NIH/GWD/NIH/15-18

Peya Jal Suraksha - Development of Six Pilot Riverbank Filtration Demonstration Schemes in Different Hydrogeological Settings for Sustainable Drinking Water Supply **(Part-I)**.

National Institute of Hydrology

Roorkee – 247 667, Uttarakhand

February, 2019.

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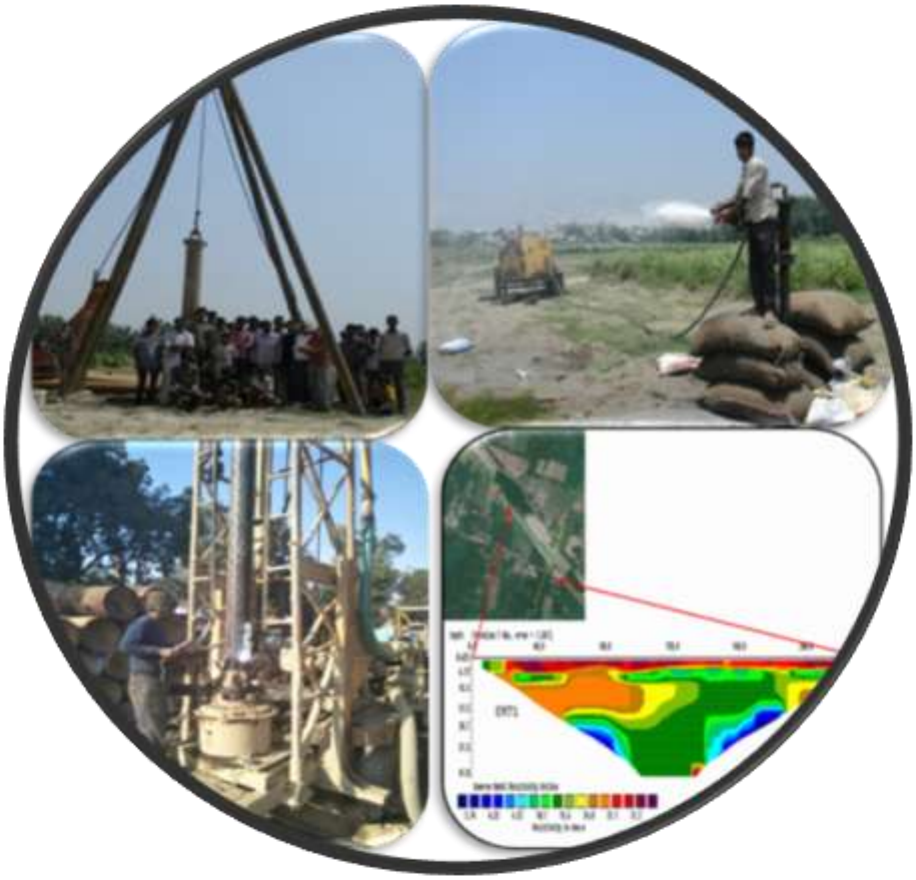

NATIONAL INSTITUTE OF HYDROLOGY
राष्ट्रीय जलविज्ञान संस्थान
आपो हि ष्ठा मयोभुवः

National Institute of Hydrology

Roorkee – 247 667, Uttarakhand

February, 2019.

FOREWORD

Growing population and booming urban agglomeration in India are posing challenges to attainment in drinking water security. In one hand, deteriorating quality of source water by the anthropogenic and geogenic sources of contamination, on the other hand, reduction on the per capita availability of water are emerging as the big issue in ensuring adequate quantity of safe water quality drinking water. The mechanized water treatment technology is very costly and requires skilled manpower to employ in all places, particularly, in rural and peri-urban areas. Riverbank filtration (RBF) or simply, bank filtration (BF), which has successfully been using in many European countries since more than 100 years, is one of the cost effective natural treatment technologies that has also been gaining popularity in India. NIH-Roorkee in association with HTWD-Germany has established an Indo-German Competent Centre for RBF (IGCCRBF) in year 2011 at NIH, Roorkee for cooperation and collaboration on RBF related activities in India. NIH, Roorkee is now acting as the knowledge repositories and in technical knowhow dissemination on RBF in India.

The project entitled "**Peya Jal Suraksha -** Development of Six Pilot Riverbank Filtration Demonstration Schemes in Different Hydrogeological Settings for Sustainable Drinking Water Supply", financially supported by the Ministry of Water Resources, River Development & Ganga Rejuvenation, is a promising step towards upscale of the technology in India as few guiding schemes in different feasible hydrogeological settings. In the present study, five, out of proposed six pilot schemes, explored and investigated to implement in different States, namely, Uttarakhand, Uttar Pradesh, Bihar and Andhra Pradesh in collaboration with the respective State departments are an attempt from NIH-Roorkee to demonstrate effectiveness of the technology as guiding scheme and helping the utility groups for its upscale.

The project and its activities have been rolled out in the field by a team comprising scientists from the Ground Water Hydrology Division (GWHD) at headquarters; CFMS-NIH, Patna; DRC-NIH, Kakinada under the leadership of Dr. N. C. Ghosh, Scientist 'G' & Head, GWHD. This report is a part of the scientific & technical outputs emerged from the comprehensive works and analyses carried out during last 3 years (2015-2018). I put on record my appreciation to all the associated scientists and scientific staff for undertaking such field demonstrative pilot schemes in different hydrogeological settings along the rivers in India.

Place : Roorkee | **(Sharad Kumar Jain)**
Date : 05th February, 2019 | Director, NIH

ACKNOWLEDGEMENT

Implementation of a project in field to demonstrate effectiveness of a technology by conserving its technicalities is, in fact, a challenging and tedious task. If the project has requirement of land and other field logistics viz., electricity, exploratory drilling, construction & installation of tube wells, etc and the project has sites in different locations in a number of States, then its working dimensions increased to manifolds and also become very challenging. To ambit with such situations, HTWD-Germany for technical collaboration, and State's Jal Sansthan/Jal Nigam/PHED /DWS&S for field logistic supports have been associated in the project as collaborating partners. The project has been financially supported by the Ministry of Water Resources, RD & GR, Government of India.

I gratefully acknowledge the support of MoWR, RD & GR for the financial grant and support of the project for implementation in the field as a R & D pilot study. I thankfully acknowledge the supports provided by the Uttarakhand Jal Sansthan (UJS), Govt. of Uttarakhand; UP-Jal Nigam Ltd., Govt. of Uttar Pradesh; PHED, Govt. of Bihar; and Rural Drinking Water Supply & Sanitation Department, Govt. of Andhra Pradesh. It is because of the cooperation and required logistic supports by the officials of the respective state; we could investigate and implement the project in the field. I convey my sincere thanks to the officials from the State Government departments. I thankfully acknowledge the technical advisory support given by HTWD-Germany, particularly, by Dr. C. S. S. Sandhu, Prof. T. Grischek, Dr. W. Schmidt, Dr. H. Bornick, and students of HTWD-Germany.

Success of a project comes when the team associated with its activities contribute efficiently and significantly. The contributions of team of scientists from the Groundwater Hydrology Division (GWHD) at Headquarters namely, Dr. Anupma Sharma, Sc. 'E'; Dr. Surjeet Singh, Sc. 'E'; Mr. Sumant Kumar, Sc. 'C'; Dr. Gopal Krishan, Sc. 'C' and Ms. Suman Gurjar, Sc. 'C' are thankfully acknowledge for the sites at Uttarakhand and Uttar Pradesh. The contributions and hard work of Shri Biswajit Chakraborti, Sc. 'G' & Head, CFMS-NIH, Patna and his team Shri N. G. Pandey, Sc.'E' & Shri Atam Prakash, RA together with Shri Sumant Kumar from headquarters for the RBF site in Bihar are appreciatively acknowledge. The contributions and dedicated work of Dr. Y. R. S. Rao, Scientist 'G' & Head, and Mr. T. Vijay, Sc.'B', DRC-NIH, Kakinada are also thankfully acknowledged. The supports of scientific staff from GWHD namely, Shri Sanjay Mittal, SRA; Shri S. L. Srivastava, SRA; Shri Dinesh Kumar, MTS; Dr. Vikrant Vijay Singh, RA; and Shri Harsh Ganapati, M. Tech student are also duly acknowledged. It is because of their collective efforts and hard work, the activities of the project could successfully be implemented in the field and the report could come out.

Place : Roorkee
Date : 5th February, 2019.

(Narayan C. Ghosh)
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- Rural Water Supply & Sanitation Department, Government of Andhra Pradesh

Abstract

River Bank Filtration (RBF) or simply, Bank Filtration (BF), as one of the alternate cost-effective natural treatment technologies for drinking water supply, has been a common practice in many European countries particularly, in urban and peri-urban areas, for more than a century. India has a large potential for use of RBF/BF for sustainable qualitative and quantitative production of drinking water, 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, surface water source is perennial and aquifers have good soil pores. Currently, only a fraction of RBF potential is in use in India. There is a pressing need to explore possibility of upscale of RBF technology in feasible locations particularly, in rural and sub-urban areas where organized drinking water supplies coverage is yet to take place. Selection of potential RBF sites, decision on appropriate distance of production well, flood proofing of the scheme, post-treatment requirement, risk and efficiency assessment, river-aquifer interaction understanding, etc. are some of the important design considerations which need a good understanding and knowledgebase before such schemes are implemented and promoted at a large scale.

To upscale the RBF technology in different hydro-geological settings in India, the Ministry of Water Resources, RD & GR, has supported development of 6 pilot demonstration schemes in different feasible locations particularly in the Gangetic basin aiming at to demonstrate the effectiveness of the RBF technology to drinking water supply utility groups about its feasibility identification, effectiveness, protection against risk, etc for sustainable safe drinking water supply in peri-urban and rural areas.

It is in those contexts; five, out of six, RBF schemes have been explored and investigated in details to identify feasibility and develop as pilot demonstration scheme. These five sites are : one in Kunwa Khera Goan at Laksar of Uttarakhand State on the bank of the Solani river, one in Mathura and one in Agra both in Uttar Pradesh on the bank of the Yamuna river, one in Barhara village of Ara district in Bihar on the bank of the Ganga river, and one in Vommavaram village of Visakhapatnam district in Andhra Pradesh on the bank of Varaha river. The explored site in the Kunwa Khera Goan on the bank of the Solani River after detailed investigations, exploratory drilling and lowering of tube wells were found not feasible from the context of ambient groundwater quality, particularly high concentration of Arsenic and Iron and hence, was dropped.

The Phase-I, of Mathura, Agra, and Vommavaram village site, comprising works of baseline water quality analysis, geophysical surveys, exploratory drillings, identifying hydraulic connectivity between river and aquifer, identification of taping zone, lowering of tube wells, well developments, etc. had been completed. For the Mathura and Agra RBF site, lowering of the tube wells and development of the wells had also been completed. The Phase-II of all the qualified RBF sites, namely, Mathura, Agra and Vommavaram village, comprising works of installation of pumps, construction of pump houses, electrical connections & fittings, pipeline laying & hydrant points installation, etc and the performance evaluation of the RBF wells and bank filtrate water are yet to be taken up. The successful completion of these four pilots RBF schemes will help upscale of RBF in feasible hydrogeological settings in India.

CONTENT

Description		Page #
Preface		**i**
Acknowledgement		**ii**
Study team		**iii**
Abstract		**iv**
Contents		**v**
List of Tables		**vi**
List of Figures		**vii-viii**
Section 1:	**Introduction**	**1-2**
1.1	Objectives of the Study	2
Section 2:	**Bank Filtration and its Physical Processes**	**2**
Section 3:	**A status review on use of RBF technology**	**3-4**
Section 4:	**Description of the Study Sites**	**4-32**
4.1	Kunwa Khera Goan near Laksar	4-7
4.2	Agra and Mathura RBF sites	8-16
4.2.1	Development of RBF scheme at Agra and Mathura	17-21
4.3	RBF site of Barhara village in Ara, Bihar	22-23
4.4	RBF site in Vommavaram village along Varaha River at Visakhapatnam	24-32
Section 5:	**Tasks ahead**	**33**
Section 6:	**Concluding remarks**	**33**
	References and some suggested reading materials	**34-35**

List of Tables

Table #	Description	Page #
Table 1:	Results of sediment core of the borelog of Kunwa Khera Goan, Laksar	6
Table 2:	Results of water samples analysis of River, Bore well and Hand Pumps	7
Table 3:	Concentration of micro-pollutants in surface and ground water	14
Table 4:	Concentration of chemical parameters in riverbed sediment of Yamuna at Agra area	15
Table 5:	Configured lithology based on the resistivity data of site S-1	23
Table 6:	Water quality of Varaha river	26
Table 7:	Water quality of the Varaha river near RBF site in Vommavaram village.	26
Table 8:	Chemical and Trace elements results of groundwater samples of Vommavaram village surrounding RBF site	27
Table 9:	Bacteriological analyzed results of groundwater and Varaha river water	27
Table 10:	Details of drilled borelog and depth-wise lithogical profile for the explored well in the Vommavaram village, S. Rayavaram Mandal, A.P.	31-32

List of Figures

Figure #	List of Figures	Page #
Figure 1:	Schematic diagram of a bank filtration processes affecting water quality of groundwater and extracted water	3
Figure 2:	Few photographs of Kunwa Khera Goan RBF well drilling works	5
Figure 3:	Snapshot of the riverbank on which the RBF well was established before and after the 2016 monsoon flood	7
Figure 4:	Selected RBF sites in Agra and Mathura	8
Figure 5:	Explored RBF site at Fatehabad in U.P. that was finally dropped due to non-availability of land	9
Figure 6:	Sampling campaign programme of Agra and Mathura area	10
Figure 7:	Location details of the sampling points in the Agra area...............	10
Figure 8:	Location details of the sampling points in the Mathura area	10
Figure 9:	Variation of EC in water samples	11
Figure 10:	Variation of Temperature in water samples of Mathura and Agra area	11
Figure 11:	Variation of Bicarbonate in water samples..................................	12
Figure 12:	Variation of Chloride in water samples	12
Figure 13:	Variation of Arsenic in water samples	13
Figure 14:	Variation of Fluoride in water samples.	13
Figure 15:	Water Quality Index of river and ground water.	14
Figure 16:	Variation of isotopic characteristics, ΔO^{18} versus D-excess, of river and ground water.	15-16
Figure 17:	% contribution of groundwater by river water during monsoon period at Agra area	16
Figure 18:	Exploratory drilling by rotary method for RBF well:	17
Figure 19:	Soil samples collected from exploratory bore of Agra site at various depths	18
Figure 20:	SP and Resistivity profile of the exploratory bore-hole of Agra and Mathura site.	18
Figure 21:	Lithology of the explored RBF site in Agra and Mathura	19
Figure 22:	Design of the exploratory bore and tube wells showing tapping zones for both Agra and Mathura site	19

Figure 23	Depth-wise variation of trace elements in the soil cores of Mathura site	20
Figure 24:	Depth-wise variation of trace elements in the soil cores of Agra site	20
Figure 25:	Variation of trace metals in the water of extracted RBF well: (a) Mathura site, and (b) Agra site	21
Figure 26:	Location of the selected RBF site in the premise of the temple in Barhara village of Ara district (Bihar): the Ganga River is also seen in the close proximity about 45/50 m from the boundary wall of the temple	22
Figure 27:	Map showing the location of resistivity survey carried out around the proposed site	23
Figure 28:	Variation of depth-wise apparent resistivity at the location S-1 in the Barhara village	23
Figure 29:	Intake Well constructed for water supply in the nearby villages at the upstream of the Varaha river and the dried up riverbed during lean period, which triggers as scarcity of drinking water supply during lean period (Feb.-May) in the villages. The upstream stretches of the river flows during monsoon period only	24
Figure 30:	Downstream of the Varaha river at the same period as in Figure 28 and details of the village can be seen on the foundation stone written in Telegu language	24
Figure 31:	Downstream of Varaha river near Vommavaram village, S. Rayavarammandal …………………………………………	25
Figure 32:	Interaction with local people and in-situ River and ground water quality measurement	25
Figure 33:	Location for the Electrical Resistivity Tomographic survey near Vommavaram village alignment in the vicinity of the Varaha River	28
Figure 34:	Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map ..	28
Figure 35:	Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map	29
Figure 36:	Electrical Resistivity Tomography (ERT) model for the Geophysical survey across the river as shon in the map	30
Figure 37:	Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map	30
Figure 38:	Exploratory drilling of RBF well near Vommavaram village on the left bank of the Varaha river ………………………………	31

1. Introduction

India's domestic water demands projected by many researchers (Kumar et al, 2005; Sandhu et al, 2011) showed rise from 6.75% (42 BCM/year) in year 2010 to 8 % (59 BCM/year) and 10% (100 BCM/year) of the total uses for the year 2025 and 2050, respectively. The risk enumerates from the deterioration of water quality on the available quantity can be one of the main hurdles in addition to the quantity to be available as utilizable water resources to secure the future demands of domestic water supply. Attainment of India's domestic water supply security with the approach of business usual may be a difficult task and would require a coordinated management approach of available water resources. Riverbank filtration (RBF) or simply, bank filtration (BF) is one of the alternate natural treatment technologies that consider conjunctive management of surface and ground water by way of inducing surface water through pumping in the vicinity of surface and ground water interaction system can bring source sustainability in the domestic water supply security. India has a large potential for use of RBF/BF for sustainable qualitative and quantitative production of drinking water. Currently, only a fraction of the potential of RBF or BF is in use. There is a pressing need to explore possibility to upscale of RBF/BF scheme in feasible locations particularly, in rural and sub-urbanized areas where organized drinking water supplies coverage is yet to be taken up. RBF/BF can also be used as an add-on supplementary scheme to the existing mechanized water supply system. Being a cost effective natural treatment technique, RBF/BF has gained enormous popularity in many European countries and also in USA (Hiscock and Grischek, 2002),

India has a lot of potential to use RBF technology 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, surface water source is perennial and aquifers have good soil pores. Selection of potential sites, decision of appropriate distance of production well, flood proofing of the scheme, post-treatment requirement and risk assessment, efficiency assessment, river-aquifer interaction understanding, etc. are some of the important design considerations which need a good understanding and knowledgebase before such schemes are implemented and promoted at a large scale. A large gap on technical knowledge and understanding amongst the utility groups and technical professionals in India exist, which has to be addressed by case study examples based on hydrologic and hydrogeologic settings of India.

To upscale the promotion of BF technology in different hydro-geological settings of India, the Ministry of Water Resources, RD & GR, Government of India has entrusted the task to develop 6 (six) pilot demonstration schemes on RBF in different feasible locations particularly, in the Ganga river system. The primary purpose of developing six pilot RBF schemes in different hydrogeological settings was aimed at to demonstrate Drinking Water Supply or Public Health Engineering Department about BF technology with regard to its feasibility identification, effectiveness, protection against risk, etc for sustainable safe drinking water supply in peri-urban and rural areas.

The locations of six RBF schemes were suggested in the project proposal as follows: One at Laksar in Uttarakhand along the Solani river, two in Uttar Pradesh, one at Mathura and one at Agra along the Yamuna river; one at Sahebganj along the Ganga river in Jharkhand; one at Ara in Bihar along the Ganga river; and one at Visakhapatnam in Andhra Pradesh along the Gosthani river. The respective State Jal Sansthan/PHED/Jal Nigam, who is the taker and beneficiary of the technology and scheme, was associated with the project as collaborating partner. NIH has a scientific and technical collaboration with the HTWD, Germany through cooperation and institutionalization of Indo-German Competence Centre for Riverbank Filtration (IGCCRBF) at NIH, Roorkee. This functional arrangement has facilitated inclusion of HTWD, Germany in the study as scientific and technical adviser.

The project has the funding from the Ministry of Water Resources, River Development and Ganga Rejuvenation for a duration of 30 months that was extended by one year more. The envisaged tasks in the project were as follows: (i) consultation with the respective State Jal Sansthan /PHED/Jal Nigam for identification of sites; (ii) feasibility survey and study of the identified sites from hydrologic, hydrogeologic and water quality perspectives; (iii) exploratory drilling and establishment of RBF well; (iv) performance analysis of bank filtrate water and risk assessment for deciding need of chemical doses; (v) flood proofing; (vi) construction of pump house and peripheral works for distribution of bank filtrate water supply; and (vii) handover of the pilot demonstration scheme to the respective State Jal Sansthan/PHED/Jal Nigam to use it as a guiding RBF scheme for further upscale.

1.1 Objectives of the Study

The study has the following objectives to attain the required goals:

(i) *Baseline investigations and development of pilot demonstration sites for riverbank filtration (RBF) in different hydrogeological settings;*
(ii) *Performance and limitations analysis of RBF schemes;*
(iii) *Effectiveness of RBF technique in different river-aquifer settings and river flow conditions;*
(iv) *Analysis of RBF under variable pollutants loads and flood situations;*
(v) *Development of technical elements for flood-proof water abstraction schemes; and*
(vi) *Scope of extending the technique in attaining drinking water security.*

2.0 Bank Filtration and its Physical Processes

Riverbank filtration (RBF) or simply, bank filtration (BF), a unified term for river and lake bank/bed filtration, is a proven natural and sustainable water treatment and production technique. BF is a process by which surface water from rivers, channels and lakes is induced by pumping from nearby production wells to flow through the natural aquifer soil, undergoing many positive changes in water quality before finally mixing with local groundwater from the land side before being abstracted for direct use or further treatment (Hiscock & Grischek, 2002). The aquifer serves as a natural filter and also biochemically attenuates potential contaminants present in the surface water. Figure 1 schematizes the RBF and water quality removal processes.

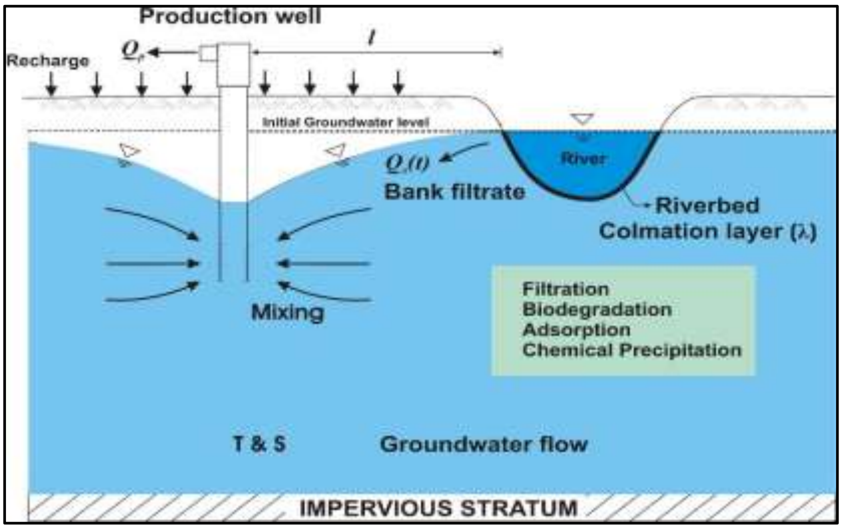


Figure 1: Schematic diagram of a bank filtration processes affecting water quality of groundwater and extracted water.

More precisely, the process of BF is initiated by lowering of groundwater table near the river or lake, which causes surface water to seep through the permeable river or lake bed and bank into the aquifer due to the difference in water levels, provided that, no artificial or natural barriers exist (e.g. brick or concrete lined bed, or a low hydraulic conductivity layer like clay) (Hiscock and Grischek, 2002). River/lake water contaminants are attenuated due to a combination of processes such as, filtration, microbial degradation, sorption to sediments and aquifer sand, and dilution with background groundwater. The process has many similarities to slow sand filtration process. Compared with direct surface water abstraction, bank filtration with its effective natural attenuation processes eliminates suspended solids, particles, biodegradable compounds, bacteria, viruses and parasites; partly eliminates adsorbable compounds and equilibrates temperature changes and concentrations of dissolved constituents in the bank filtrate (Hiscock & Grischek, 2002). The removal of microbial pathogens from drinking water is crucial. Pathogens such as; *Cryptosporidium*, *Giardia* and viruses are not completely inactivated through common drinking water disinfection using chlorine or UV radiation. Thus, expensive filtration technologies (e.g. nanofiltration) are needed to produce safe drinking water. RBF effectively removes these pathogens by natural processes during subsurface passage depending on flow path length, residence time and environmental factors. Hence, it can serve as a pre-treatment step in drinking water production, and in some instances, also as final treatment before disinfection.

3.0 A status review on use of RBF technology

Bank Filtration has been a common practice in many European cities for more than 100 years. It was originally initiated to remove pathogens and suspended solids from increasingly polluted surface waters. BF provides about 50% of potable water supplies in the Slovak Republic and 45% in Hungary (Hiscock and Grischek, 2002). In Germany, more than 300 waterworks use BF and about 16% of German drinking water is produced from bank filtrate.

In Netherlands 7%, Finland 48%, France 50%, and Switzerland 80% drinking water is produced from bank filtrate. In Central Europe, increasing chemical pollution, high concentrations of ammonia, organic compounds and micro-pollutants in the river water called for the introduction of supplementary pre- and post treatment steps to build-up a multi-barrier system. Aeration or ozone is sometime used to oxidise iron and manganese, or to activate carbon for adsorption of and protection against more persistent contaminants. Presently in Central Europe, nearly all water utilities situated along large rivers use granular activated carbon filters, often combined with isolation and filtration (Schmist et al. 2003). Largely in Europe, BF has been recognized as a proven method for drinking water treatment. In USA, not as government strategy but a number of water utilities use bank filtrate water for drinking water supply. For example, most cities in Nebraska historically have developed RBF scheme along the Platte River or its tributaries. Water utility groups in USA such as, Iowa, Kansas, Kentucky, Nebraska, New Jersey, New York, Ohio, Texas, and Wyoming are using bank filtrate water for drinking water supply. Bank filtration sites in USA mostly exist along major and some smaller rivers (Heberer et al, 2011). There are enormous literature available on BF illustrating its successful usages in different countries (Sontheimer, 1980; NWRI, 1999; Kühn & Müller, 2000; Schubert,2002; Ray, 2002; Ray et al., 2002; Berger, 2002; Grischek et al, 2002; Hrudey & Hrudey, 2004; Dillon, 2005; Bosuben, 2007; Sharma and Amy, 2009). In India, the BF technology has gained popularity by the initiative of HTWD, Germany together with the initiative of NIH-Roorkee, UJS, IIT Roorkee, and UCoST and presently, a number of other R & D organizations, and State departments have captured this technology for further upscale. With the financial support from the Department of Science and Technology (DST), Government of India, NIH-Roorkee has imparted a number of trainings mainly to the State departments under the country-wide capacity building program on ‘Bank Filtration for Sustainable Drinking Water Supply in India’. A knowledgeable workforce for more than 125 on BF has been created in India by those training programs. A handbook on “Bank Filtration Technologies’ by the financial support of DST has been brought out by UCoST, Dehradun. These eventually suggested that India has recognized this technology for upscale and promotion in large scale at feasible locations as a potential technology for peri-urban and rural areas either as a standalone or supplementary to the mechanized system.

4.0 Description of the Study Sites

Out of proposed six sites, five RBF sites were materialized for detailed investigations, they are: (i) Kunwa Khera Goan near Laksar in Uttarakhand along the Solani river, (ii) Mathura near Gakul barrage in U. P. along the Yamuna River, (iii) Agra in the premise of Agra Water Works of UP Jal Nigam along the Yamuna river, (iv) Barhara village in the premise of a temple at Ara in Bihar along the Ganga river; and (v) Near Vommavaram village at Visakhapatnam in Andhra Pradesh along the Varaha river. These sites were identified in consultation with the respective State department. The description of each site together with the investigation details is illustrated in the subsequent section.

4.1 Kunwa Khera Goan near Laksar

The Laksar site, in the Kunwa Khera Goan on the left bank of the Solani river that has population, approximately of 7,500, was selected based on the baseline data for the exploratory drilling upto 30 m depth. The exploratory drilling point has the location, latitude of 29^0 45.399 N and longitude of 77^0 58.45 E. The drilling was carried out by rotary drilling method in May, 2016 at a distance of about 42 m from the waterline of the Solani river.

Figure 2 : Few photographs of Kunwa Khera Goan RBF well drilling works: (a) exploratory drilling work in progress, (b) drilled soil cores collected at 1 m depth interval, (c) lowering of tube well pipe in progress,(d) tube well development by air compressor, (e) another view of tube well development by continuous air pressure by compressor, (f) water sample collection from Solani river for water quality detection, and (g) schematic diagram of 20 cm dia bore hole with 10 cm dia lowered tube well and litholigcal profile of explored geological strata.

The drilled hole has diameter of 20 cm with provision of 10 cm dia tube well. The lowering of the tube well was upto the depth of 28 m bgl (below ground level). Figure 2 shows few photographs of RBF drilling works in Kunwa Khera Goan (Figures 2(a)-(e)) together with the schematic diagram of the explored lithological strata and design of the lowered tube well (Figure 2(g)). The gap between the drilled hole and lowered tube well was filled by gravel pack of size ranges between 4 mm and 5 mm nominal diameter (Figure 2(g)). The slotted pipes i.e., tapping zone of the aquifer, was put in two different depth zones; the first one between the depth ranges 10.5 m and 13.5 m bgl in the coarse sand zone and the second one, between the depth ranges 17 m and 26 m bgl that has formation containing boulders, pebbles with coarse sand. The bail plug pipe of 2 m length was placed below 26 m. The slotted pipes have slot size of 1.5 mm. Sediment core samples at every meter of drilling were collected (Figure 2(b)) for soil chemical parameter analyses. Samples of river water (Figure 2(f)), groundwater and extracted water were also collected to detect water quality constituents and isotopic characteristics of water. Soil chemical parameters were analyzed in CSSRI Lab, Kernal; water quality parameters were analyzed both in CSSRI Lab, Kernal and in IIC of IIT Roorkee; isotope analysis was carried out in the isotope laboratory of NIH, Roorkee. Soil samples were analyzed to detect concentration of: total As^{+}, Cd^{2+}, Ni^{2+}, Cu^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, EC, pH, N^{2+}, P^{4+}, and K^{+}. Samples of river water, groundwater and extracted water were analyzed to detect concentration of : pH, EC, TDS, Turbidity, Total hardness, As^{+}, Ca^{2+}, Mg^{2+}, Total Fe^{2+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, NO_3, PO_4^{3-}, and F^{-}. Results of the soil cores analyses (Table 1) revealed that there are high concentration of As and Fe in the soil strata of the upper aquifer. Water samples analyses results (Table 2) also confirmed higher concentration of As than the permissible limit of 10 ppb both in the groundwater and extracted water. The upper aquifer that has slotted pipe between depth 10.5 m and 13.5 m bgl is hydraulically connected to the river that was also confirmed from the isotopic analysis of groundwater; while lower slotted pipe between depth ranges of 17 m and 26 m bgl may extract groundwater exclusively if water is produced through this tube well. There is no cost effective in-situ As removal technology and in-situ Fe removal technology is also very costly. Both the tapping zones being influenced by high concentration of As and Fe, the site seemed to be risky and vulnerable to geogenic source of contamination and hence, categorized as non feasible site for RBF from the context of water quality. On the other hand, during the unprecedented monsoon flood in the year 2016 on the Solani river, the bank on which the tube well was installed got eroded more than 50 m, while the other bank was got sediment deposit. The location of the tube well shifted almost in the centre of the re-aligned river (Figure 3). In view of such uncertainty on riverbank stability, the RBF scheme at Kunwa Khera Goan was dropped.

Table 1 : Results of sediment core of the borelog of Kunwa Khera Goan, Laksar.

Sample name	Depth	As (ppb)	Cd (ppb)	Ni (ppb)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)	EC	pH	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
KKV (Laksar)	11-12 m	17.3	18.2	39.6	52	2134.8	411	6.2	0.1039	8.59	15.7	12.992	31.36
KKV (Laksar)	17-18 m	60.2	60.9	89.9	107.1	2034.8	498	22.8	0.1299	8.53	15.7	18.816	25.76
KKV (Laksar)	21-22 m	35.9	36.6	42.4	38.3	864.8	280	8.3	0.1007	8.88	7.85	19.488	5.6
KKV (Laksar)	24-25 m	43.6	44.4	54.5	55.5	1054.8	427	16.5	0.1183	8.83	7.85	13.216	8.96

Table 2: Results of water samples analysis of River, Bore well and Hand Pumps.

Parameter	Unit	Solani River	Exploratory Bore Well (Depth:28 m; Distance from River: 42 m)	Govt. H.P (Depth: 32m; Approx distance from River:220 m)	Pvt. HP (Depth: 15m; Approx distance from River: 250 m)
pH	-	7.64	7.18	7.21	6.95
EC	µS/cm	725	705	675	650
Turbidity	NTU	52	16	9	44
Sodium	mg/l	24	12	27	15
Potassium	mg/l	17	6	11	9
Calcium	mg/l	52	46	68	54
Magnesium	mg/l	31	24	52	35
Sulphate	mg/l	21	14	14	26
Nitrate	mg/l	1.8	0.3	0.7	0.65
Fluoride	mg/l	0.25	0.99	0.65	0.52
Chloride	mg/l	27	8.6	10.5	14
TC	MPN/100 ml	≥ 2400	460	Nil	-
FC	MPN/100 ml	960	Nil	Nil	-
As	ppb	5.05	34	30.82	65.06
Ba	ppb	46.34	132	104	0.529
Cd	ppb	0.05	0.82	0.02	0.24
Cr	ppb	1.66	3.17	0.88	0.94
Cu	ppb	4.28	2.13	13.06	1.14
Fe	ppm	0.52	1.75	0.879	3.52
Mn	ppm	0.21	0.20	0.18	0.42
Pb	ppb	0.49	0.75	0.41	0.25
Se	ppb	0.31	0.15	0.17	0.54
Ni	ppb	2.70	3.51	1.48	4.63
Zn	ppb	35.95	24.31	49.01	75

Figure 3: Snapshot of the riverbank on which the RBF well was established before and after the 2016 monsoon flood.

4.2 Agra and Mathura RBF sites

The Agra and Mathura RBF site were finalized in consultation with the UP-Jal Nigam Ltd. (UPJNL). The RBF site at Agra is located in the Agra Jal Kal premise of UPJNL at latitude of 27.202657° N and longitude of 78.031522° E on the right bank of the river Yamuna (when faced towards flow direction) approximately, 195 meters from the lean period river water line, and the RBF site at Mathura is located in the premise of UPJNL at latitude of 27.447097° N and longitude of 77.712719° E on the right bank of the river Yamuna approximately, 65 meters from the lean period river water line near Gakul barrage. The location of the RBF sites at Agra and Mathura as seen on the Google map is shown in Figures 4 (a) and (b), respectively.

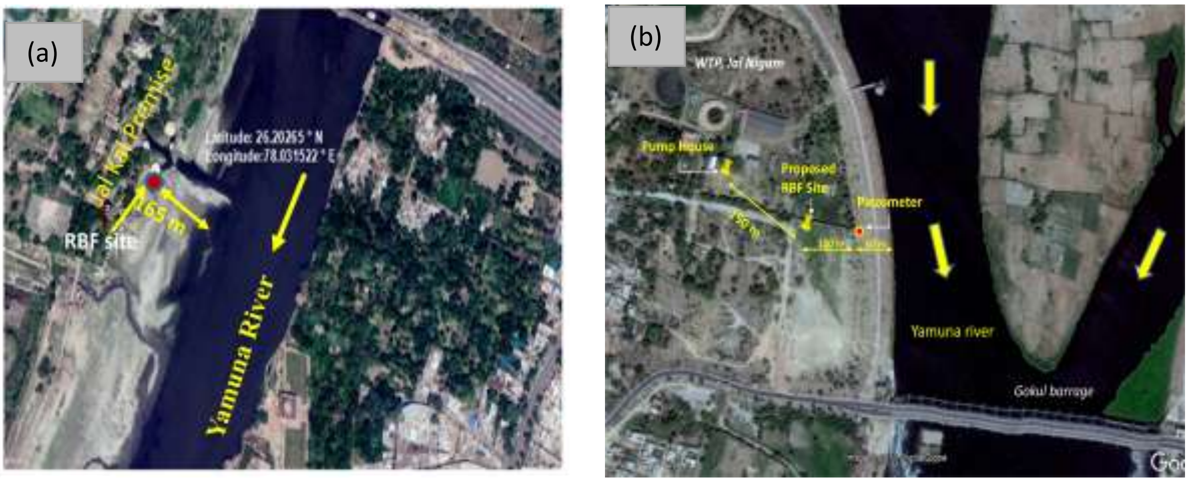


Figure 4: Selected RBF sites in Agra and Mathura: (a) Agra site in the Jal Kal premise; and (b) Mathura site in the WTP of Jal Nigam near Gakul barrange.

Before finalization of the site at Agra in the Jal Kal premise, possibility of having the RBF site at any nearby rural area along the river Yamuna where there was no organized water supply existed, was also explored. The possibility of RBF site at Fatehabad about 35 km downstream of Agra along the bank of river Yamuna was explored, and water quality of both river and ground water were also analyzed. The site at Fatehabad (Figure 5) was found suitable, however, due to non-availability of land and also local people were not interested to have RBF scheme because of upcoming government's water supply scheme at Fatehabad, the selected site was not pursued further.

Before finalizing the site at Agra and Mathura, extensive field investigations focusing to sampling campaigns of riverbed sediments (Figure 6(a)), river and ground water in and around the select locations and analysis of samples collected from Agra and Mathura area (Figures 6 (b to d)) were carried out during the year 2016. The samples were analyzed in the soil-water lab for analysis of riverbed sediments and in the water quality lab. of NIH for analysis of water chemistry. Isotopic characters of groundwater samples were also determined to identify source of groundwater. The locational details of the sampling points of Agra and Mathura area are shown in Figure 7 and Figure 8 respectively. The riverbed sediments were collected from 2 m below the top surface of the extended riverbed (Figure 6(a)). Both river and ground water samples were analyzed to determined the following parameters: Temp, EC, As^{+}, Fe^{2+}, Mn^{2+}, F^{-}, HCO_3^{-}, and Cl^{-}. Sediment samples were analyzed to detect Organic Carbon (OC), Cu^{2+}, Zn^{2+}, Mn^{2+}, Fe^{2+}, Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, Cl^{-}, and SO_4^{2-}. Based on the analyzed water quality, Water Quality Index was developed to categorize the acceptability of water. The isotopic characteristics of water detected using ΔO^{18} and D-excess were analyzed to categorize sources of groundwater. The river and ground water samples were also analyzed to determine the concentration of emerging pollutants viz., 1H-Benzotriozol ($C_6H_5N_3$), Carbamazepin (nerve pains), Diclofenac, Sulfathamexazol (antibiotic), Tolytriazol (corrosion inhibitor) using the laboratory support of HTWD, Germany. A total of 6 (six) sampling campaigns in different months (January, February, April, June. July and September) of the year 2016 were carried out.

Figure 5: Explored RBF site at Fatehabad in U.P. that was finally dropped due to non-availability of land.

The variation of water quality parameters, viz., EC, Temperature, HCO_3^{-}, Cl^{-}, As^{+}, and Fluoride (F^{-}), of water samples are given in Figures 9,10,11,12, 13, and 14 respectively for both Mathura and Agra area. Figures (9), (11), (12), (13), and (14) representing variation of EC, HCO_3^{-}, Cl^{-}, As^{+}, and F^{-} in water samples of different locations of Mathura and Agra area showed, by and large except one/two location(s), the quality of water is within permissible limit as prescribed by BIS (IS-10500:2012). The concentration of emerging pollutants in water samples of Mathura and Agra area is given in Table 3.

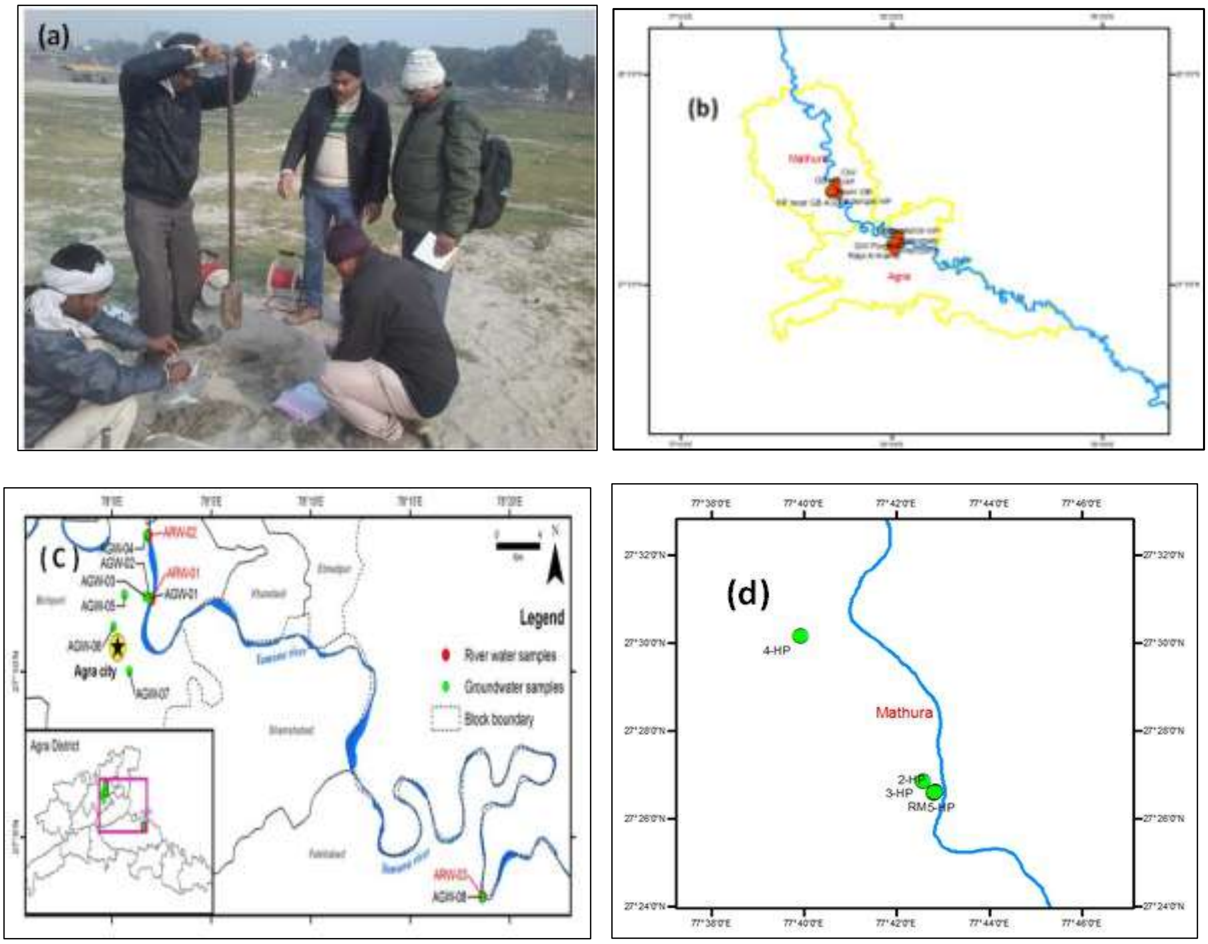


Figure 6: Sampling campaign programme of Agra and Mathura area : (a) a snapshot of the Yamuna riverbed sediment collection; (b) locations of river and ground water sampling campaign; (c) al elaborate locations of groundwater sampling campaigns in the Agra area; and (d) locations of sampling campaign in the Mathura area.

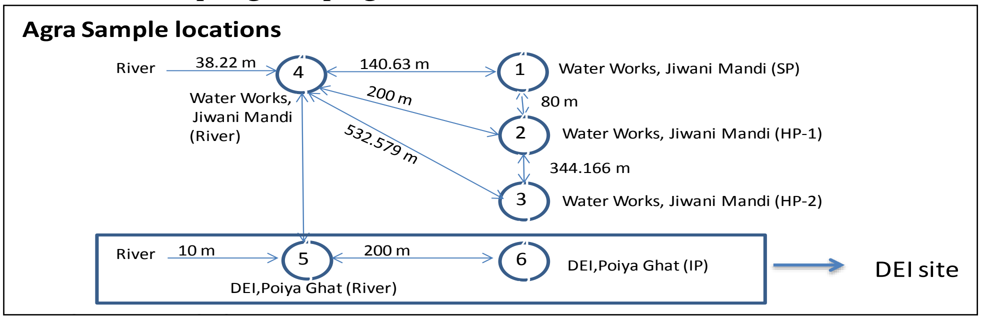


Figure 7 : Location details of the sampling points in the Agra area.

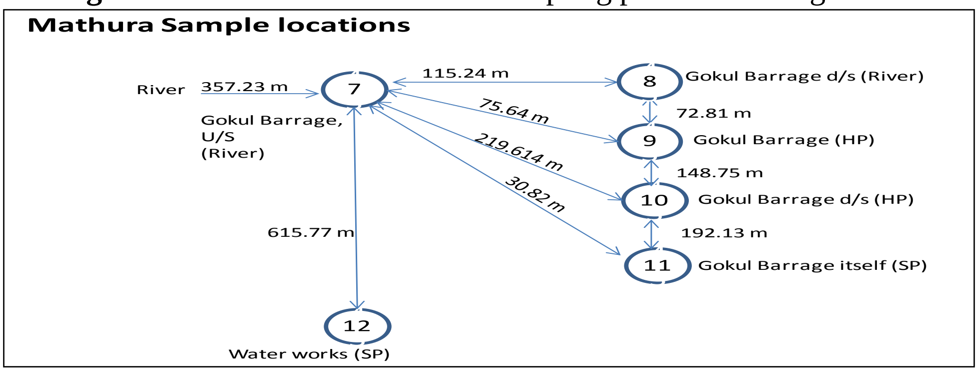


Figure 8: Location details of the sampling points in the Mathura area.

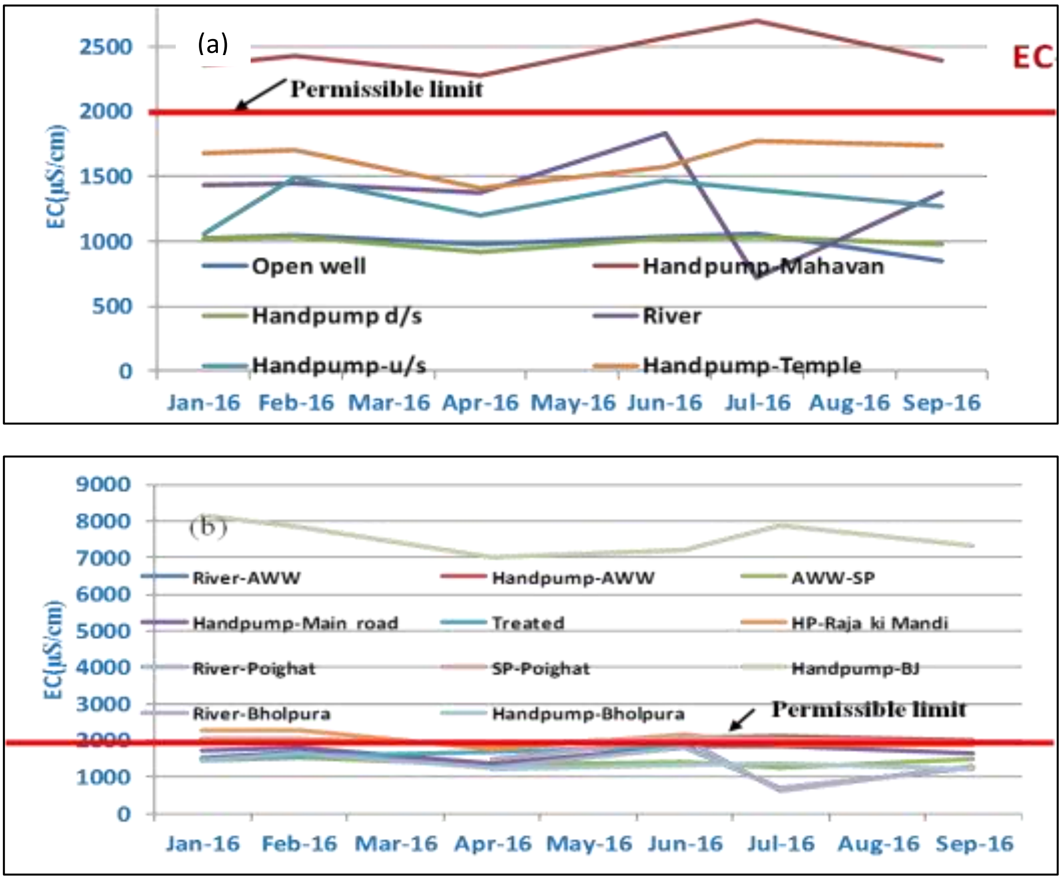


Figure 9 : Variation of EC in water samples: (a) Mathura area, and (b) Agra area.

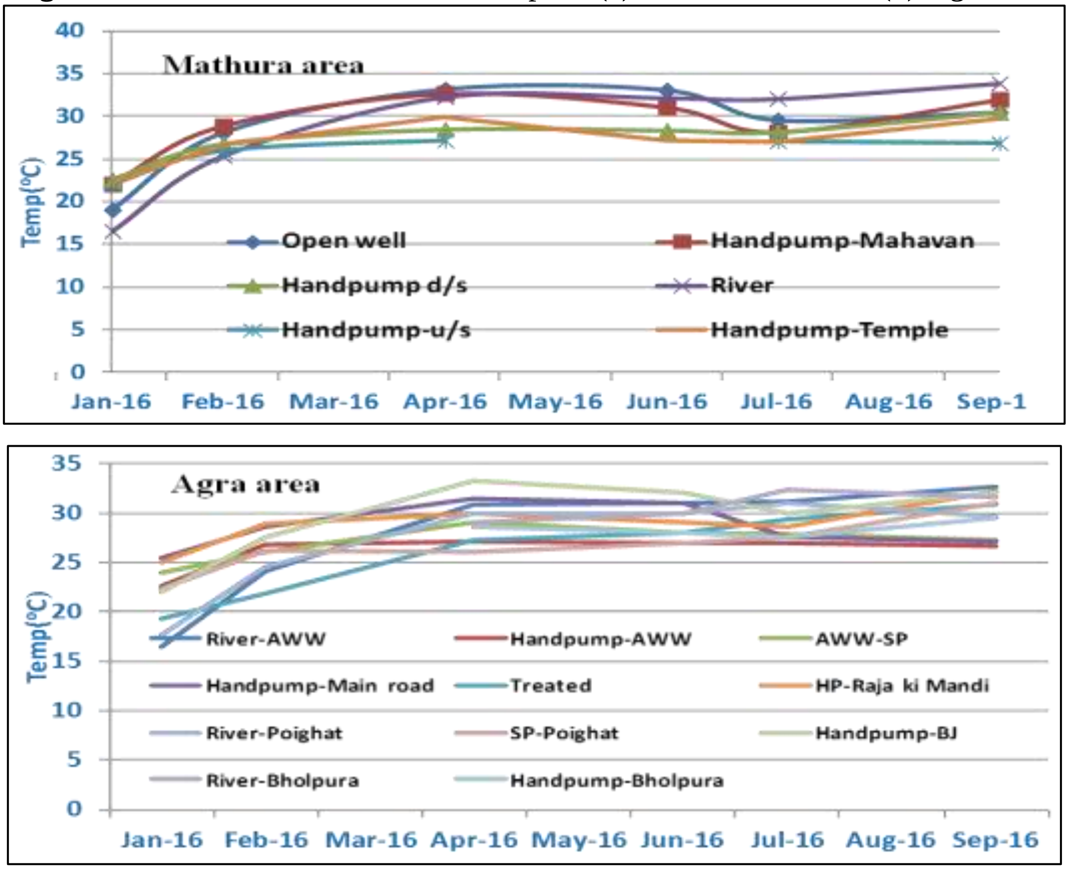


Figure 10 : Variation of Temperature in water samples of Mathura and Agra area.

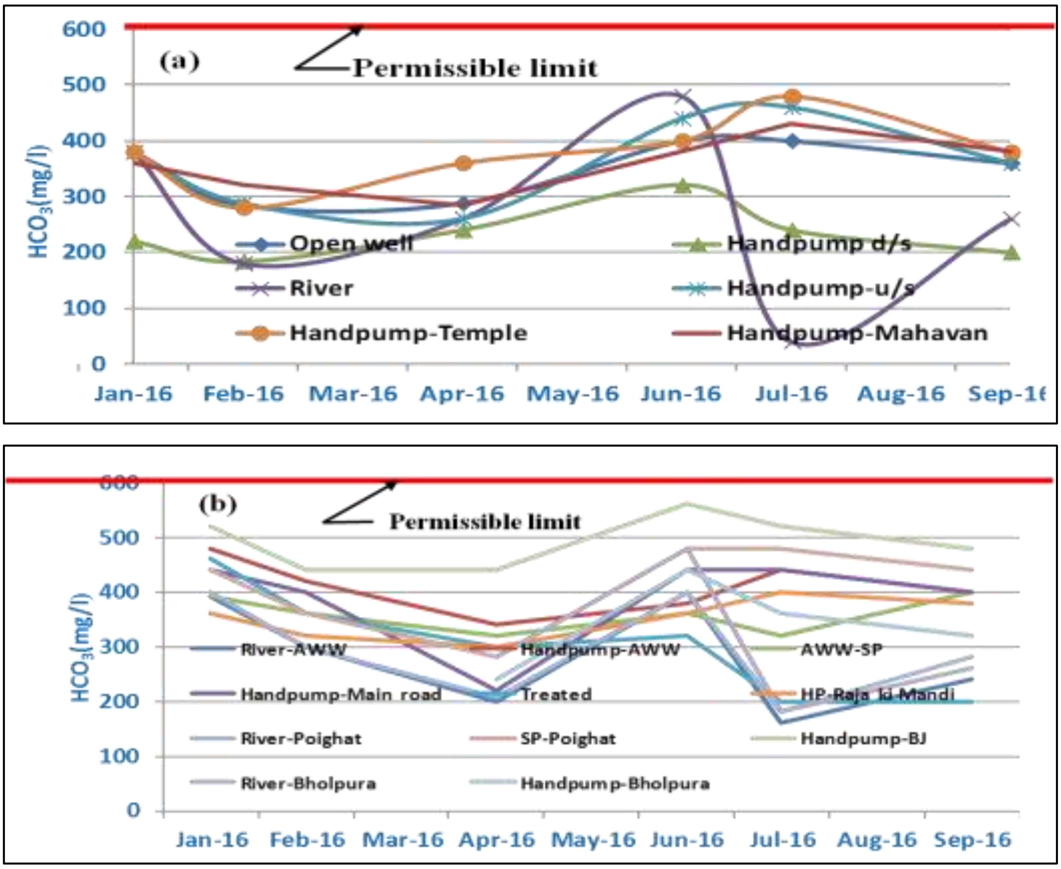


Figure 11 : Variation of Bicarbonate in water samples: (a) Mathura area, and (b) Agra area.

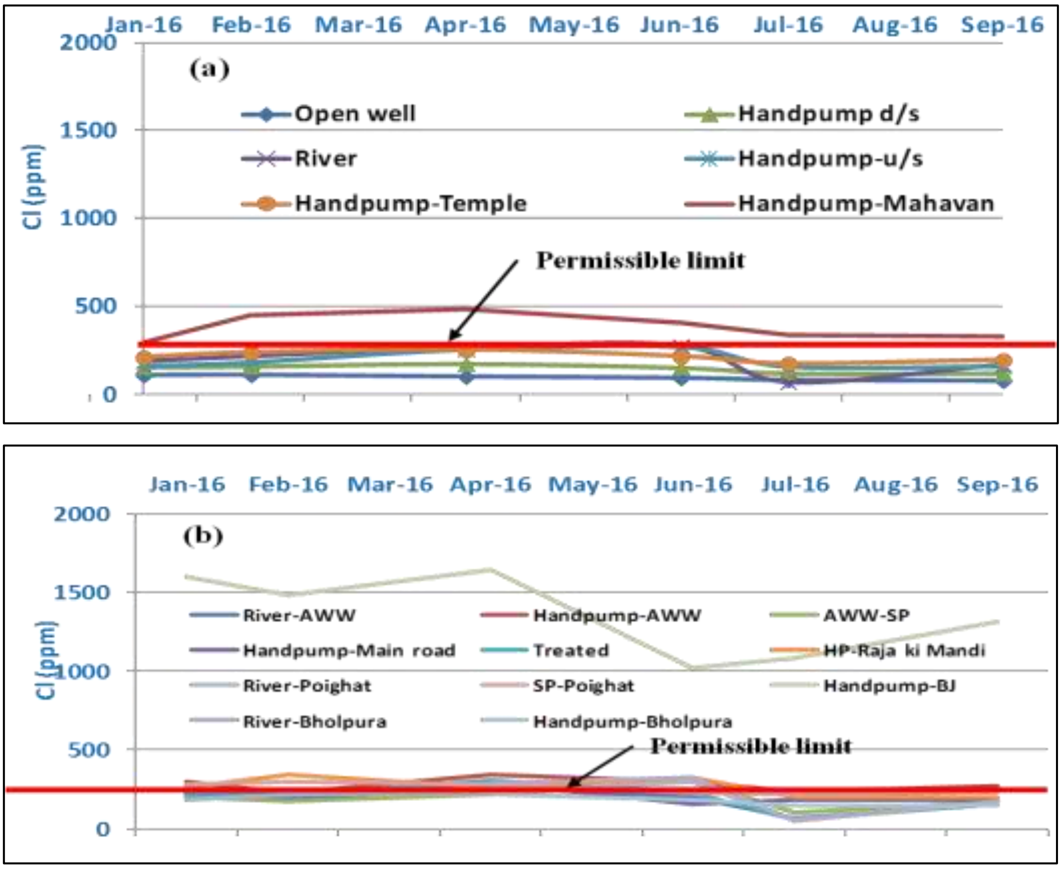


Figure 12 : Variation of Chloride in water samples: (a) Mathura area, and (b) Agra area.

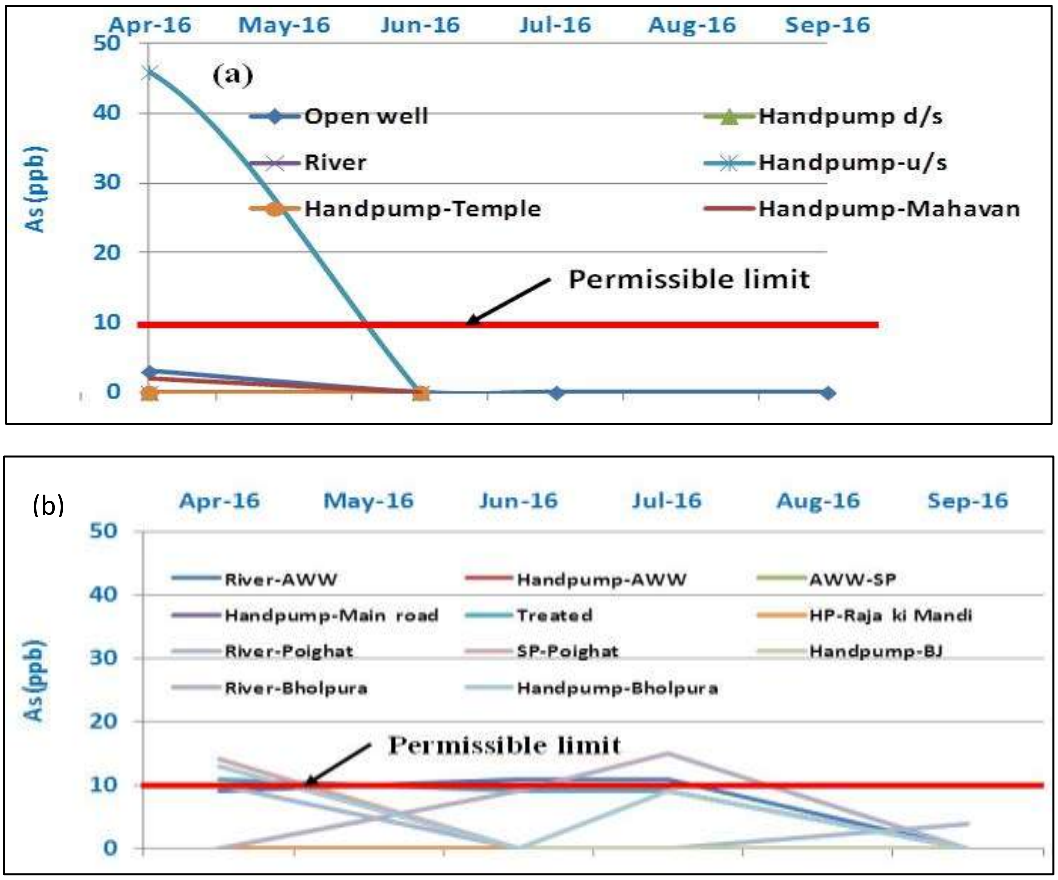


Figure 13 : Variation of Arsenic in water samples: (a) Mathura area, and (b) Agra area.

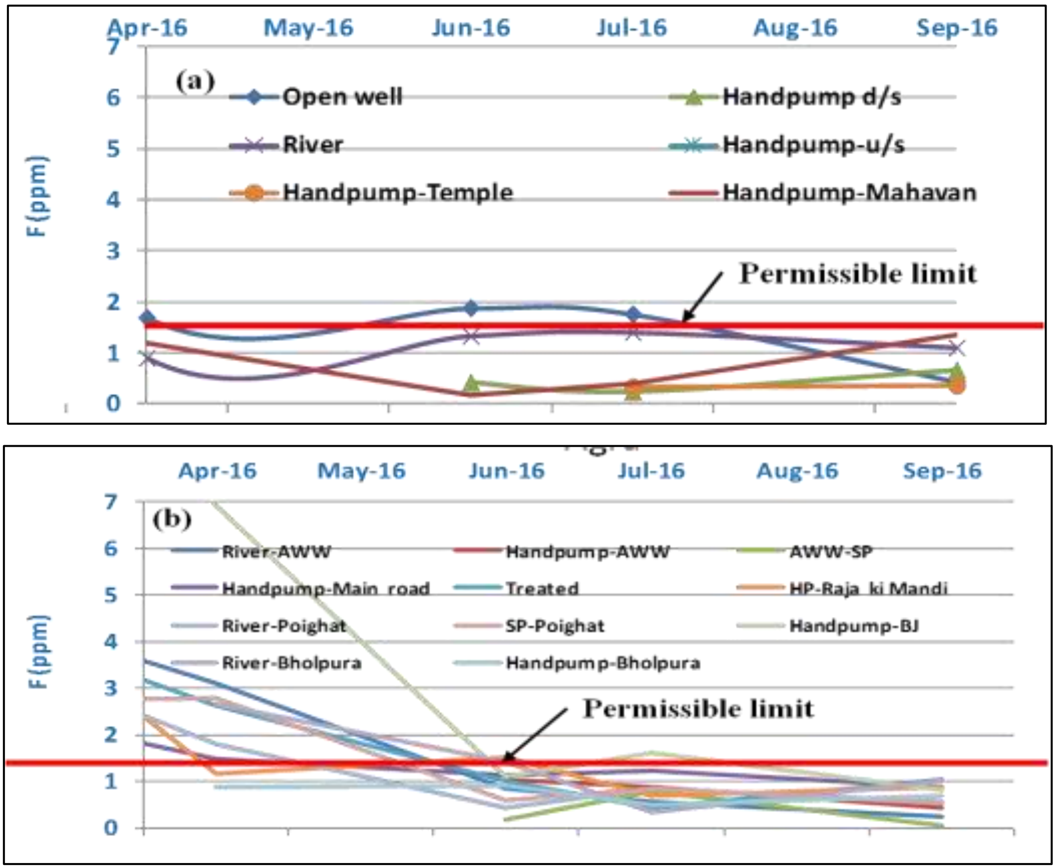
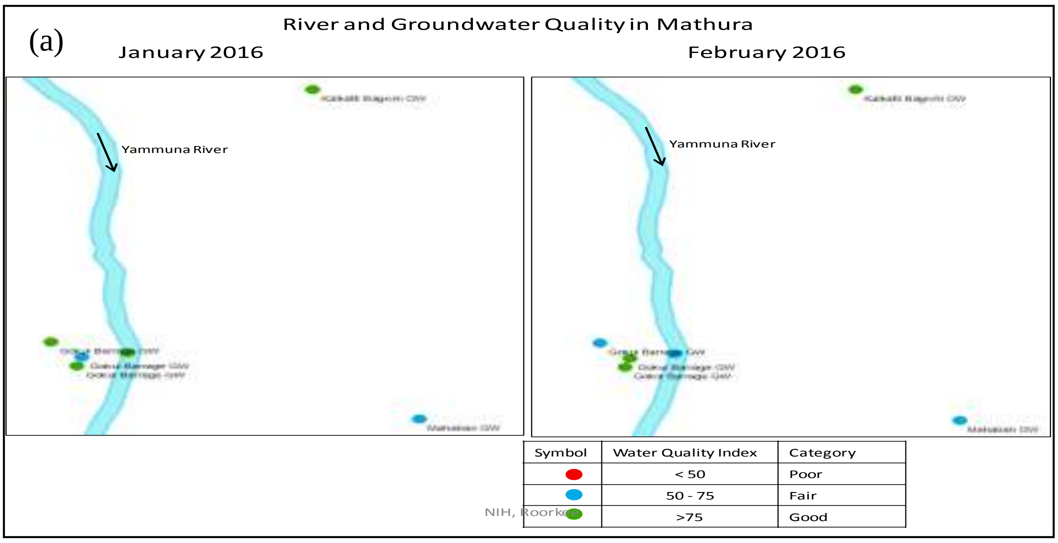


Figure 14 : Variation of Fluoride in water samples: (a) Mathura area, and (b) Agra area.

Table 3 : Concentration of micro-pollutants in surface and ground water.

Unit	ng/l				
Mathura	1H-Benzotriozol ($C_6H_5N_3$)	Carbamazepin (nerve pains)	Diclofenac	Sulfathamexazol (antibiotic)	Tolytriazol (corrosion inhibitor)
River	**158**		**9.5**	**35.8**	**157**
GW	**19.3**				**38**
Agra					
River			**14.4**	**29**	**76**
AWWSP			**17.8**		
AWW HP					
HP main road		**79.1**			**29.8**

Water Quality Index (WQI) of surface and ground water of Mathura and Agra area for the samples collected in January and February of 2016 indicated that river water of both Mathura and Agra stretches have good quality, while groundwater in Mathura area has fair to good quality and in Agra area at a large distance from the river, groundwater has poor to fair quality (Figure 15 (a) & (b)).



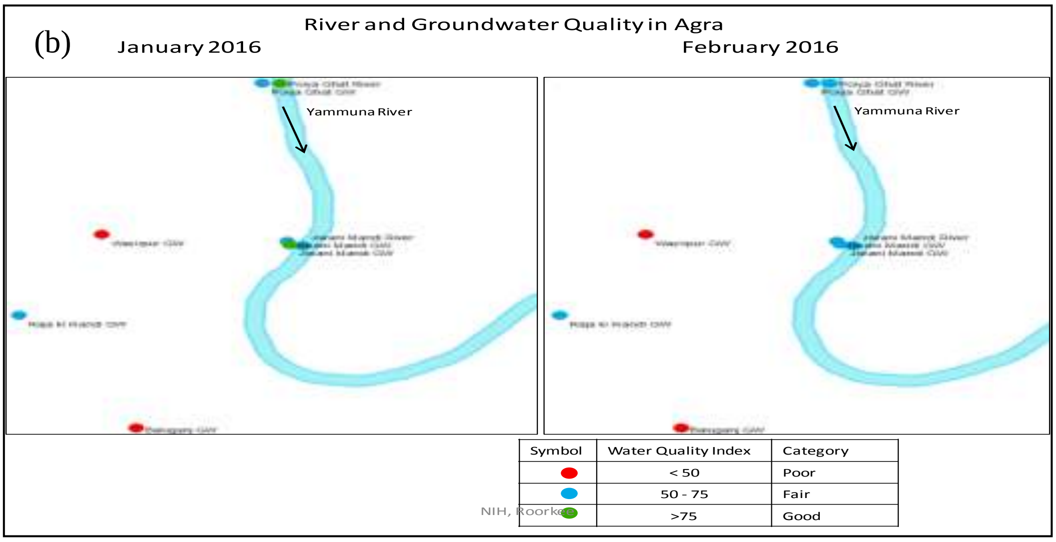


Figure 15: Water Quality Index of river and ground water: (a) Mathura and (b) Agra area.

The analyzed results of sediments of the Yamuna riverbed at Agra, carried out in the laboratory of CSSRI, Karnal, given at Table 4 showed that, in the soil, Mn^{2+} and Fe^{2+} have much higher concentration than the permissible limit in water as per the BIS standards.

Table 4: Concentration of chemical parameters in riverbed sediment of Yamuna at Agra area.

S. No.	Sample details	OC (%)	Cu (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Ca (%)	Mg (%)	Na (%)	HCO_3 (%)	Cl (%)	SO_4 (%)
	Soil sample											
1	PJSP (1) 0-21	0.307	0.899	0.846	1.523	10.480	0.080	0.066	0.016	-	0.071	0.020
2	PJSP (1) 21-42	0.130	0.524	0.427	1.098	7.246	0.080	0.006	0.010	-	0.142	0.018
3	PJSP (1) 42-63	0.489	3.532	1.550	4.982	32.320	0.130	0.006	0.014	-	0.213	0.017
4	PJSP (1) 63-84	0.228	1.576	0.900	4.670	20.600	0.180	0.006	0.019	0.122	0.178	0.017
5	PJSP (1) 84-105	0.150	1.236	0.926	2.854	12.638	0.100	0.012	0.020	-	0.178	0.018
6	PJSP (1) 105-126	0.176	1.421	0.713	3.906	19.508	0.140	0.012	0.012	-	0.107	0.019
7	PJSP (4) 0-21	0.385	0.934	0.722	2.122	4.660	0.200	0.042	0.023	0.061	0.107	0.016
8	PJSP (4) 21-42	0.372	1.289	0.510	2.028	6.400	0.200	0.012	0.047	0.061	0.142	0.016
9	PJSP (4) 42-63	0.398	2.164	1.137	2.624	12.130	0.220	0.024	0.048	0.061	0.107	0.019
10	PJSP (4) 63-84	0.470	2.383	1.235	2.291	15.208	0.160	0.012	0.049	0.061	0.142	0.016
11	PJSP (4) 84-105	0.293	1.740	0.664	2.456	7.052	0.160	0.048	0.046	-	0.142	0.015
12	PJSP (4) 105-126	0.098	0.989	0.551	1.466	4.856	0.130	0.023	0.024	-	0.213	0.016
13	PJSP (4) 126-168	0.196	0.947	0.510	1.673	6.238	0.150	0.042	0.034	-	0.213	0.015
14	PJSP (4) 168-200	0.424	3.067	1.065	5.670	14.684	0.320	0.234	0.048	-	0.178	0.013
Permissible limits (water) IS, 10500 (2012)			1.5	15	0.3	1.0	0.2	0.1	0.2	0.6	1.0	0.4

Analysis of isotopic characteristics (ΔO^{18} and D-excess) of river and ground water samples showed (Figures 16 (a) and (b)) moderate seasonal isotopic variation in the river water and predominant source of reverine base-flow often stems from isotopically stable groundwater source. The 'Deuterium excess (D-excess)' in river water during January and February is observed to be high, which indicates recycled moisture contributions to precipitations.

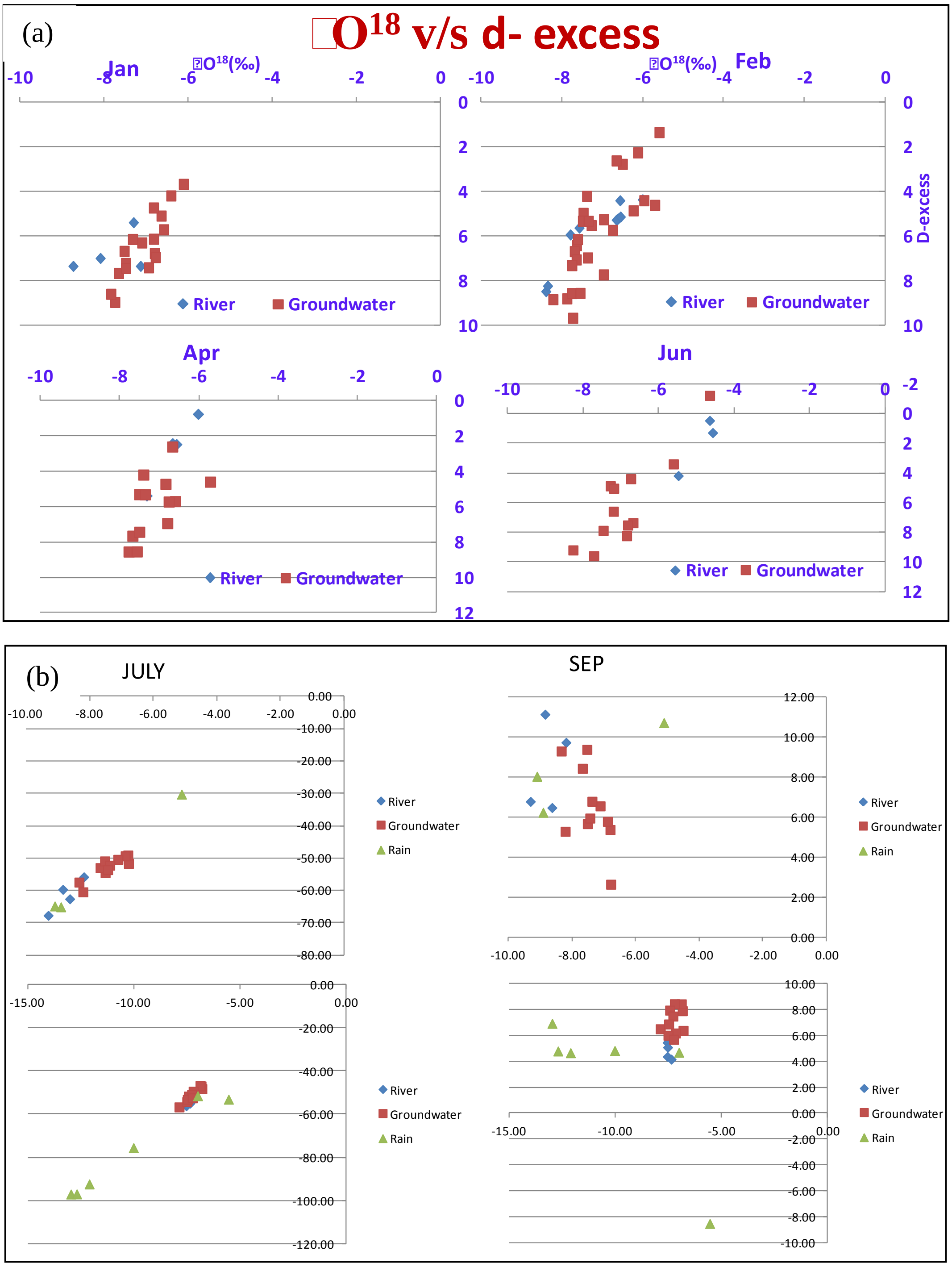


Figure 16: Variation of isotopic characteristics, ΔO^{18} versus D-excess, of river and ground water: (a) for Jan, Feb, April & June, and (b) July & Sept.

The estimation on contribution of groundwater by the Yamuna river in the Agra area indicated (Figure 17) that in and around Agra city area, major part (>75%) of groundwater during monsoon period is contributed by the Yamuna river.

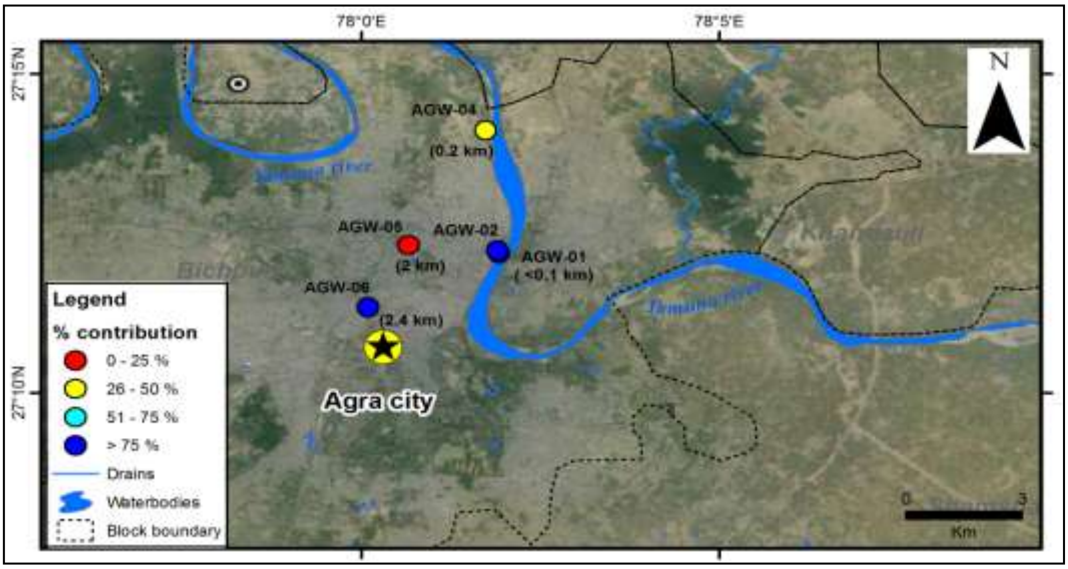


Figure 17: % contribution of groundwater by river water during monsoon period at Agra area.

With these baseline information and analyzed results of water and sediment samples, the sites selected in the premise of UPJNL at Agra and Mathura were found feasible for developing RBF schemes. The next tasks were thus to undertake exploratory drilling, analysis of soil cores chemistry and bank filtrate water quality, and finally, if passed through all these testing, installation and developing the bore well as RBF production well.

4.2.1 Development of RBF scheme at Agra and Mathura

The execution of exploratory drilling, installation & development of tube well, construction and establishment of RBF scheme, etc i.e., all field related physical works, for both the sites were given to the UPJNL-Agra Division who is the collaborating partner and beneficiary of the pilot scheme, with financial support as deposit work having NIH's role as supervisory in nature. The execution work was divided in two phases: Phase-I dealt with exploratory drilling, analysis of soil cores and extracted water chemical parameters analysis, lithological profile analysis, etc; if these are found satisfying the required conditions then continuing with the lowering and installation of tube well and also well development, and Phase-II (after accomplishment of Phase-I) would deal with installation of submersible pump, construction of pump-house, electrical fittings & fixings, installation of few hydrant points, analysis of bank filtrate water for risk/disinfectant dose assessment, etc.

The exploratory drillings as envisaged in the Phase-I for both the sites, Mathura and Agra, were carried out by the rotary drilling method to drill 450mm (18") dia bore hole upto a depth of 40 m in both the sites (Figure 18 (a) & (b)). While pursued the drilling, drilled soil core samples weighing about one kilogram were also collected almost at every 1.5 m depth interval, which could count a total 20 samples in a depth of 31 meters for Mathura site and 21 samples in a depth of 31 meters for Agra site. A snapshot of the explored soil column samples is in Figure 19. These soil samples were immediately transported to CSSRI, Karnal laboratory for analysis and determination of the soil chemical parameters.

Figure 18: Exploratory drilling by rotary method for RBF well: (a) Mathura (in the premise of UPJNL, near Gakul barrage), and (b) Agra (in the premise of Jal Kal of UPJNL).

Figure 19: Soil samples collected from exploratory bore of Agra site at various depths.

Using Spontaneous (SP) and Integrated Geophysical Resistivity Logger (IGRL), the lithological profiling of both the sites including estimate of probable water yield of different layers, and the layer that can have potential tapping zone were determined. The depths ranged between 17 m and 24 m and between 31 m and 35m in the Agra site, and depth between 11m and 30m in the Mathura site were found to be potential aquifer zones having sand layer for installation of tube well. The yield of the potential layers is estimated to be from 240 m^3/day to 360 m^3/day for the Agra site and from 480 m^3/day to 600 m^3/day for the Mathura site. The profiles of SP and Resistivity for both the sites are shown in Figure 20.

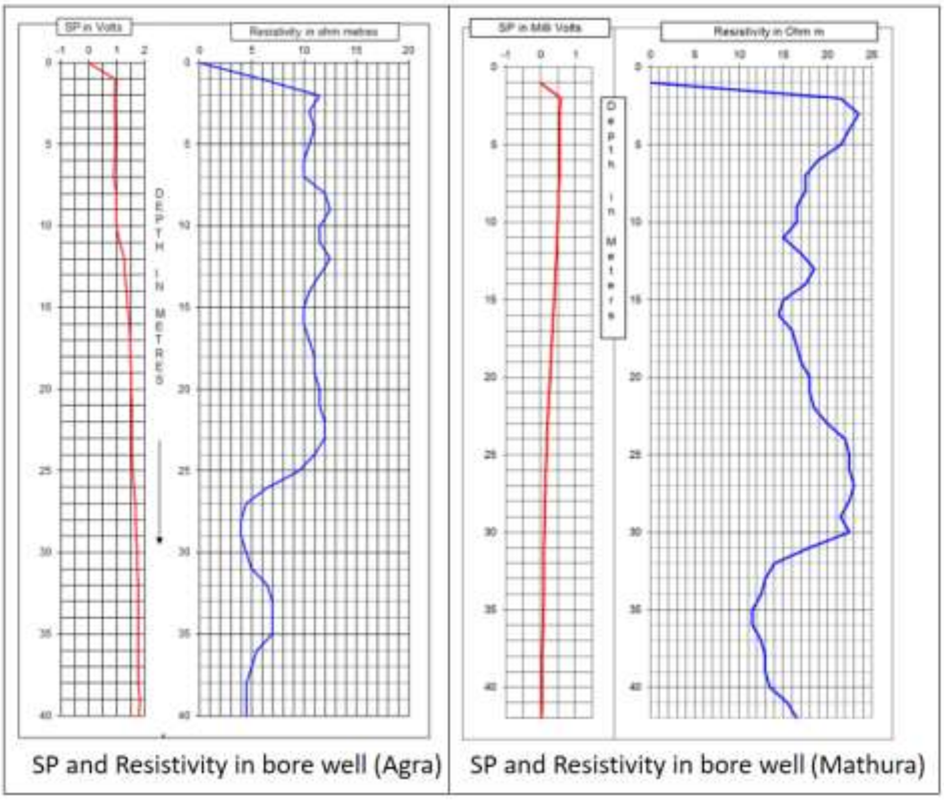


Figure 20: SP and Resistivity profile of the exploratory bore-hole of Agra and Mathura site.

Based on the SP and the resistivity logger data and profile, the lithological profile of the Agra and Mathura site was configured as given in Figure 21.

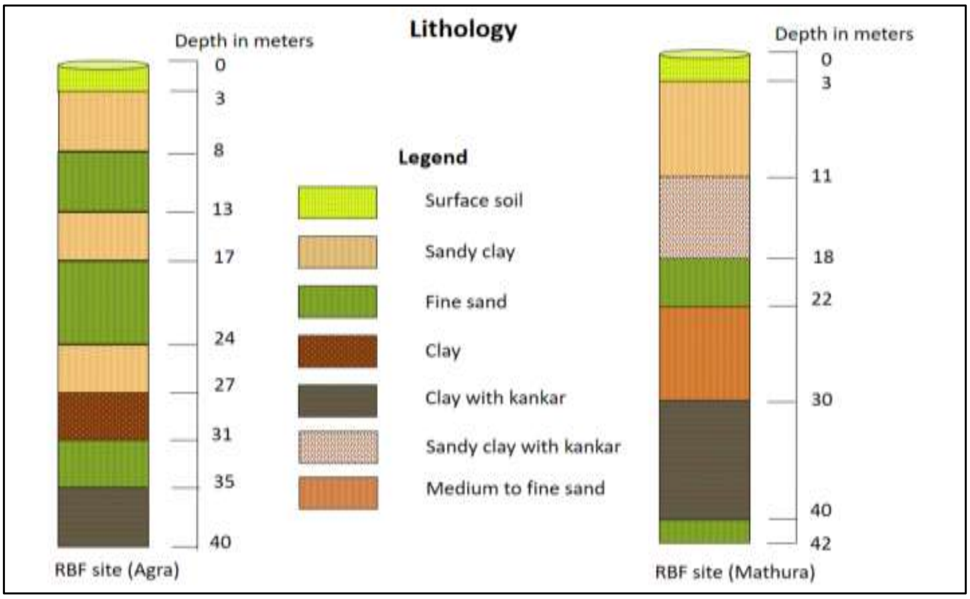


Figure 21: Lithology of the explored RBF site in Agra and Mathura.

After identifying the potential layers of aquifer, the screens for tapping the aquifer were decided and depth of slotted pipes were designed. The slotted pipes for the Agra site were placed in two depth ranges; one between 15 m and 24 m and the other one between 30 m and 33 m; while in the Mathura site, the tapping zone and well screen was placed between depth

22 m and 30 m (Figure 22). Both in Agra and Mathura site, the bail pipes were placed at 36 m depth. The diameter of the pipe including slotted and bail pipe is 150 mm. The well gap between the explored bore well of 450 mm diameter and the tube well of 150 mm diameter was developed by gravels pack of normal size 1.6 mm to 4.8 mm.

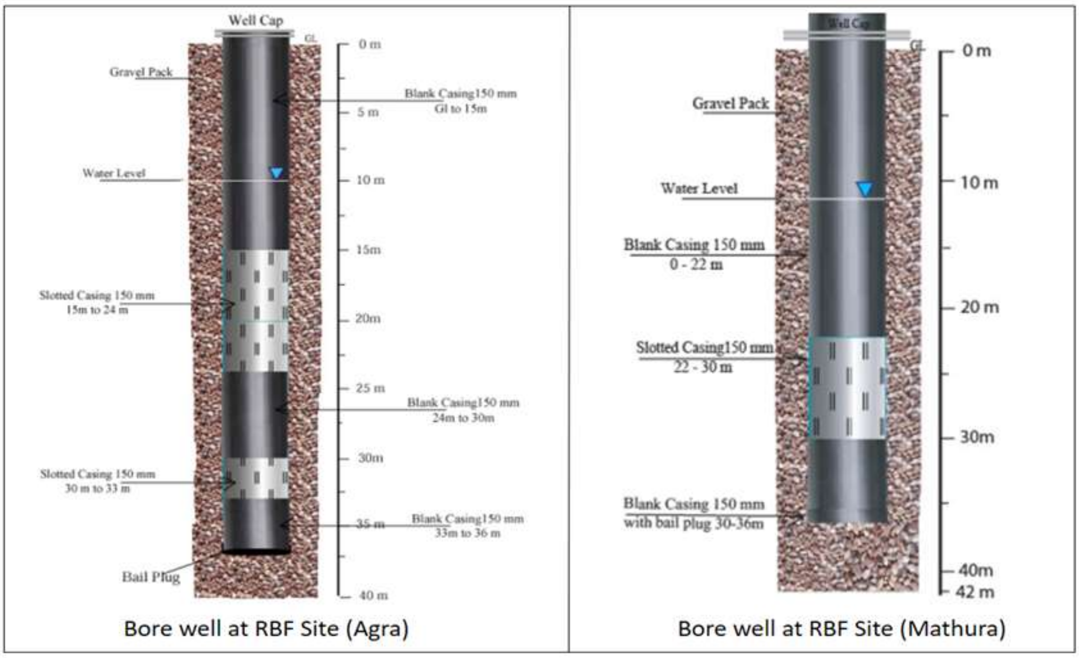


Figure 22: Design of the exploratory bore and tube wells showing tapping zones for both Agra and Mathura site.

The analyzed results of trace metals in the soil cores of Mathura site are shown at Figure 23 and that for the Agra site at Figure 24.

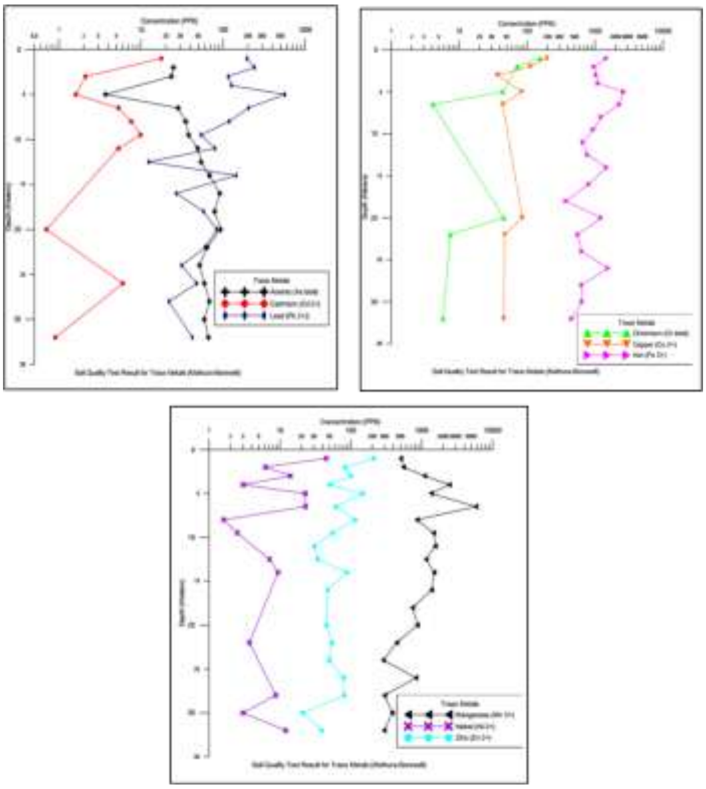


Figure 23: Depth-wise variation of trace elements in the soil cores of Mathura site.

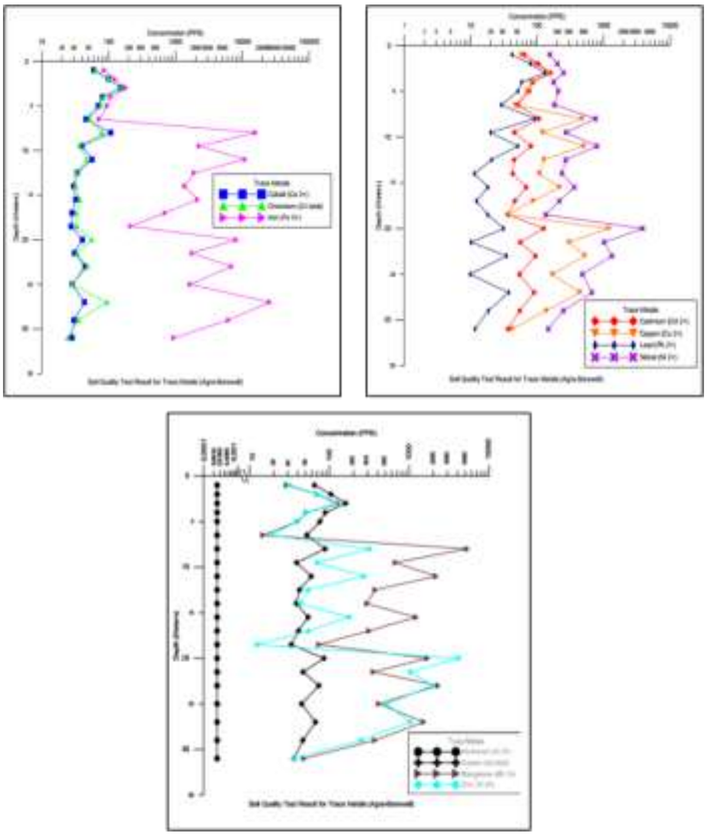


Figure 24: Depth-wise variation of trace elements in the soil cores of Agra site.

The variation of concentration of trace metals measured in the samples of extracted water from the RBF tube well installed at both the sites is shown in Figure 25. The depth-wise variation of concentration of trace metals in the soil cores showed that soils column in the Mathura site has marginally high concentration of Fe^{3+}, Pb^{2+}, As^{+}, and Mn^{2+} (Figure 23); while the soil column of the Agra site showed high concentration of Fe^{3+}, Ni^{2+}, Cu^{2+}, Zn^{2+} and Mn^{2+}(Figure 24). There is no BIS prescribed limit for trace metals in soils. The variation of concentration of trace metals in the extracted water (Figure 25) showed that both sites have concentration of trace metals below the permissible limit prescribed by BIS for drinking water (IS 10500:2012). Thus, both the sites, Mathura and Agra, are recognized as the feasible site for developing as the RBF scheme.

Having qualified through the results of chemical parameters of soil and water, hydraulic potential of the well and water yield rate, both the sites have been found feasible to develop as RBF production well through persuasion of Phase-II activities, i.e., installation of submersible pump, establishment of pump house, etc. The Phase-II comprising works of supply and fitting & fixing of 5HP submersible pump, construction of pumping plants for the tube well, pump house, stand post, etc at Mathura (Near Gokul barrage) and Agra (near Agra Water Works-I, Jeowani Mandi, Jal Kal Agra) have also been awarded to Agra-UPJNL, as a deposit work with estimated cost of Rs. 34.72 lakh and the activities of the Phase-II are in progress. The Phase-I for both the sites involved an amount of Rs.12, 23,593.

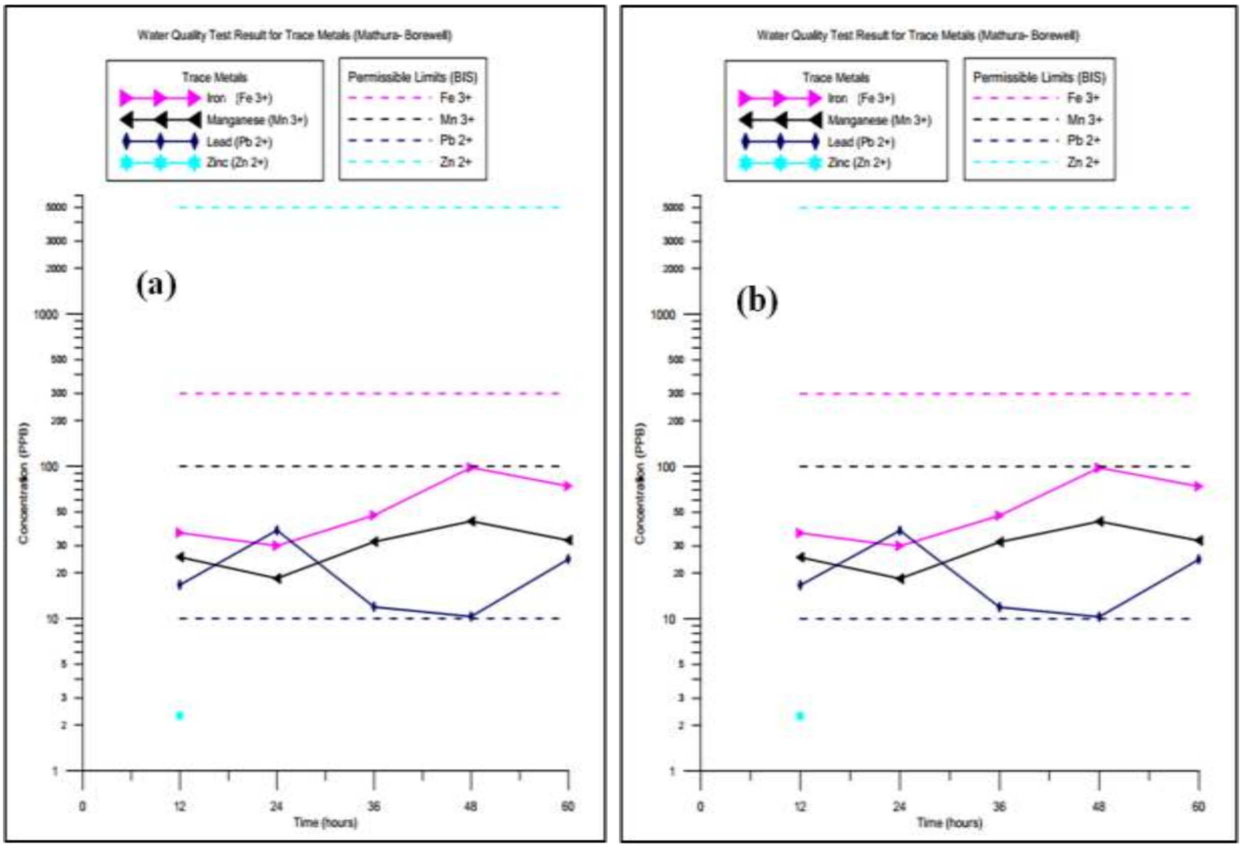


Figure 25: Variation of trace metals in the water of extracted RBF well: (a) Mathura site, and (b) Agra site.

4.3 RBF site of Barhara village in Ara, Bihar

NIH-Regional Centre, Patna is the nodal unit to pursue the RBF site in Ara district of Bihar. The reason of choosing Ara district is that, most of the villages in Ara along the Ganga River have been exposed to groundwater Arsenic contamination and villagers have no organized safe drinking water supply. The aquifer at a depth below 30/35 m is generally reported Arsenic affected in Ara & Buxar districts in Bihar. The pilot RBF scheme at Ara has been planned to demonstrate, if it could succeed as an alternate to provide safe drinking water supply in the rural Arsenic affected areas, then it would be a success story.

A number of field visits and discussions with the PHED, Govt. of Bihar were followed to finalize the site and obtain administrative clearances for a piece of required land. Despite such efforts, administrative clearance for the land in few select locations didn't materialize. Finally, the location in the premise of a temple (Figure 26) in the Barhara village has been selected in consultation with the priest (pujari) and trustee of the temple. The location has latitude of $25^{0}41'$ 0.00" N and longitude of $84^{0}43'34.94"$E.

Figure 26: Location of the selected RBF site in the premise of the temple in Barhara village of Ara district (Bihar): the Ganga River is also seen in the close proximity about 45/50 m from the boundary wall of the temple.

The site is located on the right bank of the river Ganga, and the Ganga river water at that stretch is apparently appeared to be free from contamination and looks to be clean. To investigate the hydraulic connectivity between the aquifer and the river Ganga, resistivity survey was carried out in the specified location (Figure 27). The results of resistivity survey are shown in Figure 28. From the interpretation of data in Figure 28, the depth-wise lithological profile was configured and given at Table 5. The water table is located at about 8 m below the ground surface and the depth below water table upto 50 m contains good aquifer, which is expected to be hydraulically connected to the Ganga River. Water quality of the Ganga river and the ambient groundwater were also carried out. The quality of the Ganga river water during the lean period has been found satisfying the requirement of drinking water after preliminary treatment like, disinfection. Next task is the exploratory drilling, lithological profiling, installation of tube well, RBF well development, etc.

Figure 26 : Map showing the location of resistivity survey carried out around the proposed site.

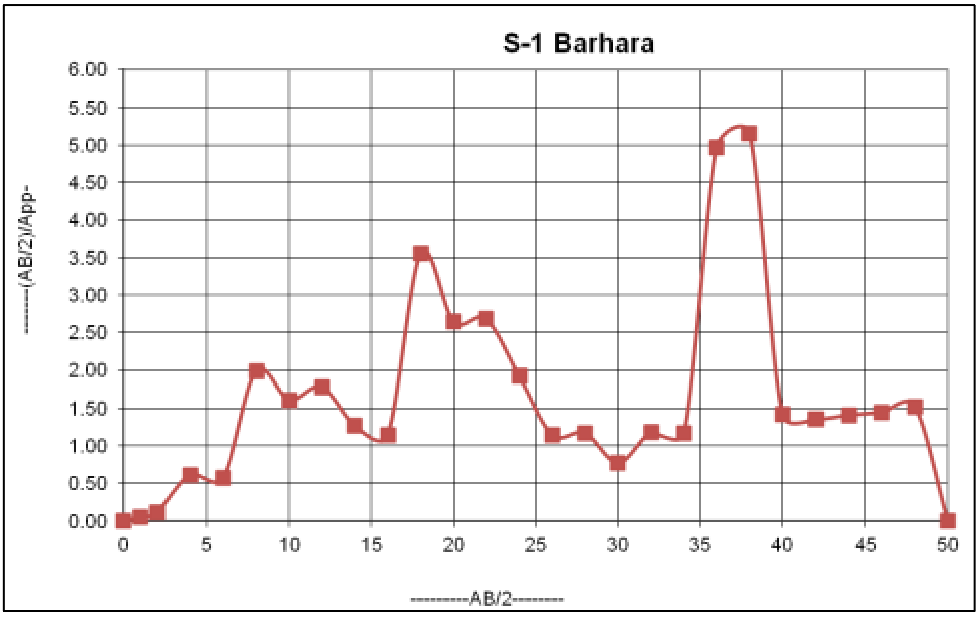


Figure 27: Variation of depth-wise apparent resistivity at the location S-1 in the Barhara village.

Table 5: Configured lithology based on the resistivity data of site S-1.

Depth (m)	Lithology
0 – 8 m	Dry Alluvium (Consisting of Sand silt and clay)
8 m	Water table depth
8 m – 40 m	Saturated Alluvium (Consisting of Sand silt and clay)
40 m – 50 m	Saturated Alluvium (Consisting of Medium to coarse Sand and clay)

The tasks of exploratory drilling, installation of tube well, development of RBF well, etc. are awarded to the PHED, Ara of Government of Bihar who is the collaborating partner and taker of the scheme in Bihar, with required financial support as a deposit work. The first phase of the work is yet to be started. Meanwhile, Hydrogeologist from the Mid Easter Region, CGWB visited the proposed site to examine the hydrogeological and lithological profile to ensure hydraulic connectivity between the river and aquifer in the proposed RBF site.

4.4 RBF site in Vommavaram village along Varaha River at Visakhapatnam

NIH-Deltaic Regional Centre, Kakinada is the nodal unit for the pilot RBF site development at Visakhapatnam. State Rural Water Supply & Sanitation Engineering Department, Government of Andhra Pradesh is the collaborating partner and taker of the pilot RBF scheme. An extensive field visit along with the State government officials were carried out to identify and select the proposed site (Figure 28). Initially, the Gosthani River stretch was proposed for development of the RBF scheme, however, the collaborating partner from the State has recommended for developing the scheme in feasible location along Varaha River. The Varaha River is located in between Kakinada and Vishapatnam city measuring about 80 km on NH-16 from the Vishapatnam city towards Kakinada. The River Varaha, originates from the Eastern Ghats in the Sannivaram Reserved Forest in Visakhapatnam District at an altitude of about 1,165 m amsl, flows 62 km towards southeast and finally joins the Bay of Bengal. It is a seasonal type river at the upstream with subsurface flow below the riverbed;

however, as it flows downstream, the river possesses the characteristics of Perennial River (Figure 29).

Figure 28: Intake Well constructed for water supply in the nearby villages at the upstream of the Varaha river and the dried up riverbed during lean period, which triggers as scarcity of drinking water supply during lean period (Feb.-May) in the villages. The upstream stretches of the river flows during monsoon period only.

Figure 29 : Downstream of the Varaha river at the same period as in Figure 28 and details of the village can be seen on the foundation stone written in Telegu language.

The river is known as ‘Varaha’ till it bifurcates into two branches just before empting into a salt creek adjoining Bay of Bengal. In the Varaha river basin, groundwater, surface water and Varaha river water samples were collected and analysed for determination of physical and chemical parameters of water, and found that, most of the groundwater samples are saline. Most of the villages along and around the downstream stretches of the Varaha River have the problem of groundwater salinity, TDS (> 1000 mg/L) (Table 6) and most of the villages don’t have organized drinking water supply system. As a result, some of the villages are forced to drink dug wells based groundwater, which has also high TDS. After several consultations with local villagers, the proposed site in the village named Vommavaram in S.Rayavarammandalhas (Figure 30) having latitude of 17^{0} 27' 20.1" N and longitude of 82^{0}47' 19.2" E located on a private land along right bank of the Varaha River has been selected for further investigation. From the interaction with the local people (Figure 31), it was noted that the river maintains perenniality in the downstream stretches including the stretch in the

Vommavaram village. Hence, the Vommavaram village is identified for river bank filtration for further investigations.

Figure 30: Downstream of Varaha river near Vommavaram village, S. Rayavarammandal.

Figure 31: Interaction with local people and in-situ River and ground water quality measurement.

Results of water quality analysis for the samples collected on different dates from different locations of the Vahara river and groundwater are given at Tables 6, 7 and 8. From Tables 6 and 7 that represent river water quality showed the high value of TDS (>1000 mg/L) and also total Alkalinity(> 600 mg/L) and in one/two stretches Cl^-, HCO_3^-, and SO_4^-; while near to Vommavaram village, i.e., near to RBF site it has minorhigh value of TDS and Total Alkalinity.

Table 6: Water quality of Varaha river (sampled on 10.01.2018)

No	Village Name	pH	EC (µmhos/cm)	TDS (mg/l)	Total Alkalinity (ppm)	Total Hard-ness (ppm)	Ca^+ (ppm)	Mg^+ (ppm)	Na^+ (ppm)	K^+ (ppm)	Cl^- (ppm)	HCO_3^- (ppm)	SO_4^- (ppm)
1	Vammavaram	7.26	2100	1344	632	528	149	38	320	49	396	632	141
2	Vakapadu	7.2	7000	4480	1932	444	19	96	2000	456	1868	1932	375
3	Pulaparthi	6.8	2300	1472	868	404	107	33	435	19	396	868	165
4	Lingarajupalem	6.8	1560	998	876	244	59	23	300	8	248	876	28
5	Upparapalli	6.9	790	506	384	180	42	18	110	16	116	384	15
6	Sarvasiddi	6.8	6000	3840	900	692	111	101	600	400	1412	900	250
7	Karrivanipalem	7.1	1170	749	456	228	51	24	180	38	220	456	32
8	Gudivada	6.7	2700	1728	648	384	64	54	415	218	640	648	104
9	Thimmapuaram	6.7	2600	1664	712	524	122	53	325	212	484	712	136

10	S.Rayavaram	6.5	2400	1536	832	288	71	27	495	17	480	832	84
11	ChinnaUppalam	6.8	2100	1344	396	568	164	39	190	62	456	396	80
12	Penugollu	6.9	650	416	384	236	40	33	50	7	68	384	15
13	PedaUppalam	6.9	690	442	220	228	22	42	45	13	72	220	8
14	Dharmavaram	6.8	1260	806	280	268	48	36	180	14	176	280	61
15	Koruprolu	6.6	1970	1261	196	512	117	53	200	100	440	196	68
16	Varaha river (Bangarampalem)	6.5	19600	12544	2932	2720	338	456	7290	393	8600	2932	1084
17	Bangarampalem	6.7	2100	1344	360	200	27	32	110	11	88	360	3
18	Varaha river (Vammavaram)	7.3	620	397	672	492	83	69	95	101	200	672	108
19	Peta Sudipuram	6.8	1570	1005	636	324	29	61	325	13	276	636	71

Table 7: Water quality of the Varaha river near RBF site in Vommavaram village (sampled on 01.02. 2018)

No	Location	pH	EC (µ.mhos/cm)	TDS (mg/l)	Total Alkalinity (ppm)	Total Hardness (ppm)	Ca^+ (ppm)	Mg^+ (ppm)	Na^+ (ppm)	K^+ (ppm)	Cl^- (ppm)	HCO_3^- (ppm)	SO_4^- (ppm)
1	Vommavaram	7	1850	1184	640	392	47	67	265	11	348	640	70
2	Vommavaram	6.6	1320	845	532	228	38	32	235	7	184	532	36
3	Vommavaram	6.7	780	499	396	144	34	15	160	6	100	396	10
4	Vommavaram	8	1630	1043	704	440	55	74	245	16	228	704	60
5	Vommavaram	7.3	1690	1082	696	376	87	39	285	15	252	696	68
6	Vommavaram	6.9	1280	819	488	260	55	30	250	8	184	488	30
7	Vommavaram	6.8	2000	1280	728	528	167	27	335	7	352	728	81
8	Vommavaram	7.3	1840	1178	540	400	59	61	325	13	340	540	61
9	Vommavaram	6.9	780	499	364	196	30	29	135	9	96	364	4
10	Vommavaram	6.9	1920	1229	804	240	95	1	405	12	324	804	81
11	Vommavaram	6.5	1870	1197	764	364	90	34	385	11	320	764	67

Table 8: Chemical and Trace elements results of groundwater samples of Vommavaram village surrounding RBF site (sampled on 11.09 2018)

Sample Name	pH	EC (µS/cm)	TDS (mg/L)	T. Alka-linity (mg/L)	Cl^- (mg/L)	T. Hardness (mg/L)	Br^+ (mg/L)	I^- (mg/L)	Po_4^{3-} (mg/L)	Si^+ (mg/L)	So_4^{2-} (mg/L)	NH_3^- (mg/L)	Mn^+ (mg/L)	F^- (mg/L)	Turbidity (NTU)
Astalaxmi Temple	7.74	1834	1173.7	296	319	328	0.06	0.06	0.17	41.1	75	0.06	0.3	1.04	0.35
River Bank (Dug/Bore)	7.15	1347	862.08	280	297	326	0.05	0.06	0.37	34.1	42	0	0.3	0.56	0.74
Pallela.Varahala Babu (Pakavenuka)	7.23	1713	1096.3	360	312	272	0.09	0.1	0.35	36.9	49	0.01	0.5	0.53	1.45
Hotel Nagababu	7.02	2470	1580.8	392	439	446	0.07	0.09	0.2	37.3	70	0.04	0.2	0.59	1.68
Hotel Nagababu (Boiled water)	7.32	2250	1440	240	477	418	0.15	0.21	0.19	39.8	75	0.36	0.5	0.48	1.54
SunkaraRamana (Boiled Water)	7.14	2690	1721.6	492	388	344	0.14	0.25	0.22	32.2	71	UR	0.2	0.66	1.88

SunkaraRamana	7.14	2640	1689.6	546	400	350	0.1	0.13	0.35	34.1	80	0.03	0.2	0.77	0.4
Panchayathi Well	8.25	1780	1139.2	378	294	338	0.2	0.27	0.13	37.2	65	UR	0.2	1.01	1.2

Table 9: Bacteriological analyzed results of groundwater and Varaha river water (sampled on 01.02. 2018)

S.No	Source	Location	Positive/ Negative	Coliform Bacteria MPN/100ml.	Remarks
1.	Ground water	Left Bank Side	Negative	0	
2.	Varaha River	River	Positive	**17**	**B**acteriologically Safe but not potable
3.	Ground water	Right Bank Side	Negative	0	Bacteriologically Safe.

Groundwater quality data showed (Table 8) that, by and large, groundwater is very good except minor high value of TDS (> 1000 mg/L) in few locations. From Bacteriological point of view, both river and ground water are largely safe. Hence, the proposed site qualifies the conditions of water quality. Next tasks are to examine the hydrogeological and hydraulic connectivity between the river and aquifer.

An in-depth geophysical survey of the proposed area through a private body was carried out to investigate river-aquifer interaction and the hydraulic connectivity between the two domains. Geophysical investigations in the form of electrical resistivity tomography (ERT) survey were carried out at 4 locations along the Varaha river near Vommavaram village stretches (Figure 32) at varying length that varied between 2.5 and 5 m electrode spacing. The standard methods for analysis of the resistivity data to delineate aquifer geometry and to identify the potential pore water seepage locations were utilized. Based on the interpretation of 2D resistivity data, the ERT maps were developed.

Figure 30: Location for the Electrical Resistivity Tomographic survey near Vommavaram village alignment in the vicinity of the Varaha River.

The resistivity model for the location showed in Figure 33 indicated, the presence of dry sand on the top soil upto the depth of 6 m (resistivity >40 Ohm.m), followed by fine sand mixed with coarse grained sand in varying proportions upto the depth of 28 m representing varied resistivity ranges between 10 Ohm.m and 30 Ohm.m. The low resistivity value < 6-10 Ohm.m indicates the presence of highly weathered Khodalitic rocks/clay in the area. Figure 33 showed the ERT model for the stretch as shown in the map. For this stretch, the profile length from 0 to 150 m indicated the dry sand, resistivity being >30 Ohm.m. The profile length from 150 m to 240 m indicated highly saturated sands, resistivity being varied between 9 Ohm.m and 12 Ohm.m. The low resistivity value <5 Ohm.m at the bottom of the profile below the depth of 30 m indicated the presence of highly weathered Khondalitic rocks.

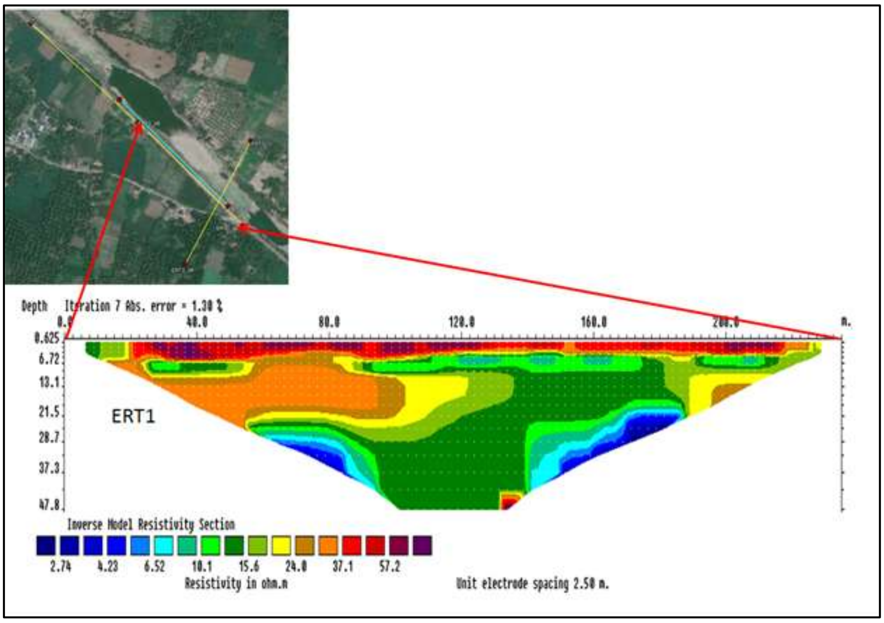


Figure 33 : Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map.

ERT survey carried out in the upstream side of the River near Vommavaram village (Figure 34) indicated that the profile length between 0 and 150 m has dry sand, resistivity being >30 Ohm.m. The profile length from 150 m to 240 m indicated highly saturated sands, resistivity being between 9 Ohm.m and 12 Ohm.m (Figure 34). The low resistivity value<5 Ohm.m at the bottom of the profile at the depth below 30 m indicates the presence of highly weathered Khondalitic rocks. The profile length between 40 m and 80 m the resistivity values of 10-15 Ohm.m revealed the presence of good potential of groundwater. This eventually suggested that the exploratory drilling of the bore well can be upto the depth of 30m between the profile length 40 m and 80 m.

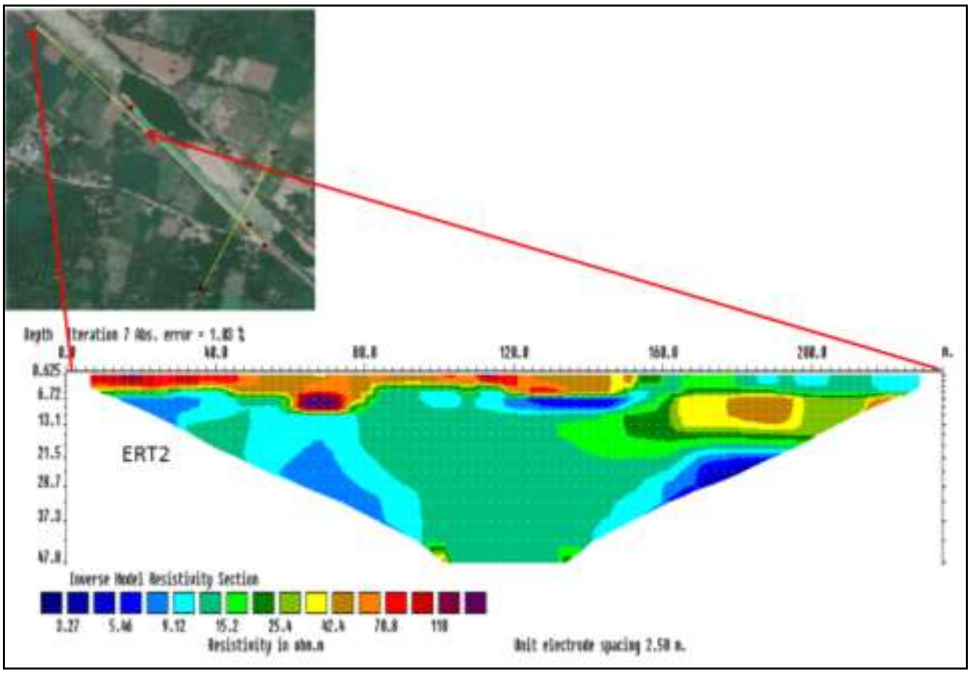


Figure 34 : Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map.

The ERT survey carried out across the river for a length of 240 m, as shown in Figure 35, indicated the depth of information of the aquifer upto about 48 m below the subsurface. The resistivity value <2 Ohm.m at both the side of the river indicated the presence of clay bed. The resistivity value between 6 Ohm.m and 10 Ohm.m indicated the presence of fine sands mixed with medium sands and the resistivity value > 30 Ohm.m indicated the presence of dry sands. In the location as shown in Figure 35 indicated that the river is hydraulically connected with the adjoining aquifer, resistivity value in the continuous length being between 4 Ohm.m and 6 Ohm.m. This also indicated the presence of highly weathered Khondalites.

The ERT survey carried out along the river stretch at the Vommavaram side, Figure 36 indicated the top 6 m soil profile is highly saturated, resistivity being between 10 Ohm.m and 12 Ohm.m for the profile length from 0 to 50 m. For the profile length from 80m to 240 m, the subsurface depth upto 6 m, it has dry coarse sand, resistivity being >30 Ohm.m. The resistivity value between 14 Ohm.m and 30 Ohm.m upto the depth of 22 m indicated the presence of fine and coarse grained sands. The resistivity value ranges from 11 Ohm.m to 14 Ohm.m in the profile length between 180 m and 205 m upto the depth of 30 m indicated the presence of good potential groundwater. Below 30 m depth, the resistivity value indicated highly weathered Khondalites which may contain more clay. These eventually suggested that the exploratory drilling of the bore well can be upto the depth of 30 m and between the profile length 180 m and 205 m.

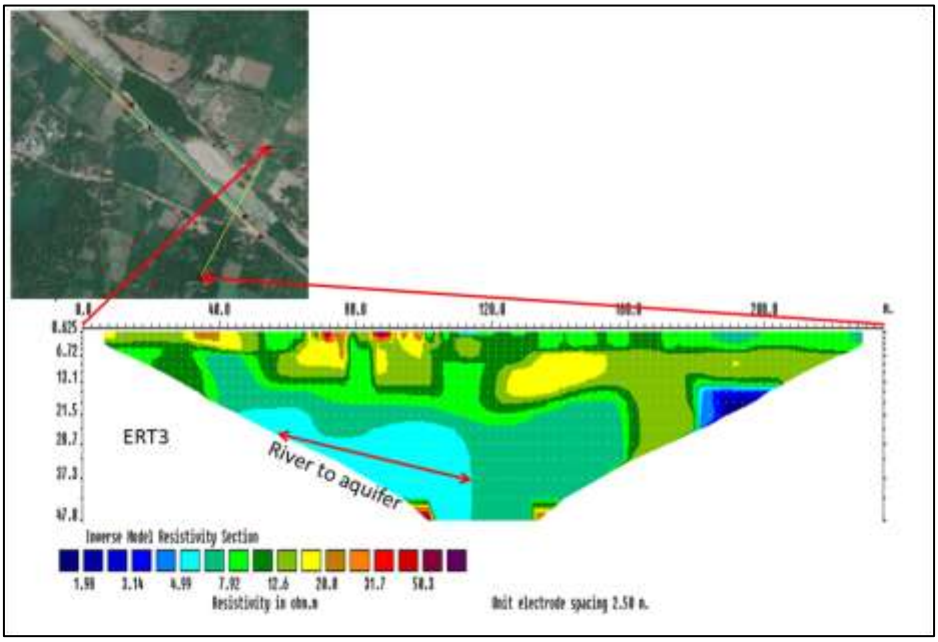


Figure 35: Electrical Resistivity Tomography (ERT) model for the Geophysical survey across the river as shown in the map.

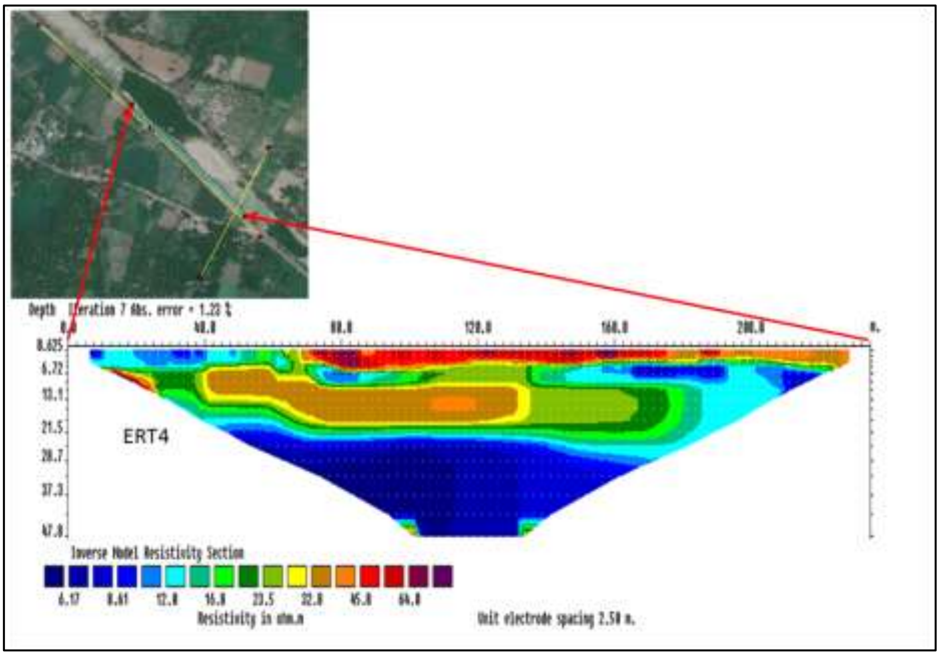


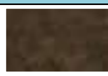
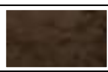
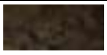
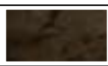
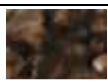
Figure 36: Electrical Resistivity Tomography (ERT) model for the Geophysical survey along the river stretch as shown in the map.

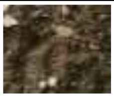
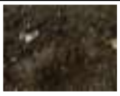
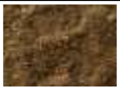
Based on the results of the geophysical survey, the exploratory drilling was decided at the location having latitude of 17^0 27' 20.1" N and longitude of $82^0$47' 19.2" E (Figure 37). The exploratory drilling work was carried out by employing rotary drilling method (Figure 37) and the work was carried out by the AP Rural Drinking Water & Sanitation Department with financial support from NIH-Roorkee as a deposit work.

Figure 37: Exploratory drilling of RBF well near Vommavaram village on the left bank of the Varaha river.

The borelog data of the exploratory drilling and illustration of the prospective lithology are given at Table 10. The drilling was carried out upto the depth of 110 ft (33.5 m). Based on the lithological profile of the bore well, the aquifer tapping depth could be in two zones; one in the depth ranges from 8 m (26 ft) to 14 m (46 ft) and the other one in the depth ranges from 25 m (82 ft) to 33 m (110 ft). However, the bottom zone has relatively high pH and there is a possibility of having saline water in the ambient groundwater. Although the upper zone has marginally high pH (> 8 upto the depth of 40 ft), but due to the mixing of induced flow by the pumping of groundwater from the river will improve the quality of bank filtrate water significantly.

Table 10: Details of drilled borelog and depth-wise lithogical profile for the explored well in the Vommavaram village, S. Rayavaram Mandal, A.P.

Depth range (ft)	Soil type (visual inspection)	pH of Soil sample	EC (µS/cm) of Soil sample	Lithology
0-3	Silty Clay, light brownish colour	7.7	221	
3-6	Clay, Brownish colour	7.57	248	
6-10	Clay, Light Black colour	8	246	
10-13	Clay, Brownish colour	8.2	268	
13-16	Clay, light black colour	8.4	281	
16-20	Clay, dark black colour	8.6	182	
20-23	Clay, Sticky black	8.6	213	
23-26	Sand, fine to medium sands, light brownish (Quartz predominant Feldspars, Garnets)	8.1	63	

26-30	Sands, medium grained dark brownish, quartz, feldspar, garnets and mafic minerals.	8.2	49	
30-33	Coarse sand, dark brownish, Mafic minerals with predo- minant black colour	8.3	49	
33-36	Coarse sand, dark brownish quartz, feldspars, mafic minerals, Quartz predominant	8.2	41	
36-40	Coarse sand, dark brownish Quartz, feldspars, mafic minerals	8.3	49	
40-43	Coarse sand, dark brownish Quartz, feldspars, mafic minerals	7.7	47	
43-46	Sand, medium to coarse, light bluish quartz with little Muscovite, Mica-dark bluish colour, Semi Transparent quartz	6.2	149	
46-50	Fine to medium grain sands, light bluish colour with little amount of muscovite, Mica, semi-transparent quartz	7.8	141	
50-55	Fine Sand mixed with clay, cement colour	8.6	385	
55-60	Clay mixed with mica Pieces and shells, Cement colour.	8.9	568	
60-65	sticky clay with shells, Black colour	8.8	703	
65-70	sticky clay, Black colour	8.6	834	
70-80	sticky clay (loose), Black colour	9	462	
80-85	Clay (loose), brown colour	8.8	286	
85-90	Clay (loose), brown colour	8.9	415	
90-95	Clay (loose), brown colour	9	319	
95-100	Clay (loose), brown colour	9	315	
100-105	Loose clay with Weathered khondalitic rock	9	127	
105-110	Hard Khondalitic rock	8.9	90	

5.0 Tasks ahead

Except the RBF site in Barhara village of Ara district in Bihar, for all other three RBF sites; Mathura & Agra in Uttar Pradesh along the Yamuna river and Vommavaram village site in

Visakhapatnam district in Andhra Pradesh along the Varaha river, Phase-I,comprising works of exploratory drilling, well development, water quality analysis, finalization of the tapping zone, etc. have been completed. For the Mathura and Agra RBF site, lowering of the tube wells and development of the wells have also been completed. For the RBF site in Barhara village (Ara), the exploratory drilling and associated works are expected to start very soon. Phase-II of the Mathura, Agra and Vommavaram village site comprising works of : installation of pumps, construction of pump houses, electrical connections & fittings, pipeline laying & hydrant points installation, etc and the performance evaluation of the RBF wells and bank filtrate water are in progress.

6.0 Concluding remarks

Out of six pilot demonstration RBF schemes proposed to establish in different hydrogeological settings of five States; one in Uttarakhand, two in Uttar Pradesh, one in Jharkhand, one in Bihar and one in Andhra Pradesh; five pilot RBF sites could explore for detailed investigations and feasibility study. Despite a lot of persuasion with the State PHED, RBF scheme in Sahebganj (Jharkhand) didn't materialize for detailed investigation and implementation of the scheme. Out of the pursued five sites, the site in Kunwa Khera Goan at Laksar sub-division of Uttarakhand State after detailed investigations and exploratory drilling and lowering of pipe were found not suitable from the context of ambient groundwater quality, particularly due to the presence of high concentration of Arsenic and Iron. On the other hand, the riverbank on which the RBF well was established was eroded by the unprecedented Solani river flood in the year 2016 and hence, the RBF scheme on the Solani River was dropped.

The Phase-I of other three sites, namely, Mathura, Agra, and Vommavaram village site in Visakhapatnam district, except RBF site in Barhara village of Ara district in Bihar, comprising works of baseline water quality analysis, geophysical surveys, exploratory drillings, identifying hydraulic connectivity between river and aquifer, identification of taping zone, lowering of RBF tube wells, well developments, etc. had been completed. The Mathura, Agra and Vommavaram village site were found suitable and feasible for developing as a full scale RBF scheme. Resistivity survey of the Barhara village in Ara district has showed promising potential. The Phase-II of all the qualified RBF sites, namely, Mathura, Agra and Vommavaram village, comprising works of installation of pumps, construction of pump houses, electrical connections & fittings, pipeline laying & hydrant points installation, etc and the performance evaluation of the RBF wells and bank filtrate water are yet to be taken up. The successful completion of these four pilots RBF schemes will help upscale of RBF in feasible hydrogeological settings in India.

References and some suggested reading materials:

Berger, P, (2002). *Removal of Cryptosporidium using bank filtration*. In: Ray, C., Melin, G., Linsky, R.B. (eds.) *Bank filtration–Improving Source-Water Quality*, Kluwer Academic Publishers, Dordrecht, pp.73-116.

Bosuben, N. K, (2007). *Framework of feasibility of bank filtration technology for water treatment in developing countries*, M.Sc Thesis, UNESCO-IHE, p. 142

Bureau of Indian Standards (BIS), (2012). *Indian Standard, Drinking Water-Specification (IS-10500:2012).* Second Revision. May, 2012. 15p.

Dash, R, I. Mehrotra, P. Kumar and T. Grischek, (2008). *Lake bank filtration at Nainital, India: water-quality evaluation*. Hydrogeology Journal, 16(6), pp. 1089- 1099.

Dillon, P. J, (2005). *Future management of aquifer recharge*, Hydrogeological Journal, 13, pp.313-316.

Ghosh, N. C., G. C. Mishra, C. S. S. Sandhu, T. Grischek, and V. V. Singh, (2014). *Interaction of Aquifer and River-Canal Network Near Well Field*. Groundwater. National Groundwater Association. pp 1-12. doi : 10.1111/gwat.12274.

Ghosh, N. C, Saroj Kumari Khatania, Shashi Poonam Indwar, Cornelius S. S. Sandhu, C. K. Jain, Sanjay Mittal, and Rakesh Goel, (2015). *Performance evaluation of riverbank filtration scheme – A case study from Haridwar*, India. Current Science. Vol. 109(2), pp.301-310.. http://www.currentscience.ac.in/ Volumes/109/02/0301.pdf

Grischek, T, D. Schönheinz, E. Worch and K. Hiscock, (2002). *Bank filtration in Europe - An overview of aquifer conditions and hydraulic controls*. In P. J. Dillon (ed.), Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse

Guenter, G , (2011). *Bank Filtration for Drinking Water Treatment. The Significance of the Water-Sediment Transition Zone.* In: Newsletter of the IWA Specialist Group on Watershed & River Basin Management

Heberer, Thomas, Ingrid M. Verstraeten, Michael T. Meyer, and Andy Mechlinski, (2011). *Occurrence and fate of Pharmaceuticals during Bank Filtration – Preliminary results from investigations in Germany and the United States*. http://opensiuc.lib.siu.edu/cgi/viewcontent.cgi?article=1153&context=jcwre.

Hiscock, K. M, and T Grischek, (2002). *Attenuation of Groundwater Pollution by Bank Filtration*. Journal of Hydrology 266, pp. 3-4.

Hrudey, S.E. and E. J. Hrudey, (2004). *Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations.* London: IWA Publishing. http://www.stmugv.bayern.de/umwelt/ boden/ download/ doc/mbode ntage2006/ seite80.pdf

Kühn, W and U. Müller, (2000). *Bank filtration: an overview*. Journal American Water works Association, 92(12), pp. 60-69.

Kumar, Rakesh, R. D. Singh, and K. D. Sharma, (2005). *Water resources of India*. Current Science. 89(5), pp. 794-811.

Maeng, S.K, S. K. Sharma, G. Amy, (2009). *Guidelines and Prediction Tool for Pharmaceuticals Removal During Bank Filtration*. Delft: 4th SWTICH Scientific Meeting.

Mueller, B, T. Scheytt, M. Sippet, S. Hannappel, J. Klein-Goedicke, and K. Duscher, (2010). *A New Approach to Calculate EMEA's Predicted Environmental Concentration for human Pharmaceuticals in Groundwater at Bank Filtration Sites*. Berlin: Springer Science+Business Media B.V.

National Water Research Institute. (1999). *Proceedings of the International riverbank filtration conference*. November 4-6, 1999. Louisville, Kentucky. 66p.

Ray, C, G. Melin, and R. Linsky (eds), (2002). *Riverbank Filtration: Improving Source Water Quality*, Kluwer Academic Publishers, Dordrech, The Netherlands, ISBN 1-4020-1133-4.

Ray, C,(2002). *Riverbank Filtration: Understanding Contaminant Biogeochemistry and Pathogen Removal*, Kluwer Academic Publishers, ISBN 1-4020-0954-2.

Sandhu C, T. Grischek, P. Kumar, and C. Ray, (2011). Potential for riverbank filtration in India. Clean Technologies and Environmental Policy 13(2), pp. 295–316.

Saph Pani, (2011-2014). *Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India*. An EU sponsored collaborative project no. 282911.

Schubert, J, (2002). *Water-Quality Improvements with Bank Filtration at Düsseldorf Waterworks in Germany*, In: Ray, C., Melin, G., Linsky, R.B. (eds.) Bank filtration – Improving Source-Water Quality, Kluwer Academic Publishers, Dordrecht, pp. 267-277.

Schmidt, C.K, F. T. Lange, H. J. Brauch, W. Kuehn, (2003). *Experiences with Riverbank Filtration and Infiltration in Germany.* Karlsruhe: DVGW-Water Technology Center (TSW).

Sharma, S. K, and G. Amy, (2009). *Bank Filtration– A Sustainable Water Treatment Technology for Developing Countries*. Delft: UNESCO-IHE.

Sontheimer, H, (1980). *Experience with bank filtration along the Rhine river*. Journal of American Water Works Association, pp. 386–390.

Sprenger, C., G. Lorensen, and A. Pakdeger, (2006): Occurence and Fate of Microbial Pathogens and Organic Compounds at Riverbank Filtration Sites in Delhi, India.

Thakur A K, C S P Ojha, T Grischek, C Ray and R Jha, (2009). *River bank filtration in extreme environment conditions.* In: Proc. Int. Conf. Water, Environment, Energy and Society (WEES-2009), 12.-16.01.09, New Delhi, 3, pp. 1340–1347.

TZW (Editor), (2006), *Exportorientierte F&E auf dem Gebiet der Wasserver- und entsorgung.*. Teil II: Trinkwasser Leitfaden. Karlsruhe: Technologiezentrum Wasser (TZW).