 | 93-2400 | 1006.63 \pm 1160.3 | 3-498 | 164.45 \pm 162.76 | 6.75-2400 | 570.21 \pm 698.35 | 150-2400 | 1120 \pm 1047.07 | 75-2400 | 1625 \pm 1342.34 | Must not be detectable |

* TC- Total Coliform, FC- Feecal Coliform

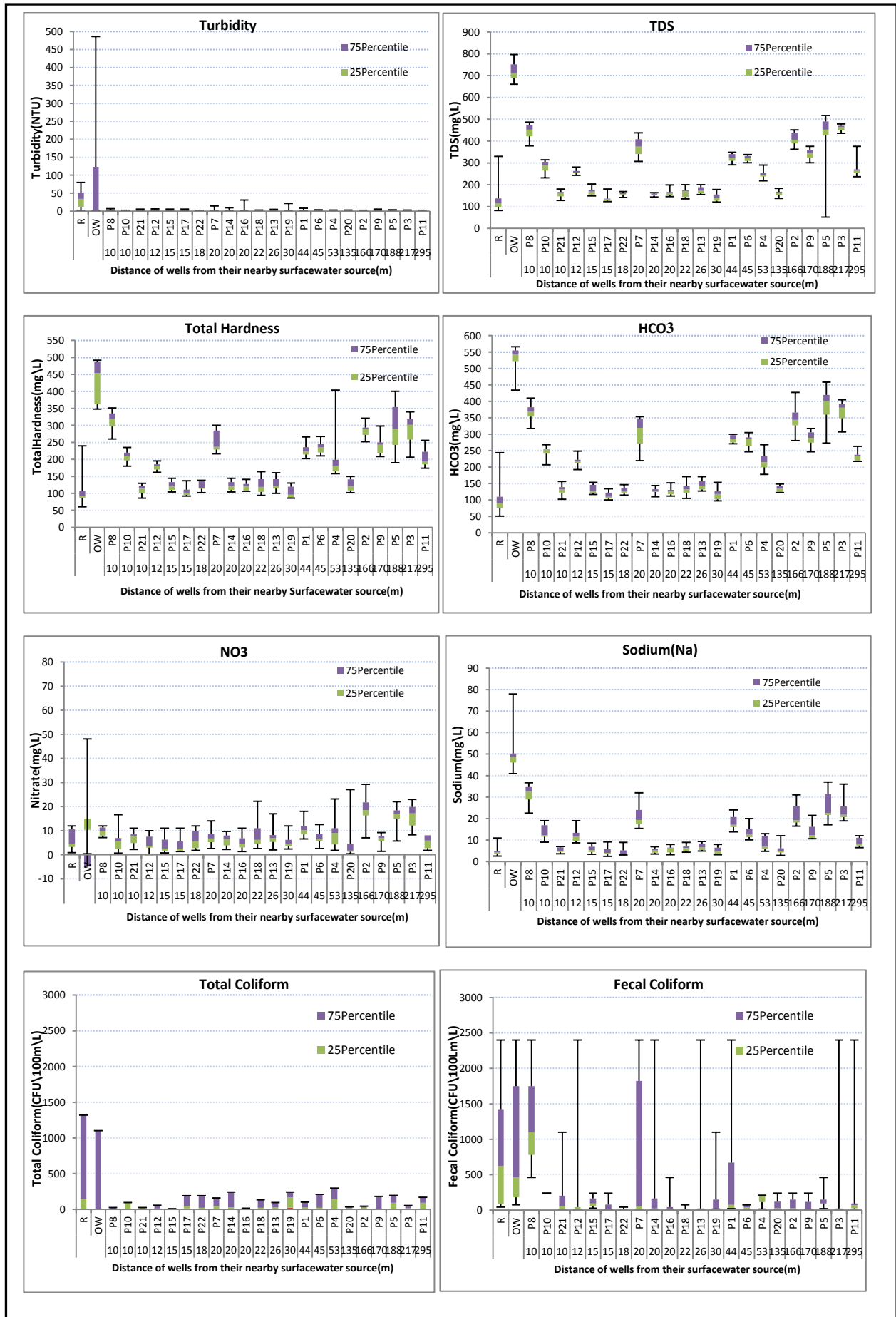


Figure11.

5.1.5 Results and Discussion

The results in Table 4 show statistical values (mean and standard deviation) of 10 physicochemical and 2 biological parameters for both non-monsoon and monsoon seasons, for three categorized sources; river/canal, groundwater and extracted (pumped) water. The values of extracted water represent statistical data of 22-RBF wells. These 22-RBF wells are located at varying distances (10 m to 295 m) from the river/canal. Largely, all physicochemical parameters except Turbidity of the extracted water, which constitutes mixing water of riverbank filtrate and groundwater, showed concentration much below the acceptable limit prescribed in IS:10500 (BIS, 2012) (Table 4) for both non-monsoon and monsoon periods. The turbidity in the extracted water although removed about 98% during the monsoon and 76% during the non-monsoon period in comparison to the river/canal water, its concentration in some of the production wells were higher than the acceptable limit of 1 NTU. The count of biological parameters, viz. Total coliform and Faecal coliform, although found to be removed considerably in the extracted water, the count still remained above the acceptable limit, for both non-monsoon and monsoon periods. The percent removal of coliform varied between 78% and 83% for Total coliform and between 65% and 85% for Faecal coliform in comparison to the quality of groundwater for both the non-monsoon and the monsoon periods. The variability of concentration of physiochemical parameters in the extracted water between the non-monsoon and the monsoon periods, by and large, was found to be very small, whereas, the variability of biological parameters was found to be very high with the monsoon period showing higher value than the non-monsoon period. As evident from Table 4, the value of all physicochemical and biological parameters (except Turbidity) of groundwater showed higher concentration than the river/canal water for both the periods. However, in the case of Turbidity, it was reverse. A comparison between the results of the extracted and river/canal water showed that there has been considerable reduction in contents of all physicochemical and biological parameters in the extracted water. One of the reasons for high contents of pathogenic contents, viz. NO_3^- , Total coliform and Faecal coliform in groundwater in Haridwar area may be because, it is a pilgrimage site and a lot of pathogenic refusals leach to aquifer during monsoon season by the process of groundwater recharge. The reason of high content of physiochemical parameters in groundwater could be due to the presence of weathered and eroded source rocks. As per the physical process of bank filtration, during pumping, the induced bank filtrate from river water after mixing with the groundwater gets withdrawn, which leads to modification of quality of bank filtrate water by the quality of

groundwater. Thus, the quality of extracted water depends on mixing proportion of groundwater with the bank filtrate water.

For examining the spatial variation of quality of bank filtrate water, graphs are plotted (Fig.11) between various parameters of the extracted water measured from different RBF wells and their respective distance from the river/canal. In these graphs, parameters measured in the river/canal water and groundwater is also plotted. It is evident from Fig.11 that, a persistence trend of reduction of physicochemical and biological parameters with distances is not visible. This may be because of the mixing of bank filtrate water with the groundwater having high contents of the respective parameters. For example, the concentration of chemical and biological constituents in the groundwater namely, TDS, total hardness, HCO_3^- , NO_3^- , Na^+ , total Coliform and Faecal Coliform are higher than the surface water source. The reasons for high concentration of cations in groundwater could be due to geogenic source and that of anions and biological parameters could be from the refusals from the anthropogenic sources, such as, septic tanks or leaching from land surface. The bank filtrates, in such circumstances, facilitate dilution of contaminants' content present in the groundwater by the process of mixing surface water, and thus improve the quality of extracted groundwater. The biological parameters exceeded the acceptable and permissible limits in the present analysis. Therefore, a post-treatment of the extracted water, particularly disinfection of the biological parameters, would be necessary before supply of water to users for drinking purposes. As post-treatment, Uttarakhand Jal Sansthan (UJS) who is responsible for domestic water supply has been using the appropriate doses of *Sodium hypochlorite* (NaClO) solution as disinfectant to remove biological contents in the extracted water.

5.2 Isotope analysis for Haridwar site

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 altitude effect (Kumar and Nachiappan, 1992).

In case of river contributing to the groundwater regime, there are two possible sources of recharge to groundwater, viz. Pumping of local precipitation and Pumping 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 than 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 Pumping 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.

5.2.1 Isotopic Characterises of water

At the Haridwar site, 26 sampling locations were identified for collection of isotopic samples. The sampling locations include 23 sites for subsurface water samples, 2 sites for the river Ganga water samples, and 1 for Upper Ganga canal water (Table-5). Most of the Pumping wells are located in the flood plain of the river Ganga. The locations of sampling points for isotopic characterisation of Haridwar site are given in Fig.3.

Table 5: Location of sampling stations for isotopic analysis.

| S. No | Location | Well No. | Sample No | Latitude | Longitude (E) |
|--------------|-----------------------|-----------------|------------------|-----------------|----------------------|
| 1 | Pantdweep (PW18) | (PW18) | G-1 | 29.961150 | 78.175983 |
| 2 | Pantdweep (PW40) | (PW40) | G-3 | 29.959667 | 78.174167 |
| 3 | Sarvanand Ghat (PW16) | (PW16) | G-4 | 29.970983 | 78.178917 |

| | | | | | |
|----|------------------------------------|---------|------|-----------|-----------|
| 4 | Sarvanand Ghat (PW26) | (PW26) | G-5 | 29.971233 | 78.180367 |
| 5 | Bhupatwala (PW2) | (PW2) | G-6 | 29.974317 | 78.186067 |
| 6 | Bhupatwala (PW3) | (PW3) | G-7 | 29.975100 | 78.184900 |
| 7 | Bhupatwala (PW31) | (PW31) | G-8 | 29.986983 | 78.196017 |
| 8 | Rodibalwala (PW25) | (PW25) | G-9 | 29.951083 | 78.171200 |
| 9 | Vishnughat (PW44) | (PW44) | G-10 | 29.950667 | 78.167183 |
| 10 | Alaknanda Hotel (PW21) | (PW21) | G-11 | 29.944067 | 78.160183 |
| 11 | Bairagi Camp (PW29) | (PW29) | G-12 | 29.938433 | 78.157733 |
| 12 | Mahila Milan (PW28) | (PW28) | G-13 | 29.939183 | 78.155000 |
| 13 | Lalita Rao Pul (PW17) | (PW17) | G-14 | 29.947050 | 78.162667 |
| 14 | Bhupatwala (PW27) | (PW27) | G-15 | 29.982867 | 78.191883 |
| 15 | Bhupatwala (PW4) | (PW4) | G-16 | 29.982200 | 78.191167 |
| 16 | Bhupatwala (PW1) | (PW1) | G-17 | 29.971567 | 78.182900 |
| 17 | Pantdweep (PDPW2) | (PDPW2) | G-18 | 29.968167 | 78.177950 |
| 18 | Pantdweep (PDPW1) | (PDPW1) | G-19 | 29.960800 | 78.173417 |
| 19 | Rodibelawala (PW24) | (PW24) | G-20 | 29.950367 | 78.170467 |
| 20 | Rodibelawala (PW43) | (PW43) | G-21 | 29.949467 | 78.169317 |
| 21 | Rodibelawala (PW42) | (PW42) | G-22 | 29.949183 | 78.169000 |
| 22 | Bairagi Camp (PW49) | (PW49) | G-23 | 29.940100 | 78.158183 |
| 23 | Kabir Ashram, Bhupatwala (OW-1) | (OW-1) | OW1 | 29.974139 | 78.178389 |
| 24 | Upper Ganga Canal near PW40 | (PW40) | R-1 | 29.959667 | 78.174167 |
| 25 | UGC near PW28 | (PW28) | R-5 | 29.939183 | 78.155000 |
| 26 | Bairagi Camp near PW-29 | (PW-29) | R-6 | 29.938433 | 78.157733 |

(Note: OW: Open well; R: River water)

Water samples had 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 post monsoon season (October, November, December, January and February). The samples collected from the Haridwar experimental site had been analysed for isotopic composition of oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) at Stable Isotope Laboratory of the National Institute of Hydrology, Roorkee. The results of the isotopic analysis are given in Appendix – 1.

5.2.2 Methodology

The approach is based on the fact that the river originated at higher altitudes, as the river Ganga, normally has a different stable isotopic composition than that of groundwater recharged by Pumping of local precipitation. The isotopic composition for $\delta^{18}\text{O}$ 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 Pumping of local precipitation in plains. This distinct difference helps in identifying the contribution of one to the other. The studies carried out by NIH, Roorkee and few others have revealed that the river Ganga has stable isotopic signatures ($\delta^{18}\text{O}$) in the range of -9.5‰ to -13‰. In the areas, where groundwater recharge due to precipitation dominates, $\delta^{18}\text{O}$ 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:

$$m_r = m_1 + m_2 \quad (1)$$

$$m_r C_r = m_1 C_1 + m_2 C_2 \quad (2)$$

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 (1), we get:

$$m_1 = 1 - m_2 \quad (3)$$

Substituting equation (3) in (2) and rearranging, we get:

$$m_2 = \frac{C_1 - C_r}{C_1 - C_2} \quad (4)$$

Equations (1) and (4) could be used to compute the fraction of the two components of the stream flow at a given point in space and time.

5.2.3 Result of Isotope Analysis

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. 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 river Ganga is shown in Fig.12.

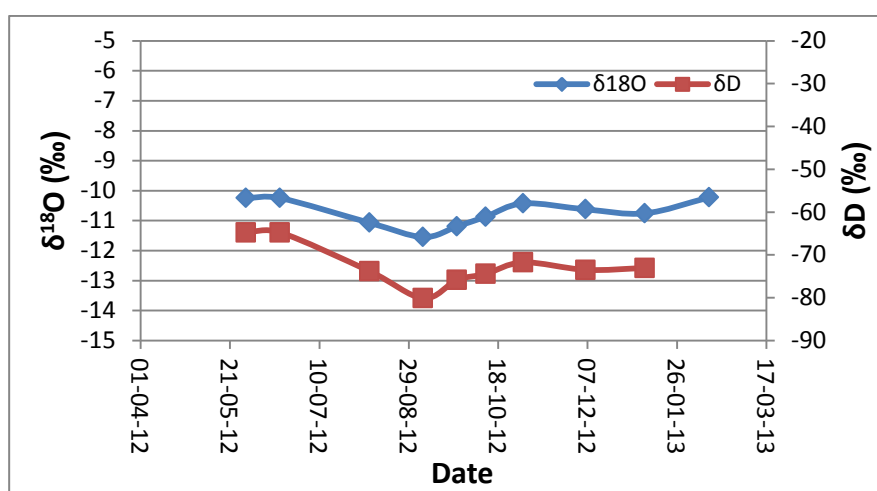


Figure 12. Isotopic characteristics of Ganga River water at Haridwar

Fig.12. 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 $\delta^{18}\text{O}$, respectively. With the advancement of monsoon, the isotopic values get depleted due to enhanced melting of snow and ice (Rai et.al. 2009). After the monsoon is over, it again gets enriched, with relatively higher contribution of groundwater generated due to monsoon rains.

Isotopic variation ($\delta^{18}\text{O}$) in Pumping 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 Pumping wells 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 in the month has been considered, whereas for determining the isotopic indices of the river water 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 indices for that month. The indices for different sampling dates are given in Table 6.

Table 6. Isotopic indices ($\delta^{18}\text{O}$) of groundwater and river water

| 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 | | | | | | | | | | |
| GW | -7.5 | -7.6 | -7.5 | -7.1 | -7.2 | -7.5 | -7.5 | -7.1 | -7.2 | -7.4 |
| RW | -10.8 | -10.7 | -11.1 | -11.7 | -11.3 | -11.1 | -11.2 | -10.8 | -10.9 | -10.7 |

Based on these indices, the proportion of the river water in groundwater wells has been computed and is given in Table 7.

Area wise analysis of the interaction of groundwater with the river water is given below:

Bhupatwala area:

In the Bhupatwala area, seven samples for isotopic analysis had been collected. The variation of $\delta^{18}\text{O}$ is shown in Fig.13.

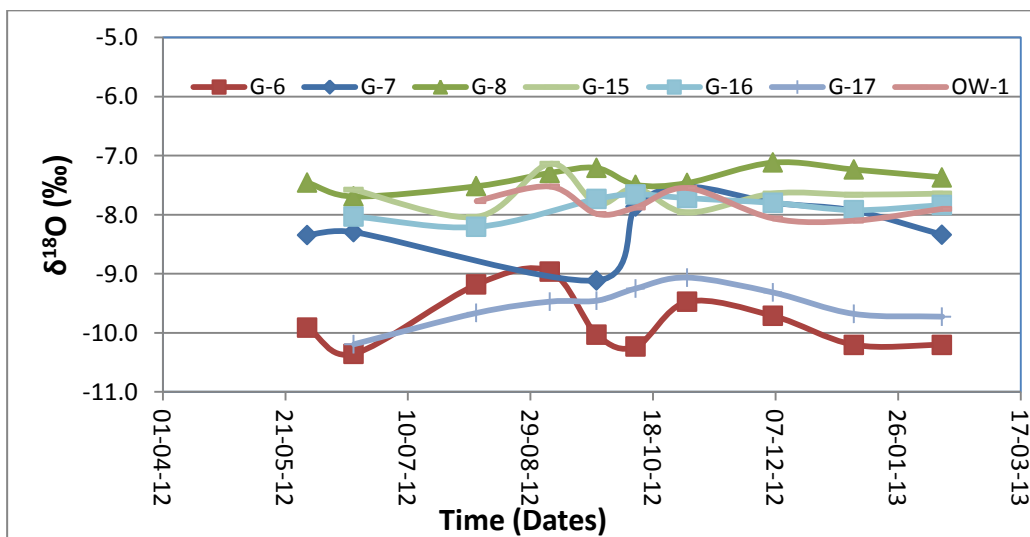


Figure 13. Isotopic ($\delta^{18}\text{O}$) variation in Bhupatwala area.

Fig.13. indicates that the samples from G8 (PW31), G15 (PW27), G16 (PW4) and OW-1 are mostly groundwater generated locally and has almost negligible component of river water. The sample G7 (PW3) indicates that river water recharges this location only during monsoon,

after that the groundwater is the major component. The samples G6 (PW2) and G17 (PW1) indicate good interaction of river water and contribution in the well is substantial.

Sarvananda Ghat

From this area, samples from two sites, G-4(PW16) and G-5(PW26), had been collected. The isotopic ($\delta^{18}\text{O}$) variation with time for the well water of this area is shown in Fig.14.

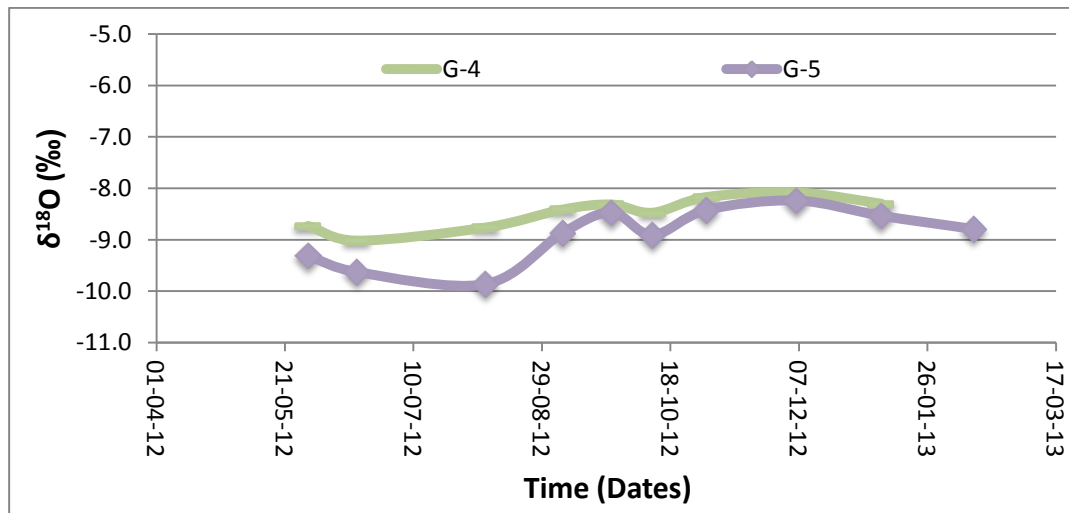


Figure 14. Isotopic ($\delta^{18}\text{O}$) variation in Bhupatwala area.

Fig. 14 indicates that in both the wells there is little interaction with river water. The contribution of river water is less than 50%. This interaction is more in G-5(PW26) than in G-4(PW16).

Pantdeep area

In the Pantdeep area, samples from 4 Pumping wells had been collected. Isotopic ($\delta^{18}\text{O}$) variation with time in the well water is shown in Fig. 15.

Table 7: Relative proportion of river water in well water at Haridwar site

| S. No. | Sample No. | Location | 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 |
|--------|------------|--------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1 | G-1 | Pantdeep (IW18) | 100 | 98 | | 47 | 63 | 72 | 80 | 82 | 80 | 91 |
| 2 | G-3 | Pantdeep (IW40) | 75 | 84 | 77 | 58 | 68 | 66 | 72 | 73 | 68 | 78 |
| 3 | G-4 | Sarvanand Ghat (IW16) | 39 | 46 | 35 | 28 | 27 | 27 | 19 | 26 | 29 | |
| 4 | G-5 | Sarvanand Ghat (IW26) | 56 | 65 | 66 | 38 | 31 | 39 | 26 | 30 | 36 | 42 |
| 5 | G-6 | Bhupatwala (IW2) | 74 | 88 | 47 | 40 | 68 | 75 | 54 | 70 | 81 | 84 |
| 6 | G-7 | Bhupatwala (IW3) | 27 | 23 | | | 46 | 10 | 2 | 18 | 19 | 29 |
| 7 | G-8 | Saptrishi, Bhupatwala (IW31) | 0 | 4 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | G-9 | Rodibelawala (IW-25) | 97 | 100 | 84 | 73 | 77 | 87 | 87 | 97 | 93 | 96 |
| 9 | G-10 | Vishnughat (IW44) | 95 | 95 | 83 | 81 | 76 | 95 | 90 | 97 | 98 | 97 |
| 10 | G-11 | Alaknanda Hotel (IW21) | 98 | 95 | 83 | 84 | 89 | 100 | 84 | 94 | 96 | 96 |
| 11 | G-12 | Bairagi Camp (IW29) | 95 | 94 | 86 | 87 | 100 | 96 | 100 | 96 | 95 | 98 |
| 12 | G-13 | Mahila Milan (IW28) | 90 | 90 | 89 | 84 | 93 | 89 | 96 | 95 | 93 | 87 |
| 13 | G-14 | Lalita Rao Pul (IW17) | 95 | 93 | 81 | 69 | 85 | 96 | 93 | 93 | 95 | 100 |
| 14 | G-15 | Bhupatwala (IW27) | | 0 | 15 | 0 | 15 | 1 | 13 | 14 | 12 | 8 |
| 15 | G-16 | Bhupatwala (IW4) | | 14 | 19 | | 13 | 4 | 7 | 18 | 19 | 14 |
| 16 | G-17 | Bhupatwala (IW1) | | 83 | 60 | 51 | 54 | 48 | 43 | 60 | 67 | 70 |
| 17 | G-18 | Pantdeep (PDIW-2) | | 81 | | 63 | 51 | 61 | 39 | 46 | 58 | 66 |
| 18 | G-19 | Pantdeep (PDIW-1) | | 91 | 82 | 68 | 81 | 84 | 87 | 87 | 88 | 91 |
| 19 | G-20 | Rodibelawala (IW24) | | 89 | 84 | 62 | 76 | 80 | 88 | 94 | 95 | 99 |
| 20 | G-21 | Rodibelawala (IW43) | | 97 | 96 | 68 | 76 | 88 | 80 | 100 | 100 | 97 |
| 21 | G-22 | Rodibelawala (IW42) | | 96 | 95 | 70 | 69 | 85 | 85 | 96 | 98 | 97 |
| 22 | G-23 | Bairagi Camp (IW49) | | 95 | 75 | 74 | 90 | 95 | 92 | 98 | 97 | 99 |
| 23 | G-24 | Jhanda Chowk Jawalapur (OW-15) | | 25 | 24 | | 40 | 33 | | 51 | 54 | 56 |
| 24 | G-25 | Firahediyar Jawalapur (OW-34) | | 42 | 39 | 26 | 36 | 31 | | 33 | 38 | 30 |
| 25 | OW-1 | Kabir Ashram, Bhupatwala OW-1 | | | 7 | 8 | 19 | 10 | 2 | 26 | 24 | 16 |

Colours indicate proportion of river water

Dark green >75%;
 Light green 50-75%;
 Light blue 25-50%
 Pink <25%

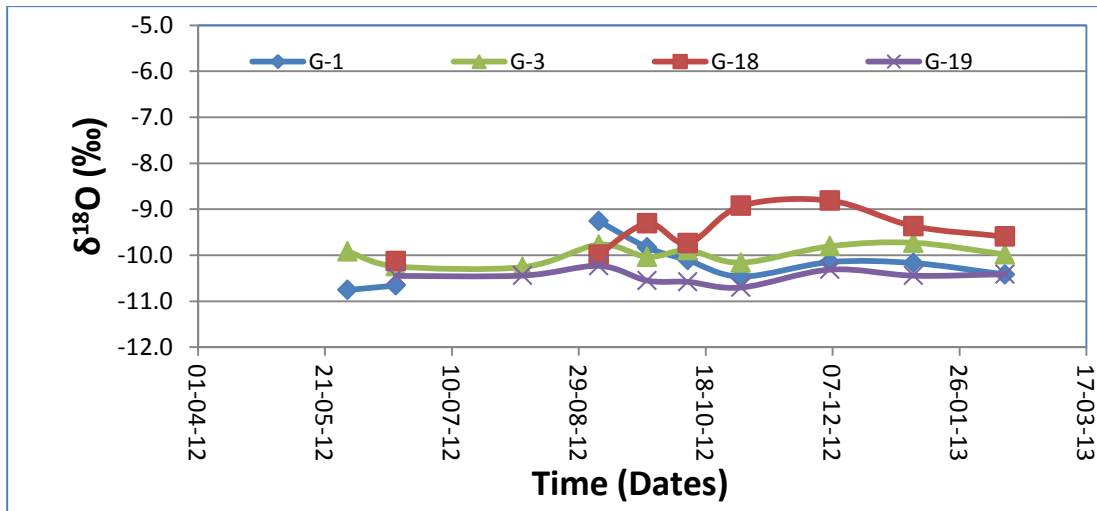


Figure 15. Variation of $\delta^{18}\text{O}$ with time in Pantdeep area.

Fig.15 indicates that all the four wells receive water from the river Ganga in different proportions. Samples G-1(PW18) and G-19(PDPW1) indicate more river water and show depleted signatures which are quite close to river water.

Rodibelawala area

From this area, samples from five locations, i.e., G-9(PW25), G-10(PW44), G-20(PW24), G-21(PW43), and G-22(PW42) had been collected. All these Pumping wells lie between Upper Ganga Canal and the Ganga River. The isotopic ($\delta^{18}\text{O}$) variation with time in the well water is shown in Fig.16.

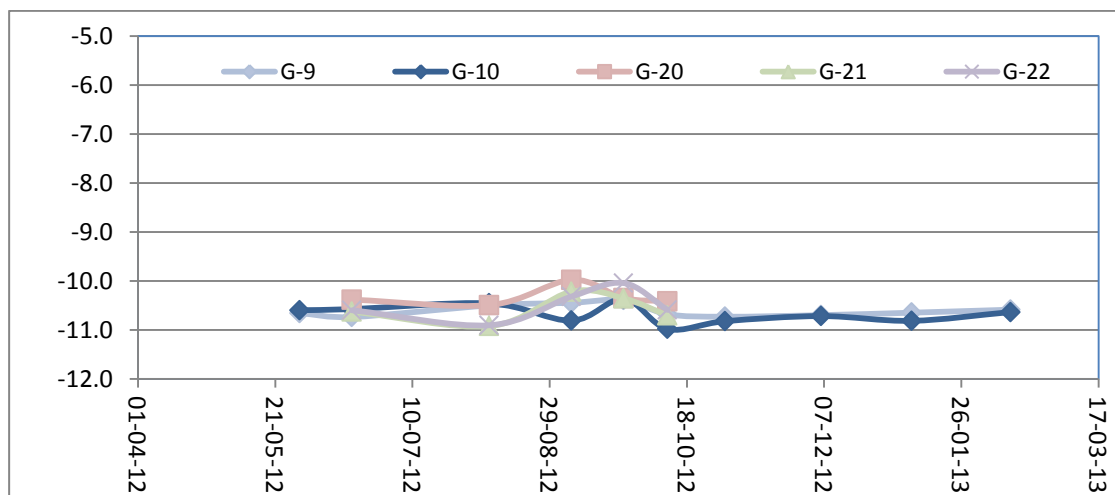


Figure 16. Variation of $\delta^{18}\text{O}$ with time in Rodibelawala area.

Fig.16 and the isotopic data show that all the wells receive river water in large quantity (>75 %).

Area near Alaknanda Hotel

This area represents two sampling sites; G-11(PW21) and G-14(PW17). The area lies between the River Ganga and very close to the UGC. The isotopic variation ($\delta^{18}\text{O}$) at different times is shown in Fig.17.

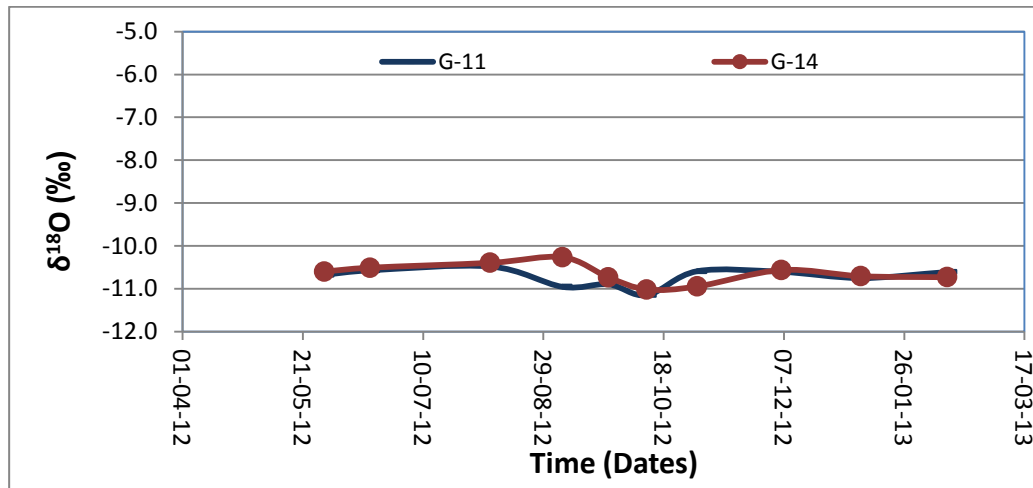


Figure 17. Variation of $\delta^{18}\text{O}$ with time in Alaknanda Hotel area.

Fig.17 shows almost constant value of $\delta^{18}\text{O}$ with time and is very close to the isotopic values of the river / canal water, which indicates that the wells in this area are recharged by the canal water.

Area near Bairagi Camp

Three sampling sites G-12(PW29), G-13(PW28) and G-23(PW49) are located near the Bairagi Camp and Mahila Milan. The area lies between the River Ganga and near to the UGC. The isotopic variation ($\delta^{18}\text{O}$) at different times is shown in Fig.18.

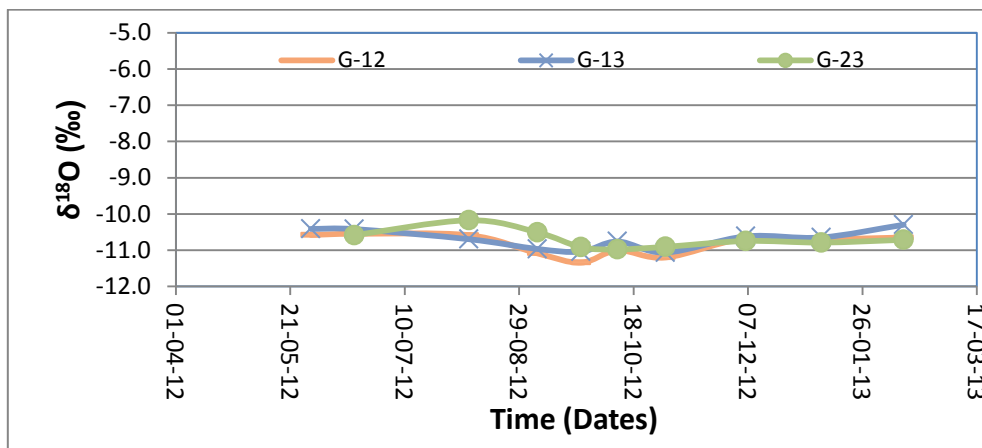


Figure18. Variation of $\delta^{18}\text{O}$ with time in area near Bairagi Camp.

The isotopic variation as shown in Fig.18 indicates that the wells in this area also receive water from the river Ganga or the Upper Ganga Canal. Almost all the water is contributed by the UGC.

5.2.4 Concluding remarks

Out of the twenty three wells studied for isotopic composition of the groundwater samples taken from the pumping wells / open wells, only 16 wells G-1, G-3, G-6, G9-G14, and G17-23 i.e. (PW18, PW40, PW2, PW25, PW44, PW21, PW29, PW28, PW17, PW1, PDPW2, PDPW1, PW24, PW43, PW42, PW49) have good interaction with the river Ganga / UGC water. Other seven wells G4, G-5, G-7, G-8, G15, G16, and OW-1 i.e. (PW16, PW26, PW3, PW31, PW27, PW4 and OW1) have limited interaction with the river Ganga / UGC.

6 Modelling of Bank Filtration

6.1 Simulation Software Visual MODFLOW

To setup these numerical models and visualize the consequences and results of the above mentioned computations, the software package Visual Modflow™ v.9.1. by Waterloo Hydrogeologic, Inc. was utilized. Visual Modflow™ (in the following sections referred to as VM) is a modelling environment for applications in groundwater flow and contaminant transport simulations.

(i) Basic principles

Numerical groundwater-flow models provide a solution to a governing groundwater flow equation which is subject to initial and boundary conditions. A general form of such an equation looks like as follows

$$\frac{\partial}{\partial x} \left(k_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad Eq1$$

K_{xx} , K_{yy} , K_{zz}hydraulic conductivity along the x-, y- and z-coordinate axes,
which are assumed to be parallel to the major axes of hydraulic conductivity [L/T]

hhydraulic head [L]

Wsource/sink term (e.g. pumping, recharge) [1/T]

S_sspecific storage [1/L]

t time [T]

x , y , zspace coordinates [L]

The solution to Eq. 1 provides a transient prediction of hydraulic head in a three dimensional domain for an anisotropic hydraulic-conductivity field. Among the main numerical approaches for solving such equations are the finite-difference methods (FDM) that replace the governing differential equation by a system of algebraic equations. For that purpose the model domain is subdivided into a three-dimensional rectangular grid of cells which yields to a system of columns, rows and layers with cell-centred nodes. These nodes represent the points where the unknown hydraulic heads are calculated and one algebraic equation is solved for each node in the model grid.

The finite-difference form of the flow equation can be derived in several different ways. One method is to directly apply the governing flow equation, expressing the derivatives in difference

form. In VM, the numerical approach is based on the equation of continuity which states that the sum of flows into and out of any cell is equal to the time rate of storage plus or minus additions of water from sources or sinks. It can be written as

$$\sum Q_i = S_s \cdot \frac{\Delta h}{\Delta t} \cdot \Delta V \quad Eq2$$

with

Q_iGW-flow into the cell from adjacent cells and through addition or withdrawal of water (e.g. through pumping, recharge) [L^3/T]

S_sspecific storage [1/L]

Δhchange in head over a time interval [L]

Δttime interval [T]

ΔVvolume of the cell [L^3]

Q_i in Eq. 2 can be expanded using the Darcy equation, written in terms of the gradients between nodes. Doing this substitution and rearranging terms leads to a system of equations

$$[A] \times \{h\} = \{q\} \quad Eq. 3$$

where [A] is the coefficient matrix, {h} is the vector of unknown head values and {q} is a vector of constant head terms.

VM approaches the solution of this system of equations through iteration which involves making some initial guess at the unknowns (“initial hydraulic head” in the VM terminology) and refining these guesses through a series of repeated calculations until an accurate solution is obtained.

Additionally, in order to solve the system of equations, it is necessary to specify boundary conditions. Boundary conditions for groundwater-flow problems can be classified into three types:

| Type | Explanation | Example |
|-----------------------------|---|--------------------|
| 1 st „Dirichlet” | provides a value of hydraulic head at a boundary, H | Edge 3-4 |
| 2 nd „Neumann“ | provides the water flux at a boundary | Edge 1-2, 2-3, 1-5 |

| | | |
|---|---|----------|
| | (including no-flow), Q | |
| 3 rd „, Cauchy ^{cc} | relates hydraulic head to the water flux, Q = f(H) | Edge 4-5 |

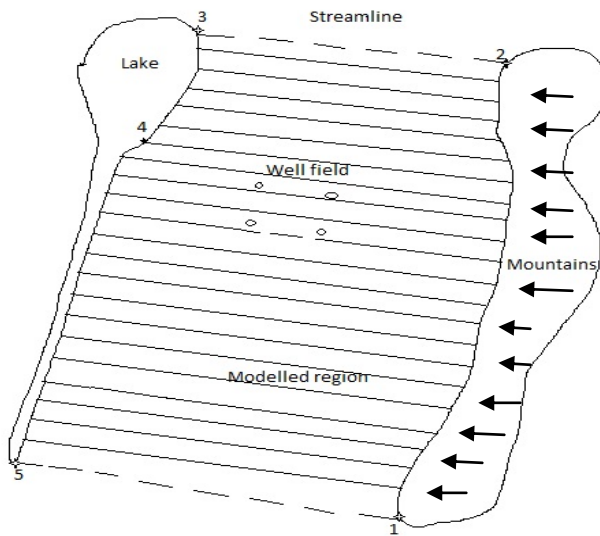


Fig 19. Example of boundary conditions

As it will be revealed in section 6.3, it is necessary to conduct simulations of contaminant transport with VM when dealing with RBF calculations. The way VM handles such computations is similar to that which groundwater-flow problems are treated.

The partial differential equation describing the fate and transport of contaminants of species k in 3-D, transient groundwater flow systems can be written as follows:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial k_i} \left(\theta D_{ij} \frac{\partial C^k}{\partial k_j} \right) - \frac{\partial}{\partial X_i} (\theta V_i C^k) + q_s C_s^k + \sum R_n \quad Eq. 4$$

with

q.....porosity of the subsurface medium [-]

C_kdissolved concentration of species k [M/L³]

ttime [T]

x_i, jdistance along the respective Cartesian coordinate axis [L]

D_i, j.....hydrodynamic dispersion coefficient tensor [L²/T]

V_iseepage velocity [L/T]

q_Svolumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative) [1/T]

C_S^k.....concentration of the source or sink flux for species k [M/L³]

$\sum R_n$chemical reaction term [M/L³/T]

The first term on the right-hand side of Eq. 4 accounts for dispersion caused by mechanical dispersion, a result of deviations of actual velocity on a micro scale from the average groundwater velocity, and by molecular diffusion driven by concentration gradients.

The advection term of the transport equation, $\partial(\theta V_i C_s^k)/\partial k$ describes the transport of miscible contaminants at the same velocity as the groundwater.

The fluid sink/source term of the governing equation, $q_s C_s^k$ represents solute mass entering the model domain through sources or leaving the model domain through sinks.

The chemical reaction term in Eq. 4 can be used to include the effect of general biochemical and geochemical reactions on contaminant fate and transport.

Eq. 4 is essentially a mass balance statement, i.e., the change in the mass storage at any given time is equal to the difference in the mass inflow and outflow due to dispersion, advection, sink/source, and chemical reactions (Zheng and Wang, 1999).

VM obtains the solution to Eq. 4 by substituting it by a system of algebraic equations this is solved iteratively for each node in the model grid:

$$[A] \cdot \{C\} = \{b\} \quad Eq. 5$$

where [A] is the coefficient matrix, {c} is the vector of unknown concentration values and {b} is a vector containing all the known quantities.

Just like for groundwater flow calculations, specification of initial and boundary condition is required in order to solve the system of equations. Three general types of boundary condition are considered in the transport model:

- concentration known along a boundary (Dirichlet Condition)
- concentration gradient known across a boundary (Neumann Condition)
- a combination of both (Cauchy Condition)

A Dirichlet boundary in a transport model acts as a source providing solute mass to the model domain or as a sink taking solute mass out of the model domain. A special case of a Neumann condition is a no -dispersive-mass-flux boundary. For the Cauchy boundary condition, both the concentration value and the concentration gradient are specified.

6.2 Setup of MODFLOW (numerical model)

For constructing and running a numerical groundwater model, a variety of different tasks have to be done. The main steps include:

- collection and evaluation of available data and information
- conceptualization of this hydrogeologic setting in a model framework
- setup and running of the model
- model calibration: modification of model parameters until a good match between measured and calculated values is achieved
- either re-evaluation and collection of new data or model verification: to check that the model is a valid representation of the hydrogeologic system by using the calibrated model to simulate a hydrologic response that is known

Once a model is successfully verified, it can be used as a predictive instrument. This means that it will be much easier to forecast the consequences of future scenarios (e.g. changing water tables, pumping rates and schedules) to drinking water supply through RBF wells.

For model setup and calibration in VM, extensive collection of hydrogeological and hydraulic data is necessary:

Aquifer properties:

- hydraulic conductivity: knowledge of soil structure and soil properties for an adequate number of points within the model domain (preferably with a uniform distribution of the points throughout the model domain)
- storage coefficient and specific yield
- horizontal flow barriers

Aquifer geometry:

- Model Grid
- Model perimeter and extent (active and inactive cells)
- Pumping well and observation well locations and attributes
- Top elevations of layers: surveyed locations of an adequate number of points within the model domain
- Bottom elevations of layers: knowledge of soil structure for an adequate number of points within the model domain for determining different stratigraphical units
- Water levels: hydrographical and geometrical data for pumping wells, observation wells, rivers and other surface water bodies

Boundary conditions and fluxes:

- Pumping: pumping schedules and pump test data (if available)

- Surface water interaction: rivers and other surface water bodies
- Recharge
- Groundwater evapotranspiration
- Top, bottom and lateral boundaries

To take account for the model's relationship with surrounding systems the user can assign different boundary conditions. Within VM, boundary conditions are divided into two sections: flow boundary conditions (e.g. constant head, recharge) and transport boundary conditions (e.g. constant concentration, point source).

Minimum requirements for setting up a groundwater-model would include:

- model perimeter and extent (area of interest)
- pumping well and observation well locations
- rivers and other surface water bodies
- water levels: hydrographical and geometrical data for pumping wells, observation wells, rivers and other surface water bodies
- hydraulic conductivity: at least a coarse clue of soil structure and soil properties for a few number of points within the model domain; a more detailed knowledge can be gained through calibration processes

6.3 Modelling with respect to RBF

With respect to riverbank filtration, the following questions had to be answered:

- How to model a river and the subsequent surface water/groundwater interaction?
- How to simulate seepage for different aquifer/aquitard systems?

In VM, a surface water body is modelled via the *River* item from the boundaries menu.

River simulates the surface water/groundwater interaction via a seepage layer separating the surface water body from the groundwater system.

The *River* boundary condition requires the following input data (also see Fig. 20):

- *River Stage*: the free water surface elevation
- *Riverbed Bottom*: the elevation of the bottom of the seepage layer (bedding material)
- *Riverbed Thickness*: thickness of the riverbed (seepage layer)
- *Riverbed kz*: vertical hydraulic conductivity of the riverbed material
- *River Width*

For calculation VM transforms the entered data via a conductance formula:

$$C = K \cdot L \cdot W / M \quad \text{Eq. 6}$$

Where

C.....conductance [L^2/T]

K.....vertical hydraulic conductivity of the riverbed material [L/T]

L.....length of a reach cell [L]

W.....width of the river [L]

M.....thickness of the riverbed [L]

Conductance is a numerical parameter representing the resistance to flow between the surface water body and the groundwater caused by the seepage layer (riverbed). If desired, the *Use default conductance formula* option can be turned off and any value or alternate formula may be entered.

If a *River* boundary condition is assigned to the model, VM simulates the seepage flow only through the riverbed bottom and assumes the riverbanks to be impermeable walls (Fig. 20).

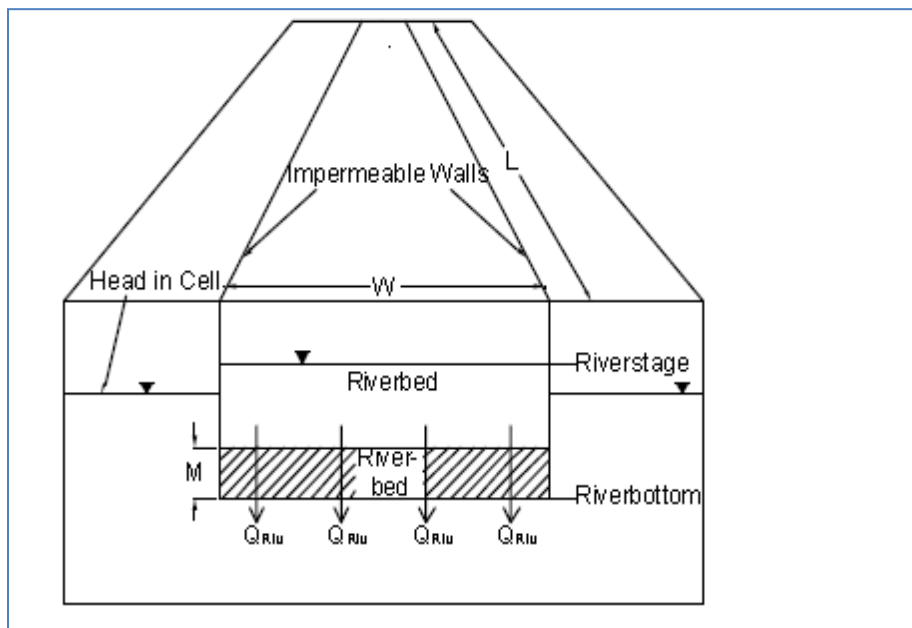


Figure20. Schematic of River boundary (modified from VM, 2003)

In cases where the riverbed width is large compared to the wetted part of the riverbanks and hence the major portion of water percolates through the riverbed this circumstance may be negligible. But in cases of

- a narrow width and/or
- an aquitard situated directly below the riverbed

the following steps may be taken to account for these problems:

- assigning a *Constant Head* boundary condition simulating the river stage instead of a *River* boundary condition
- assigning an additional vertical layer between river and aquifer to simulate the flow interaction through the riverbank (Fig. 21)
- assigning an additional horizontal layer between river and aquitard to simulate the riverbed if necessary defining kz values for the additional layers

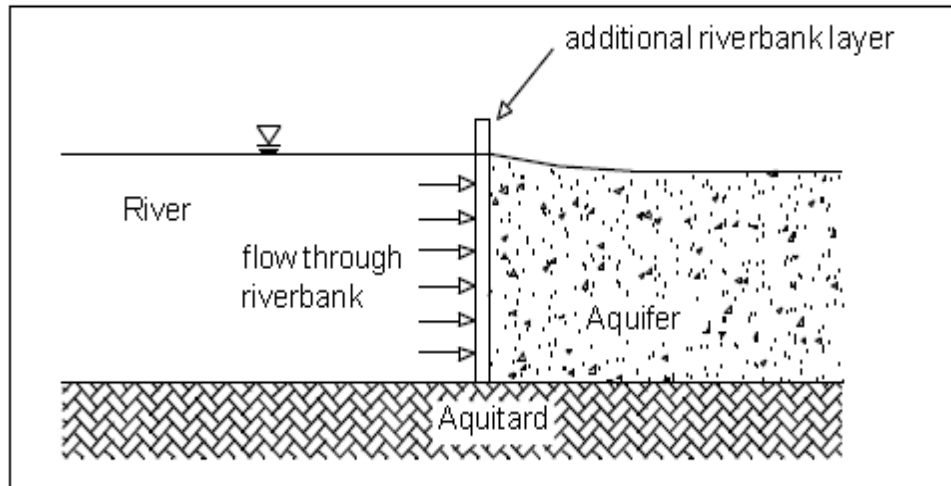


Figure 21. Modelling of an additional riverbank layer

For comparability of the properties of different RBF sites which are presented in chapter 3, it is necessary to compute the portion of water originating from the river which is abstracted by a pumping well. Within VM it is not possible to calculate that values directly. To overcome this problem, the following steps were taken:

To every grid cell containing a *River* boundary condition, a *Point Source* boundary condition was assigned. Then, a concentration observation well was defined at the location of the pumping well. The *Point Source* boundary condition acts as a contaminant source providing solute mass entering or leaving the model domain through a flow boundary condition (*River* in this case) in the form of a known concentration. With this value and the calculated concentration at the concentration observation well it is possible to determine the portion of RBF-water with the following equations:

$$Portion\ RBF = Q_{Riv} / Q_{well} \text{ Eq. 7}$$

with

$$C_{well} = \frac{Q_{GW} \cdot C_{GW} + Q_{Riv} \cdot C_{Riv}}{Q_{GW} + Q_{Riv}} = \frac{Q_{GW} \cdot C_{GW} + Q_{Riv} \cdot C_{Riv}}{Q_{well}} \text{ Eq. 8}$$

and

$C_{GW} = 0$ (no concentration is defined for cells other than *River*-cells) Eq. 9

Eq. 7 can be rewritten as follows

$$Portion\ RBF = \frac{Q_{Riv}}{Q_{well}} = \frac{Q_{well} \cdot C_{well} / C_{Riv}}{C_{well}} = \frac{C_{well}}{C_{Riv}} \quad Eq. 10$$

Where

Q_{Riv} abstracted water flow originating from the river [L³/T]

Q_{GW} abstracted ground water flow [L³/T]

Q_{Well} total water flow abstracted by the pumping well [L³/T]

C_{Riv} concentration assigned to *River*-cells [M/L³]

C_{GW} concentration assigned to cells other than *River*-cells [M/L³]

C_{Well} calculated concentration in the concentration observation well [M/L³]

6.4 MODPATH

MODPATH is a particle tracking post-processing package that was developed to compute three-dimensional flow paths using output from steady state or transient groundwater flow simulations by MODFLOW. MODPATH uses a semi-analytic particle-tracking scheme that allows an analytical expression of the particle's flow to be obtained within each finite-difference grid cell. Particle paths are computed in MODPATH by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source or satisfies some other termination criterion. Input requirements to MODPATH are the output from MODFLOW, porosity and assumed starting point for particles. Data input for MODPATH is a combination of data files and interactive keyboard input. Output from steady state or transient MODFLOW simulations is used in MODPATH to compute paths for imaginary "particles" of water moving through the simulated groundwater system. In addition to computing particle paths, MODPATH keeps track of the time of travel for particles moving through the system. By carefully defining the starting locations of particles, it is possible to perform a wide range of analyses such as delineating capture and recharge areas or drawing flow nets. Output from MODPATH shows the complete paths of all particles and points of origin (starting points) for all particles discharging to a specific feature or destination points

for all particles at a given location. Because of the above attributes, MODPATH can be used to determine the contributing area of a well by calculating the path of all pathlines that end at the well. This can also be used to determine the destination of all particles in a plume by forward tracking.

6.5 Data Collection

In Haridwar the riverbank filtration scheme was constructed in the late 1970's or early 1980's despite the lack of recorded data of long term water level and quality investigations and information on spatial aquifer properties. To describe and conceptualize the study area, data of different categories has been collected. Information about well and aquifer characteristics was collected from published and unpublished sources by the involved project partners (NIH, HTWD & UJS). Groundwater and river water levels were measured, and water quality samples were collected during field visits. In Table the collected information used for the preparation of a groundwater flow model for Haridwar is summarized. Additionally, the locations of wells, gauging stations and borehole-logs are summarized in a map in Appendix , 3.

Table 8. Data used to prepare the groundwater flow model for Haridwar

| Category | Information about |
|--------------------|--|
| Well data | Location, diameter, depth, groundwater levels and discharge, running hours |
| River data | water levels, cross-sections, discharge(Ganga River) |
| Water Quality data | Isotopes, major ions, iron, turbidity, coliforms |
| Borehole-log data | Large-diameter caisson well 18 (Pant Dweep), vertical filter well Bhupatwala, vertical filter well Mayapur |
| GIS data | well, river and borehole-log locations, digital elevation model |
| Literature data | Range for hydraulic conductivity of the riverbed (Ganga River at Bhimgoda Barrage, UGC, NSC), monthly rainfall and temperature |

6.6 Water levels

To develop the groundwater flow model and perform simulations, different categories of data are required. Beside the invariant hydro-geologic and topographic characteristics of the study area, which are required to conceptualize the model, the spatial- and time-variant groundwater and river-water levels are relevant to set the boundary conditions and to evaluate

the model performance. Thus, the groundwater level within each well has been measured weekly during the monsoon season and monthly during non-monsoon season using a water-level tape. To determine the river water levels, five existing gauging stations (Central Water Commission, OSC, Bhimgoda Barrage upstream and downstream, Link Channel and the Dam Kothi barrage on UGC, (see Appendix 2) have been read out in the mentioned time intervals. Additionally the surface-water levels at particular locations, especially downstream of Bhimgoda Barrage and at Pant Dweep Island, have been measured at reference dates using a levelling instrument (auto level and dumpy level).



Plate2.Surface water level measurement and pumping unit of RBF well at Haridwar



Plate 3.Groundwater level measurement in RBF wells



Plate4.RBF well at Haridwar

6.7 MODFLOW Model Development

6.7.1 Model Configuration: Model Domain

In GIS framework using Arcgis pumping wells, river Ganga and its respective canal and channels of Haridwar study area were digitised to the extent of 5000m×5600m in X-Y direction, hence 50 columns and 60 rows defined the study area in model domain of visual modflow, each grid being 100m ×93.33m. Grid is refined by 2 four times to represent the wells, river Ganga and its canals, channels i.e. 12.5m×11.6m for detailed simulation especially in those areas that represent steep hydraulic gradient(i.e. drawdown near wells).To avoid numerical instability the size difference between adjacent cell is not more than factor of 2. The final spatial resolution for horizontal grid ranges from 12.5 to 100m (Fig.23). Borelog data from Pantdweep implies that aquifer is 21 m deep for the entire modelled area. The aquifer comprises of two layers, upper layer consists of coarse sand and gravel up to a stretch of 12 m depth imbibing partially penetrating large diameter bottom entry caisson well and second layer consists of finer material of silty sand to a depth of 21 m below ground surface(Fig 24). To input the two layers, input file consisting wells locations, their surface elevation, elevation of wells bottom, and bottom of 21 m deep aquifer is created. Inverse distance approach of Visual MODFLOW is used to interpolate the elevation between each point.

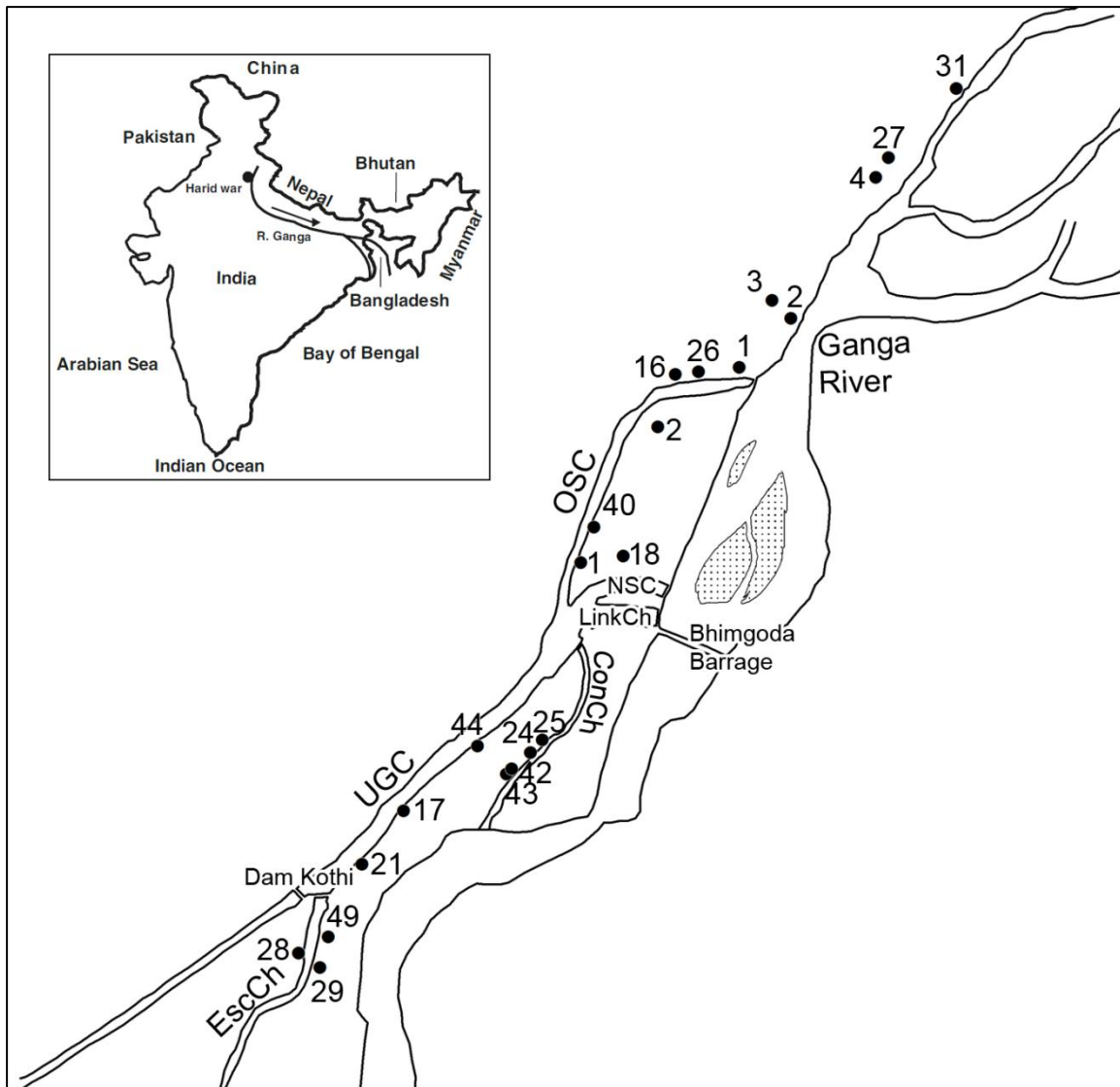


Figure 22. Study area of the riverbank filtration site with 22 production wells in Haridwar, India

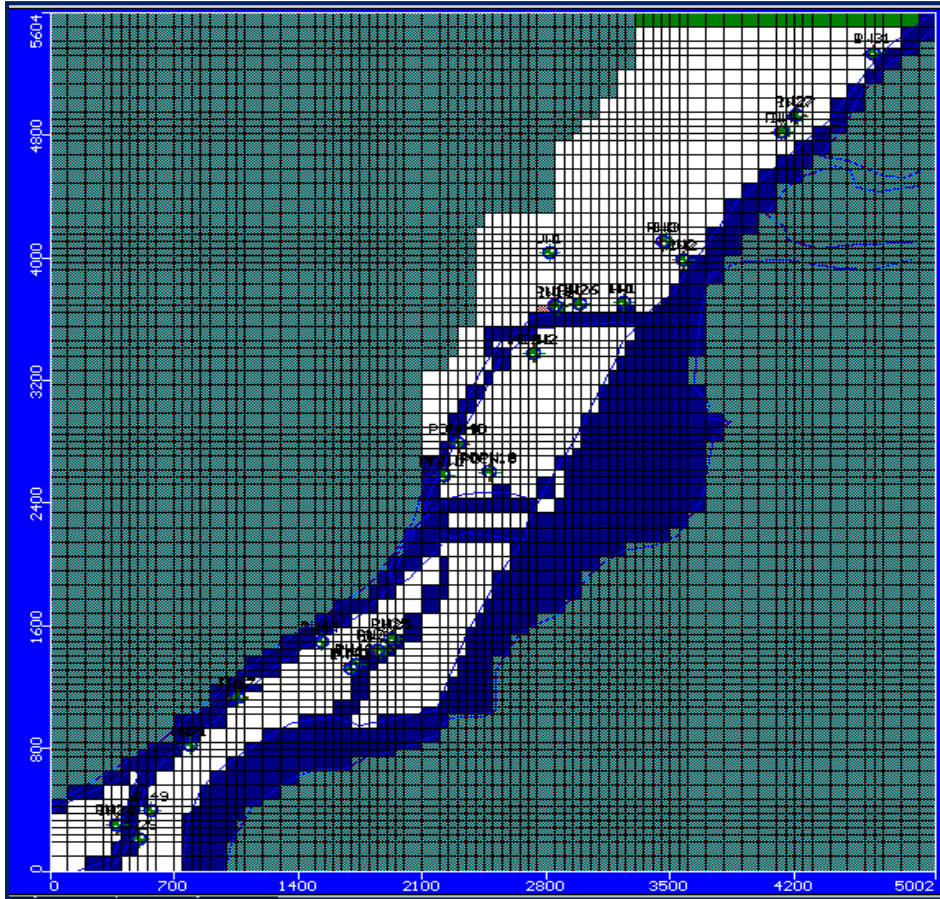


Figure 23. Discretized model domain of Haridwar showing 22 RBF wells and River Ganga

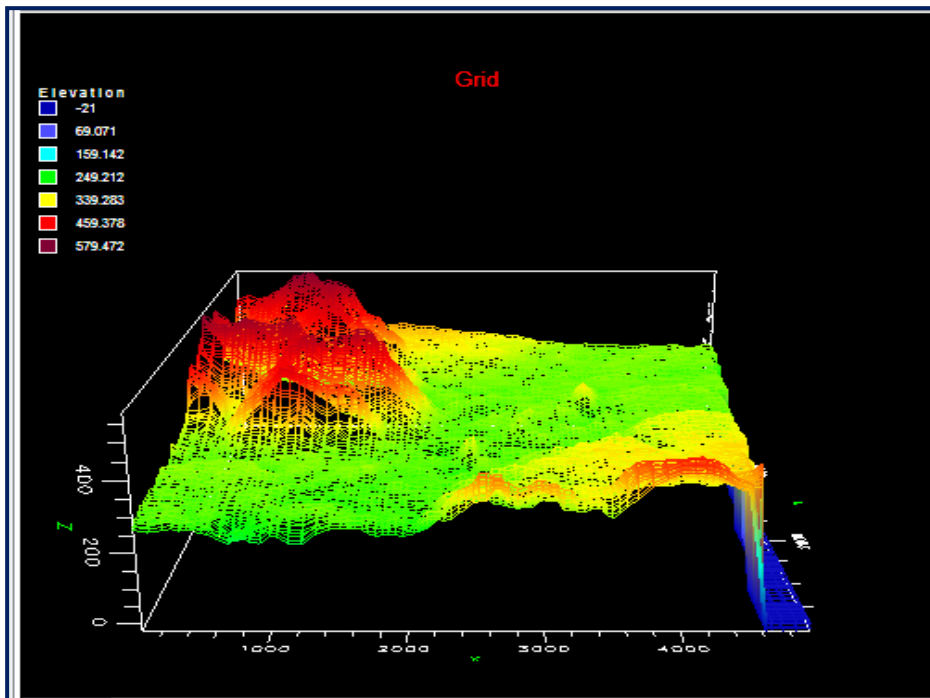
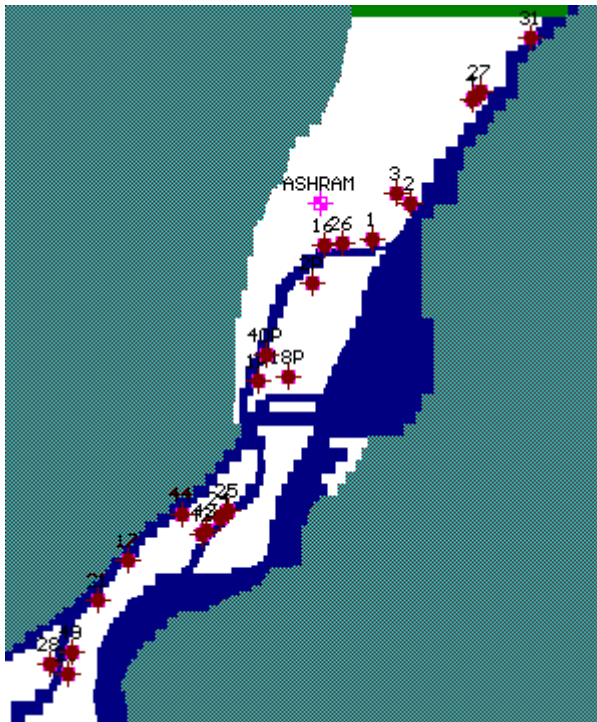


Figure24. DEM (ASTER data) generated for Haridwar study area and interpolated in model domain using inverse distance technique of Visual MODFLOW.



Due to the fact that the area of interest is only the floodplain of Haridwar and to avoid unnecessary computational effort, the mountains in the western part and the cells next to the Ganga River in the eastern part of the model area have been assigned as inactive cells. Figure 25 shows the model domain including pumping wells (dark red points), the observation well Kabir Ashram (pink point), inactive cells (turquoise), general head- (green cells) and river boundaries (dark blue cells).

Figure 25. Conceptualized model domain area of the 22 RBF wells in Haridwar

6.7.2 Model properties and boundary conditions

For groundwater flow modelling purposes information on filter screen depth, pumping rate of each well, aquifer characterization as well as storage of the large diameter well based on hydraulic conductivities of the model layers is necessary. In present scenario the caisson well do not have vertical filter installed in them, rather the water is entering from the bottom of the well. Such well has good storage capacity allowing the Groundwater flow from aquifer to store in well storage and water being extracted to the whole saturated depth of the caisson well. Therefore, the required screen in Visual MODFLOW is defined from the top up to the well bottom. The rated discharge Q_p , the daily duration of operation and the daily abstracted amount Q_{ex} for each well are summarized. The required amount of extracted water Q_{ex} depends upon the daily running hours of the pumps. The duration of operation (in hours) for some wells varies between monsoon and non-monsoon season, as a result of higher surface water levels (in monsoon) and the seasonal variation in demand for water. A higher well yield during monsoon season allows a longer operation of the pumps to cater the increased demand for water (the bathing frequency of the resident of Haridwar usually increases to twice per day during monsoon, compared to once per day during non-monsoon). During the non-monsoon season, the operating hours of some wells are reduced to avoid drying of the wells and due to less demand, especially during the post-monsoon season up to the onset of the hot dry weather season (October to March)(Table 9).

Table 9 Rated discharge, operating hours and the daily discharge of water (Q_{ex}) abstracted during monsoon and non-monsoon season for each RBF well (listed from north to south)

| Well ID | Q_p [L/min] | Monsoon | | Non-Monsoon | |
|---------|---------------|---------------------------|------------------------------|---------------------------|------------------------------|
| | | Duration of operation [h] | Q_{ex} [m ³ /d] | Duration of operation [h] | Q_{ex} [m ³ /d] |
| PW 31 | 2500 | 20 | 3000 | 10 | 1500 |
| PW 27 | 1800 | 20 | 2160 | 14 | 1512 |
| PW 4 | 1600 | 20 | 1920 | 20 | 1920 |
| PW 2 | 1700 | 20 | 2040 | 10 | 1020 |
| PW 3 | 1200 | 20 | 1440 | 20 | 1440 |
| PW 1 | 1500 | 20 | 1800 | 20 | 1800 |
| PW 26 | 1800 | 16 | 1728 | 16 | 1728 |
| PW 16 | 1800 | 12 | 1296 | 12 | 1296 |
| PDPW 2 | 2000 | 10 | 1200 | 10 | 1200 |
| PDPW 40 | 2100 | 22 | 2772 | 22 | 2772 |
| PDPW 18 | 1200 | 10 | 720 | 10 | 720 |
| PDPW 1 | 2000 | 12 | 1440 | 12 | 1440 |
| PW 25 | 1700 | 22 | 2244 | 15 | 1530 |
| PW 24 | 1700 | 23 | 2346 | 15 | 1530 |
| PW 42 | 1800 | 22 | 2376 | 22 | 2376 |
| PW 43 | 1900 | 22 | 2508 | 22 | 2508 |
| PW 44 | 1600 | 24 | 2304 | 24 | 2304 |
| PW 17 | 1800 | 23 | 2484 | 23 | 2484 |
| PW 21 | 2500 | 16 | 2400 | 16 | 2400 |
| PW 49 | 1800 | 23 | 2484 | 23 | 2484 |
| PW 28 | 2300 | 23 | 3174 | 23 | 3174 |
| PW 29 | 2300 | 23 | 3174 | 23 | 3174 |

According to Sandhu et al. (2010), the initial horizontal hydraulic conductivity k_x and k_y of the aquifer was assigned within a range of $1.9 \cdot 10^{-04}$ to $4.7 \cdot 10^{-04}$ m/s. The k -value in Z -direction was set to $2.6 \cdot 10^{-05}$ m/s, while the final hydraulic conductivity in X - and Y -direction was determined during the model calibration (sec. 6.7.3).

To solve the groundwater flow equations, boundary and initial conditions are required. The boundary condition in the north of the study area has been interpolated using the triangulation method for undisturbed groundwater levels and river water levels. Since well no. 31 is located close to the northern boundary of the model, a general head boundary was assigned to account for groundwater influxes instead of the more common used constant head. So the boundary head is not directly influencing the water level of PW 31.

The hydraulic connection between the river Ganga, its canal and the aquifer is represented by the river boundary conditions. To assign river boundary condition, stage of river, riverbed bottom, riverbed thickness and hydraulic conductivity of the riverbed are required. Consequently, the conductance value for each grid cell, which changes due to different cell sizes within the model, is calculated automatically. The river level is assigned at particular points where the stage has been measured. Riverbed elevation and width have been determined using cross-sections constructed from field measurements. Between those points, the required physical dimensions of the river are interpolated automatically by Visual MODFLOW. The hydraulic conductivity of the riverbed is finally set during the calibration. After Sandhu et al. (2010), the k-value of the Old Supply Channel and Ganga River at Bhimgoda Barrage ranges between $0.4 \cdot 10^{-05}$ to $7.3 \cdot 10^{-03}$ m/s and $0.2 \cdot 10^{-06}$ to $9 \cdot 10^{-06}$ m/s, respectively.

6.7.3 Steady-state model calibration and validation

The model is calibrated for steady state conditions. The PEST programme of the model looks for the difference between the models calculated values (determined with the initial values) and the observed field values. PEST runs the model MODFLOW as many times as may be necessary and searches for an optimal parameter set for which the sum of squared deviations (objective function) between model – computed and the experimental observation is reduced to a minimum. In order to optimize the number of iterations, the default values of coefficients were used. Accordingly, head observation wells are required to compare calculated and measured heads. Since the groundwater levels were directly measured in the RBF wells, imaginary observation wells have been assigned for each RBF well in the model. The hand-pump in Kabir Ashram has been used as a monitoring well to measure undisturbed groundwater levels and is also considered within the model (Figure 25, 23; Appendix 2). The calibration has been performed for two different steady state scenarios, using the observed groundwater levels on 23.08.2012 and 11.10.2012, which represent the monsoon and the non-monsoon (post-monsoon) season, respectively (Appendix 6, 9, 10). A flow chart, summarizing the calibration procedure of the groundwater flow model, path lines and portion of extracted bank filtrate from each well is given in Figure 26.

The adjustable modelling parameters are the hydraulic conductivity of the aquifer and the riverbed (sec. 6.7.2). Table 10 summarizes the adjusted hydraulic conductivities after the completed calibration process. In order to optimise the calibration result the aquifer in the northern area of Pant Dweep Island was assigned with a higher hydraulic conductivity as

determined from pumping tests and a previous modelling study (Sandhu et al. 2010). The riverbed material of the Ganga River contains of coarse material (Appendix 5), which results in high k-values of $2.0 \cdot 10^{-04}$ m/s whereas the beds in the reservoir of Bhimgoda Barrage have a high silt content of 40 to 70% (Sandhu et al. 2010) as a result of low surface flow velocities, which results in increased deposition and limits the hydraulic connection with the aquifer to an assumed k-value of $5.0 \cdot 10^{-06}$ m/s. The k-values of the remaining riverbeds (Old Supply-, Link-, Connection- and Escape Channel) are constant over the whole channel-length. The hydraulic conductivity values of the upper and bottom aquifers are varied iteratively so that root mean square (RMS) error could be kept below 10 m.

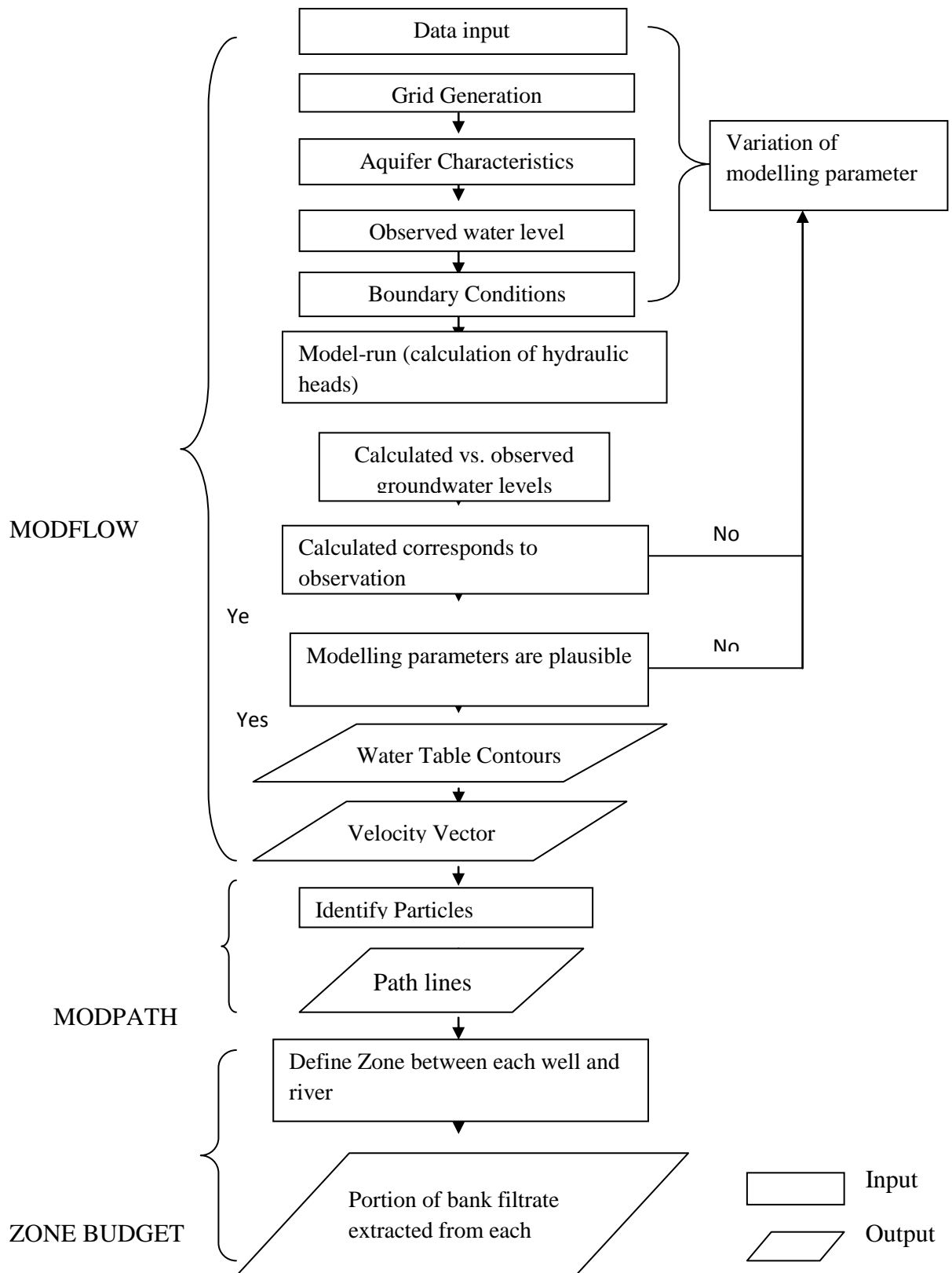


Figure 26. Flow Chart of the methods involved in calibration of the groundwater flow model, path lines and portion of extracted bank filtrate from each well.

Table 10: Calibrated Hydraulic conductivities for the hydrogeological set-up of the model.

| Hydro-geological unit | Calibrated hydraulic conductivity [m/s] |
|-----------------------|---|
| Aquifer | $K_x=1.9 \cdot 10^{-05}$ $K_y=4.7 \cdot 10^{-05}$ $K_z=2.6 \cdot 10^{-05}$ |
| Aquifer (North) | $K_x=K_y=9.0 \cdot 10^{-04}$ $K_z=2.5 \cdot 10^{-05}$ |
| Ganga River | $2.0 \cdot 10^{-04} \dots 5.0 \cdot 10^{-06}$ |
| OSC | $1.0 \cdot 10^{-04}$ |
| NSC, UGC | $1.0 \cdot 10^{-04}$ |
| ConCh | $2.0 \cdot 10^{-04}$ |
| EscCh | $1.0 \cdot 10^{-05}$ |

Table 11: Statistical Evaluation of the calibrated model

| Statistical evaluation | Monsoon | Non-Monsoon |
|------------------------|---------|-------------|
| Residual Max [m] | 5.303 | 5.01 |
| Residual Min [m] | 0.746 | 0.74 |
| Residual Mean [m] | 3.503 | 3.08 |
| Standard error [m] | 0.292 | 0.427 |
| RMS [m] | 3.75 | 3.65 |
| Norm. RMS [%] | 23.4 | 22.45 |
| Correl.-Coeff. [-] | 0.957 | 0.896 |

The calibration has been evaluated by comparing the measured and calculated groundwater levels (Appendix 6). The measured groundwater levels from RBF wells which show maximum drawdown were considered while the pump was in operation during the model calculation. However some of the pumping wells were not showing maximum drawdown due to interruption in pumping operation by power failure and too short pumping times. Therefore for such pumping wells undisturbed groundwater levels has been taken into consideration by interpolating between known surface water levels bounding the aquifer on both sides. Here, the surface water levels around the wells have been measured at particular points, to apply the interpolation method, which is visualized in Figure. The gradient I between the river water levels H_1 and H_2 , with a distance L_1 , is calculated by equation (11). The undisturbed water level of the well H_{well} can be derived by (12), using the gradient I and the distance L between one of the rivers to the RBF well.

$$I = \frac{(H_1 - H_2)}{L_1} \quad (11)$$

$$H_{well} = H_1 - (I \cdot L_2) \quad (12)$$

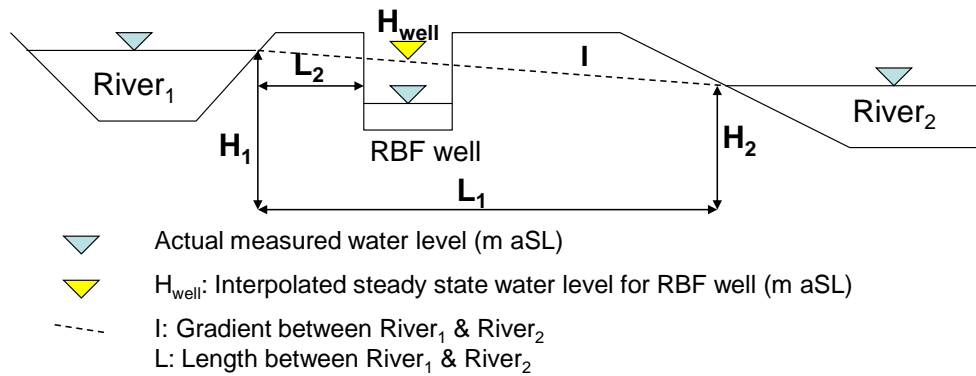


Figure 27. Cross-section schemes to estimate the steady state (undisturbed) groundwater level for an RBF-well using the interpolation method

Source: Report on Groundwater Flow model (Saph Pani)

Table 11 shows the evaluation of the final results for monsoon and post monsoon period. The difference between the calculated and the observed groundwater levels mainly varies within a range of -0.74 to 1.5 m, which was taken as threshold for a good calibration result. This is shown by the residual minimum and average in Table 11 with a value range of 0.746 to 3.5 m. However, it was not possible to fit the simulated and observed water level for each well within this threshold. For some wells, where it was not possible to interpolate the undisturbed groundwater level according to the procedure illustrated in Figure 27 and where the simulated heads were calibrated to the maximum observed drawdown, the difference between calculated and observed heads exceeds the value of ± 3 m. This is emphasized by the residual maximum in Table 11. For those wells with significantly overestimated groundwater levels, the plausibility of the calibration result has been validated by modelling the steady state groundwater level without pumping. Here, each modelled groundwater level has been compared with the corresponding surface elevation level. The result was proven reliable, when the elevation of the modelled groundwater levels is lower than the elevation of the surface level (when the groundwater is not passing out of the aquifer).

In order to analyse flow direction and travel time of extracted water and proportion of bank filtrate as well as groundwater a comparison between the wettest and driest periods of the year is of particular interest. Therefore, a steady state modelling according to the water levels of the pre-monsoon season (08.10.2013) was realized with the calibrated model. This model output validates the parameterised model by comparing the observed and calculated heads. Here, again interpolated steady state groundwater levels were used as well as measured draw-downs within the wells. The result is similar to the calibration under monsoon and post-monsoon conditions as indicated by the statistical parameters in Table 11. Considering the

mentioned problems in detecting the maximum draw-downs of the well and the missing undisturbed observation wells, the quality criteria in Table 12 emphasize an adequate validation output (Appendix 11). As a consequence, the following model study is realized for the monsoon and pre-monsoon period under steady state conditions.

Table 12 Validation result for the measured and interpolated water levels in pre-monsoon (08.01.2013)

| Residual Max [m] | Residual Min [m] | Residual Mean [m] | Standard error [m] | RMS [m] | Norm. RMS [%] | Correl.- Coeff. [-] |
|------------------|------------------|-------------------|--------------------|---------|---------------|---------------------|
| 5.23 | -0.06 | 3.4 | 0.343 | 3.77 | 22 | 0.932 |

Statistical Analysis

Mean error

The mean error (ME) is defined by the equation

$$\text{Mean Error} = \frac{1}{n} \sum_{i=1}^n (X_{\text{calc}} - X_{\text{obs}}) i \quad \text{Eq.13}$$

Where X_{obs} is observed value and X_{calc} is the calculated value for a data series.

It is to be noted that there may be cases where over-calculated and under calculated values will negate each other and produce a mean error value close to zero. This can lead to false interpretation of model calibration.

Mean absolute

The mean absolute error is the same as the mean error except the absolute values of each calculated and observed head difference, are summed. In other words,

$$\text{Mean Absolute Error} = 1/n \sum_{i=1}^n |X_{\text{calc}} - X_{\text{obs}}| i \quad \text{Eq.14}$$

This measures the magnitude of the calibration residuals and therefore provides a better indication of calibration than the mean error.

Standard error of the estimate

The standard error of the estimate is expressed by the equation,

$$S.E.E = \sqrt{\frac{\sum_{i=1}^n (X_{\text{calc}} - X_{\text{obs}})^2 - (\sum_{i=1}^n (X_{\text{calc}} - X_{\text{obs}} i))^2}{N-1}} \quad \text{Eq.15}$$

The error of the estimate is also commonly referred to as the calibration residual.

Root mean squared

The root mean squared error (RMS) is defined by the equation,

$$RMS = 1/n \sqrt{\sum_{i=1}^n (X_{calc} - X_{obs})^2} \quad \text{Eq.16}$$

Normalized RMS

The normalized root mean squared error is the RMS divided by the maximum difference in the observed values. In other words

$$\text{Normalized RMS} = \frac{RMS}{(X_{obs})_{max} - (X_{calc})_{max}} \quad \text{Eq.17}$$

If there is one data value, then this denominator will be 100.

6.7.4 Particle tracking and zone budgeting

MODPATH and ZONEBUDGET subroutines were used for the determination of flow direction, travel times and composition of extracted water from each RBF wells. Flow-path and travel times of the extracted water were determined with the backward tracking approach in MODPATH. Here, imaginary particles extracted by each RBF-well were tracked backwards to their place of origin in relation to time. To calculate the portion of bank filtrate within the extracted water, a zone between each well and the adjacent river was defined. For each zone a sub-regional water budget was calculated for one pump-operating day using ZONEBUDGET.

6.1.5 Result and Discussion

Modelled data

6.1.5(a) Particle tracking

Using the backward tracking tool in MODPATH enables to visualize the flow-path and travel times of the extracted water for each well. PW27, PW4, PW3, PW1 in the Bhupatwala region are extracting groundwater as shown by the path lines in the maps. For PW31, PW1, PW26 and PW16 most of the extracting particles are originating from groundwater. Comparing the particle- flow under premonsoon & monsoon condition some difference in particle source and their required time to enter the wells are noticeable due to the difference in pumping rates. Most wells are operating with higher (maximum) pumping rates during monsoon, resulting in particles of a greater perimeter entering the RBF wells in same or shorter span of time compared to pre-monsoon as indicated by the flow path lines of PW3, PW16, PW26, PW24, PW25 and PW42. PW 18, located in Pantdweep Island, the maximal pumping rates are similar for both seasons. However, the origin of the particle flow differs due to changed surface water

levels. During monsoon, most of the particles originate from Bhimgoda Barrage as a reason of a high gradient between maximum drawdown and Ganga water level. In the dry pre-monsoon season, the water level of Ganga River and Bhimgoda Barrage decreases while the water level of the channels is controlled to remain nearly constant. In the pre-monsoon scenario, a higher portion of particles from OSC and NSC is flowing towards PW 18 as a result of changed gradients.

Shortest travel-times can be observed for PW44, PW17 and PW21 where bank filtrate from UGC reaches the well within 30 days. Regarding the other wells; it depends upon the source how long a particle needs to enter the well. In the Bhupatwala area PW 1, PW 26 and PW 16 extract bank filtrate from OSC within 30 days as well as PW 40 and PW 1 located on Pantdweep Island. However, the bank filtrate from OSC and NSC extracted by PDPW 2 and PW 18 respectively, has a residence time of more than 120 but less than 365 days. Downstream, PW 24, PW 25, PW 42 and PW 43 receive riverbank filtrate from Connection Channel in less than 30 days and from UGC in around 150-300 days of operation. The residence time of RBF from Escape Channel is also less than 30 days before it is extracted by PW 28, PW 29 and PW 49. Additionally, PW 28 is receiving bank filtrate from UGC in around 365days. Considering steady state monsoon conditions, bank filtrate from Ganga River would be extracted by PW 29 within around 365 days of operation. A detailed summary of the maximum needed travel times of bank filtrate for each well is given in Figure 28.

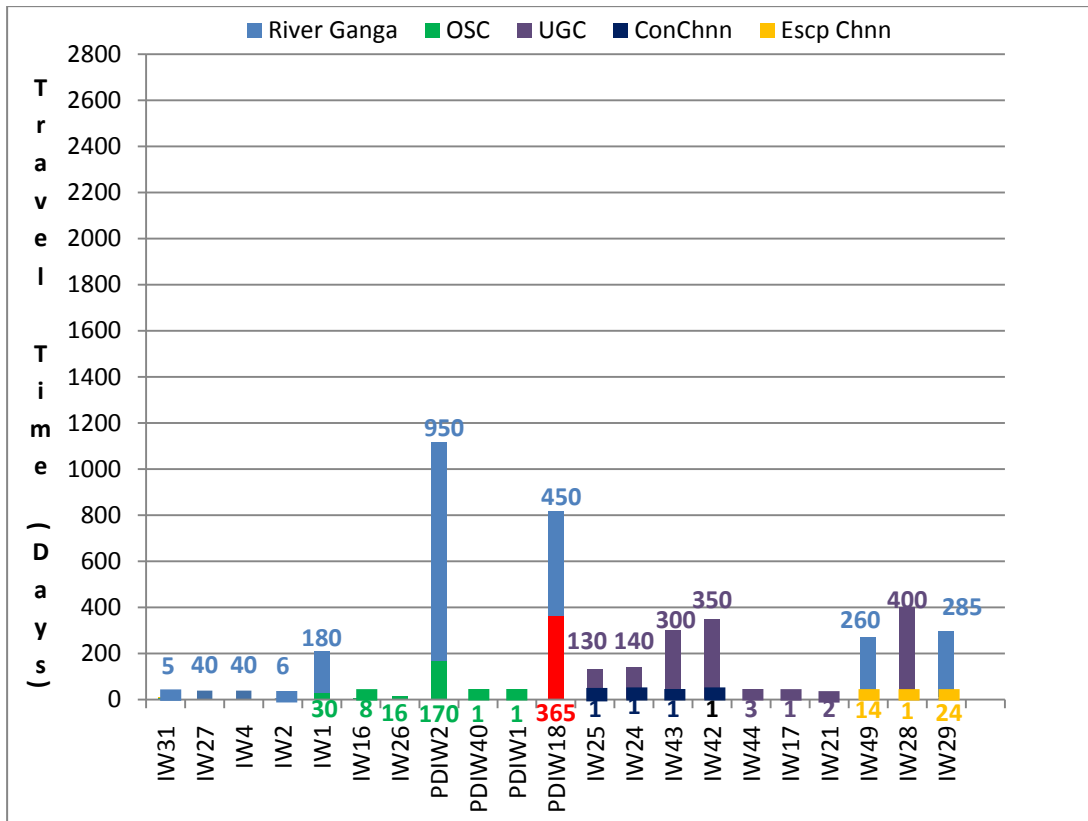


Figure 28. Summary of the modeled maximum travel times from each source to each well

River water is channelized through OSC, NSC, UGC, Con Channel and Escape Channel hence source is river water and its respective travel time to each well.

6.1.5(b) Zone budgeting

Figure 28 shows the sources of bank filtrate and the needed travel times through the sub surface passage before entering the corresponding well. Zone budgeting enables to calculate the proportion of the extracted water shown in Figure 29 for pre-monsoon (upper) and monsoon (lower) condition. PW27, PW4, PW3 are predominantly groundwater extraction wells. PW31, PW2, PW1, PW26 and PW16 are receiving high proportion of groundwater. Off all the mentioned pumping wells PW2 is receiving highest amount of BF (74%) from river Ganga with maximum travel time of six days. PW1 located at the beginning of old supply channel is extracting 30%(BF) and 20%(BF) during monsoon and pre monsoon season respectively, whereas rest amount is groundwater. In Pantdweep areas, pumping well are bounded by OSC & river Ganga hence these wells are extracting only river water. Here, the total amount of BF is from Ganga River 10% more under monsoon conditions. The amount of BF from OSC (river water) extracted by PW16 and PW26 is higher during the monsoon season with 41.03% and 30.55% as compared to 12.3 and 25.7% in pre-monsoon season

respectively. The proportion of bank filtrate of Ganga River during monsoon season and pre-monsoon for PW40 is 50.4% and 56.18% whereas for PW2 it is 56% and 70.35% respectively.(Appendix 9,10,11)

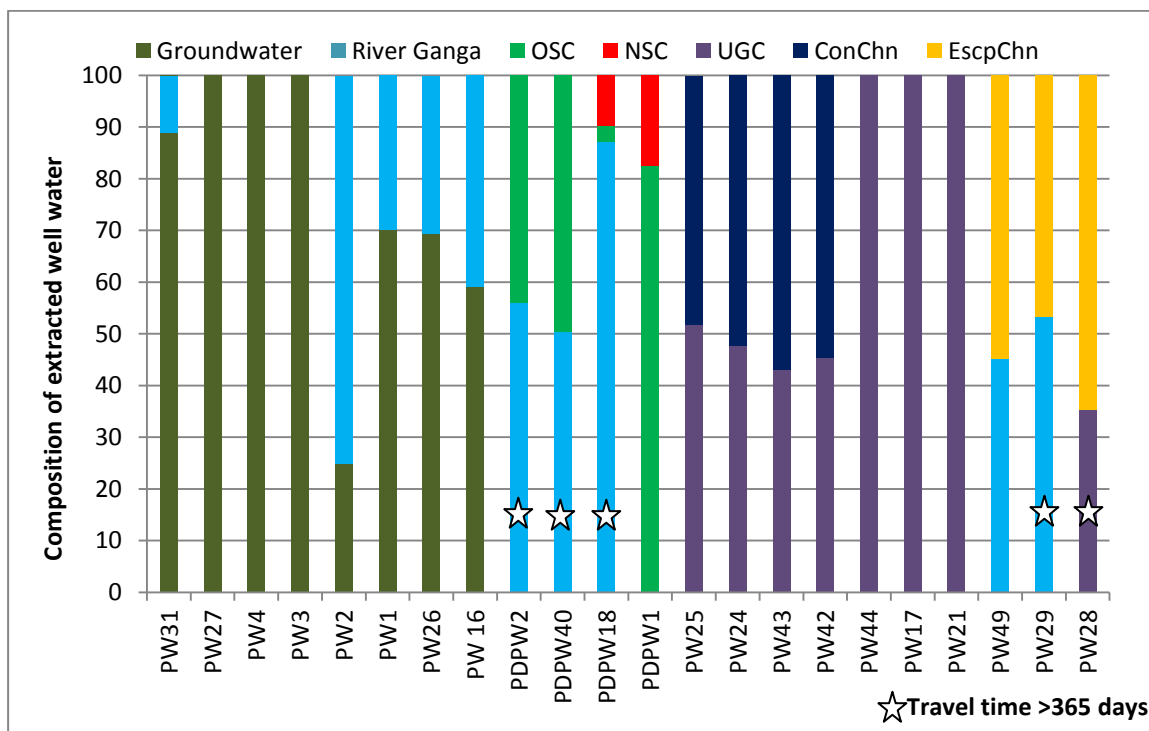
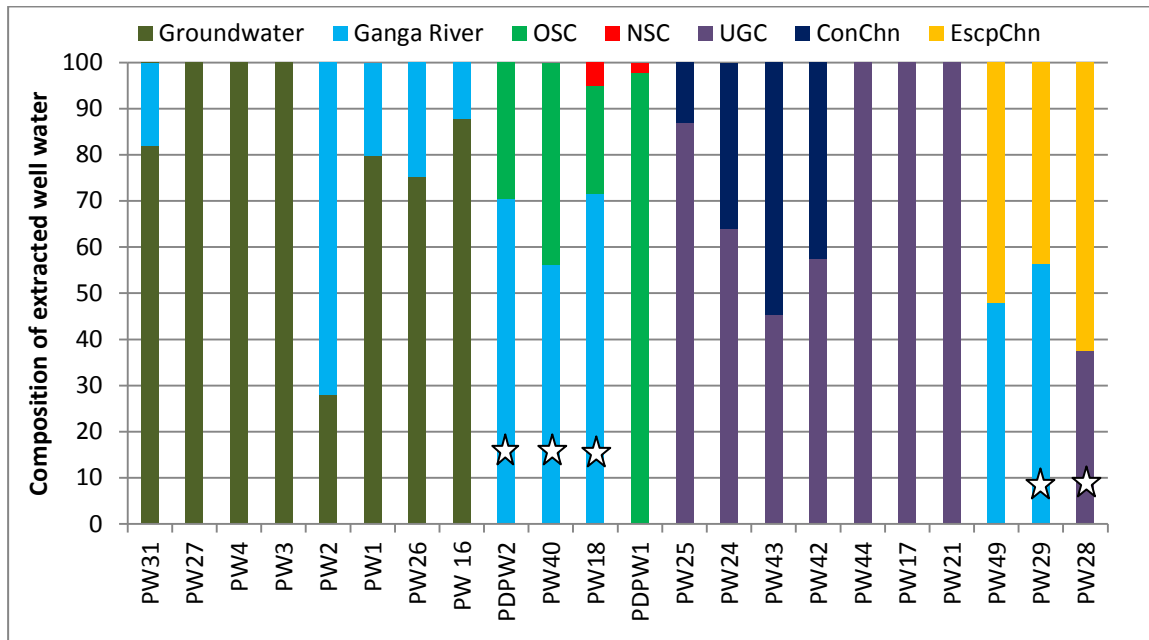


Figure 29.Proportion of the extracted water for each well under pre-monsoon (upper) and monsoon (lower) conditions

The proportion of bank filtrate of Ganga river are higher during monsoon season with 56% for PW2 and 50.4% PW40.During pre-monsoon condition the amount of water received from OSC amounts 29.64% for PW2 and 43.81% for PW40 respectively.PW18 mainly extracts

water from Ganga river with residence times more than 365 days. It also receives small proportion of river water from NSC which range from 9.85% and 5.03% in monsoon and pre-monsoon season respectively. The different portion of river bank filtrate for both model scenario are a result of changed surface water levels and thus, changed gradients leading to the flow of sub surface water.

The RBF wells located close to UGC (PW 44, PW 17 and PW 21) are receiving 100 % bank filtrate from the channel. Under pre-monsoon conditions when the water level of the Connection Channel is low, PW 24, PW 25, PW 42 and PW 43 are extracting mainly bank filtrate from UGC (64, 87, 57 and 45 %). With increased water levels during monsoon (in ConChn), the portion of bank filtrate extracted from the Connection Channel increases to 52, 48, 55 and 57 % for PW 24, PW 25, PW 42 and PW 43, respectively. PW28 which is located between UGC and Escape channel receives bank filtrate from both surface water. Hence the river water extracts from UGC is (3%) more under pre-monsoon condition with an amount of 38%. Under monsoon condition both PW 49 and PW 29 receives also a portion of 45% and 53% from Ganga River.

6.8 Correlation of model output with Isotope result

The isotopes within the samples have been analysed to gain an insight of the actual mass transport of the water. This approach gives a rough estimation whether the extracted well-water is mainly containing groundwater or riverbank filtrate. The isotopic signature is used to evaluate the model performance regarding the flow patterns of the extracted water.

Modelled output result shows that PW27, PW4, PW3 are predominantly groundwater extraction wells (Fig 29) and PW31, PW2, PW1, PW26 and PW16 (Fig 29) are receiving high proportion of groundwater. When compared with Isotope analyses result shows, that PW16, PW26, PW3, PW31, PW27, PW4 and OW1 have limited interaction with the river Ganga / UGC (Fig 13,14) hence mainly containing groundwater, thus validating the modelled output and vice-a- versa.

7. Summary and Conclusion

On the basis of Water Quality analyses it was ascertained that sub surface passage of surface water renders improved water quality as the river water percolates through the underlying soil. Largely, all physicochemical parameters except Turbidity of the extracted water, which constitutes mixing water of riverbank filtrate and groundwater, showed concentration much

below the acceptable limit prescribed in IS: 10500 (BIS, 2012) for both non-monsoon and monsoon periods. The turbidity in the extracted water although removed about 98% during the monsoon and 76% during the non-monsoon period in comparison to the river/canal water, it's concentration in some of the production wells were higher than the acceptable limit of 1 NTU. The count of biological parameters, viz. Total coliform and Faecal coli form, although found to be removed considerably in the extracted water, the count still remained above the acceptable limit, for both non-monsoon and monsoon periods. The percent removal of coliform varied between 78% and 83% for Total coliform and between 65% and 85% for Faecal coliform in comparison to the quality of groundwater for both the non-monsoon and the monsoon periods. The variability of concentration of physiochemical parameters in the extracted water between the non-monsoon and the monsoon periods, by and large, was found to be very small, whereas, the variability of biological parameters was found to be very high with the monsoon period showing higher value than the non-monsoon period. As per the physical process of bank filtration, during pumping, the induced bank filtrate from river water after mixing with the groundwater gets withdrawn, which leads to modification of quality of bank filtrate water by the quality of groundwater. Thus, the quality of extracted water depends on mixing proportion of groundwater with the bank filtrate water. Isotope analyses results ensured that, production wells in Bhupatwala area (PW31, PW27, PW4, PW3, PW16, PW26, and OW1) are mainly extracting high proportion of groundwater. The modeling results confirmed that probably PW 27, PW 4 and PW 3 are just groundwater extraction wells. Production wells located within the Pantdweep Island, Old Supply channel, Upper Ganga canal and Escape Channel are receiving bank filtrate within 365 days except PW28 and PW29. The RBF wells, PW21, PW17 and PW44 are extracting water from only one source i.e. Upper Ganga canal whereas PW 2, PW 40, PW 18, PW 1, PW 24, PW 25, PW 42, PW 43 and PW 29 are receiving a mix from River Ganga through several surface water channels. The travel-times of riverbank filtrate depend on the extraction rates of the wells and the surface water levels as shown by the model results compared for pre-monsoon and monsoon conditions.

Due to the shortcomings of observation wells and gauges to measure the (undisturbed) ground- and surface water levels extensively, only two steady state scenarios were considered to analyze the performance of the riverbank filtration facility in Haridwar. The model has been calibrated and validated using interpolated undisturbed groundwater levels and maximum draw-downs. However, for some wells reliable reference data was missing regarding groundwater levels as well as information about the operating hours and the

discharges of the pumps. Additionally, the calculation of boundary and initial conditions was only possible for a few reference dates. Due to these uncertainties, the model was only applied for two steady state conditions, representing the dry pre-monsoon and the wet monsoon season. This approach enabled to analyze a wide range of possible residence times and to track back the origin of riverbank filtrate extracted by the corresponding wells.

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Appendix: 1 Isotope analysis result summarised

| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 1 | G-1 | Pumping Well | 30-May-12 | -10.76 | -70.15 |
| 2 | G-3 | Pumping Well | 30-May-12 | -9.92 | -65.41 |
| 3 | G-4 | Pumping Well | 30-May-12 | -8.73 | -57.13 |
| 4 | G-5 | Pumping Well | 30-May-12 | -9.31 | -59.51 |
| 5 | G-6 | Pumping Well | 30-May-12 | -9.91 | -63.79 |
| 6 | G-7 | Pumping Well | 30-May-12 | -8.35 | -54.34 |
| 7 | G-8 | Pumping Well | 30-May-12 | -7.46 | -49.12 |
| 8 | G-9 | Pumping Well | 30-May-12 | -10.65 | -70.18 |
| 9 | G-10 | Pumping Well | 30-May-12 | -10.59 | -68.39 |
| 10 | G-11 | Pumping Well | 30-May-12 | -10.67 | -67.25 |
| 11 | G-12 | Pumping Well | 30-May-12 | -10.58 | -65.60 |
| 12 | G-13 | Pumping Well | 30-May-12 | -10.41 | -68.53 |
| 13 | G-14 | Pumping Well | 30-May-12 | -10.60 | -68.55 |
| 14 | G-15 | Pumping Well | N.A. | N.A. | N.A. |
| 15 | G-16 | Pumping Well | N.A. | N.A. | N.A. |
| 16 | G-17 | Pumping Well | N.A. | N.A. | N.A. |
| 17 | G-18 | Pumping Well | N.A. | N.A. | N.A. |
| 18 | G-19 | Pumping Well | N.A. | N.A. | N.A. |
| 19 | G-20 | Pumping Well | N.A. | N.A. | N.A. |
| 20 | G-21 | Pumping Well | N.A. | N.A. | N.A. |
| 21 | G-22 | Pumping Well | N.A. | N.A. | N.A. |
| 22 | G-23 | Pumping Well | N.A. | N.A. | N.A. |
| 23 | G-24 | Pumping Well | N.A. | N.A. | N.A. |
| 24 | G-25 | Pumping Well | N.A. | N.A. | N.A. |
| 25 | OW-1 | Open Well | N.A. | N.A. | N.A. |
| 26 | R-1 | Ganga River | 30-May-12 | -10.18 | -63.62 |
| 27 | R-5 | Ganga River | 30-May-12 | -10.19 | -64.75 |
| 28 | R-6 | Ganga River | 30-May-12 | -10.37 | -64.74 |
| 1 | G-1 | Pumping Well | 18-Jun-12 | -10.66 | -70.54 |
| 2 | G-3 | Pumping Well | 18-Jun-12 | -10.24 | -67.38 |
| 3 | G-4 | Pumping Well | 18-Jun-12 | -9.02 | -59.09 |
| 4 | G-5 | Pumping Well | 18-Jun-12 | -9.63 | -62.91 |
| 5 | G-6 | Pumping Well | 18-Jun-12 | -10.35 | -67.99 |
| 6 | G-7 | Pumping Well | 18-Jun-12 | -8.30 | -55.52 |
| 7 | G-8 | Pumping Well | 18-Jun-12 | -7.69 | -50.02 |
| 8 | G-9 | Pumping Well | 18-Jun-12 | -10.73 | -70.13 |
| 9 | G-10 | Pumping Well | 18-Jun-12 | -10.57 | -69.39 |
| 10 | G-11 | Pumping Well | 18-Jun-12 | -10.57 | -66.48 |
| 11 | G-12 | Pumping Well | 18-Jun-12 | -10.55 | -67.18 |
| 12 | G-13 | Pumping Well | 18-Jun-12 | -10.42 | -67.46 |
| 13 | G-14 | Pumping Well | 18-Jun-12 | -10.51 | -68.40 |
| 14 | G-15 | Pumping Well | 18-Jun-12 | -7.58 | -50.68 |
| 15 | G-16 | Pumping Well | 18-Jun-12 | -8.03 | -52.39 |
| 16 | G-17 | Pumping Well | 18-Jun-12 | -10.19 | -65.22 |
| 17 | G-18 | Pumping Well | 18-Jun-12 | -10.13 | -66.26 |
| 18 | G-19 | Pumping Well | 18-Jun-12 | -10.45 | -68.14 |
| 19 | G-20 | Pumping Well | 18-Jun-12 | -10.38 | -67.66 |
| 20 | G-21 | Pumping Well | 18-Jun-12 | -10.62 | -68.54 |
| 21 | G-22 | Pumping Well | 18-Jun-12 | -10.60 | -68.07 |

| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 22 | G-23 | Pumping Well | 18-Jun-12 | -10.59 | -67.36 |
| 23 | G-24 | Pumping Well | 30-Jun-12 | -8.36 | -57.21 |
| 24 | G-25 | Pumping Well | 30-Jun-12 | -8.90 | -59.51 |
| 25 | OW-1 | Open Well | N.A. | N.A. | N.A. |
| 26 | R-1 | Ganga River | 18-Jun-12 | -10.18 | -63.62 |
| 27 | R-5 | Ganga River | 18-Jun-12 | -10.19 | -64.75 |
| 28 | R-6 | Ganga River | 18-Jun-12 | -10.37 | -64.74 |
| 1 | G-1 | Pumping Well | N.A. | N.A. | N.A. |
| 2 | G-3 | Pumping Well | 07-Aug-12 | -10.26 | -66.80 |
| 3 | G-4 | Pumping Well | 07-Aug-12 | -8.76 | -55.85 |
| 4 | G-5 | Pumping Well | 07-Aug-12 | -9.86 | -64.62 |
| 5 | G-6 | Pumping Well | 07-Aug-12 | -9.18 | -61.62 |
| 6 | G-7 | Pumping Well | N.A. | N.A. | N.A. |
| 7 | G-8 | Pumping Well | 07-Aug-12 | -7.52 | -51.20 |
| 8 | G-9 | Pumping Well | 07-Aug-12 | -10.50 | -69.48 |
| 9 | G-10 | Pumping Well | 07-Aug-12 | -10.46 | -68.86 |
| 10 | G-11 | Pumping Well | 07-Aug-12 | -10.48 | -69.21 |
| 11 | G-12 | Pumping Well | 07-Aug-12 | -10.59 | -70.48 |
| 12 | G-13 | Pumping Well | 07-Aug-12 | -10.70 | -70.91 |
| 13 | G-14 | Pumping Well | 07-Aug-12 | -10.39 | -68.90 |
| 14 | G-15 | Pumping Well | 07-Aug-12 | -8.04 | -53.04 |
| 15 | G-16 | Pumping Well | 07-Aug-12 | -8.21 | -53.02 |
| 16 | G-17 | Pumping Well | 07-Aug-12 | -9.66 | -64.98 |
| 17 | G-18 | Pumping Well | N.A. | N.A. | N.A. |
| 18 | G-19 | Pumping Well | 07-Aug-12 | -10.44 | -69.92 |
| 19 | G-20 | Pumping Well | 07-Aug-12 | -10.49 | -69.27 |
| 20 | G-21 | Pumping Well | 07-Aug-12 | -10.92 | -71.64 |
| 21 | G-22 | Pumping Well | 07-Aug-12 | -10.90 | -71.34 |
| 22 | G-23 | Pumping Well | 07-Aug-12 | -10.17 | -66.96 |
| 23 | G-24 | Pumping Well | 08-Aug-12 | -8.36 | -57.21 |
| 24 | G-25 | Pumping Well | 09-Aug-12 | -8.90 | -59.51 |
| 25 | OW-1 | Open Well | 07-Aug-12 | -7.77 | -52.93 |
| 26 | R-1 | Ganga River | N.A. | N.A. | N.A. |
| 27 | R-5 | Ganga River | 07-Aug-12 | -11.07 | -73.80 |
| 28 | R-6 | Ganga River | N.A. | N.A. | N.A. |
| 1 | G-1 | Pumping Well | 06-Sep-12 | -9.26 | -64.15 |
| 2 | G-3 | Pumping Well | 06-Sep-12 | -9.77 | -67.69 |
| 3 | G-4 | Pumping Well | 06-Sep-12 | -8.41 | -58.22 |
| 4 | G-5 | Pumping Well | 06-Sep-12 | -8.87 | -59.25 |
| 5 | G-6 | Pumping Well | 06-Sep-12 | -8.96 | -61.40 |
| 6 | G-7 | Pumping Well | N.A. | N.A. | N.A. |
| 7 | G-8 | Pumping Well | 06-Sep-12 | -7.29 | -50.92 |
| 8 | G-9 | Pumping Well | 06-Sep-12 | -10.44 | -70.05 |
| 9 | G-10 | Pumping Well | 06-Sep-12 | -10.81 | -70.92 |
| 10 | G-11 | Pumping Well | 06-Sep-12 | -10.96 | -73.08 |
| 11 | G-12 | Pumping Well | 06-Sep-12 | -11.09 | -76.34 |
| 12 | G-13 | Pumping Well | 06-Sep-12 | -10.97 | -73.54 |
| 13 | G-14 | Pumping Well | 06-Sep-12 | -10.27 | -70.87 |
| 14 | G-15 | Pumping Well | 06-Sep-12 | -7.14 | -51.22 |
| 15 | G-16 | Pumping Well | N.A. | N.A. | N.A. |
| 16 | G-17 | Pumping Well | 06-Sep-12 | -9.47 | -64.03 |
| 17 | G-18 | Pumping Well | 06-Sep-12 | -9.99 | -67.75 |

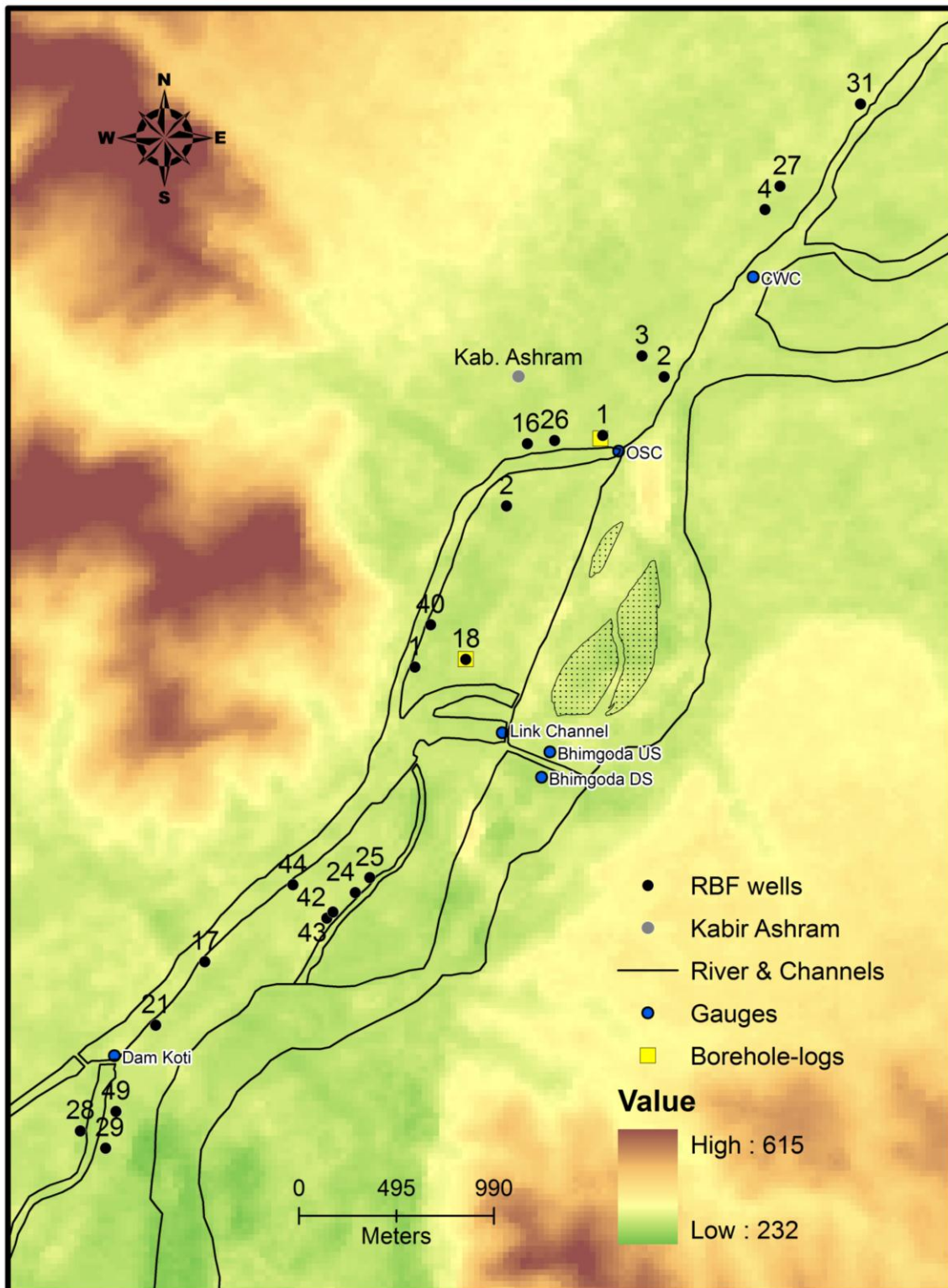
| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 18 | G-19 | Pumping Well | 06-Sep-12 | -10.23 | -70.93 |
| 19 | G-20 | Pumping Well | 06-Sep-12 | -9.97 | -68.26 |
| 20 | G-21 | Pumping Well | 06-Sep-12 | -10.22 | -71.85 |
| 21 | G-22 | Pumping Well | 06-Sep-12 | -10.31 | -72.12 |
| 22 | G-23 | Pumping Well | 06-Sep-12 | -10.51 | -69.31 |
| 23 | G-24 | Pumping Well | N.A. | N.A. | N.A. |
| 24 | G-25 | Pumping Well | 06-Sep-12 | -8.34 | -56.04 |
| 25 | OW-1 | Open Well | 06-Sep-12 | -7.52 | -55.41 |
| 26 | R-1 | Ganga River | 06-Sep-12 | -11.42 | -79.01 |
| 27 | R-5 | Ganga River | 06-Sep-12 | -11.68 | -80.10 |
| 28 | R-6 | Ganga River | 06-Sep-12 | -11.54 | -80.15 |
| 1 | G-1 | Pumping Well | 25-Sep-12 | -9.83 | -67.86 |
| 2 | G-3 | Pumping Well | 25-Sep-12 | -10.04 | -68.35 |
| 3 | G-4 | Pumping Well | 25-Sep-12 | -8.32 | -56.84 |
| 4 | G-5 | Pumping Well | 25-Sep-12 | -8.47 | -58.76 |
| 5 | G-6 | Pumping Well | 25-Sep-12 | -10.03 | -66.24 |
| 6 | G-7 | Pumping Well | 25-Sep-12 | -9.11 | -56.83 |
| 7 | G-8 | Pumping Well | 25-Sep-12 | -7.21 | -50.93 |
| 8 | G-9 | Pumping Well | 25-Sep-12 | -10.39 | -69.82 |
| 9 | G-10 | Pumping Well | 25-Sep-12 | -10.36 | -71.59 |
| 10 | G-11 | Pumping Well | 25-Sep-12 | -10.90 | -73.51 |
| 11 | G-12 | Pumping Well | 25-Sep-12 | -11.34 | -77.33 |
| 12 | G-13 | Pumping Well | 25-Sep-12 | -11.04 | -74.79 |
| 13 | G-14 | Pumping Well | 25-Sep-12 | -10.73 | -71.93 |
| 14 | G-15 | Pumping Well | 25-Sep-12 | -7.81 | -51.51 |
| 15 | G-16 | Pumping Well | 25-Sep-12 | -7.73 | -51.87 |
| 16 | G-17 | Pumping Well | 25-Sep-12 | -9.46 | -62.59 |
| 17 | G-18 | Pumping Well | 25-Sep-12 | -9.31 | -63.23 |
| 18 | G-19 | Pumping Well | 25-Sep-12 | -10.55 | -70.54 |
| 19 | G-20 | Pumping Well | 25-Sep-12 | -10.35 | -68.45 |
| 20 | G-21 | Pumping Well | 25-Sep-12 | -10.35 | -69.73 |
| 21 | G-22 | Pumping Well | 25-Sep-12 | -10.04 | -69.11 |
| 22 | G-23 | Pumping Well | 25-Sep-12 | -10.92 | -72.99 |
| 23 | G-24 | Pumping Well | 25-Sep-12 | -8.86 | -59.02 |
| 24 | G-25 | Pumping Well | 25-Sep-12 | -8.72 | -56.67 |
| 25 | OW-1 | Open Well | 25-Sep-12 | -7.98 | -55.94 |
| 26 | R-1 | Ganga River | 25-Sep-12 | -11.21 | -76.56 |
| 27 | R-5 | Ganga River | 25-Sep-12 | -11.23 | -76.02 |
| 28 | R-6 | Ganga River | 25-Sep-12 | -11.13 | -75.66 |
| 1 | G-1 | Pumping Well | 11-Oct-12 | -10.11 | -69.23 |
| 2 | G-3 | Pumping Well | 11-Oct-12 | -9.90 | -68.45 |
| 3 | G-4 | Pumping Well | 11-Oct-12 | -8.47 | -58.04 |
| 4 | G-5 | Pumping Well | 11-Oct-12 | -8.91 | -60.94 |
| 5 | G-6 | Pumping Well | 11-Oct-12 | -10.23 | -69.20 |
| 6 | G-7 | Pumping Well | 11-Oct-12 | -7.86 | -55.55 |
| 7 | G-8 | Pumping Well | 11-Oct-12 | -7.49 | -50.53 |
| 8 | G-9 | Pumping Well | 11-Oct-12 | -10.68 | -71.62 |
| 9 | G-10 | Pumping Well | 11-Oct-12 | -10.98 | -75.11 |
| 10 | G-11 | Pumping Well | 11-Oct-12 | -11.15 | -75.84 |
| 11 | G-12 | Pumping Well | 11-Oct-12 | -11.00 | -75.32 |
| 12 | G-13 | Pumping Well | 11-Oct-12 | -10.76 | -73.60 |
| 13 | G-14 | Pumping Well | 11-Oct-12 | -11.02 | -74.14 |

| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 14 | G-15 | Pumping Well | 11-Oct-12 | -7.55 | -52.77 |
| 15 | G-16 | Pumping Well | 11-Oct-12 | -7.65 | -52.95 |
| 16 | G-17 | Pumping Well | 11-Oct-12 | -9.25 | -63.55 |
| 17 | G-18 | Pumping Well | 11-Oct-12 | -9.74 | -65.60 |
| 18 | G-19 | Pumping Well | 11-Oct-12 | -10.58 | -72.09 |
| 19 | G-20 | Pumping Well | 11-Oct-12 | -10.41 | -71.15 |
| 20 | G-21 | Pumping Well | 11-Oct-12 | -10.70 | -71.72 |
| 21 | G-22 | Pumping Well | 11-Oct-12 | -10.59 | -71.20 |
| 22 | G-23 | Pumping Well | 11-Oct-12 | -10.98 | -75.35 |
| 23 | G-24 | Pumping Well | 11-Oct-12 | -8.69 | -58.93 |
| 24 | G-25 | Pumping Well | 11-Oct-12 | -8.62 | -57.63 |
| 25 | OW-1 | Open Well | 11-Oct-12 | -7.88 | -56.44 |
| 26 | R-1 | Ganga River | 11-Oct-12 | -10.74 | -73.61 |
| 27 | R-5 | Ganga River | 11-Oct-12 | -10.92 | -74.39 |
| 28 | R-6 | Ganga River | 11-Oct-12 | -10.94 | -74.50 |
| 1 | G-1 | Pumping Well | 01-Nov-12 | -10.46 | -70.38 |
| 2 | G-3 | Pumping Well | 01-Nov-12 | -10.16 | -68.02 |
| 3 | G-4 | Pumping Well | 01-Nov-12 | -8.17 | -55.80 |
| 4 | G-5 | Pumping Well | 01-Nov-12 | -8.42 | -57.35 |
| 5 | G-6 | Pumping Well | 01-Nov-12 | -9.47 | -66.39 |
| 6 | G-7 | Pumping Well | 01-Nov-12 | -7.53 | -55.31 |
| 7 | G-8 | Pumping Well | 01-Nov-12 | -7.46 | -51.11 |
| 8 | G-9 | Pumping Well | 01-Nov-12 | -10.73 | -73.35 |
| 9 | G-10 | Pumping Well | 01-Nov-12 | -10.82 | -74.22 |
| 10 | G-11 | Pumping Well | 01-Nov-12 | -10.59 | -73.76 |
| 11 | G-12 | Pumping Well | 01-Nov-12 | -11.20 | -75.11 |
| 12 | G-13 | Pumping Well | 01-Nov-12 | -11.06 | -73.99 |
| 13 | G-14 | Pumping Well | 01-Nov-12 | -10.95 | -72.56 |
| 14 | G-15 | Pumping Well | 01-Nov-12 | -7.96 | -54.06 |
| 15 | G-16 | Pumping Well | 01-Nov-12 | -7.72 | -53.59 |
| 16 | G-17 | Pumping Well | 01-Nov-12 | -9.06 | -62.69 |
| 17 | G-18 | Pumping Well | 01-Nov-12 | -8.93 | -63.39 |
| 18 | G-19 | Pumping Well | 01-Nov-12 | -10.70 | -71.61 |
| 19 | G-20 | Pumping Well | 01-Nov-12 | -10.77 | -72.62 |
| 20 | G-21 | Pumping Well | 01-Nov-12 | -10.47 | -71.08 |
| 21 | G-22 | Pumping Well | 01-Nov-12 | -10.65 | -71.87 |
| 22 | G-23 | Pumping Well | 01-Nov-12 | -10.91 | -74.34 |
| 23 | G-24 | Pumping Well | N.A. | N.A. | N.A. |
| 24 | G-25 | Pumping Well | N.A. | N.A. | N.A. |
| 25 | OW-1 | Open Well | 01-Nov-12 | -7.55 | -54.58 |
| 26 | R-1 | Ganga River | N.A. | N.A. | N.A. |
| 27 | R-5 | Ganga River | N.A. | N.A. | N.A. |
| 28 | R-6 | Ganga River | 01-Nov-12 | -10.42 | -71.74 |
| 1 | G-1 | Pumping Well | 06-Dec-12 | -10.15 | -70.22 |
| 2 | G-3 | Pumping Well | 06-Dec-12 | -9.80 | -67.52 |
| 3 | G-4 | Pumping Well | 06-Dec-12 | -8.08 | -56.06 |
| 4 | G-5 | Pumping Well | 06-Dec-12 | -8.24 | -57.20 |
| 5 | G-6 | Pumping Well | 06-Dec-12 | -9.71 | -66.88 |
| 6 | G-7 | Pumping Well | 06-Dec-12 | -7.80 | -54.21 |
| 7 | G-8 | Pumping Well | 06-Dec-12 | -7.12 | -49.60 |
| 8 | G-9 | Pumping Well | 06-Dec-12 | -10.70 | -72.99 |
| 9 | G-10 | Pumping Well | 06-Dec-12 | -10.71 | -73.40 |

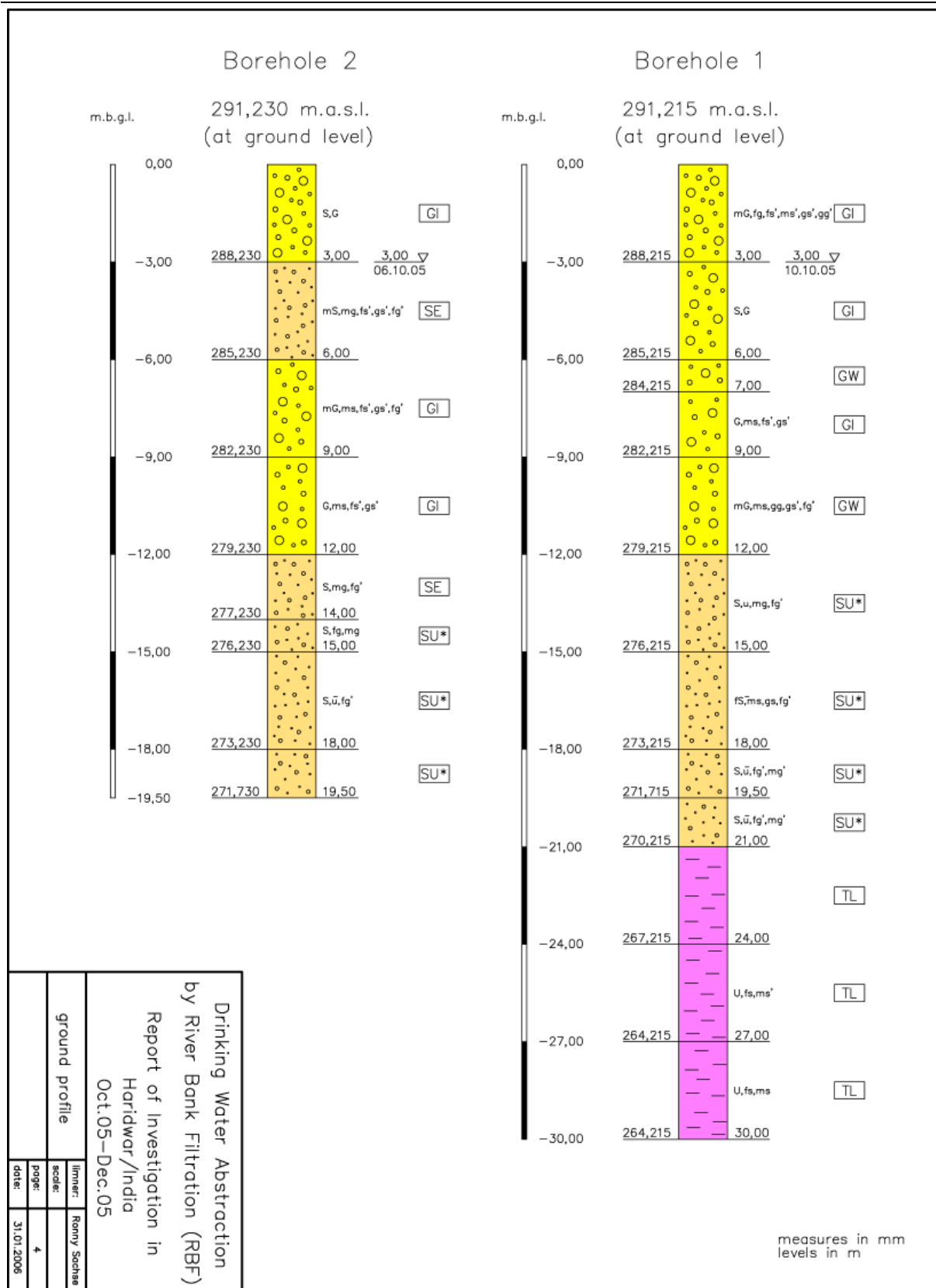
| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 10 | G-11 | Pumping Well | 06-Dec-12 | -10.61 | -72.25 |
| 11 | G-12 | Pumping Well | 06-Dec-12 | -10.67 | -73.45 |
| 12 | G-13 | Pumping Well | 06-Dec-12 | -10.62 | -72.58 |
| 13 | G-14 | Pumping Well | 06-Dec-12 | -10.56 | -71.48 |
| 14 | G-15 | Pumping Well | 06-Dec-12 | -7.64 | -53.16 |
| 15 | G-16 | Pumping Well | 06-Dec-12 | -7.80 | -53.41 |
| 16 | G-17 | Pumping Well | 06-Dec-12 | -9.32 | -63.49 |
| 17 | G-18 | Pumping Well | 06-Dec-12 | -8.81 | -60.67 |
| 18 | G-19 | Pumping Well | 06-Dec-12 | -10.31 | -71.31 |
| 19 | G-20 | Pumping Well | 06-Dec-12 | -10.60 | -73.56 |
| 20 | G-21 | Pumping Well | 06-Dec-12 | -10.81 | -73.39 |
| 21 | G-22 | Pumping Well | 06-Dec-12 | -10.66 | -72.93 |
| 22 | G-23 | Pumping Well | 06-Dec-12 | -10.75 | -72.91 |
| 23 | G-24 | Pumping Well | 06-Dec-12 | -8.98 | -60.44 |
| 24 | G-25 | Pumping Well | 06-Dec-12 | -8.34 | -57.18 |
| 25 | OW-1 | Open Well | 06-Dec-12 | -8.06 | -55.57 |
| 26 | R-1 | Ganga River | 06-Dec-12 | -10.47 | -72.01 |
| 27 | R-5 | Ganga River | 06-Dec-12 | -10.75 | -73.65 |
| 28 | R-6 | Ganga River | 06-Dec-12 | -10.65 | -73.33 |
| 1 | G-1 | Pumping Well | 08-Jan-13 | -10.17 | -70.73 |
| 2 | G-3 | Pumping Well | 08-Jan-13 | -9.73 | -67.50 |
| 3 | G-4 | Pumping Well | 08-Jan-13 | -8.30 | -57.39 |
| 4 | G-5 | Pumping Well | 08-Jan-13 | -8.53 | -58.91 |
| 5 | G-6 | Pumping Well | 08-Jan-13 | -10.20 | -69.33 |
| 6 | G-7 | Pumping Well | 08-Jan-13 | -7.93 | -55.20 |
| 7 | G-8 | Pumping Well | 08-Jan-13 | -7.23 | -50.26 |
| 8 | G-9 | Pumping Well | 08-Jan-13 | -10.64 | -72.76 |
| 9 | G-10 | Pumping Well | 08-Jan-13 | -10.81 | -72.50 |
| 10 | G-11 | Pumping Well | 08-Jan-13 | -10.75 | -72.21 |
| 11 | G-12 | Pumping Well | 08-Jan-13 | -10.69 | -73.30 |
| 12 | G-13 | Pumping Well | 08-Jan-13 | -10.65 | -72.28 |
| 13 | G-14 | Pumping Well | 08-Jan-13 | -10.71 | -72.59 |
| 14 | G-15 | Pumping Well | 08-Jan-13 | -7.66 | -52.87 |
| 15 | G-16 | Pumping Well | 08-Jan-13 | -7.92 | -54.02 |
| 16 | G-17 | Pumping Well | 08-Jan-13 | -9.68 | -65.58 |
| 17 | G-18 | Pumping Well | 08-Jan-13 | -9.37 | -64.10 |
| 18 | G-19 | Pumping Well | 08-Jan-13 | -10.45 | -71.57 |
| 19 | G-20 | Pumping Well | 08-Jan-13 | -10.72 | -73.86 |
| 20 | G-21 | Pumping Well | 08-Jan-13 | -10.89 | -73.31 |
| 21 | G-22 | Pumping Well | 08-Jan-13 | -10.81 | -73.45 |
| 22 | G-23 | Pumping Well | 08-Jan-13 | -10.79 | -73.06 |
| 23 | G-24 | Pumping Well | 08-Jan-13 | -9.19 | -61.72 |
| 24 | G-25 | Pumping Well | 08-Jan-13 | -8.61 | -57.95 |
| 25 | OW-1 | Open Well | 08-Jan-13 | -8.10 | -55.78 |
| 26 | R-1 | Ganga River | 08-Jan-13 | -10.63 | -72.00 |
| 27 | R-5 | Ganga River | 08-Jan-13 | -10.82 | -72.74 |
| 28 | R-6 | Ganga River | 08-Jan-13 | -10.81 | -73.37 |
| 1 | G-1 | Pumping Well | 13-Feb-13 | -10.42 | N.A. |
| 2 | G-3 | Pumping Well | 13-Feb-13 | -9.98 | N.A. |
| 3 | G-4 | Pumping Well | 13-Feb-13 | N.A. | N.A. |
| 4 | G-5 | Pumping Well | 13-Feb-13 | -8.79 | N.A. |
| 5 | G-6 | Pumping Well | 13-Feb-13 | -10.20 | N.A. |

| S.No. | Sample ID | Source | Date of Sample | $\delta^{18}\text{O}$ | δD |
|-------|-----------|--------------|----------------|-----------------------|------------------|
| 6 | G-7 | Pumping Well | 13-Feb-13 | -8.34 | N.A. |
| 7 | G-8 | Pumping Well | 13-Feb-13 | -7.37 | N.A. |
| 8 | G-9 | Pumping Well | 13-Feb-13 | -10.58 | N.A. |
| 9 | G-10 | Pumping Well | 13-Feb-13 | -10.63 | N.A. |
| 10 | G-11 | Pumping Well | 13-Feb-13 | -10.61 | N.A. |
| 11 | G-12 | Pumping Well | 13-Feb-13 | -10.65 | N.A. |
| 12 | G-13 | Pumping Well | 13-Feb-13 | -10.30 | N.A. |
| 13 | G-14 | Pumping Well | 13-Feb-13 | -10.73 | N.A. |
| 14 | G-15 | Pumping Well | 13-Feb-13 | -7.64 | N.A. |
| 15 | G-16 | Pumping Well | 13-Feb-13 | -7.84 | N.A. |
| 16 | G-17 | Pumping Well | 13-Feb-13 | -9.73 | N.A. |
| 17 | G-18 | Pumping Well | 13-Feb-13 | -9.60 | N.A. |
| 18 | G-19 | Pumping Well | 13-Feb-13 | -10.41 | N.A. |
| 19 | G-20 | Pumping Well | 13-Feb-13 | -10.69 | N.A. |
| 20 | G-21 | Pumping Well | 13-Feb-13 | -10.62 | N.A. |
| 21 | G-22 | Pumping Well | 13-Feb-13 | -10.64 | N.A. |
| 22 | G-23 | Pumping Well | 13-Feb-13 | -10.71 | N.A. |
| 23 | G-24 | Pumping Well | 13-Feb-13 | -9.26 | N.A. |
| 24 | G-25 | Pumping Well | 13-Feb-13 | -8.38 | N.A. |
| 25 | OW-1 | Open Well | 13-Feb-13 | -7.90 | N.A. |
| 26 | R-1 | Ganga River | 13-Feb-13 | -10.01 | N.A. |
| 27 | R-5 | Ganga River | 13-Feb-13 | -10.35 | N.A. |
| 28 | R-6 | Ganga River | 13-Feb-13 | -10.32 | N.A. |

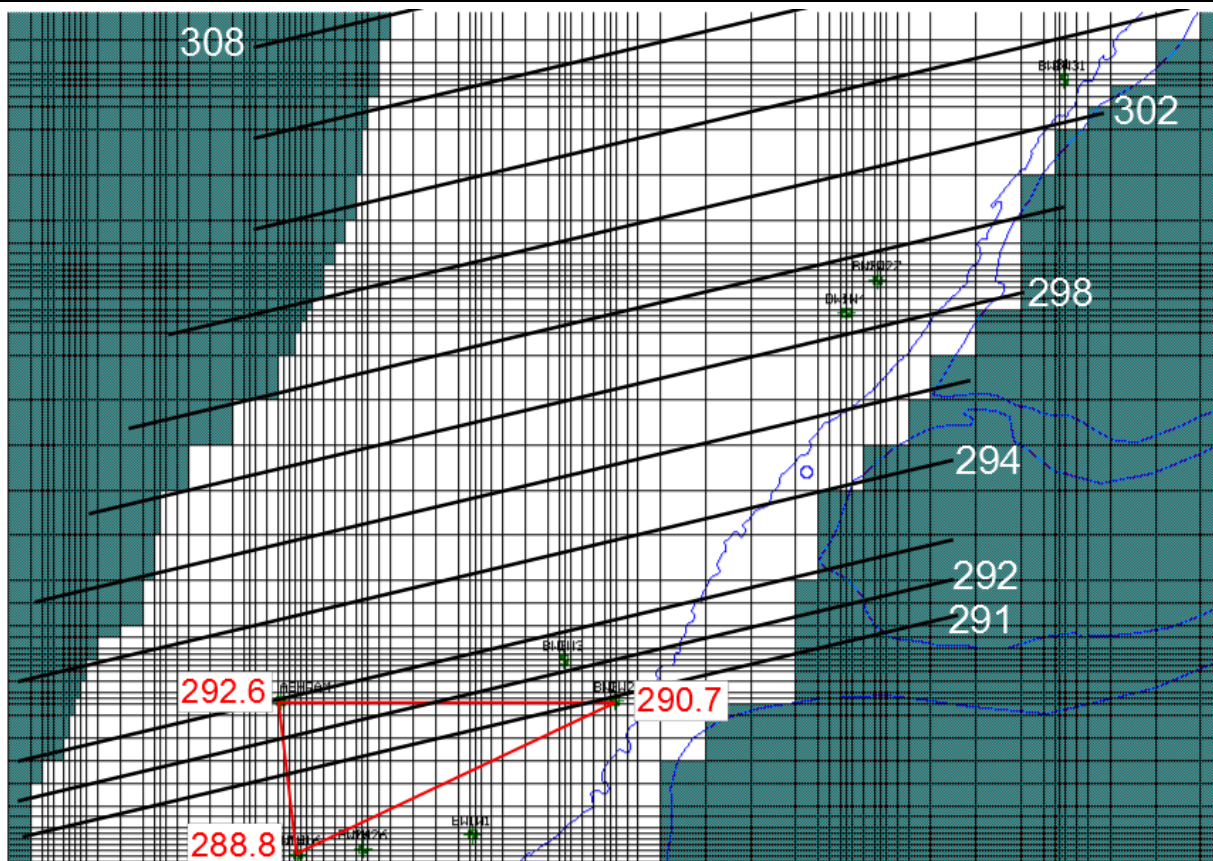
Appendix 2 GIS-Map of the study area including the RBF wells, gauging stations and borehole-log locations



Appendix 3 Borehole profiles of Monitoring Well 1 and 2 located at IW18, Pant Dweep, Haridwar [Sachse 2005]



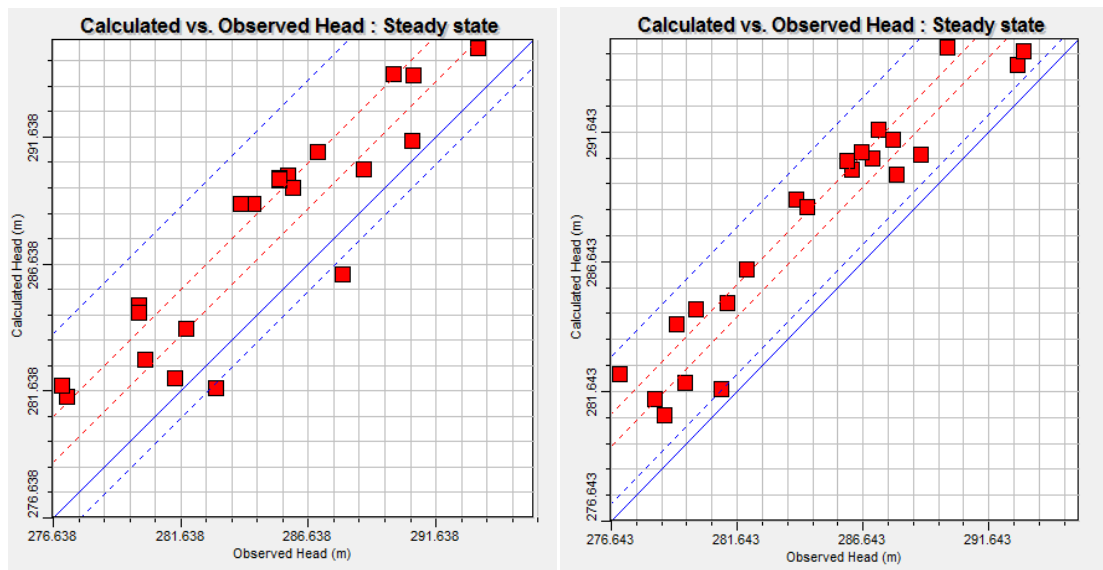
Appendix 4 Triangulation method to estimate the northern boundary condition of the model



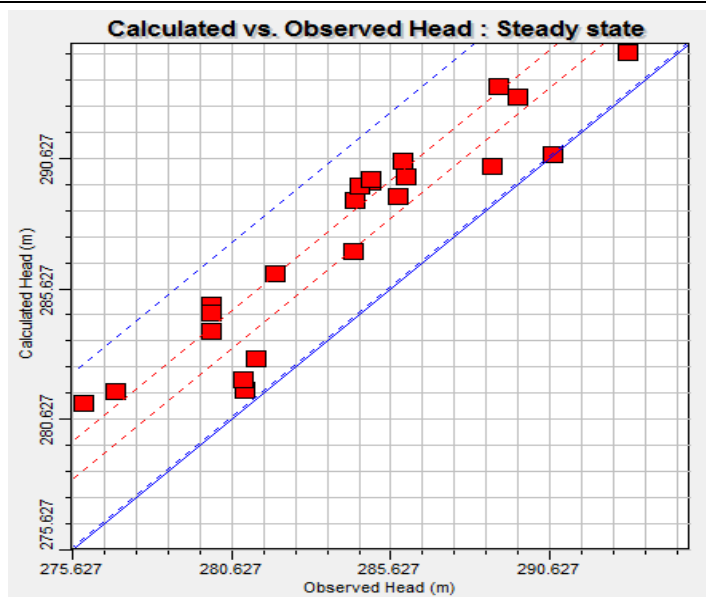
Appendix 5 Riverbed material of Ganga River



Appendix 6 Calibration result for water-levels measured at post-monsoon: 10.10.2013 (left) and monsoon: 23.08.2012 (right) during steady state modelling



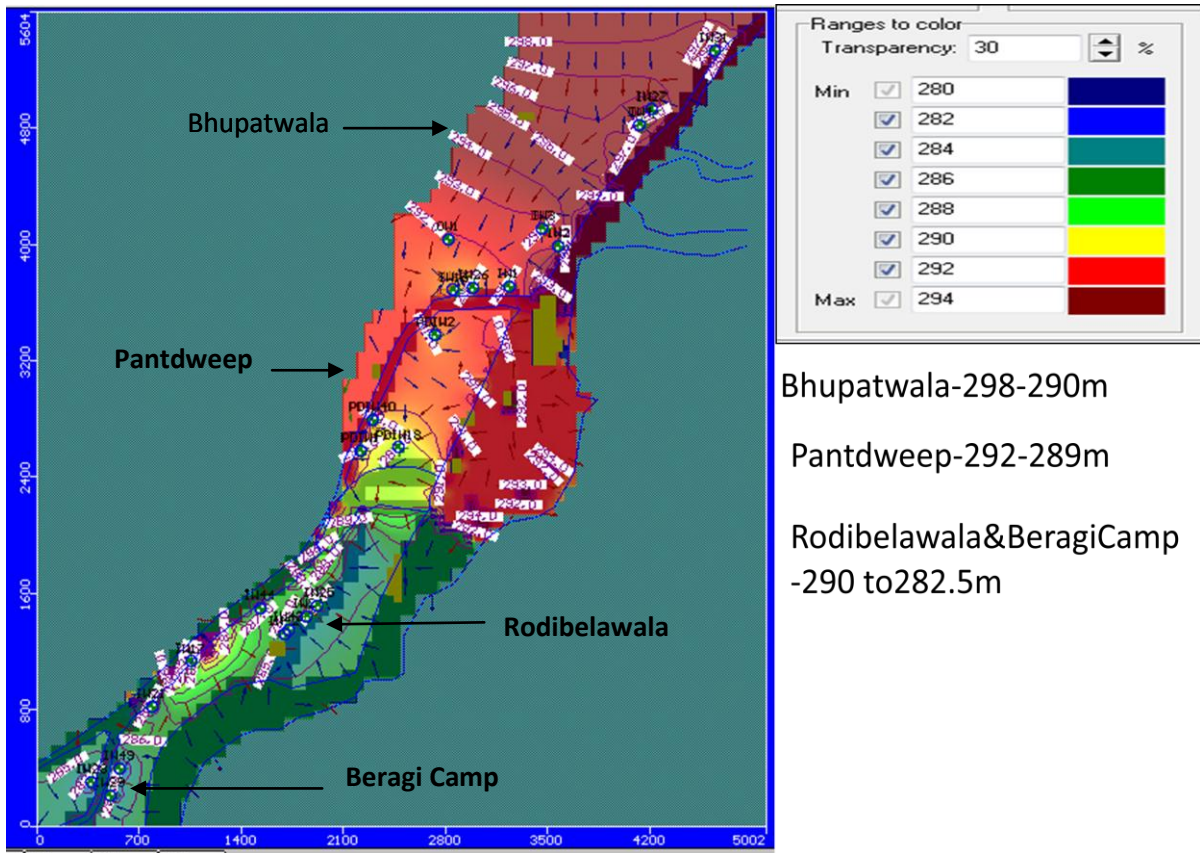
Appendix 7 Validation result for water levels measured at pre-monsoon (08.01.2013) during steady state modelling



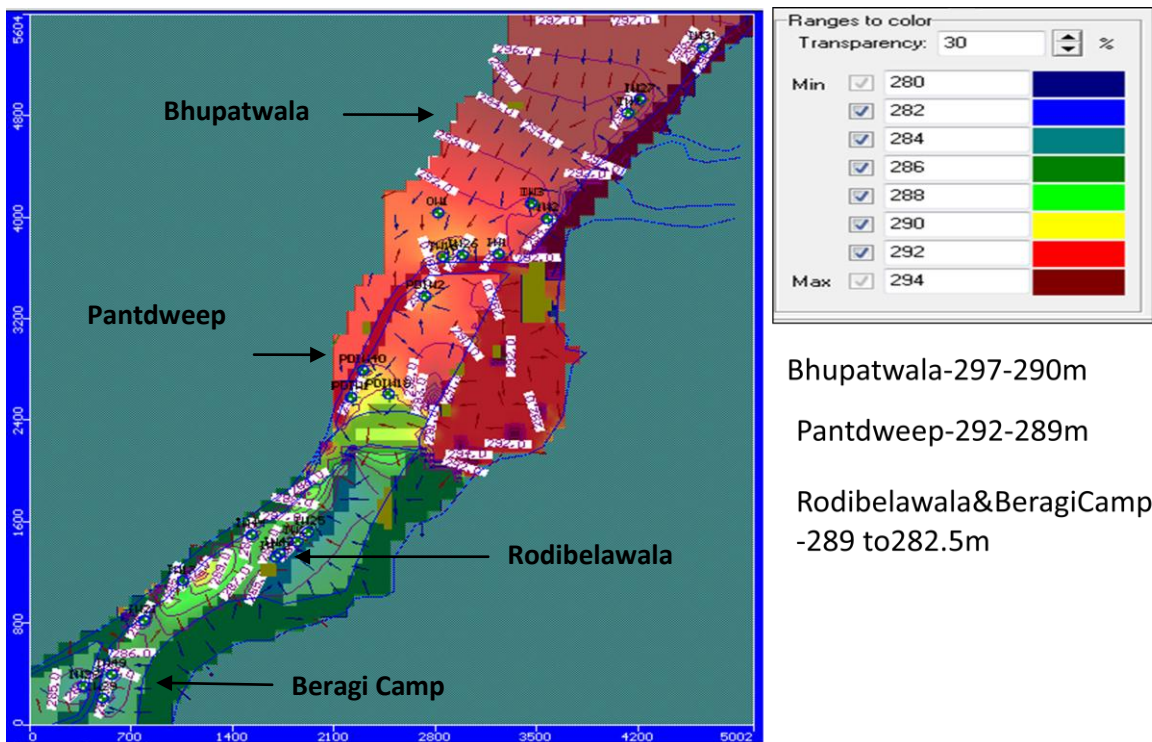
Appendix 8 Maximum possible pumping rates under monsoon (23.08.2012) and pre-monsoon (08.01.2013) steady state flow conditions

| Well ID | Q [L/min] | monsoon | | pre-monsoon | |
|---------|-----------|-------------|-----------------------|-------------|-----------------------|
| | | pumping [h] | Q [m ³ /d] | pumping [h] | Q [m ³ /d] |
| BWIW 31 | 2500 | 24 | 3600 | 12 | 1800 |
| BWIW 27 | 1800 | 24 | 2592 | 20 | 2160 |
| BWIW 4 | 1600 | 24 | 2304 | 24 | 2304 |
| BWIW 2 | 1200 | 24 | 1728 | 21 | 1512 |
| BWIW 3 | 1700 | 24 | 2448 | 16 | 1632 |
| BWIW 1 | 1500 | 24 | 2160 | 24 | 2160 |
| BWIW 26 | 1800 | 24 | 2592 | 17 | 1836 |
| BWIW 16 | 1800 | 19 | 2052 | 12 | 1296 |
| PDIW 2 | 2000 | 24 | 2880 | 12 | 1440 |
| PDIW 40 | 2100 | 24 | 3024 | 24 | 3024 |
| PDIW 18 | 1200 | 24 | 1728 | 24 | 1728 |
| PDIW 1 | 2000 | 18 | 2160 | 16 | 1920 |
| IW 25 | 1700 | 24 | 2448 | 14 | 1428 |
| IW 24 | 1700 | 24 | 2448 | 19 | 1938 |
| IW 42 | 1800 | 24 | 2592 | 20 | 2160 |
| IW 43 | 1900 | 24 | 2736 | 24 | 2736 |
| IW 44 | 1600 | 24 | 2304 | 24 | 2304 |
| IW 17 | 1800 | 24 | 2592 | 24 | 2592 |
| IW 21 | 2500 | 19 | 2850 | 16 | 2400 |
| IW 49 | 1800 | 24 | 2592 | 24 | 2592 |
| IW 28 | 2300 | 24 | 3312 | 24 | 3312 |
| IW 29 | 2300 | 24 | 3312 | 24 | 3312 |

Appendix 9 Equipotential lines and flow paths of groundwater flow domain of 22-RBF wells in Haridwar for steady-state condition in monsoon season.



Appendix 10 Equipotential lines and flow paths of groundwater flow domain of 22-RBF wells in Haridwar for steady-state condition in non-monsoon season.



Appendix 11 Equipotential lines and flow paths of groundwater flow domain of 22-RBF wells in Haridwar for steady-state condition in pre-monsoon season.

