EFFICACY OF RIVERBANK FILTRATION IN HILLY AREA

Ph.D. THESIS

by

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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
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ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"EFFICACY OF RIVER BANK FILTRATION IN HILLY AREAS"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the **Department of Civil Engineering** of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from 2009 to 2015 under the supervision of Dr. Indu Mehrotra, Dr. Pradeep Kumar, Professors, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee and Dr.-Ing. Thomas Grischek, Professor, Fachbereich Bauingenieurwesen/Architektur, Hocshule für Technik und Wirtschaft Dresden, Dresden, Germany.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(MEDALSON RONGHANG)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(Indu Mehrotra)	(Pradeep Kumar)	(Thomas. Grischek)
Supervisor	Sup	Supervisor

The Ph. D. Viva-Voce Examination of **Medals nghang**, Research Scholar, has been held on **Jan 8th, 2016.**

Chairman, SRC **Signature of External Examiner**

This is to certify that the student has made all the corrections in the thesis.

Signature of Supervisor (s) **Head of the Department**

Dated: ____

ABSTRACT

Riverbank filtration (RBF), a natural filtration process, is in practice in several parts of the world. The quality of the filtered water mainly depends on the aquifer characteristics and quality of the source water i.e. rivers or lake water. It has proved to be successful in many cities such as Dresden, Berlin, Budapest, Louisville, Haridwar, Nanital, Mathura, Ahmedabad, etotal coliform.

RBF is a process where the subsurface water collected is directly under the influence of surface water. During the transport process, the contaminants from surface water are attenuated by a combined effect of filtration, degradation, sorption, dilution with ambient groundwater etotal coliform. The success of RBF in the middle and lower courses of the rivers in many parts of mainly Europe, North America and Asia has motivated to investigate RBF systems in the hilly/mountainous regions. Mountainous areas, in general, are remote areas and are difficult to access. Rivers in the mountainous areas are not polluted but have a very narrow discontinuous aquifer deposits with high flow velocities.

Field investigations were carried out at four sites along the river Alaknanda and its tributaries at an elevation ranging from 551-769 m above mean sea level in Uttarakhand, India namely Srinagar, Karnaprayag, Agastyamuni and Satpuli for the purpose of assessing bank filtration systems. The hydro geology and water quality of the mountainous/hilly RBF systems were investigated from 2010-2013. To understand the process, (i) columns packed with same grading of aquifer material were operated at different flow rates in the Environmental Engineering Laboratory, IIT Roorkee and (ii) columns packed with various materials were continuously fed with the Elbe River water at Flügelweg, Dresden, Germany under ambient conditions. The river water was pumped to an overhead tank maintained at a constant level. Columns were operated under controlled conditions. Results obtained there from suggesting the effect of the operating parameters or conditions on the performance of an RBF system.

RBF systems for reasonably clean rivers during non-monsoon and for high-suspended loadings in monsoon were investigated through hydro geological test such as sieve analysis from the sediment/aquifer materials, infiltration test, pumping tests in two phases (short and long duration). The first pumping test was carried out just after the drilling and commissioning of the production wells. The second set of experiments was carried out after operating pumps for one and half years. The temperatures at different depths were measured in the monitoring

wells to study the nature of the interaction between the two sources i.e. river and groundwater. Double ring infiltration test was conducted to study the surface water infiltration rate during floods.

The qualities of the river water, production well water, and ground water were assessed to evaluate the performance of the RBF. Water samples from production wells, hand pumps and from the River Alkananda at Srinagar and Karnaprayag, the Eastern Nayar at Satpuli and the Mandakini River at Agastyamuni were collected and analyzed for water quality parameters including stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) over a period of fourteen months in 2012-13. The mixing ratios of the groundwater to the river water in the bank filtrate were first established by analyzing stable isotopes $\delta^{18}O$ and $\delta^{2}H$ in water samples. Water qualities of the bank filtrates were compared with the drinking water standards. Factors influencing filtration of suspended solids and entrapment of coliform were investigated through column studies.

Observations from the hydro geological investigations suggest the suitability of these sites for RBF. Hydraulic conductivity ranged from 4.0×10^{-3} to 6.8×10^{-4} m/s. The depths of the aquifers were more than 20 m below ground level and the grain size distribution was in the range of fine silt to coarse boulders. However, the gravel and sand were predominant. The infiltration rates were found to be in the range of values of existing established RBF sites. The maximum extractable safe yield of the wells at each location was determined to be between 1200 and 4000 L/min.

The mean travel time was found to be less than one month at Satpuli and more than 10-12 months at Srinagar and Agastyamuni. Data, however, was inadequate to estimate precisely (i) travel time and (ii) seasonal variation in the mixing ratio.

Analysis of stable isotope data suggests that the production well at Satpuli is connected to the river round the year. At Srinagar, bank filtrate is isotopically similar to the river water but chemically close to the ground water i.e. water has high mineral content including nitrate. A few leaching experiments with sediment/rock samples of that area were performed. Minerals were leached on soaking or stirring the distilled water with the sediment/aquifer material and a few phyllite rocks for less than 15 mins. The leaching experiments explain mineralization of the river water during its passage through the aquifers. Some of the phyllite rocks from the Pauri road leached nitrate as much as 500-2000 mg/kg of their mass. Nitrate concentration in many samples was more than 100 mg/L. Leaching of soil/rock samples indicates the geogenic source of nitrate. $\delta^{15}N$ isotope analysis of nitrate rich water from leaching experiments, and well water further substantiated the geogenic source of nitrate.

Mineralization is maximum at Srinagar and minimum at Satpuli this is because of the short travel time between the river and production well. Total coliforms were detected once or twice in a year during monsoon. Fecal coliforms, however, were always less than the detectable numbers. Although the turbidity of the river water in monsoons was as high as 2000 NTU, in water of production well it was always less than 5 NTU.

Water from the production well in Agastyamuni has up to 30-40 % of the river water. Since the production well in Karnaprayag has so far not been connected to the supply networks, there is no flux of river water into the well. As a result riverbank filtrate is less than 10% of the river water.

At Satpuli, the production well draws the bank filtrate largely for most part of the year. Nearly, 90 % of the abstracted water is from the Eastern Nayar River. The temperature profile in the monitoring wells also suggests the minimum exchange of the river and subsurface water at Karnaprayag and maximum at Satpuli site.

To assess the bank filtration under a broad range of operational conditions, two sets of column experiments were conducted with the sediment/aquifer materials collected from the bank filtration site. Columns packed with Srinagar aquifer material were operated at a flow rate from close to 0.91 to 12.60 m/d for 72 days. The experiments suggest that there is no effect of flow rates on turbidity removal. Turbidity of all the samples was less than 5 NTU. Coliform removal, however, was sensitive to the flow rates. Coliform was not detected in the water filtered at a rate of 1 mL/min. The hydraulic conductivity of the aquifer material in the column was reduced during operation, and the maximum reduction was in the column operated at 20 mL/min. In other words, filter material is clogged if operated continuously.

Another set of four columns packed with materials of different effective sizes were operated for 31 days. Water was fed by gravity from a tank maintained at a constant level. The flow rate of the column was different due to the difference in material properties and head loss. One of the columns was filled with glass beads of uniform size representing coarser material or erosive conditions. Filtrate turbidity was always less than 5 NTU. The minimum flow rate was in the column filled with aquifer material and fine loamy soil at the top simulating the pre and post flooding condition when river beds are clogged. The maximum coliform removal occurred in the latter scenario. It was also observed that increasing the head results in de-clogging in the column filled with coarser materials (glass beads). The rise in the head at other columns(C-I to C-III) was not sufficient to remove the infiltrated solids. In glass beads column (coarser material), the entrapped solids were also removed when the flow was increased by increasing the head. However, in other columns solids deposited at the interface could not be dislodged by gravity flow suggesting that particles have entered deep into the filter material. These indicate the potential for clogging and de-clogging that can occur simultaneously during monsoon and non-monsoon in coarse materials but not in fine filter materials.

The production wells by the side of the rivers can be effective in removing turbidity and coliform at pumping rates ranging from 490-4000 L/min. The water from the wells does not have removable impurities like turbidity and coliform other than minerals. The high velocities of the rivers in hilly areas are likely to reduce the probability of clogging of the aquifer. The RBF system is sustainable in the hilly/mountainous areas.

The thesis has been organized into seven chapters. Chapter-1 defines the objective of the research. A brief literature and methodology adopted are presented in Chapter-2 and Chapter-3 respectively. The hydro geolpgy investigations along with the description of the four RBF locations in Uttarakhand, India form the subject matter of the Chapter-4. Observations on water quality monitoring at the four sites and the analysis of the data form the subject matter of the Chapter-5. Column experiments generating different scenario of RBF conditions have been described in the Chapter-6. Conclusion, limitation of the work and future scope of work are included in the Chapter-7.

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MEDALSON RONGHANG

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ABBREVATIONS

Abbreviations	Expansion	Unit of Expression
AGHP	Agastyamuni Hand pump	-
AGMW	Agastyamuni Monitoring Well	-
AGPW	Agastyamuni Production Well	-
APHA	American Public Health Association	-
ASTM	American Society for Testing and Materials	-
BRO	Border Roads Organization	-
BTC	Breakthrough curves	-
CGWB	Central Ground Water Board	-
DO	Dissolved oxygen	-
DOC	Dissolve Organic Carbon	mg/L
E.Coli	Escherichia Coli	-
EC	Electrical conductivity	µS/cm
EC	Electrical conductivity	-
EDTA	Ethylene Diamine Tetra Acetic	-
GPS	Global Positioning System	-
HP	Hand pumps	-
IC	infiltration capacity	-
IIT	Indian Institute of Technology	-
KPHP	Karna Prayag Hand pump	-
KPMW	Karna Prayag Monitoring Well	-
KPPW	Karna Prayag Production Well	-
LPM	Liter Per Minute	-
LTB	Lauryl Tryptose Broth	-
m BGL	Meters Below Ground Level	m
mm	millimeter	-
MS	Mild Steel	-
NIH	National Institute of Hydrology	-
NOM	Natural Organics Mater	-
NTU	Nephelometric Turbidity Unit	-
OCPs	Organo Chlorine Pesticides	-
ODEX	Overburden Drilling with Excentric	-
PW	RBF production wells	-
RB	Riverbed	-
SNHP	Srinagar Hand pump	-
SNMW	Srinagar Monitoring Well	-
SNPW	Srinagar Production Well	-
SPHP	Satpuli Hand pump	-
SPMW	Satpuli Monitoring Well	-
SPPW	Satpuli Production Well	-
SUVA	specific UV absorbance (	-
SW	Source water (rivers)	-
THMFP	Tri Halomethane Formation Potential	-
TOC	Total Organic Carbon	mg/L
TSS	Total Suspended Solids	mg/L
UFZ	Helmholtz Centre for Environmental Research	-
UJS	Uttarakhand Jal Sansthan	-
VSMOW	Vienna Standard Mean Ocean Water	-
W	Public tube wells,	-

NOTATIONS

Symbol	Meaning	Unit of Expression
A_s	Cross sectional area of the column	cm^2
c	Constant	-
C	Concentration at time t	[M/L]
Co	Initial concentration	[M/L]
C_u	Uniform coefficient	[-]
d	Days	Unit
d	Casing diameter	[L]
$_f$	Infiltration capacity at any time	[L/T]
f_o	Infiltration capacity at the start	[L/T]
H	Horizontal	-
H	Pre-test rest water level measured from the aquifer base	[L]
h	Steady-state water level after a constant drawdown is obtained	[L]
h	Height of static water	[L]
H	Saturated thickness of aquifer	[L]
h_{GW}	Available saturated thickness for partially penetrating well	[L]
I	Infiltration rate,	[L/T]
K	Hydraulic conductivity	[L/T[
k	Hydraulic conductivity	[L/T]
K_c	Deposition coefficient,	-
L	Length of the column.	[L]
LPM	Liter Per Minute	[T]
m BGL	Meters Below Ground Level	[L]
MSL	Mean Sea Level	[L]
Q	Discharge	$[L^3/T]$
QA	The steady state flow rate	[L3/T]
QF	Yield	[L3/T]
R	Radius of influence	[L]
r	Radius of the well-bore	[L]
R_w	Radius of influence	[L]
s	Constant drawdown	[L]
S	Storage coefficient	
S_s	Specific storage	[1/L]
t	Time from the beginning of rainfall	[T]
T	Transmissivity	$[L^2/T]$
t_{50}	Effective contact time	[T]
V	Vertical	-
V	Volume	(L3)
V	Volume	L^3
v	Interstitial pore velocity,	[L/T]
Z	Cumulative infiltration	[T]
Z_0	Saturated thickness of the aquifer above the hard rock after steady state drawdown.	[L]
$\delta^{18}O$	Stable isotopes of oxygen	‰
δ^2H	Stable isotopes of Hydrogen	‰
ρ_b	Bulk density	$[M/L^3]$
ρ_p	Particle density	$[M/L^3]$
η	Porosity	[%]

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CHAPTER-1
INTRODUCTION

Planning, development and management of water resources to fulfill the demand of drinking water is of prime importance (World bank 2010; Kathpalia and Kapoor, 2002). It has become increasingly necessary to get safe drinking water at minimal cost. One of the options is to supply water through riverbank filtration (RBF) as an alternative to direct surface water abstraction followed by extensive treatment. The success of RBF schemes depends on suitable hydro geology conditions.

Many cities in India are situated on the banks of the perennial rivers where hydro geology conditions are appropriate for the RBF projects. RBF system has been a proven low cost, sustainable and efficient water treatment technology. In RBF, sub-surface water, which is in direct connectivity with the surface water, is abstracted. Surface water (from a river, lake or pond) either flows naturally towards the abstraction/production well or the flow is induced towards the production well during pumping. The surface water that flows through the aquifer undergoes changes in quality due to the combined effects of physical, chemical and biological processes such as filtration, dilution, sorption, biodegradation, etotal coliform. (Kühn and Müller, 2000; Boulding and Ginn, 2003 &2004). The naturally filtered water or the bank filtrate is supplied with or without disinfection (Dash et al., 2008).

1.1. BACKGROUND

Surface and ground waters are the primary sources of water supply. Artificial recharge like rainwater harvesting is also becoming common in several parts of the country. Rivers and lakes are getting polluted due to extensive runoffs from agriculture and urban watersheds. Groundwater is a critical resource in India, accounting for over 65% of irrigation and 85% of the drinking water supplies. Due to heavy pumping, groundwater is depleting with time (Rosegrant et al., 2002; World Bank, 2010). RBF is a natural process of surface water purification. The wells are drilled in alluvial aquifers along the riverbank. The flow of the river is induced provided the well on the bank is hydraulically connected to a river or any other surface water body (Hiscock and Grischek, 2002; Ray, 2008). These wells extracting bank filtrate can be vertical (e. g. tube wells), horizontal (e.g. Ranney®/collector/radial wells) or an inclined well. In India, RBF has proven to be successful in Haridwar, Delhi, Mathura, and Ahmedabad to name a few (Dash et al., 2010; Sprenger et al., 2008; Lorenzen et al., 2010;

Singh et al., 2010; Kumar et al., 2012; Singh, 2008; Gurunadharao and Gupta, 1999; Sandhu et al 2011). The water supply of Nainital in Uttarakhand is entirely through Lake Bank filtration (Dash et al, 2008).

1.2. OBJECTIVE

To explores the possibility of the riverbank filtration in the hilly region.

1.3.MOTIVATION

The stretches of the rivers in the mountainous areas have a different morphology than the rivers in the plains. The river valleys in the hills/mountains are V-shape or narrow U-shape whereas in plain areas valleys are broad U-shape type. The slope of the riverbeds in the hills are steep whereas in plains rivers flow down at a moderate/low gradients. Floodplains are narrow in the hills (e.g. Arkansas River) with high gradient (water slope: 0.023) and stream mean velocity higher than 2.64 m/s. Whereas plains have vast flood plains with lower gradient (water slope: 0.004) and stream mean velocity lower than 1.82 m/s (Raymond et al., 1989). Meanders may be present in rivers in hills, but they are not as curvy as those found in rivers of the plain region

Considering (i) the success of RBF in plains and (ii) differences between the stretches of the rivers in hilly/mountainous and plain areas it became necessary to investigate RBF in the hilly areas.

1.4 EXPECTED OUTOTAL COLIFORMOME OF THE RESEARCH

The expected outcome of the research is as under:

(i) to gain an insight in to the bank filtration in the hilly area where the aquifer is localized or discontinuous,

(ii) to understand the effect of steep morphological gradient and coarse breaded river bank

(iii) Whether riverbank filtration can augment the existing water supply in the mountainous area.

1.5. SCOPE OF WORK

With the above facts in view, RBF facilities at four sites namely Srinagar, Satpuli, Agastyamuni and Karnaprayag in Uttarakhand have been investigated. Steps given as under were followed to achieve the set objective:

1. Reconnaissance in Srinagar, Karnaprayag, Satpuli and Agastyamuni to identify sites suitable for installation of RBF facilities particularly wells
2. On-site hydrogeology investigations
3. Water quality monitoring to assess the performance of RBF facilities
4. Groundwater interaction with the rivers

Also, columns packed with aquifer and other materials were run.

CHAPTER 2
LITERATURE REVIEW

The Glasgow Waterworks Company in the United Kingdom developed the first known utility of RBF for public water supply in 1810. They installed perforated collector pipes parallel to the bank of the River Clyder to extract river water (Ray et al., 2002). RBF, a natural treatment process has been in use for the production of drinking water in many parts of the world such as Austria, India, Germany, The Netherlands, United Kingdom, United States, Serbia etc. (Sontheimer, 1980 and 1991; Kühn and Müller, 2000;Sacher and Brauch, 2002;Dillon et al., 2002; Hiscock and Grischek, 2002; Ray et al., 2002, 2011; Lorenzen et al., 2008; Hubbs, 2006; Ray, 2008; Sandhu et al., 2011). RBF has also been used for replenishing groundwater in The Netherlands and Slovenia (Grützmacher et al., 2008; Grünheid et al., 2005; Hiemstra and Kolpa, 2003; Jekel and Heinzmann 2003).RBF accounts for 45-50% of potable supplies in the Slovak Republic and Hungary, 16% in Germany and 5% in The Netherlands(Grischek et al., 2002; Hiscock and Grischek, 2002; Tufenkji et al., 2002; Eckert and Irmscher, 2006; Lee and Lee, 2009). The riverbank filtrate is abstracted by siphon system, radial wells, dug wells or vertical wells.

In India dug wells or open wells on the bank of the river Ganga are in use for more than 25 years in the cities like Haridwar, and Rishikesh in Uttarakhand ((Sandhu et al., 2011).). RBF facility comprising of 22 RBF wells located at a distance of 4-250 m from shoreline between the river Ganga and the Upper Ganga Canal (UGC) pump around 25000 m^3 of water every day (Thakur and Ojha, 2010; Dash et al., 2010). Vertical wells on the bank of the Naini Lake in Nainital (Uttarakhand) abstract lake water through Lake Bank filtration. RBF through Ranney collector wells on the bank of the river Yamuna is in operation in New Delhi (Mann, 2007; Lorenzen et al., 2008, 2010; Sprenger et al., 2011).

The water supply of Mathura (Singh et al., 2010) and Ahmadabad (Singh, 2008) is through horizontal collector wells on the bed of the rivers Yamuna and Sabarmati respectively. Small diameter bore well/tubes well are also being used at various locations like Patna, Kharagpur, New Delhi, etc. (Sandhu et al., 2011, Sprenger et al., 2011; Dalai and Jha, 2014).

2.1 RIVERBANK FILTRATION

Bank filtration technology is the generic term applied to a natural treatment process of surface water. Bank filtration induces the flow of surface water through a hydraulically connected aquifer by controlled pumping from the abstraction well located adjacent to the surface source like river or lake (Figure 2.1).

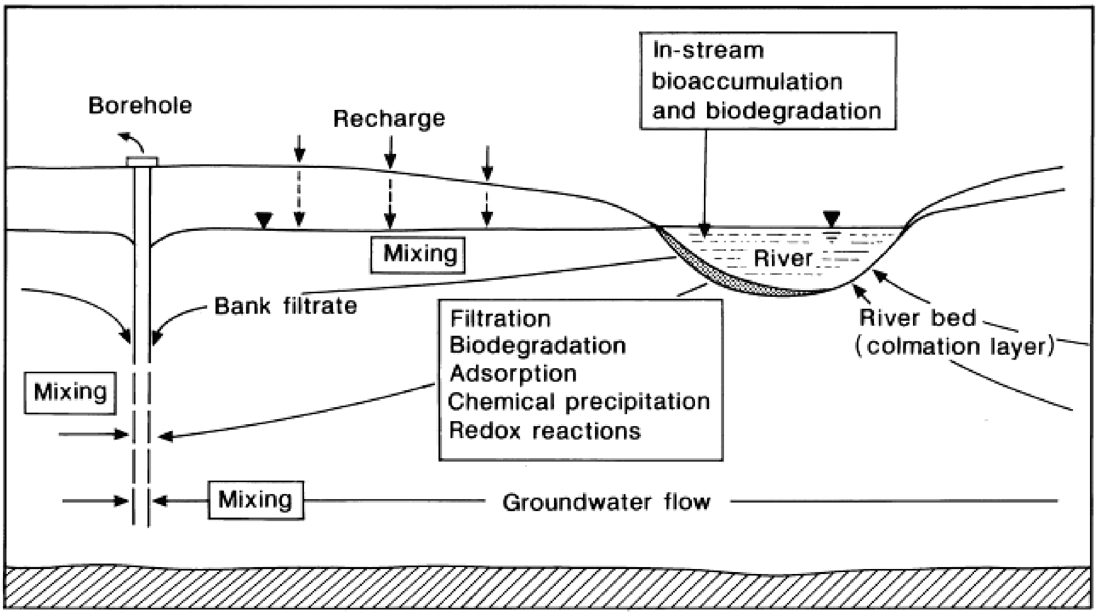

Figure 2.1 Conceptual sketch of Riverbank filtration system (Hiscock and Grischek, 2002).

The aquifer serves as a natural filter, where processes such as filtration, dilution, sorption, precipitation, redox reactions, leaching and biodegradation take place thereby improving the quality of the river water (Kühn and Müller, 2000; Boulding and Ginn, 2004). Sizes of such filtration schemes vary widely. Some RBF well fields produce more than 378541 m^3/d (Ray et al., 2002).

The summary of the existing bank filtration scheme with the aquifer characteristic is given in Table 2.1

Table 2.1 Summary of the existing bank filtration Scheme in the world

Site Location	Well type*	Aquifer thickness (m)	Travel time (d)	Number of well	Distance from the well –river (m)	Hydraulic conductivity (m/s)	Well Capacity (L/min)	River
Cincinnati, Ohio	V	~30	-	10	-	8.8×10^{-4}-1.5×10^{-3}	105000	Great Miami
Independence, Missouri	H	-	-	1	-	-	39600	Missouri
Columbus, Ohio	H	-	-	4	-	-	105000	Scioto/Big Walnut
Jacksonville, Illinois	H	25-27	-	1	-	$2\text{-}3\ \times10^{-3}$	21000	Illinois
Kalama, Washington	H	-	-	1	-	-	6600	Columbia
Kansas City, Kansas	H	-	-	1	-	-	105000	Missouri
Galesburg, Illinois	H	-	-	1	-	-	6840	Mississippi
Kennewick, Washington	H	-	-	1	-	-	7860	Columbia
Lincoln, Nebraska	H & V	-	-	2H &44V	-	1.4×10^{-3}	91800	Platte
Mt Carmel, Illinois	V	-	-	1	-	-	2640	Wabash
Sacramento, California	H	-	-	1	-	-	26400	Sacramento
Terre Haute, Indiana	H	-	-	1	-	-	31800	Wabash
Louisville, Kentucky	H &V	21-35		1+1	-	6×10^{-4}	52500	Ohio
Maribor, Slovenia	V	-	-	~13	-	2×10^{-3} -4×10^{-3}	45000	Drava
Mockritz, Germany	V	-	-	74	-		75600	Elbe
Torgau, Germany	V	10-55	-	42	-	2.0×10-3-6×10-4	104220	Elbe
Torgau-Ost, Germany	V	40-55	-			1×10^{-2}-7.5×10^{-5}m/s	-	Elbe
Haridwar, India	V	3-21	-	16	-	-	44 444	Ganga
Saloppe, Goelitz	-	-	7 -15	-	200	2×10^{-4}-4.8×10-^{5}	11798	Elbe
Hosterwitz , Dresden	-	3-70	25-300	-	>50	-	14-416400	Elbe
Göttwitz, Germany	V	10		4	200	2×10^{-4}	1179.8	Elbe
Görlitz Weinhübd sati	-	10	8-24	32	50-150	1×10^{-4}	7806.1	Lausitzer Neisse
Meissen-Siebeneischen	-	15-20	-	3	1000	$1.2\text{-}1.4\times10^{-4}$	2637	Elbe

Chiang Mai, Thailand		20-40	-	-	-	$1.2\text{-}5.7\times10^{-4}$	-	Ping
Haridwar, Uttarakhand, India	V	7-10	2->100	22	15-110	-	33000	Ganga
Patna, Bihar, India	V	150-300	-	-	9-236	-	-	Ganga
Naital, UK, India	V	22-37	8->30	9	4-94	-	16737	Naini Lake
Bhintal,UK,India	V	48	-	1	16	-	225	Bhimtal lake
Henry,Illlinoi, US	-	15-20	-	-	-	$2\text{-}3\ \times10^{-3}$	-	Illinois
Cedar Rapids, Iowa	V&H	12-18	5	53	19.5	$7.5\times10^{-5}\text{-}1\times10^{-3}$	-	Cedar
Boardman, Oreon, US	H	13	-	2	-	3.7×10^{-3}	63000	Columbia
Casper, Wyoming	-	3-12	-	-	-	$9\times10^{-4}\text{-}3\times10^{-4}$	-	North Platte
Dresden-Tolkewitz, Germany	-	10-13	-	-	-	$1\times10^{-3}\text{-}2\times10^{-3}$	-	Elbe
Auf dem Grind, Dusseldrof, Germany	-	25-30	-	-	-	$1\times10^{-3}\text{-}1\times10^{-2}$	-	Rhine
Flehe, Dusseldrof, Germany	-	10-12	-	-	-	$3\times10^{-3}\text{-}6\times10^{-3}$	-	Rhine
Böckingen, Germany		3-5	-		-	1×10^{-2}	-	Neckar
Karany, Czech Republic	-	8-12	-		-	4×10^{-4}	-	Jizera
Palla, Delhi, India	V	15.5-18	1.5-3	90	-	-	1667	Yamuna
Muzeffar Nagar, UP, India	V	8-15	-	-	68	-	20-208	Kali
Mathura, Utter Pradesh	-	15.5-18	1.5-3	-	Beneath riverbed	-	-	Yamuna
Ahmadabad, Gujarat	H	10-11	-	7	Beneath riverbed	-	76389	Sebarmati
Budapest, Hungary	-	20-25	-	700	850	-	506945	Danube
Penbroke, New Hampshire	-	9.7-18.9	5	-	55	-	-	Soucook
Milford, New Hampshire	-	19.8	-	1	23	-	-	Souhegar
Kharagpur, WB, India	H	6-8	-	1	Beneath riverbed	-	15764	Kangsabati
Medinipur, WB, India	H	6-11	-	1	Beneath riverbed	-	11042	Kangsabati
Kesarwala, India	V	48	-	1	40	-	625	Song
*(H= Horizontal; V=Vertical); - information not available; (compilation from Ray et al., 2002; Dash et al., 2010; Sandhu. 2011; Grischek et al. 2002)								

2.2. WATER QUALITY IMPROVEMENT DURING RIVERBANK FILTRATION

During RBF turbidity, total coliform, total aerobic spores and microscopic particulate impurities in the river water are removed. Most of the removal occurs within the first meter of filtration (Dash et al., 2010; Wang et al., 2003).

2.2.1. Turbidity Removal

The effectiveness of the bank filtration in removing significant level of turbidity has been demonstrated by Dash et al. (2008); Dillon et al. (2002); Wang et al. (2003), Ray (2002). Dash et al. (2010) and Thakur and Ojha (2010) has reported up to 2.5-3 log removal (Eq. 2.1) of turbidity from the river Ganga at Haridwar RBF well. The turbidity of the river water as high as 1600 NTU has been found to reduce to < 1 NTU in the bank filtrate

Log removal = log influent concentration – log effluent concentration …………. …..2.1

2.2.2. Removal of Microorganisms

Weiss et al. (2002) studied three RBF sites in the US and observed 2.6-3.3 log reductions in *E. Coli* bacteriophage and 1.9-2.3 for *E.Coli* F-amp bacteriophage. Sprenger et al. (2014) have also conducted a similar study at RBF sites in Delhi by using coliphages and enteric viruses. They found approximately 5-log removal after flow path of only 3.8 m. Under steady state conditions in the saturated sand aquifer, RBF can achieve up to 8-log virus removal over a distance of 30 m in 25 days (Schijven et al., 2003; Personné et al., 1998). It also attenuates micro particles of organic origin (Grischek et al., 2003; Kühn and Müller, 2000; Schijven et al., 2003; Baveye et al., 2003)

Hurst et al. (1980), Yates et al. (1987), Blanc and Nasser (1996), Gerba (1985), Matthess and Pekdeger. (1988), Sinton et al. (2000 & 2012), Bitton et al. (1992), and Sinton et al. (2000) documented the factors influencing the inactivation of microorganisms. Also, Partinoudi and Collins (2004&2007, Skark et al. (2006), Lee et al. (2009) have shown that the bacterial removal capabilities of RBF are independent of any groundwater dilution.

2.2.3. Removal of Inorganic and Organic Micro-Pollutants (OMP)

Jüttner (1995 & 1999) described the odorous compounds removal from river water in Germany through bank filtration. Sontheimer (1980) has demonstrated removal of heavy metals from the lower Rhine River. Grischeck et al. (1998) have shown the attenuation of organics and nitrates from the Elbe River. Vertraeten et al. (2003) have shown the elimination of triazine and acetamide herbicides from the river Platte through RBF in Nebraska. Overall, these studies suggested that the removal and transformation of pollutants are site-specific and highly dynamic (Hiscock and Grischek, 2002)

Logsdon et al. (2002), Weiss et al. (2004), Quanrud et al. (2005), Hoppe-Jones et al. (2010) studied and found 50% removal of TOC, trihalomethane formation potential (THMFP) and synthetic organic chemicals in the riverbank system. The studies conducted by Singer et al. (1993), Singer (1999), Weiss et al. (2003) and Wang (2003) at RBF systems on the Ohio, Wabash and Missouri Rivers in the US have shown 50-60% DOC removal during RBF.

Removal of organics and DBPs forming potential during RBF has been reported across the world by many authors like Ray et al. (2008), Grützmacher et al. (2009), Massmann et al. (2005), Hubbs (2010), Wang (2003a), Weiss et al. (2003), Kühn and Müller (2000). The removal of organic micro pollutants (non-polar volatile compounds and pentachlorophenol, EDTA etc.) was studied in Switzerland (Ray et al., 2003, Schaffner et al., 1987). Long-term measurements have indicated that RBF systems have a nearly constant performance in removing dissolved organic constituents in the river water without significantly accumulating in the subsurface (Sontheimer and Nissing, 1977; Kühn and Müller, 2000, Stuyfzand, 1998) showed a strong relationship between the removal of organic constituents and the redox environment

Various studies conducted reveal that RBF systems placed in the deposits of sand and gravel like Esker Inland, Hietasalo abstract high bank filtrate with less microbial removal (Miettinen et al., 1997). RBF located in sandy alluvium are found to be effective in removing natural organics matter (NOM) and organic contaminants present in surface water (Kuhlmann and Kaczmarcyk, 1995). However, removal largely depends on their biodegradability and anthropogenic contaminants found in the surface water.

2.3. ADVANTAGES AND DISADVANTAGES OF RBF

Advantages and disadvantages of the RBF are summarized as under:

2.3.1. Advantages

- Elimination of suspended particles with the attached pollutants (Wang, 2003)
- Reduction in the fluctuations of water quality (Hiscock and Grischek, 2002)
- Removal of heavy metals (Lorenzen et al., 2010;Dubey et al., 2012)
- Removal of organic micropollutants, bacteria, and viruses (Weiss, 2005; Schijven et al., 2003; Sprenger et al., 2008 & 2014).
- Free from carbon footprint if a photovoltaic system is integrated with the RBF wells (Ray and Jain. 2011; Nayar et al., 2007).
- RBF can help to reduce the use of chemicals and accumulation of disinfection by-products in drinking water (Weiss, 2005; Luckins, 2014; Singer, 1999).
- Lower maintenance compared to the convention treatment methods due to it simpler technique and no involvement of sophisticated components (Hunt et al., 2003).
- RBF systems can moderately sustain draught or high flood conditions (Squillace, 1996 Chen and Chen. 2003; Doble et al., 2012).

2.3.2. Disadvantages

- Clogging of the aquifer /filter bed
- Geochemical interactions of the bank filtrate with rock and aquifer materials and mixing with the groundwater that result in raising the concentrations of notably ions like Fe^{2+}, Mn^{2+}, As, NH_4^+, CH_4, Ca^{2+} and bicarbonate which cannot be fully regulated.
- The formation of unsaturated conditions beneath the river occurs if groundwater abstraction rates are not adapted to the hydraulic conductivity of the riverbed or if the hydraulic conductivity of the riverbed material is reduced due to surface water pollution (Type 4 in Figure 2.3).

2.4. TYPE OF FLOW DURING BANK FILTRATION

The interaction of surface water and groundwater are different in different landscapes ranging from the mountain to the coastal regions. Within these landscapes, groundwater systems range from local to regional (Winter, 1995; Sophocleous, 2002; Anderson, 2003)

Few authors have discussed important aspects such as mountain terrain, riverine systems, hummocky terrain, karst terrain, and coastal terrain in the context of bank (Grischek and Ray, 2009). Figure 2.2 shows the different stages of river system from origin to mouth with geological formation along the stretch

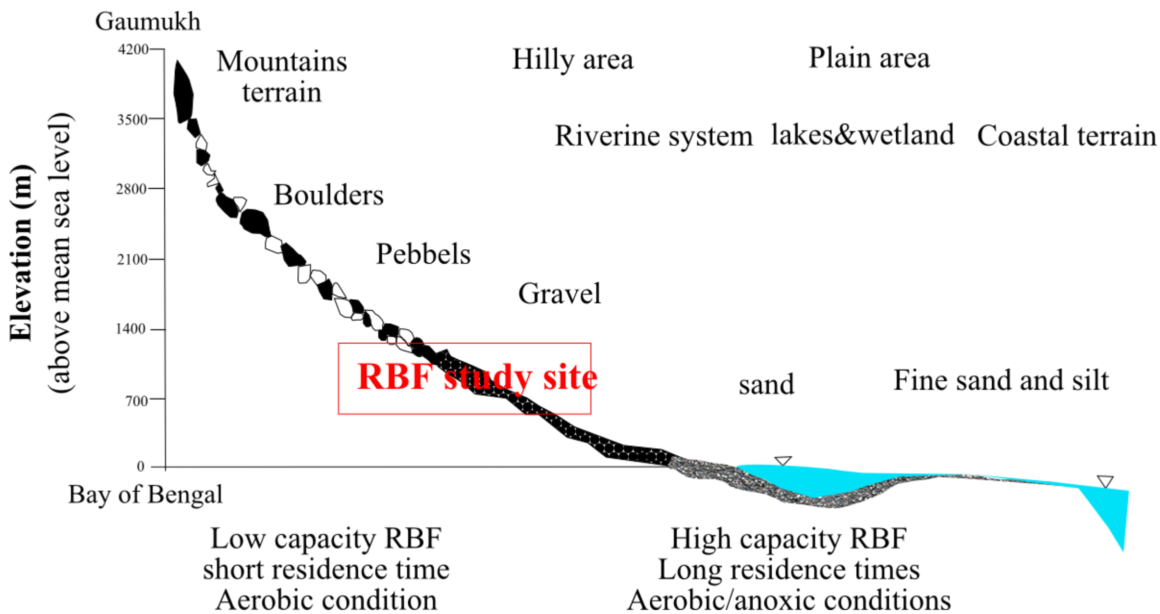

Figure 2.2 RBF location along the river stages (modified after Grischek and Ray, 2009)

The rivers at the high ridge are very different than that in the plain areas. The flows are very dynamic, has high energy that make the bank very erosive. The river flow suddenly drifts or turns in the valley. Boulder and pebbles is the main riverbed characteristic (Weiss, 2001; Bayley, 1995). The rivers are very dynamic and oxic in nature in the hills. However, in plain the river is relatively calm, and primary phenomenon that occurs is the deposition of material transported with the river flow.

Bank filtration can occur under natural as well as in engineered conditions. If abstraction wells are hydraulically not connected with the river or if the hydraulic conductivity of the riverbed material depletes due to clogging, in such scenario the wells may draw groundwater.

Typical flow conditions during the bank filtration are shown in Figure 2.3 (Hiscock and Grischek, 2002; Forster, 1989; Wett et al., 2002; MartÍn-Alonso, 2005; Wilson and Guan, 1995). The hydraulic conductivity decreases due to clogging and changes the preferential flow path in time (Wett et al., 2002). The RBF site near Barcelona, Spain on the Llobregat River is one of the examples for well operating under extreme conditions. The riverbed is fully clogged under normal flow conditions, and the aquifer is not directly connected to the river at the RBF location (Type 4, Figure 2.3). Infiltration occurs only in the specific area in case of flooding.

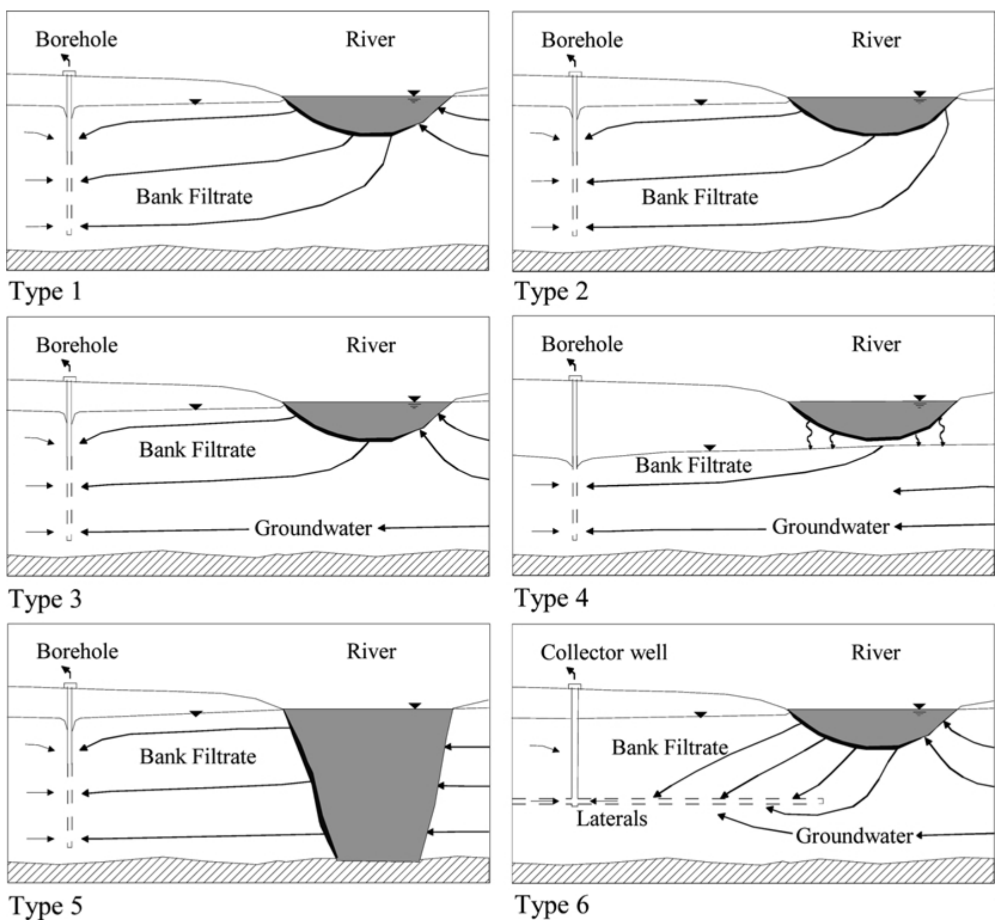

Figure 2.3 Schematic representation of flow conditions at bank filtration sites (after Hiscock and Grischek, 2002)

The elements for controlling long-term sustainability of RBF systems depend on the riverbed connections to the wells. However, this conductance varies with the function of time and topography (Hubbs, 2006, Caldwell, 2005). In the course of time, many factors can alter the well specific capacity, one of that is termed as riverbed clogging. The formation of gas bubbles, microbial growth, and exopolymer production are amongst the mechanisms that can change the hydraulic conductivity of the active layer (Heeger, 1987; Grischek et al., 1994; Machleite et al., 2006; Ray et al., 2002; Schubert, 2002)

2.5. PROCESSES OF GEOCHEMICAL TRANSFORMATION

The movement of water through the aquifer is primarily controlled by porosity, hydraulic gradient, hydraulic conductivity, moisture content and climate (Dash et al., 2011, Sprenger et al., 2011; Eckert et al., 2008). During that travel of water, leaching, precipitation, hydrolysis, oxidation-reduction and sorption are some of the primary geochemical subsurface processes that occur. In the unsaturated zone, water in contact with the underlying materials may result in leaching out one or more soluble species. Precipitation of saturated species, sorption of inorganic ions or certain organics is the major process involved (Boulding and Ginn, 2004). Distribution and transformation processes are the two broadly classified subsurface geochemical processes (Boulding and Ginn, 2004).

Sorption is one of the major mechanisms affecting the mobility of pollutants (Grathwohl and Kleineidam, 1995; Boulding and Ginn, 2004). Precipitation is a phase distribution process whereby insoluble solids are formed and separated from a solution. Dissolution involves a change from the solid or gaseous phase to the aqueous phase. In the sub-surface environment, precipitation-dissolution reactions are often evaluated by the use of mineral stability diagram that delineate the pH, Eh, temperature and pressure conditions under which a particular mineral is stable. Ionic precipitation-dissolution reactions are often fully reversible. Precipitation can only be considered to effectively immobilize contaminant if environmental conditions in an aquifer are sufficiently stable to prevent dissolution (Ainsworth et al., 2000; Boulding and Ginn, 2004). Different distribution processes have been tabulated in Table 2.2

Hydrolysis occurs when a compound reacts chemically with water, a new chemical species are formed by the reaction. According to Boulding and Ginn, (2004) hydrolysis reactions fall into 2 majors types:

- Replacement is the most common hydrolysis reaction. In this reaction, one functional group is replaced by an OH- (hydroxide ion) originating from a water molecule.
- Addition reactions involve the incorporation of water into the chemical structure of compound.

Table 2.2 Significance of chemical processes in the subsurface (Boulding and Ginn, 2004)

Process	**Detoxification**	**Mobility**	**Conditions**
Distribution process			
Acid-base equilibrium	×	√	Both
Adsorption-desorption	×	√	Abiotic
Precipitation-dissolution	×	√	Abiotic
Immiscible phase separation	×	√	Both
Volatilization	×	√	Abiotic
Transformation process			
Biodegradation	√	√	Biotic
Complexation	×	√	Abiotic
Hydrolysis	√	√	Both
Neutralization	√	×	Abiotic
Oxidation-reduction	√	√	Both

2.6. FACTOR AFFECTING ON PURIFICATION OF WATER IN BANK FILTRATION

Purification by bank filtration strongly depends on environmental conditions, well designed, location at shoreline, well operation, travel time, runoff regime, and surface and groundwater qualities (Hiscock and Grischek, 2002; Grischek et al., 2003; Kühn and Müller, 2000; Schijven et al., 2003; Schön, 2006).

Most of the RBF systems are constructed in alluvial aquifers along the riverbanks (Hunt et al., 2003; Ray et al., 2003; Hiscock and Grischek, 2002). These aquifers consist of a variety of deposits ranging from sand to sand and gravel, to large cobbles and boulders of various thicknesses. RBF systems can be constructed in low permeability zones (typically, clay and silt layer) within the alluvial aquifer. If confining layers are extensive and continuous, well screens can be placed above or below the confining layer to collect infiltrate water from the surface source as well as from groundwater. The conceptual design of an RBF well has been discussed by Hunt et al., 2003.

2.7. RIVERBANK FILTRATION IN PLAIN AND HILLY AREA

The promising sites for the bank filtration are those sites where the alluvium thickness is more than 5 m and the flow velocity is low to moderate (0.5-2.5 m/s) for impoundment of surface water (Ray et al., 2002; Hubbs, 2006). These sites have slow sediment transport whereas foothill and deep gorges, which are characterized by the large bend and high velocity, have entirely different river morphology (Table 2.3). Aquifers in such reach are often limited to low thickness and narrow extent. The riverbed and sediments are coarse; thus, conditions for RBF are not favorable in general (Grischek and Ray, 2009; Schubert, 2002).

Table 2.3 Classification of river stage and their characteristics

Classification of river system	**Mountainous**	**Hilly Area**	**Channel in alluvial plain**	
			Flood plain	**Delta**
	Young stage (Upper course)		**Mature stage (Middle course)**	**Old Stage (Lower course)**
Characteristic riverbed material	Rocks/ Gravels	Boulders, Gravels, Sand	Sand	Mud
Channel width	Very narrow width and steep valley	Narrow width and steep valley	Wider width and floodplain	
Flow type	Turbulent	Turbulent	Transitional flow	Laminar flow
Nature of the bank	Very Erosive	Erosive	Erosion-Deposition	
Transportation by running water	Debris flow, traction	Traction	Traction, suspension	Suspension (Deposition)
Depth of channel	Deep	Deep-Shallow	Shallow	Very Shallow
Gradient of riverbed*	>1/10-1/100	1/50 to 1/500	1/500 to 1/2000	<1/2000
*Matsuda, 2004				

The geometry of the river also influences the RBF systems. In hilly regions, the flow is of type-3 and type-5 (Figure 2.3; Hiscock and Grischek, 2002). The width and depth of the river are important particularly for sustainable abstraction of water. The width of the river can act to compensate for the loss of capacity by enabling the infiltration area to spread across a wider area, which are widely unknown in hilly regions. Hubbs and Caldwell (2007) documented this phenomenon during a pumping test of a horizontal well in Louisville, KY. The factors affecting the geometry of RBF sites are summarized in Table 2.3

Table 2.4 Factors affecting the well location for construction

Factors	**Remarks**	
	in Hills	**in Plain**
Distance from the river to the centre of the well	√	√
Location relative river bends	×	√
Length of the river impacted	×	√
Type and number of wells	-	-
Total length of the well screen	√	√
Depth of the river to average discharge	×	√
Depth of the river to bank full discharge	×	√
Width of the river at average discharge	×	√
Width of the river at bank full discharge	×	√
Note: × not known; √ available in literatures; - undefined, develop from Rahn (1968); Young et al., (1990); Cadwell et al., (2006)		

2.8. LABORATORY STUDIES

Bench scale column experiments are conducted to study various processes occurring during bank filtration of the river water, to evaluate transport model, fate of trace organics, DOC, microbes, heavy metals, organochlorine pesticides (OCPs), non-aqueous phase liquids etotal coliform. (Kott, 1988; Quanrud et al., 1996; Schäfer et al., 1998; Börnick et al., 2001; Worch et al., 2002; Schoenheinz and Grischek, 2011; Kolehmainen et al., 2009). Column studies show that the flow rate (infiltration rate for a particular surface area) to be an important factor determining the efficiency of filtration (SaphPani, 2014).

Reductions of virus like hepatitis A, poliovirus 1, echovirus and the indicator virus MS-2 in 10 cm columns at different temperature and different filter grading was observed to be of >99.98 % by Sobsey et al. (1980 & 1988), John (2003), Blanc and Nasser (1996). The transport of bacteria on different grain size in column study was carried out by Brown et al. (2002), Foppen et al. (2005; 2006 & 2007); Schijven et al. (2002) and Kim et al. (2008).

Effect of various factors like flow, packing nature, measuring location, etc. on the column experiments were studied by Reynolds et al. (1992), Thullner (2004), Engesgaard et al. (2006), Stuyfzand et al. (2006), Ghodrati et al. (1999) and Macheleidt et al. (2006). Column studies on particle mobilization and attenuation under different conditions were also carried out by Siriwardene et al. (2007), Dininkya et al. (2008); Mucha et al. (2006); Kandra et al. (2010); Reddi et al. (2000).

Engesgaard et al. (2006) and Stuyfzand et al. (2006) studied the removal of bacteria and physical clogging caused by the variation in feeding water and operational conditions. Studies were also done on various grading of sand for filtration in water with a column and sand tank (Stevik et al., 2004; Sinton et al., 2000).

To understand the transport of bacteria and viruses in the porous media a study was carried out by Bauer et al. (2011). Smith et al. (1985) and Sarkar et al. (1994) have shown higher recovery of bacterial coliform and *E. coli* at high discharge. Baars (1954) and Kristiansen (1981) have reported that the bacterial removal efficiency of biologically clogged filtered media is better than unclogged media. However, McCaulouet al. (1994); StenstrØm (1989); Gilbert et al. (1991) emphasized the hydrophobic character such as adhesion capacity of the porous media for efficient removal of bacteria. StenstrØm and Hoffner (1982), Lawrence and Hendry (1996) and Gitis et al. (2008) found that retention time and filtering depth influenced the removal efficiency to a vast extent. Marlow et al. (1991); Rusciano and Obropta (2007) investigated the ability of microbial penetration of an aquifer for bio-remediation. Chrysikopoulos and Syngoung (2012) conducted a large number of experiments to study the effects of grain size and pore-water velocity on the transport of bio-colloids in water saturated columns packed with quartz sand. Sen and Khilar (2006) summarized the transport of colloids and its associated contaminants to understand and develop the role of clogging in porous media.

In spite of the recent findings from both the laboratory and fieldwork, the manner in which the coliforms interact under different flow conditions and different sizes of filter materials remain largely unknown. Various disadvantages, as given in Section 2.3, give an impulse to investigate the different aspect of sustainability of BF in relatively shallow alluvial aquifers (compared to typical thicker floodplain aquifers) in the hilly/mountainous regions. The implementation of RBF system is a challenging task particularly in the light of conditions prevailing in hilly/mountainous areas.

CHAPTER 3
MATERIALS AND METHODOLOGY

The initial task was the reconnaissance at the four proposed sites namely Srinagar, Agastyamuni, Karnaprayag and Satpuli followed by fieldwork and data collection. The sequence of activities undertaken at the four RBF sites is given in Figures 3.1 and 3.2.

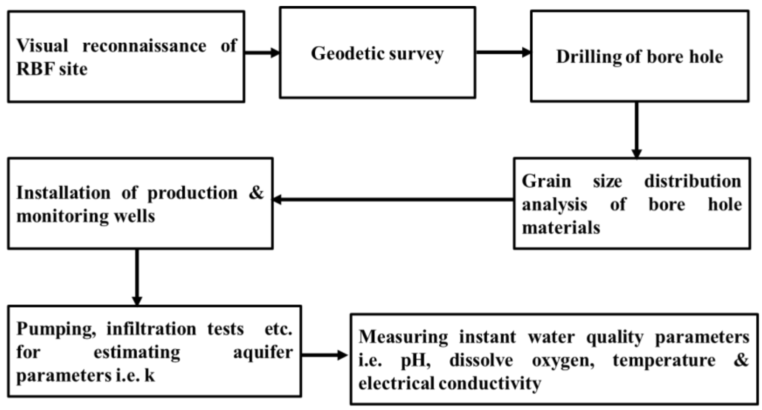

Figure 3.1 Schematic layout of the approaches for bank filtrate investigation

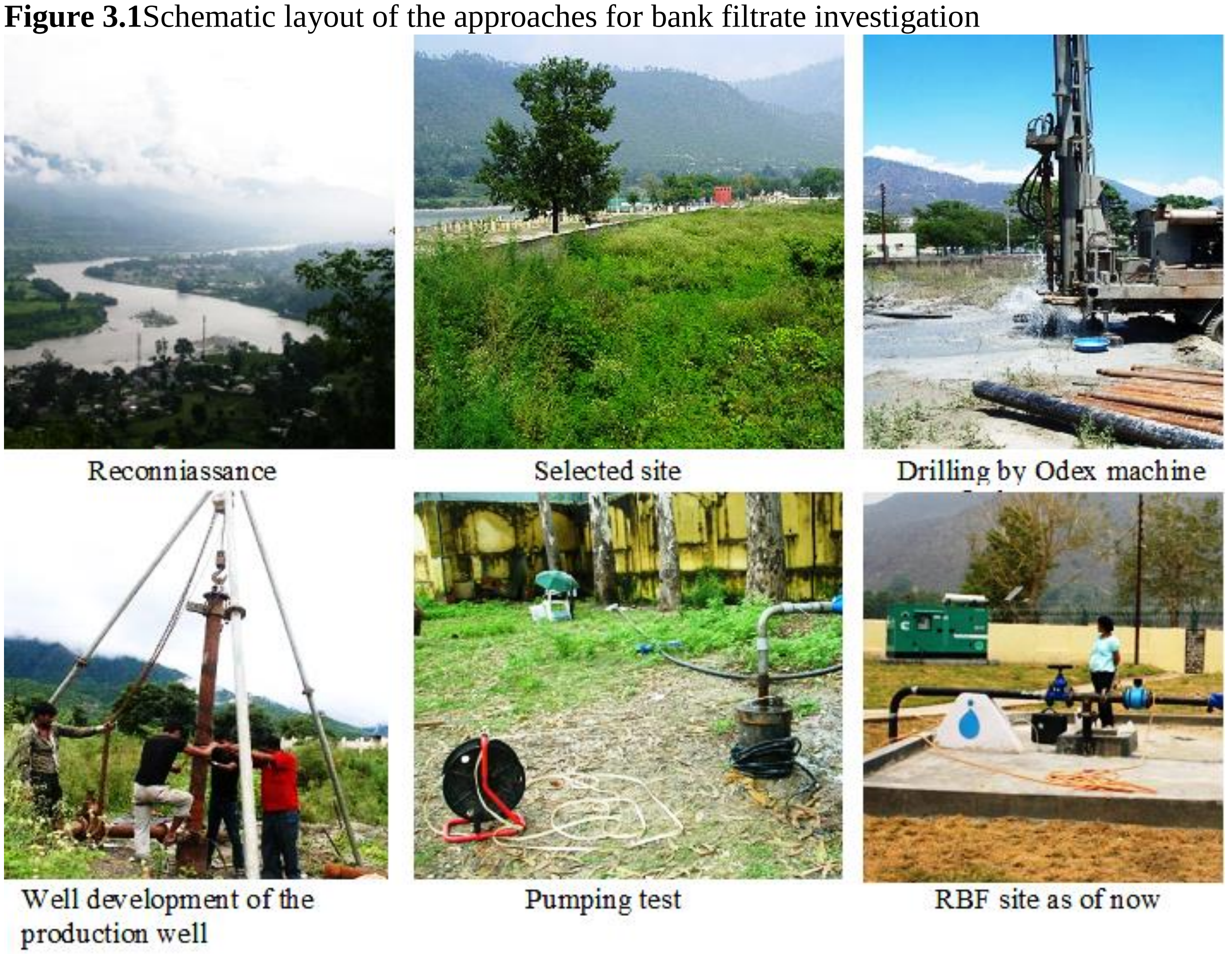

Figure 3.2 Development of RBF scheme

The relatively flat area at four sites was identified through reconnaissance. Location of the wells was decided after examining the grain size distribution of the outcrop from the dune at the proposed location (Figure 3.3; Detail in Table B1 of Appendices B).

Laboratory investigations were carried out where materials from the riverbeds and aquifers, and the water samples from all the sites were collected and analyzed. Columns experiments were conducted in the Environmental Engineering Laboratory, IIT Roorkee, Roorkee, India and Water Science Division, HTW Dresden, Dresden, Germany.

Figure 3.3 Outcrop at the Srinagar RBF site

3.1. GEODETIC SURVEY

The surface elevation of the proposed production and monitoring wells at the sites and the elevation of the water table of the adjoining river were determined in meters above mean sea level with measurements being conducted using one particular datum (benchmark) near each site. The benchmarks were transferred from the kilometer stones fixed by Border Roads Organization (BRO) on the main roads at various locations using a theodolite (Sokkia C410,

Figure 3.4). Accordingly, GPS locations were also marked on it. Geodetic map of each site and corresponding vertical profiles of the terrain and the adjoining river water level were prepared

Figure 3.4 Transferring the datum from a kilometre stone to the RBF site

The difference in surface elevation of the proposed sites and the adjoining river water levels and the depth to the groundwater table helped in assessing the required length of the casing pipes (blind pipes) for the proposed wells. Additionally, due to the low river flow conditions at Agastyamuni and Satpuli, it was possible to determine the profile of the riverbeds.

3.2 CONSTRUCTION OF WELL

Drilling and installation techniques were chosen by the Uttarakhand Jal Sansthan (UJS) based on the local geology of the area, the type and/or size of the well and past knowledge of drilling conditions in the area (Ronghang and Sandhu. 2011).Therefore, it was decided to use the ODEX (overburden drilling with an excentric bit) method for drilling the boreholes. However, drilling was not an easy operation due to the presence of cobbles, boulders and loose unconsolidated sand, gravel and silt.

3.2.1. Well Drilling

Consequent to the reconnaissance and geodetic surveys, two monitoring wells and one production well were installed in Agastyamuni. In Srinagar, Karnaprayag and Satpuli one monitoring and one production wells were commissioned in April–May 2010. Another production well was built in Srinagar in 2011 using rotary method (Figure 3.5c). Monitoring well in Agastyamuni (AGMW1) does not have a filter section as it was initially decided to drill for determining the aquifer depth, and thus it is just a blind casing pipe with an opening at the bottom. Also, the monitoring well in Satpuli (SPMW) is located towards the landward side of the production well. At the other two sites, wells were installed considering the topography of the area. The drilling and installation of wells were done as per the recommendation from Murphy (1991), Asad-uz-Zaman and Rushton (2006); Raghunath (2006) and Walker (1974).

Figure 3.5 Srinagar RBF site. (a) Construction of production and monitoring well using ODEX method; (b) Pumping test; (c) Direct rotary technique; (d) Well assembly

Figure 3.5(d) shows the fitting of the filter screen and mild steel (MS) pipe for the production well. Wells were developed by pumping compressed air into the well and flushing out the mixture of sand and water. Sand was first removed from the well bottom and after that from the filter section using a high discharge pump and a compressor (Figure 3.6).

Figure 3.6 Well development process: **(a)** Pumping at high rate **(b)** sand abstracted out from the well **(c)** water mixed sand from the production well

3.3 WATER LEVEL MEASUREMENT

The static water levels were measured at the production wells (PWs) and monitoring wells (MWs) using water meter or tape with sound and LED (dipper-T, Heron instrument, USA). Water levels were measured before commencing abstraction of water from the production wells (Figure 3.7a). The depth of the water level in the wells was measured from the casing top and after deducting the elevation of the casing head above the ground level, the depth of the water table was obtained in meters below ground level (m BGL).

3.4 PUMPING TEST

The short and long pumping tests were carried out at the four sites. Details are given in Table 3.1 & Figure 3.7(b). While pumping test water levels were measured using data loggers (Schlumberger Mini-Diver Model DL505) and the water meter (Figure 3.7 a&b).

Figure 3.7 (a) Measurement of the water level in the monitoring well, **(b)** Conducting pumping test.

The cumulative volumes abstracted were manually recorded from the flow meter at varying time intervals, which were then converted into discharges. After the pumping phase had been completed, the duration of the recovery phase was recorded until static groundwater levels were attained.

Table 3.1 Summary of short and long duration pumping tests

Location	29th April-17th May 2011 (short duration test)				4th November-4December 2011 (long duration test)		D* (m)
	Test 1		Test 2				
	Discharge (LPM)	Time (h)	Discharge (LPM)	Time (h)	Discharge (LPM)	Time (h)	
Srinagar	90	4.72	620	10.08	710	47	9.9
Agastyamuni	85	2.38	320	3.82	230	48	8.57
Satpuli	ND		650	0.88	630	57	0.74
Karanprayag	95	3.08	450	2.61	~ 420	48	9.41

* distance between production well (PW) and monitoring well (MW); ND not determined

3.5 DETERMINATION OF HYDRAULIC CONDUCTIVITY AND WELL YIELD

The pumping test data were analyzed analytically using the Thiem-Dupuit (Eq. 3.1) formula for unconfined aquifers. All the sink and raise data from data logger were also analyzed by analytical software tool AQTESOLVE for window version 4.5 demo (Duffield, 2007). The software program is used to estimate the hydraulic conductivity, specific storage, transitivity, etc. Following the long duration pumping tests (November – December 2011), the maximum safe well yield for each production well was calculated using Equations 3.1 and 3.2. The steady state flow rate (Q_A) and yield (Q_F) were plotted as a function of the water column above the aquifer base. The intersection of Q_A and Q_F corresponds to the maximum safe yield (Figure 3.8).

$$Q_A = \frac{\pi \cdot K \cdot \left(H^2 - h^2\right)}{\ln R - \ln r_0} \qquad 3.1$$

and the yield of the abstraction well ($Q_{F,}$ m^3/s), given by DIN 1055 (2004)

$$Q_F = \frac{2}{15} \cdot \pi \cdot r_0 \cdot h \cdot \sqrt{K} \qquad 3.2$$

Where K is the hydraulic conductivity of the aquifer [m/s],

Q_A is the steady-state radial flow to a well in an aquifer [m^3/s],

H is the pre-test rest water level measured from the aquifer base [m],

h is the steady-state water level after a constant drawdown is obtained [m],

R is the radius of influence [m] of the well at a steady drawdown [s],

and is the radius of the well bore [m]

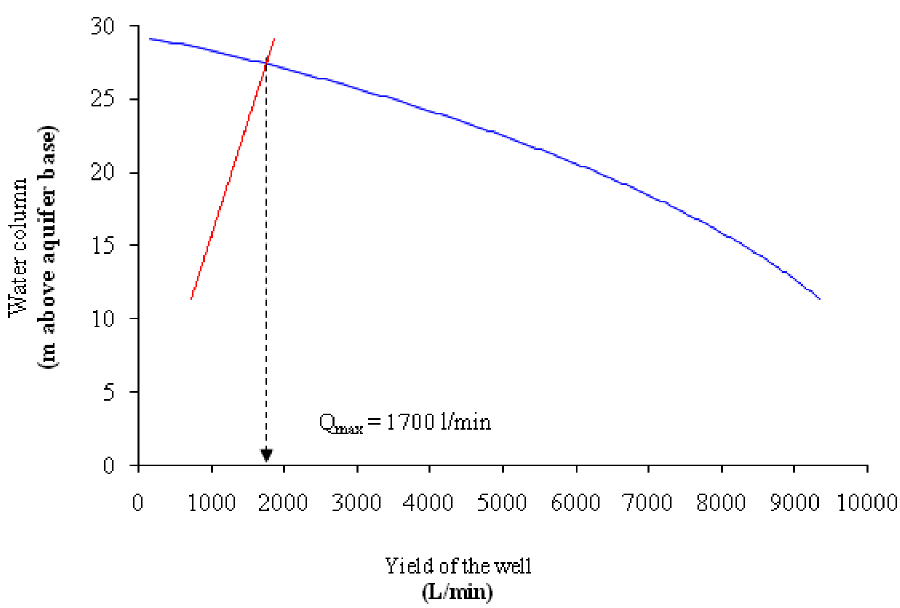

Figure 3.8 Graphical representations for calculating safe well yield

3.6 INFILTRATION TEST

Soil infiltration test were generally done using a standard double-ring infiltrometer as par the American Society for Testing and Materials (ASTM: D 2434-68), which consists of two concentric rings, a driving plate, and two calibrated Mariotte tube assemblies to deliver water to the rings during the test (Burgy and Luthin, 1956; Angulo-Jaramillo et al., 2000; Gregory et al., 2005)

3.6.1. Double Ring Infiltration

Double ring infiltrometer was used to determine the infiltration capacity of the soil above the aquifer. The infiltration capacity (IC) curve is the graphical representation on how the IC varies with time during the rains (Garg, 2002). Generally IC is very high at the beginning of the rains that occurs after a long dry period. IC reduces considerable in due course of time. After a certain period (of the order of 1 to 3 hours) the IC tends to become constant. Typical IC curve with infiltration rate, I, and cumulative infiltration, Z, are shown in is presented in Figure 3.9.

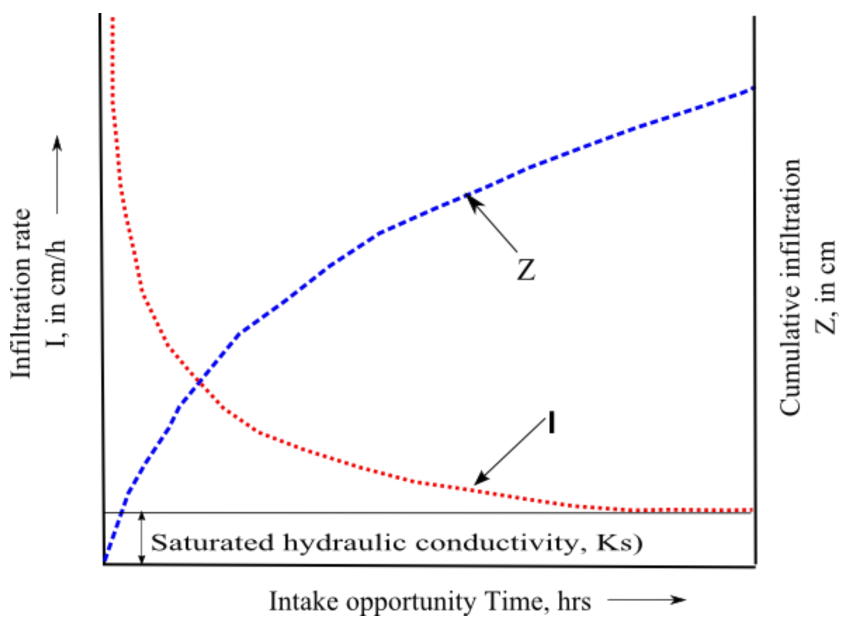

Figure 3.9 Typical infiltration rate and cumulative infiltration function

Factors affecting IC are surface detention, soil moisture, compaction due to rain, washing of fines, etc.

Horton mathematical Equation 3.3 is represented as given below:

$$f = f_c + (f_o - f_c)e^{-ct} \quad (3.3)$$

Where f_c= Value of infiltration after it reaches constant value [LT^{-1}]

f_o= Infiltration capacity at the start [LT^{-1}]

f = infiltration capacity at any time [LT^{-1}]

c= constant

t= Time from the beginning of rainfall [T]

3.6.1.1 Methods for computing infiltration capacity

Figure 3.10 shows the procedure for measuring the water level during the double ring infiltrometer experiment. Cylindrical of mild steel infiltrometer of length 0.45 m and diameter 0.3 m was hammered into the ground near the production wells.

- Topsoil was removed before hammering the outer and inner rings up to 10 cm and 15 cm, respectively.
- The change in water level in the inner ring was recorded using Schlumberger diver (Mini and boro-Diver). A manual measurement was also done to calibrate the measurement.

Figure 3.10 During measurement of water level in the double ring infiltrometer

3.7 WATER QUALITY ANALYSIS

3.7.1 Sample Collection for Water Quality Monitoring

The longitude, latitude, and altitude of the sampling sites were measured using a GPS (Garmin eTrex 10). The longitude and latitudes were precise to ±0.5 m, and altitudes were correct to ±5m. Water samples from the river, the production wells, and the hand pump(s) from each of the four sites were collected during every sampling campaign. Samples were collected in May 2010 at the time of well drilling, and post drilling in August 2010 before it became fully operational in October 2011. The samples were then collected almost monthly from November 2011 to September 2013.

Water was pumped out before collecting the sample as per guideline (Lorenzen et al., 2007). The volume of water flushed is calculated as per Equation. 3.4.

$$V = 3 \times \frac{\pi}{40} \times d^2 \times h \quad \text{.......} \quad 3.4$$

Where:
V = Volume (L)
d= casing diameter (cm)
h= height of static water (m)

About 40L of water from the hand pumps was initially pumped before collecting the samples. For the analysis of dissolved ions, water samples were collected in 100-1000mL polyethene and polypropylene bottles. Samples for bacteriological analysis were collected in sterilized glass bottles (1501-Bottles, Borosil). All the collected samples were stored in the thermostat box (ice box) maintained at a temperature around 4^0C before transporting to the Environmental Engineering Laboratory, IIT Roorkee for further analysis within 24 hours.

Details about a few site-specific sampling are included in sections describing the water quality of the particular site (refer to Chapter 5 of section 5.1.1 to 5.3.1).

3.7.2 Stable Isotope Analysis

Stable isotopes of oxygen (δ^{18}O) and hydrogen (δ^{2}H) in the water from the river, production well and hand pumps were analyzed to estimate mixing of the bank filtrate with ground water in production well water. Samples for isotope analysis were collected in 20 mL polypropylene bottles and transported to National Institute of Hydrology, Roorkee (NIH, Roorkee), India. It was ensured that no air bubble was trapped in the bottles during water collection. The samples were analyzed using GV-Isoprime Dual InletIsotope Ratio Mass Spectrometer.

3.8 SAMPLE TESTING AND ANALYSIS

3.8.1. Onsite Measurement

Electrical conductivity (EC), *p*H, temperature, and dissolved oxygen (DO) were measured on site using a portable multi-parameter probe (HQ40d, Hach, Loveland, USA, (Figure 3.11). The instrument is calibrated with the standard solution before the measurement.

Figure 3.11 Measurement of instant parameter in the river water

3.8.2 Laboratory Measurement

Turbidity of the water sample was measured using turbidity meter, model 2100N turbidimeter (Hach, USA). Nitrate was measured on site using the field test kits (OR-NO_3-01, Orlab) as well as in the Environmental Engineering Laboratory using spectrophotometer (DR500) as per procedure laid in Eaton et al. (2005).

The specific UV absorbance (SUVA) was calculated from UV absorbance and DOC. Water samples filtered through the 0.45 µm filter (FM-Millipore®) were used to measure DOC and UV absorbance.DOC was measured using TOC analyzer (TOC-V_{CSN}, SHIMADZU, Kyoto, Japan) UV absorbance (UV_{Abs}) was measured at 254nm using the UV spectrophotometer (DR5000) Hach, USA.

The sampling, transportation, storage, and analyses were carried out in agreement with the procedures given in APHA Standard Methods (Eaton et al., 2005).).

3.8.2.1 Total and fecal coliform

The multiple tube fermentation technique using *lauryl tryptose broth* for total coliform and *EC medium* for fecal coliform was used to determine the bacterial concentration in the water samples as par APHA 2005(Eaton et al., 2005).

3.8.2.2 Dissolved ions

For analysis of dissolved ions, the samples were double filtered through a 0.22µm size cellulose acetate filter and diluted (Millipore, GVWP) before analysis. The ions (Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Cl^-, F^-, NO_3^-, NO_2^-, SO_4^{2-}, and ortho - phosphate) were determined by ion chromatography using 861-advanced compact IC (Metrohm AG, Switzerland) using cation column Metrosep C 2-250 (6.10.10.230) anion column Metrosep A Supp 5-250(6.1006.530).

Alkalinity was determined by titration with N/50 H_2SO_4 (aq.) with bromocresol green as an indicator. Concentration of HCO_3^- was then estimated from alkalinity, based on the assumption that at the given pH, the alkalinity is entirely due to bicarbonate.

3.8.2.3 Oxygen-18 and deuterium stable isotope analysis

Isotopic analysis of $\delta^{18}O$ and δ^2H in H_2O in the samples was done at National Institute of Hydrology, Roorkee (India) using GV Isoprime Dual Inlet Isotope Ratio Mass. For $\delta^{18}O$ analysis, 400µL of water samples were equilibrated for 23 hours with CO_2 reference gas. For δ^2H analysis, equilibration was done for 7 hours with H_2 reference gas and Pt catalyst. The measured delta (δ) values are with respect to Vienna Standard Mean Ocean Water (VSMOW). The precision of measurement for $\delta^{18}O$ is ± 0.1‰ and for δ^2H is ± 1‰.

3.8.2.4 Nitrogen stable isotope analysis

Nitrogen isotope measurements were conducted at the Department Catchment Hydrology at the Helmholtz Centre for Environmental Research (UFZ), Germany, on a Gasbench II/delta V plus combination (Thermo) using the denitrifier method producing N_2O gas by controlled reduction of sample nitrate (Sigman et al., 2001; Casciotti et al., 2002). *Pseudomonas Chlororaphis* (ATCC #13985) were used as denitrifying bacteria. The $\delta^{15}N$ values are reported about the standard air. The standard deviation of the analytical measurement for $\delta^{15}N$ is ± 0.4 ‰. Isotope results represent the mean value of real double measurements of each sample. For calibration of nitrogen isotope values, the reference nitrates IAEA-N3 (^{15}N:+4.7 ‰ air), USGS32 (^{15}N: +180 ‰ air; ^{18}O: +25.7 ‰ VSMOW), USGS34 (^{15}N: -1.8 ‰ air; ^{18}O: -27.9 ‰ VSMOW), and USGS35 (^{15}N: +2.7 ‰ air; ^{18}O: +57.5 ‰ VSMOW) were used.

The denitrifier method enables the simultaneous determination of $\delta^{15}N$ and $\delta^{18}O$ of nitrate. Accordingly, oxygen isotope signatures were also measured for the samples. However, due to the hydro chemical matrix of the samples and its impact on the bacterially-induced oxygen isotope exchange of nitrate degradation products with the ambient water, no reproducible oxygen isotope results were obtained. Therefore, those values cannot contribute to a conclusive interpretation and are consequently not referred to in this study.

3.8.2.5 Soil/aquifers sample analysis

(i) Sieve analysis

The collected aquifers materials were then washed using 75 microns to remove the bentonite clay (refer Figure 3.12), the washed sample is oven dried at 105^{0}C for 24 hrs at the IIT Roorkee Lab. The PWs drilled in 2010 also has the same profile as in the current RBF well (drilled in 2012). Grain size analyses were carried out according to BIS 1607-1977 in the geotechnical laboratory from IIT Roorkee. The oven dried sample were weighted and placed in the sieve and then to sieve shaker (Tohniwal).

Figure 3.12 Removing bentonite clay from the formation material and sample preparation for sieve analysis

(ii) Leaching experiment

The soil samples were oven dried at 105° for 24 hours. Some of the rock samples were also oven dried, but no significant reduction in mass was observed; hence this step was omitted for the rest of the rock samples. Rock samples were powdered to less than 100µm particle size in an iron mortar and pestle. Then 50 g of dried soil/ rock sample was soaked in 150mL distilled water for ~3 days. During soaking, the mixtures were stirred with a glass rod or a spatula for few minutes daily, and EC of the supernatant liquid was monitored. The electrical conductivity of the leachate achieved steady state usually within two days. After the third day, the leachate was filtered with 0.22µm for further analyses.

3.9. COLUMN EXPERIMENT

Eight numbers of column experiments were conducted during the research periods, four sets in Environmental Engineering Laboratory of IIT Roorkee, Indian and four sets in the Water Science Division, HTW Dresden, Germany

3.9.1 Experimental Setup at the Environmental Engineering Laboratory, IIT Roorkee

Laboratory experiments were conducted in stainless steel columns filled with aquifer materials of size ranging from 0.212-0.425 mm. The column specification and characteristic of aquifer materials are given in Table 3.2. Filling of column and operation conditions were carried out in accordance with the procedure given by Oliviera et al. (1996), Simon et al. (2000), Powelson and Mills (2001), Mahvi et al. (2003) and Lewis and Sjöstom (2010).

Table 3.2 Column specifications and aquifer characteristics

Column	A	B	C	D
Specification				
Length (cm)	45.7	45.7	45.3	45.3
Internal diameter (cm)	4.5	4.5	5.4	5.4
Cross section (cm^2)	15.9	15.9	22.9	22.9
Volume (cm^3)	727	727	1037	1037
Bulk density (g/cm^3)	1.33	1.42	1.61	1.59
Porosity $^{++}$ (%)	49.7	46.5	39.2	40.1
Aquifer material				
Mean grain size*(mm): 0.30;		Uniform coefficient* (Cu): 1.5		

Two size of polyethylene meshes (0.1mm and 0.2 mm) were placed at both ends of the column. The slurry of the aquifer materials was added from the top and water was pumped from the bottom after medium ramming (Oliviera et al., 1996; Sakaguchi et al., 2005; Lewis and Sjöstrom, 2010).This was done to avoid air bag/pockets between the grains of the aquifer material and wall of the column (Sentanac et al., 2001; Sak aguchi et al., 2005; Zlotnik et al., 2007). The tap water was pumped from the bottom through columns for one week to check any leakage and to stabilize the flow rate in the columns. The schematics of the experimental set up indicating operation of a single column is shown in Figure 3.13. Experiments were carried out during Nov 2010-Jan 2011 in a temperature-controlled cabinet (Aqualytic, Liebherr model FKS 3602) maintained at 20^0C. Natural water (60L every day) collected from the Ganga canal at Roorkee ($29^0 52'$N; $77^0 53'$E) was stored in a reservoir and pumped through these columns. Water in the tank was continuously stirred using magnetic stirrer (Remi, Model 1MLH) to avoid the settling of suspended solids. Air bubble separator was used to remove entrapped air bubble.

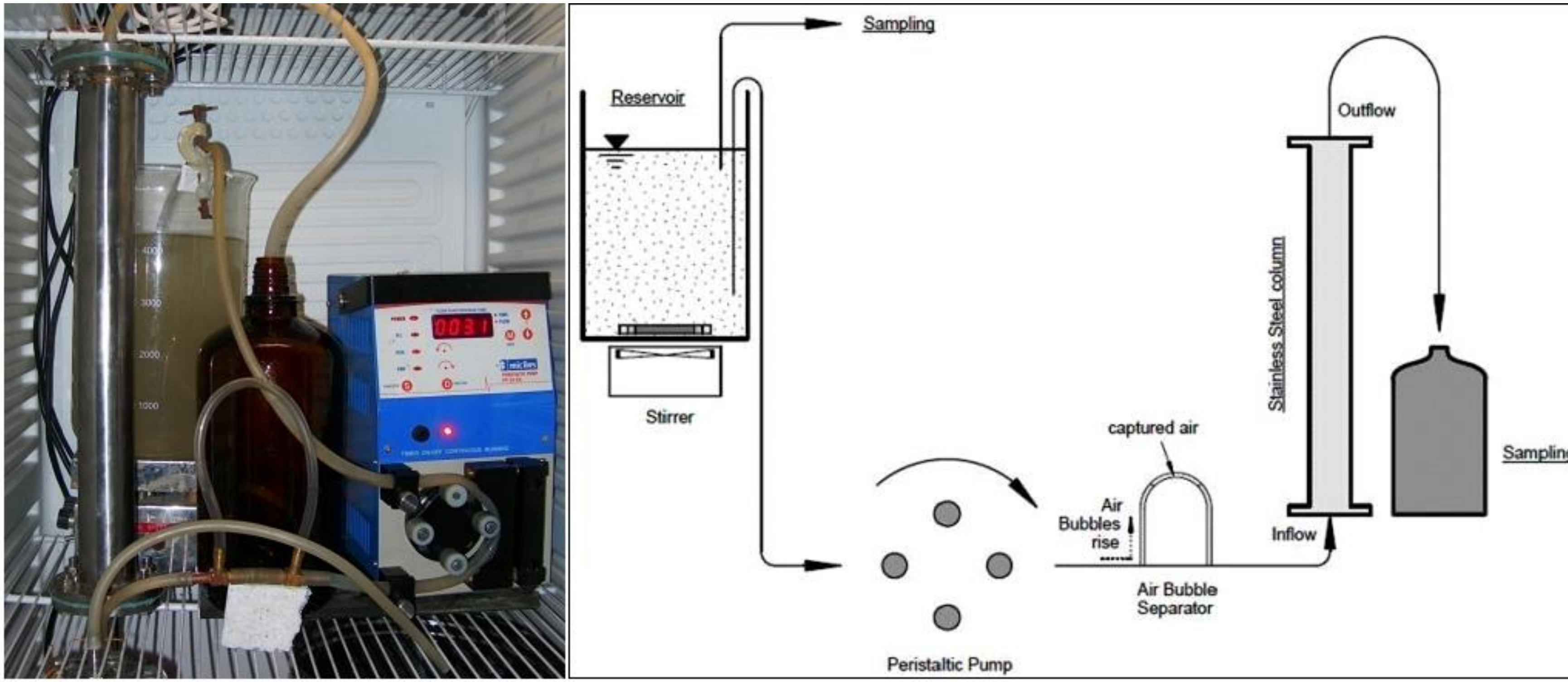

Figure 3.13 Experimental setup showing the entire configuration for column experiment

3.9.1.1 Tracer test

Tracer test was conducted on the aquifer material in the columns to determine the effective porosity of each column prior to and after the column operation. The salt solution was prepared using 99.9 % pure sodium chloride (SDFCL) by dissolving (1g/L) in tap water. Sodium chloride concentration as electrical conductivity was measured and monitored in the outlet water for analyzing the breakthrough the curve (BTC). Peristaltic pumps (Miclins, Model PP20 EX) were used to feed the canal water/sodium chloride solution into the columns (Figure 3.14).

Figure 3.14 Conducting tracer test on the filter media

Breakthrough curves (BTC) were obtained by plotting fractions (C/C_0) of the input concentrations (C_0) as a function of time (t). Effective porosity was estimated from Equation 3.5. The breakthrough curve is used for estimating the effective contact time.

$$\phi = \frac{Qt_{50}}{V} \qquad \text{……………………………………………………………………………….. 3.5}$$

Where ϕ is the effective porosity of the material used in the column,

t_{50} is the effective contact time i.e. time at which $C/C_o = 0.5$,

Q is the discharge of the column experiment, $[L^3T^{-1}]$

V is volume of the column, $[L^3]$

3.9.1.2 Source and filtered water analysis

Canal water and filtered water were analyzed for electrical conductivity (EC), pH, UV-absorbance (UV-A), coliforms (total and fecal coliform), and turbidity. The parameters like turbidity, pH, EC, and flow rate were measured twice a day. UV-A and coliforms, however, were initially recorded once a day and subsequently at intervals of 3-4 days. Electrical conductivity and pH were monitored by HACH USA model HQ 40d. UV-A was measured at 254 nm by HACH, USA model DR 5000. Total coliform and fecal coliform were determined by multiple tube fermentation technique using lauryl tryptose broth (LTB) and EC medium (Eaton et al., 2005). Peristaltic pumps (Miclins, Model PP20 EX) were used to feed the canal water/ sodium chloride solution into the columns.

3.9.1.3 Determination of effective porosity

The effective porosity of each column was determined by tracer test prior to and after the column operation. Sodium chloride dissolved in tap water (1g/L) was used as a tracer. Sodium chloride concentration as electrical conductivity was monitored in the outlet water.

3.9.2 Experimental Setup at Water Sciences Laboratory, HTW Dresden

Four identical stainless steel columns of diameter 10 cm and length 55 cm were packed with different material. The configuration of the columns and characteristics of the materials are given in Table 3.3.

Table 3.3 Characteristics of filter media used in column experiment

Parameters	**Column (C- I)**	**Column (C-II)**	**Column(C- III)**	**Column(C- IV)**
Column configuration				
Material used	Glass beads	Sorted sand**	Aquifer material	River bed material#
Bulk density (g/cm^3)	1.18	1.69	1.98	Top layer: 0.59
				Below layer:2.06
Grain size range(mm)	1.7-2.1	0.2-2.0	0.06-20	0.06-20
Operational conditions				
Discharge range (m^3/s)	1.5×10^{-2}-1.1×10^{-5}	4×10^{-5}-1.1×10^{-6}	6.3×10^{-6}-5.0×10^{-7}	1.2×10^{-5}-2.3×10^{-7}

Layer in combination with finer material (top 10cm) above natural riverbed material as in column 12 + estimate based on particle and bulk density of the media; **collected from artificial recharge basin at Dresden

Column C-I and C-II were packed with clean glass beads (*Sigmund Lindner GmbH*) and highly uniform sorted sand from an artificial recharge basin at the waterworks Hosterwitz, Dresden, respectively. The sorted sand was collected after removing the top 5 cm surface layer at the recharge basin. Columns C-III and C-IV were filled with sediment obtained from a depth of 30 cm below the Elbe riverbed adjacent to the RBF well field at Tolkewitz, Dresden. But, Column (C-IV) was filled with a 10 cm thick hydrophobic loamy soil of finer grain size (also from the river shoreline) with the remaining 35 cm composed of identical sediment (size range 0.6-10 mm) to Column (C-III).

The material in all columns was filled gradually by the wet-filling procedure as laid down by Vandevivere and Baveye. (1992), Oliviera et al. (1996), Schwarzenbach and Westall (1981) and Syngouna et al. (2011). To avoid the trapping of air in the void spaces between the grains, water was added after filling every cm with slight compaction to maintain the natural particle density of the material (Vandevivere and Baveye. 992). All the columns were filled up to 45 cm with the material, and the top 10 cm was left empty to allow the water to cover uniformly the entire cross section of the columns. To avoid leakage and also to remove the trapped air bubbles, degassed water was fed into the columns at the bottom prior to the experiment.

The schematic diagram of the experimental setup is given in Figure 3.15 (a). All the four columns were installed in a trailer (*BöckmanFahrzeugwerke GmbH*) at the riverbank (Figure 3.15b). The columns were connected hydraulically to a constant level overhead tank fitted on the roof of the trailer with a Teflon tube, gasket and a column adapter (polyethylene cap). A submersible pump (AL-KO, model number- TDS 1001/3) was installed in the river for pumping the river water to the overhead tank (up to the head of 7.2 m above the river water level). The water stored in the overhead tank was allowed to flow by gravity into the columns. The experiment was divided into two phases with first 13 days constituting the first phase, after which the water head was raised from 0.09 to 0.13 m to represent high infiltration system (like in flooding) marking the second phase that lasted up to the 31st day.

The outlets (sampling points) of the columns were located at a higher elevation than the column inlets to avoid negative pressure (air entering them). Two (2) m high manometer (attached to the door of the trailer) was connected to the columns at inlet and outlet for measuring the head loss in the filter media inside the column. The discharge was measured daily at the sampling point manually using a stopwatch and measuring cylinder. (Refer to Figure A11 (b) of appendices A)

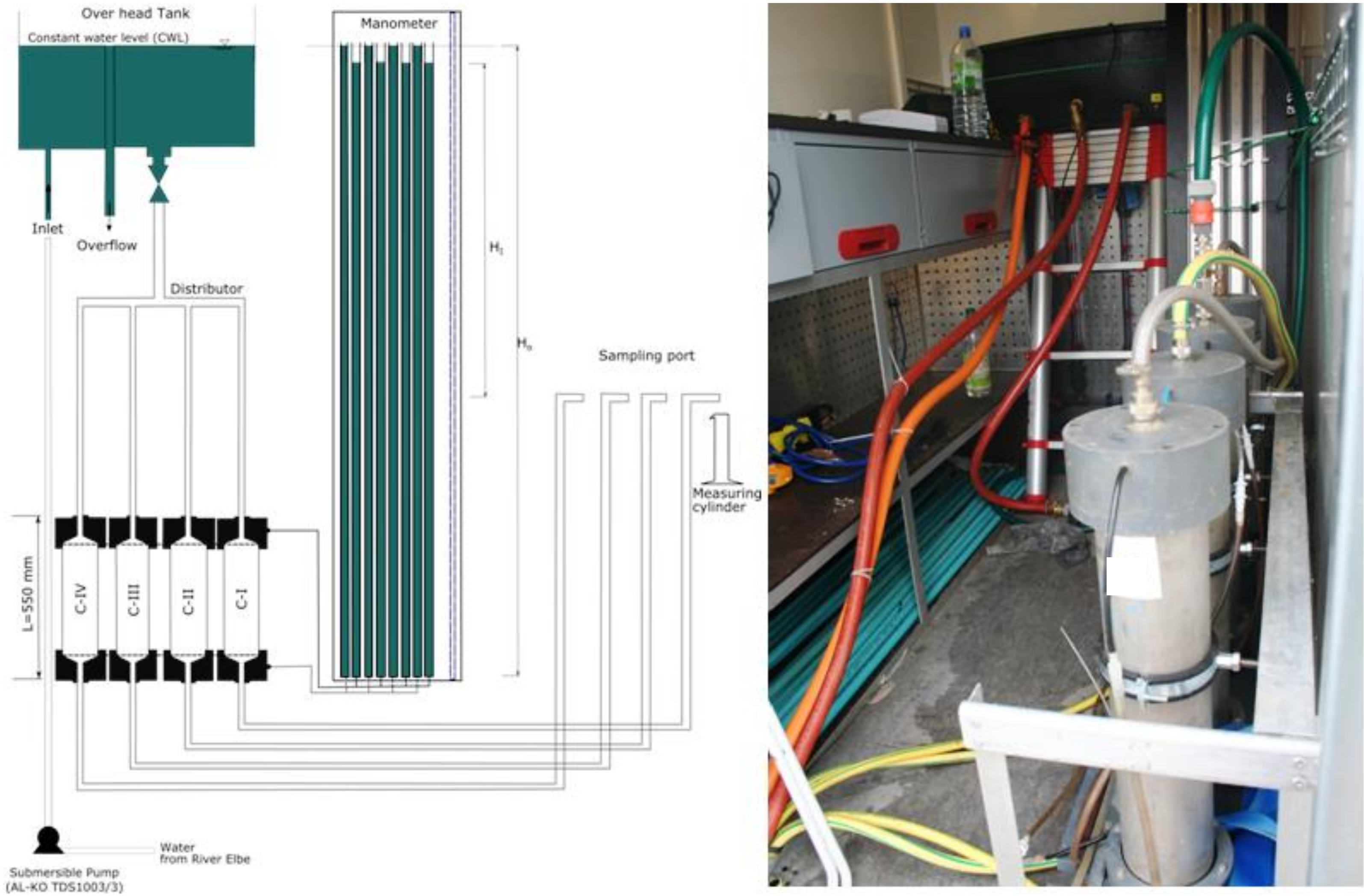

Figure 3.15 (a) Schematic layout; **(b)** details of experimental setup modified after Macheleidtet al., 2006. (H_I and H_0 are the head differences between inlet and outlet)

3.9.2.1 Water quality from the column experiment

Water samples were collected daily for one month to measure turbidity, pH and electrical conductivity from both the inlet (Elbe river water) and the outlet of each column. For the analysis of total coliforms and E. coli, the water sample was collected every day after a week of operation. The head lost in the manometer was recorded daily.

Electrical conductivity, temperature and turbidity were measured on site (WTW LF197-5 and 2100P Hach 150 Turbidimeter). For total coliform and *E. coli* analysis, 100 mL sample was collected in sterilized containers with antifoam solution and stored in a thermos-box at 4 – 7°C before analysis in the laboratory of the Division of Water Science at University of Applied Sciences, Dresden. The analyses of total coliforms and *E. Coli* were carried out using the Colilert-18® procedure of IDEXX as per the procedure laid out in the Environmental Protection Agency Region 4 Policy (EPA, 2010). The Colilert-18 reagent was added to the 100 mL water sample, and the resultant mixture was introduced into IDEXX's 51-Well Quanti-Trays and incubated for 18-19 hours at 35°C±0.5°C. The most probable number of total coliforms and E. coli were enumerated using a standard comparator and a UV lamp with a wavelength of 365 nm.

3.9.2.2 Estimation of hydraulic conductivity

For grain size analysis, the standard procedure as per DIN 2011 was carried out in the geotechnical laboratory at the University of HTW Dresden.

The hydraulic conductivity of filter material used in each column was calculated using the constant head method (ASTM, 2011) based on Darcy's Law; Equation 3.6:

$$k = \frac{Q}{A_s(h_1 - h_2)/l} \quad \text{……} \quad 3.6$$

Where k is the hydraulic conductivity (m/s), Q is the volumetric flow rate (measured at the outlet of the column, m^3/s), A_s is cross-sectional area of the column (m^2), h_1-h_2 is the total head loss across the filter media and *l* is the length of the filter media whose hydraulic conductivity is being tested.

The porosity of the filter material was also determined from Equation 3.7 as employed in Harleman et al. (1963)

$$\eta = 1 - \frac{\rho_p}{\rho_b} \quad \text{……} \quad 3.7$$

Where η is the porosity, ρ_p and ρ_b are the particle density and bulk density of the filter material, respectively.

CHAPTER 4
DEVELOPMENT OF RBF SCHEMES AT SRINAGAR, SATPULI, AGASTYAMUNI AND KARNAPRAYAG

4.1 BACKGROUND DETAIL OF THE STUDY AREA

In 2010-11 water supply systems based on RBF at four locations namely Srinagar, Satpuli, Agastyamuni and Karnaprayag were commissioned to augment existing water supply (Figure 4.1). Before the implementation of RBF, the drinking water supply systems in Srinagar and other places of Uttarakhand were based on the abstraction of (i) direct surface water (until end 2009) and (ii) the ground water from hand pumps and springs.

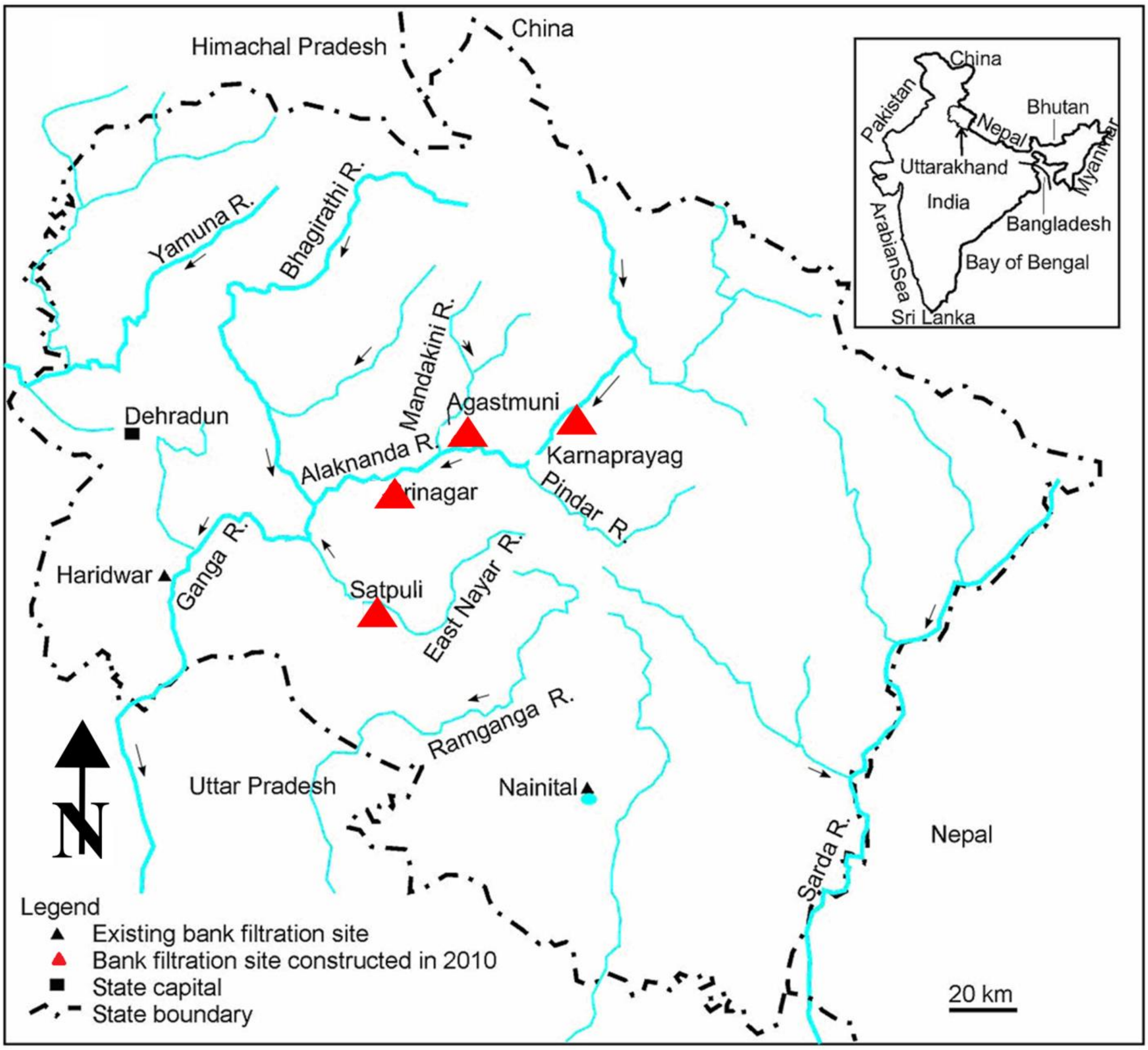

Figure 4.1 Location of RBF schemes (adopted from Sandhu et al., 2013)

Details about the existing water supply at four towns along with proposed RBF sites are summarized in Table 4.1. Location of sites is shown in Table 4.1. At all the sites, water samples were collected from the river, RBF wells or production wells, a few selected hand pumps, and tube wells. Besides, samples of soil, rocks and springs were collected at Srinagar. Samples are represented by alphanumeric labels (SW) for the source water (rivers), (W) for public tube wells, (PW) for the RBF production wells, (HP) for hand pumps, (S) for springs, (T) for wastewater, and (G) for sediment/soil/rock samples (Detail of sampling location is given in Table B1 of Appendices B). The findings from the site investigations carried out are given in subsequent sections. Results from the water quality analysis are presented in Chapter 5 from section 5.1.1 to 5.3.1.

Table 4.1 Description of the study area

Location and details	**Srinagar**	**Karnaprayag**	**Agastyamuni**	**Satpuli**
Longitude and Latitude	$30^0$13′12″N $78^0$46′48″E	$30^0$16′12″N $79^0$15′0″E	$30^0$23′26″N $79^0$1′34″E	$29^0$55′0″N $78^0$42′0″E
Rain fall (mm)[1]	1355	1710	1243	1547
River (source water for RBF)	Alaknanda	Alaknanda	Mandakini	Eastern Nayar
Distance from the river (m)[2]	165	50	70	50
Estimated population including pilgrims[3]	31,500	8,700	5,700	7,900
Mean altitude [m above mean sea level]	551	769	733	580
Existing Water Supply as in 2010				
Surface water source in use[3]	Alaknanda	Ghat Gad	SauGaun Stream	Redul Stream
Min. discharge of existing water source (m^3/day)	$9\times10^{6**}$	5251[+]	86[+]	345[+]
Average drinking water production (m^3/day)	3,750	640	70	310
Demand (m^3/day)	4,880	1,340	880	1,070
Deficit (m^3/day)	1,130	700	810	760
Per capita availability (Liter/person/day)	119	74	12	39
[1]Annual rainfall; [2]non-monsoon; [3]Ronghang and Sandhu (2011); [**]Chakrapani and Saini. (2009); [+]Kimothi et al., (2011); (All the hand pump were located along the motorable road)				

4.1.1 Srinagar RBF Site

The study area, Srinagar is situated in the foothills of Himalayas and on the bank of the Alaknanda River. It has recorded several floods and cloud bursts in the past; the latest one is from 16-17 June 2013. The present study was conducted in the Srinagar town and its neighboring upstream town Srikot (30°13’26”N, 78°48’57”E).

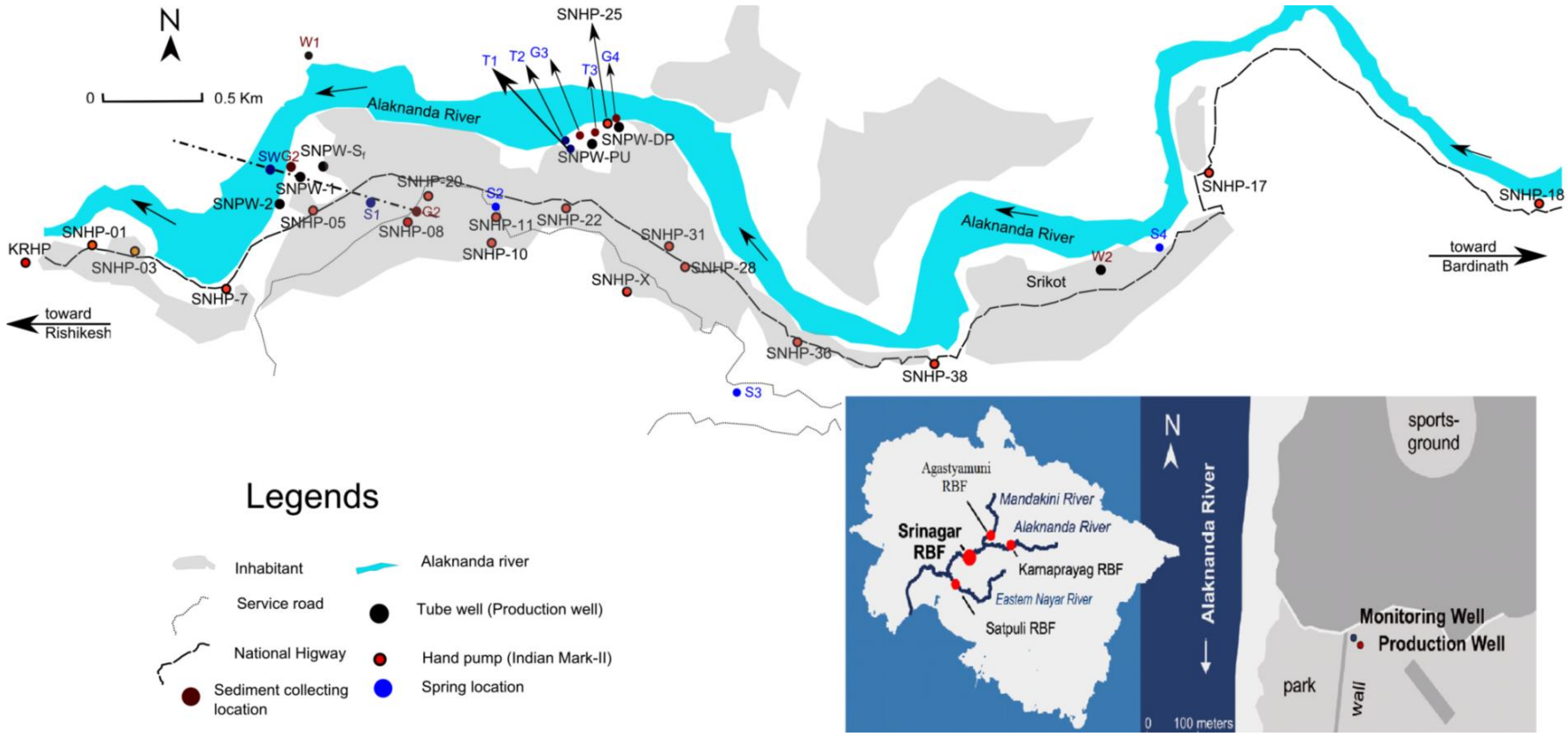

Figure 4.2 Topographic map and RBF location at Srinagar

Srikot is also located on the left bank of river Alaknanda. A topographic map of the region along with sampling locations is shown in Figure 4.2. The river flows in a meandering path through the area surrounded by steep mountain ranges.

4.1.2 Agastyamuni RBF Site

Agastyamuni, a small town is located in the district Rudraprayag. The town is situated on the left bank of the river Mandakini covering an area of about 5.01 Km^2 (Urban Development Directorate, 2013). Agastyamuni is around 18 km upstream of the confluence of the Mandakini River and the Alaknanda River at Rudraprayag (Figure 4.3)

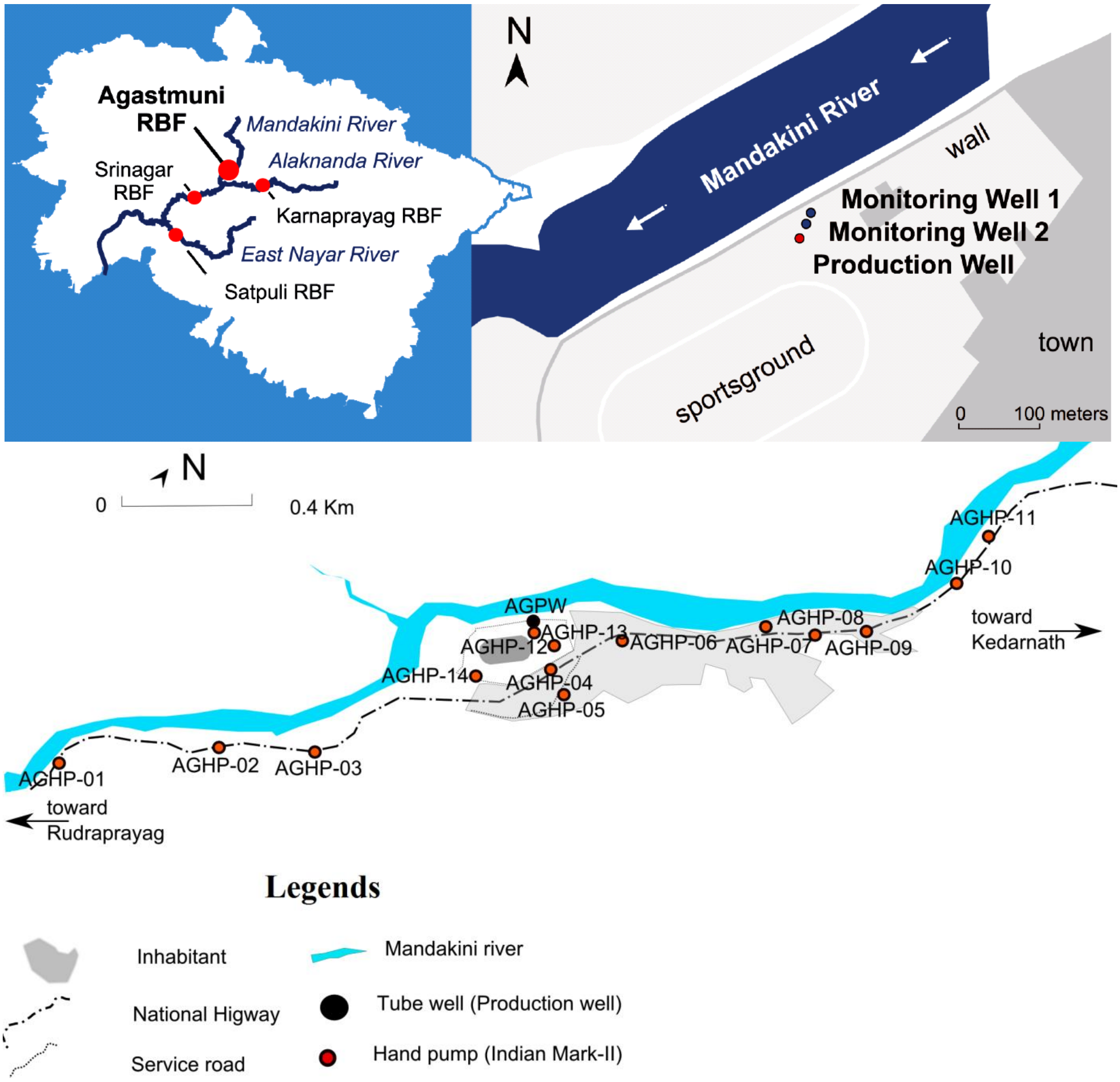

Figure 4.3 Topographic map and RBF location at Agastyamuni. The dashed lines represent the national highway NH-109

4.1.3 Karnaprayag RBF Site

Karnaprayag, the third site is located in the district Chamoli. The site is situated at the confluence of the rivers Alaknanda and Pindar. The town falls on the National Highway NH-58 that connects New Delhi to Mana and Badrinath in Uttarakhand. It makes this location an important stopover for tourists and pilgrims. The study site is approximately 66 Km upstream of Srinagar RBF well field. The topography is highly undulating, and geological formations are moderate to steep (CGWB 2011a&b). The study area, located at Kaleshwar is around 6 Km upstream of the town Karnaprayag (Figure 4.4). The local people are engaged in farming and mining of the riverbed material. The area has a water-ponding problem in monsoon.

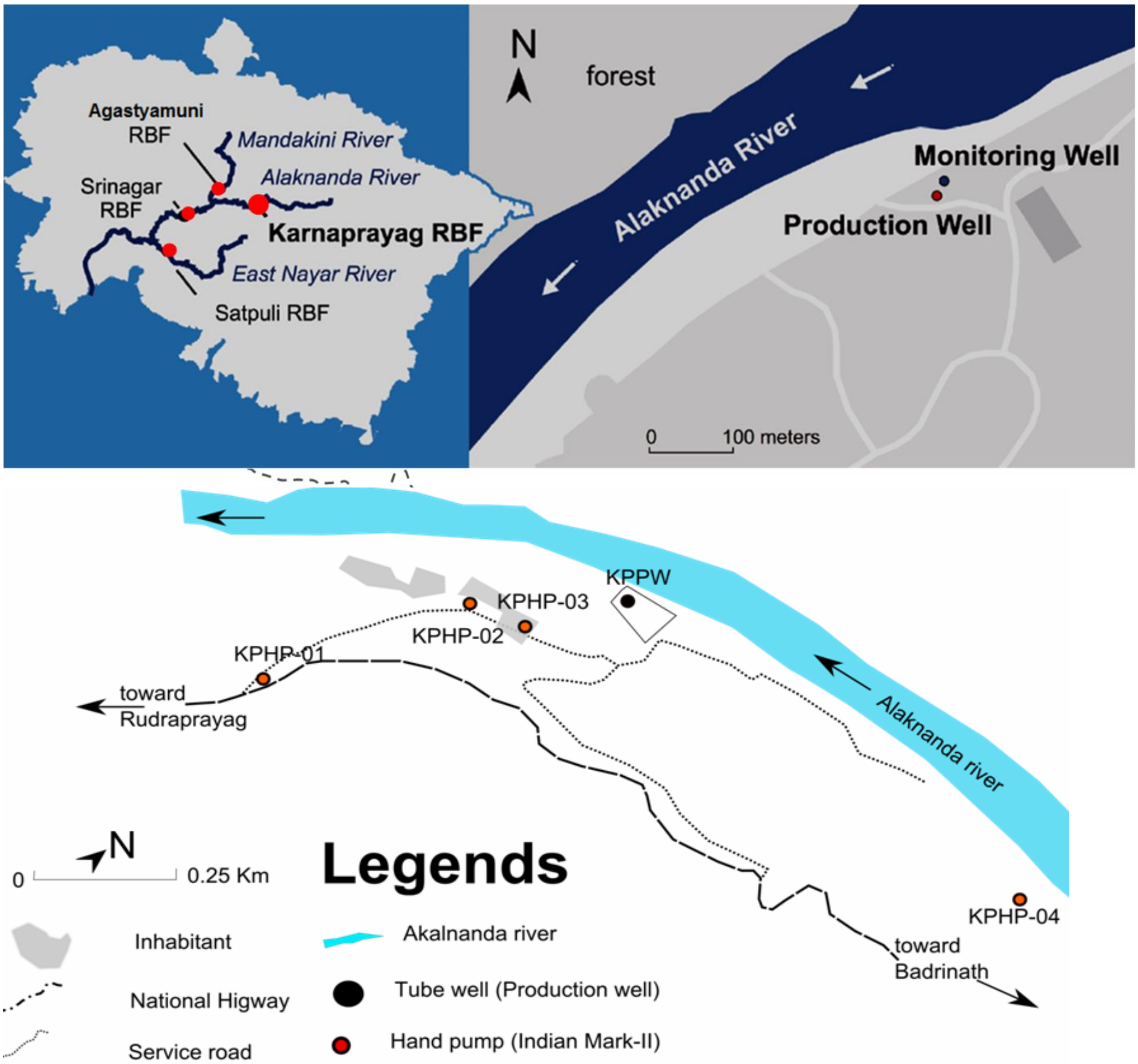

Figure 4.4 Topographic map and RBF location at Karnaprayag.

4.1.4 Satpuli RBF Site

Satpuli in the Pauri district is the fourth location. The name of the town is derived from the fact that there are seven bridges (sat-pul), between Kotdwar and Pauri towns. The RBF site is located at the meandering of the Eastern Nayar River (Figure 4.5).

The area around Satpuli has a very complicated geologic and surface structure due to mountainous folds and faults (Gairola and Saxena, 1980). A steeply inclined rock face characterizes the right bank of the river across the RBF site.

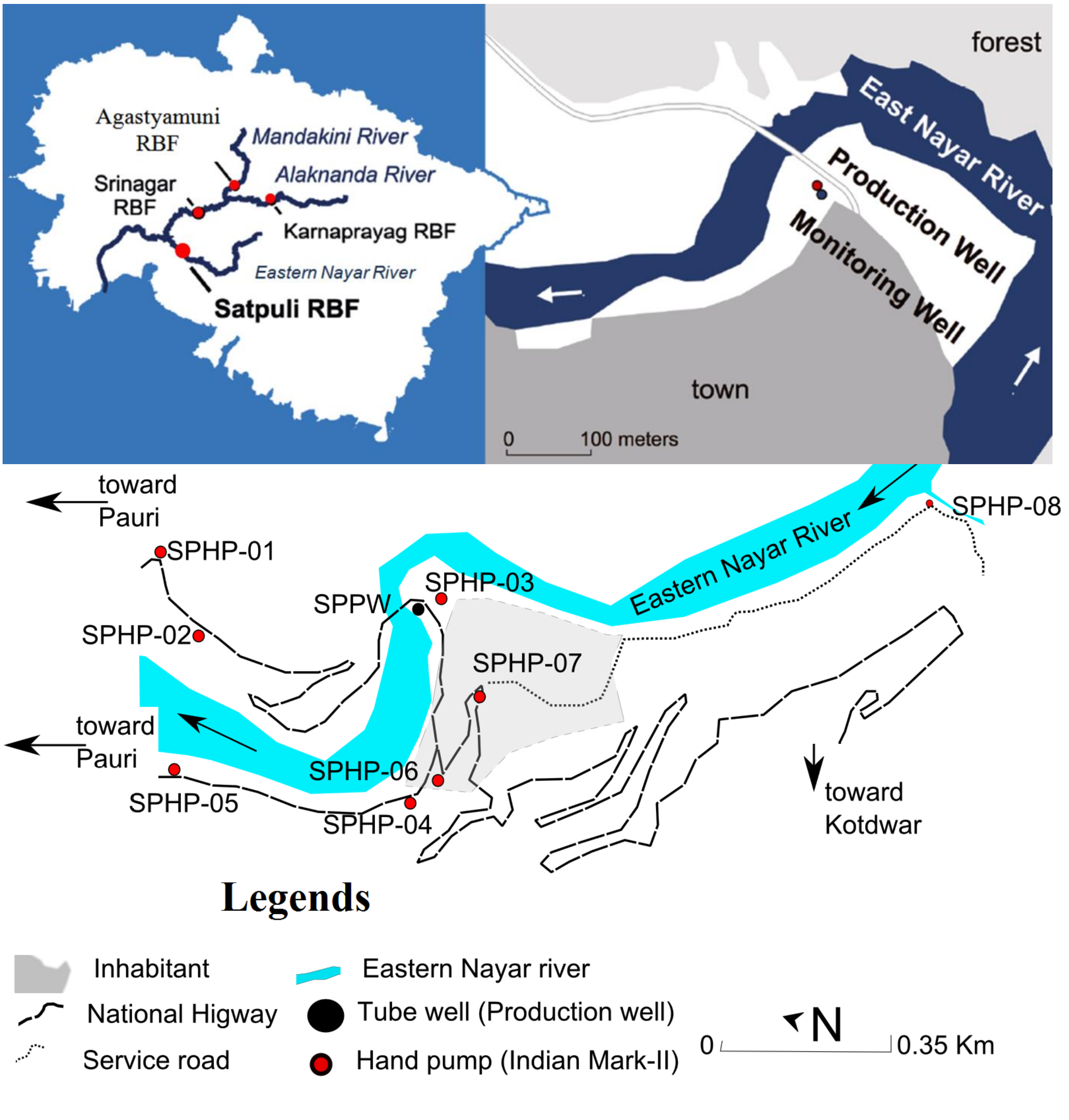

Figure 4.5 Topographic map and RBF location at Satpuli

4.2 HYDROGEOLOGICAL INVESTIGATIONS

Grain size distribution was carried out at Srinagar and Satpuli. Pumping tests were performed at all the four locations in Apr-May 2010 and Nov.-Dec. 2011. Continuous water level and temperature measurement using data logger and infiltration test were also carried out. Water level and temperature measurements made manually at the time of sampling are also presented here.

4.2.1. Grain Size Distribution and Analysis of Boreholes

The aquifer material up to the depth of 20 m below the surface and the sediment from the riverbed were collected during the drilling of wells. Physical observations at the time of drilling were as under:

- Top 1.5 m from the surface had the higher fraction of coarse sand and cobbles.
- From 1.5 to 4.5 m, the mixture of the coarse sand and fine sand was found.
- Coarse sand and coarse gravel were found in abundance at a depth of 4.5 to 36 m.
- Water table at (i) Satpuli was 569.92 m above MSL (5.76 m BGL), (ii) Srinagar was 540.68 m above MSL (6.64 m BGL), (iii) Karnaprayag was 761.77 m above MSL (7.24 m BGL) and (iv) Agastyamuni was 714.43 m above MSL (18.27 m BGL)

The sieve analysis of the collected material was carried out at geotechnical laboratory, IIT Roorkee. Aquifer samples from Srinagar RBF site at different depths were collected and subjected to sieve analysis. The sub-surface soil from the riverbed was also collected and analyzed. Grain size distribution and hydraulic conductivity based on grain size have been incorporated in Table 4.2, Figure 4.6 & Figure 4.7

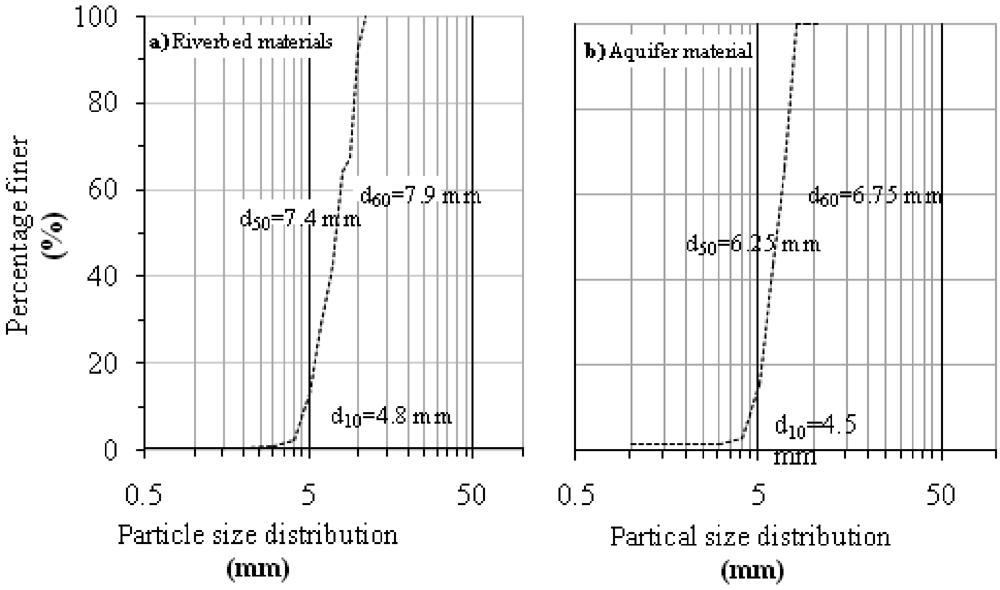

Figure 4.6 Particle size distributions (a) Riverbed (SP-RB) and (b) aquifer material (from SPPW) from Satpuli RBF site

Table 4.2 Characteristic of the riverbed and aquifer material from production wells at Srinagar and Satpuli

Sample (depth from the surface, m)	d_{10} (mm)	d_{60} (mm)	Uniformity coefficient U	Porosity (%) η	Coefficient of gradation Cc	Hydraulic conductivity k (m/s)#	Aquifer type interpreted	
							borehole log	Nature of materials
SNPW2 (Srinagar Production Well 2), Water Table < 3m BGL (July11) (FigureA3 and A5 in Appendix A)								
(0-4)	0.18	0.63	3.5	38.8	0.9	9.40×10^{-4}	fine- coarse sand	Well graded
(4-8)	0.2	0.41	2.05	42.9	0.92	1.29×10^{-3}	fine sand –fine gravel	
(8-15)	0.12	0.4	3.33	39.2	1.3	4.54×10^{-4}		
(15-18)	<0.075	0.53	-	-	-	-	coarse silt–fine gravel	-
(18-20)	0.11	0.7	6.36	33.3	2.63	3.09×10^{-4}	fine sand –fine gravel	Poorly graded
River Bed Sediment from different locations G1, G2, G3, G4 (Figure A4 in Appendix A)								
G1 in Dec.11	0.27	10.7	39.85	25.5	0.17	1.08×10^{-3}	fine sand – coarse gravel	Poorly graded
G2 in Dec.11	0.18	1.16	6.44	33.18	1.2	8.27×10^{-4}		Well graded
G3 in Dec.11	0.22	0.68	3.09	39.83	0.82	1.44×10^{-3}		Poorly graded
G4 in Dec.11	0.29	5.5	18.97	26.2	0.23	1.61×10^{-3}		
G3 in May10	0.13	0.30	2.31	42.1	1.24	5.33×10^{-5}		Well graded
SNPW 1 (Srinagar production well 1)(water table; 2.6 m BGL (August 11), 6.6m BGL(June))								
(3.2-6.4 m)	0.12	0.41	3.42	39.0	1.02	4.21×10^{-4}	fine sand – coarse gravel	Well graded
(12 m)	0.25	10.3	41.2	25.5	1.55	9.16×10^{-4}		Poorly graded
(21 m)	0.15	0.36	2.4	41.8	1.25	4.01×10^{-4}		Well graded
Satpuli river bed (SPRB) and production well (SPPW)								
SPRB	4.80	7.90	1.60	48.3	0.96	0.78	medium sand- coarse sand	Well graded
SPPW	4.5	6.75	1.50	48.0	0.82	0.69		

d_{10}=10% finer; d_{60}=60% finer; # Computed from Breyer's empirical equations[2] (Odong. 2007);[1] $\eta = 0.255\,(1 + 0.833^{U})$; $U = \frac{d_{60}}{d_{10}}$; [2] $k = \frac{g}{v} \times 6 \times 10^{-4} log_{U}^{500} d_{10}^{2}$;

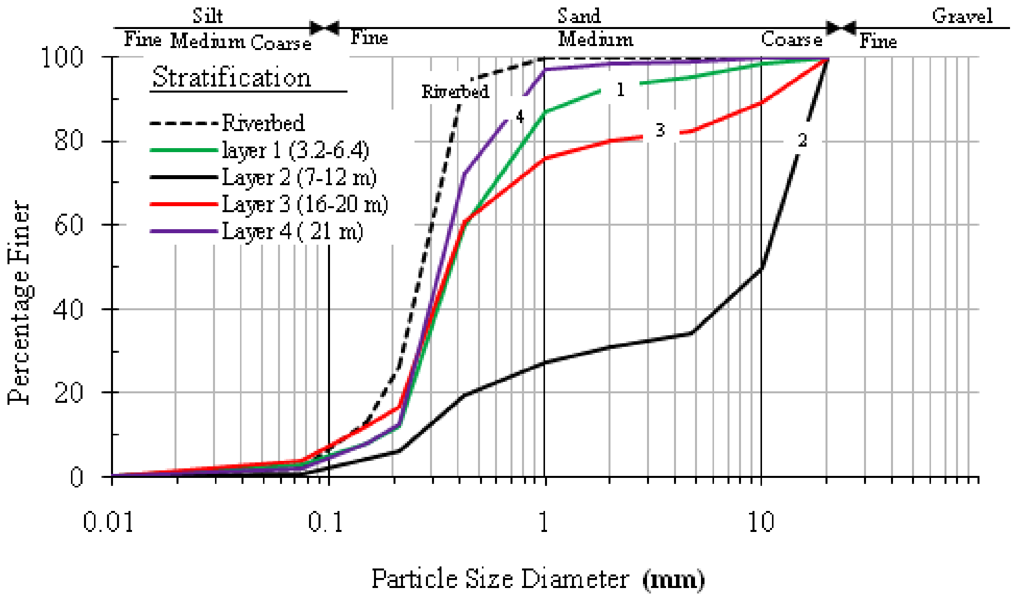

Figure 4.7 Sieve analyses: aquifer (SNPW-1) and riverbed materials (SNRB) from Srinagar RBF site

The perusal of data in Table 4.2 suggests that the aquifer material at Srinagar and Satpuli are coarse sand with gravel and boulder. Based on the borehole log, the aquifer can be considered unconfined. The grain size distribution and characteristics of the riverbed and aquifer materials from the production well are similar.

The aquifer at Srinagar has been found to be heterogeneous in nature. The riverbank consists of coarse to medium sand, medium gravel, and small boulders deposited by the river. Figure 4.8(a) shows the aquifer profile at the RBF site and nearby silk farm. The aquifer at the RBF well consists mainly of coarse to medium sand with bedrock starting at a depth of ~21 m. The aquifer profile changes sharply at very short distances. For instance, the silk farm, located at a distance of ~135 m from the well, has significantly different aquifer profile than the RBF site with weathered rock starting at a depth of 17 m and extending up to 25 m. There are locations in the town where the bedrock is exposed at the surface. Such information at other sites was not available.

Three more wells were drilled at Srinagar and the thickness of the aquifer in Srinagar ranged between 7-20 m from the surface. The thickness of the aquifer at the time of drilling at other sites was found between 15 and 25 m BGL. The thickness of the aquifer lies in the range of existing RBF sites (Table 2.1). Ray et al., (2003) have reported the aquifer thickness at RBF sites to vary from 3 to 300 m (Table 2.1 of section 2.1). At Agastyamuni, Satpuli and Karnaprayag, accurate assessment of the actual grain-size distribution could not be made because of the use of Odex (DTH) drilling machine. In this process, borehole material is crushed and flushed out. However, the borehole log obtained from drilling is incorporated in Figure 4. (c) & (d). Details pertaining the aquifer are given in appendices A from Figure A6 (a)-(d)

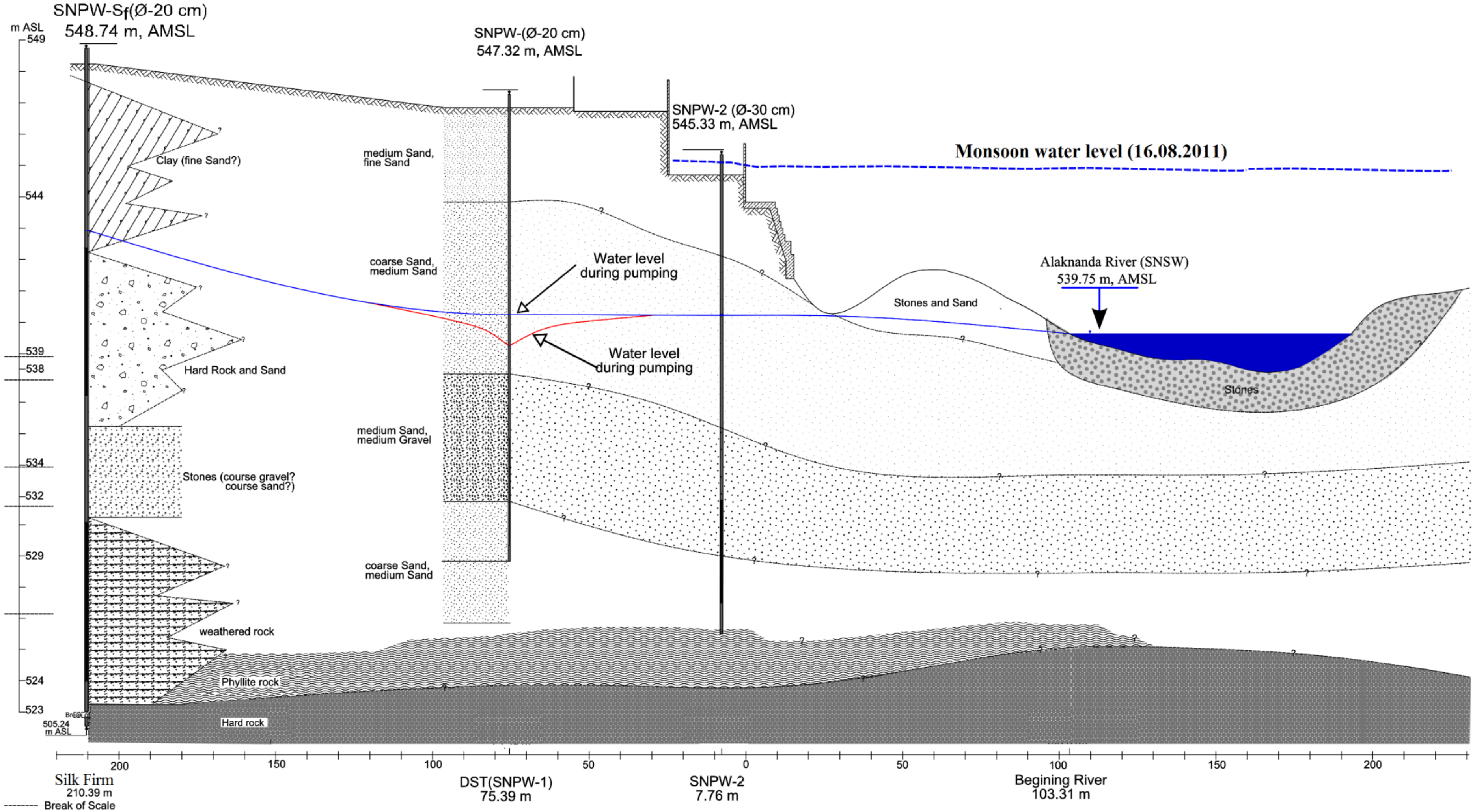

Figure 4.8 (a) Aquifer profile at the RBF site in Srinagar (adapted and modified from Saph Pani, 2014)

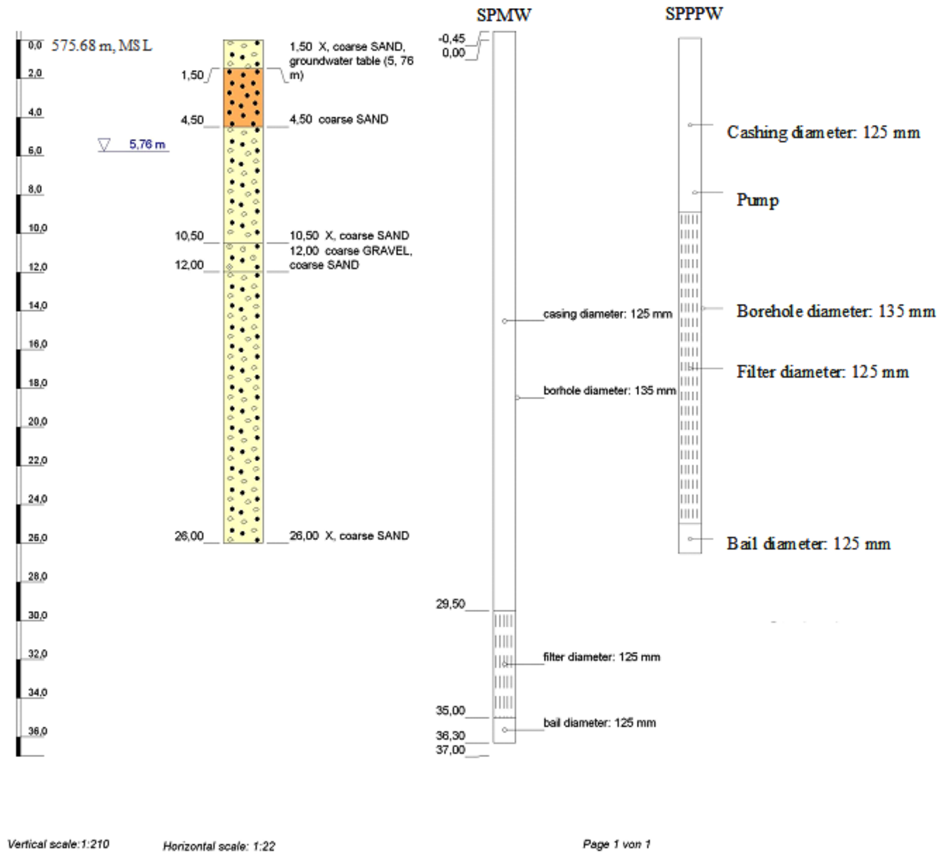

Figure 4.8(b) Details of the bore log and the well assembly at Satpuli (Ronghang and Sandhu, 2011)

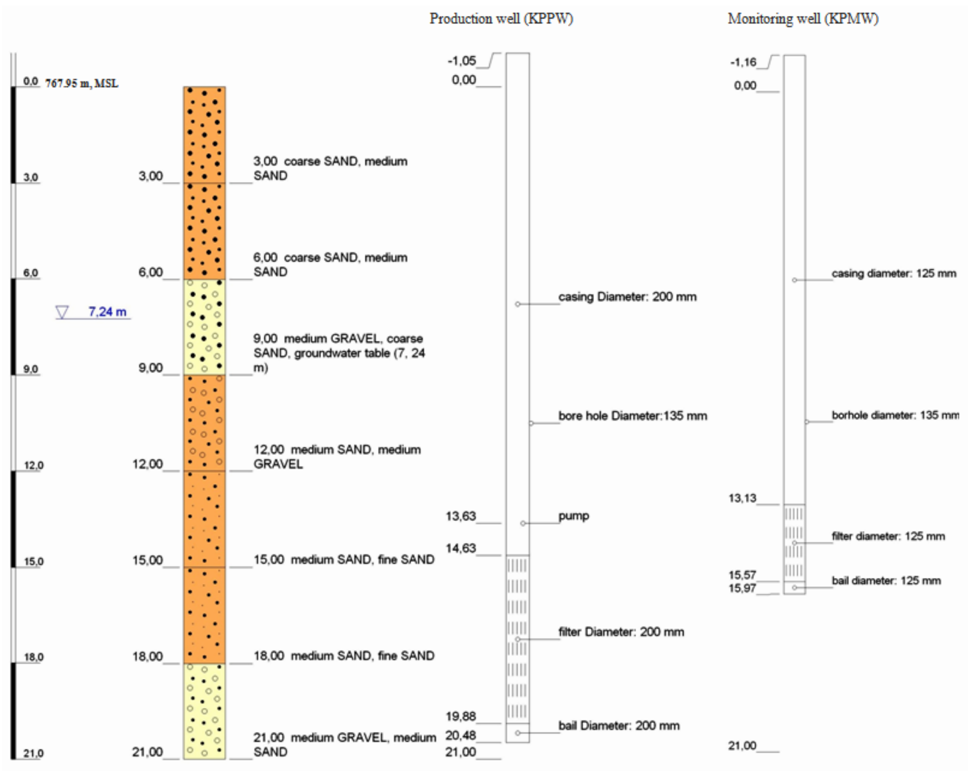

Figure 48(c) Details of the bore log and the well assembly at Karnaprayag (Ronghang and Sandhu, 2011)

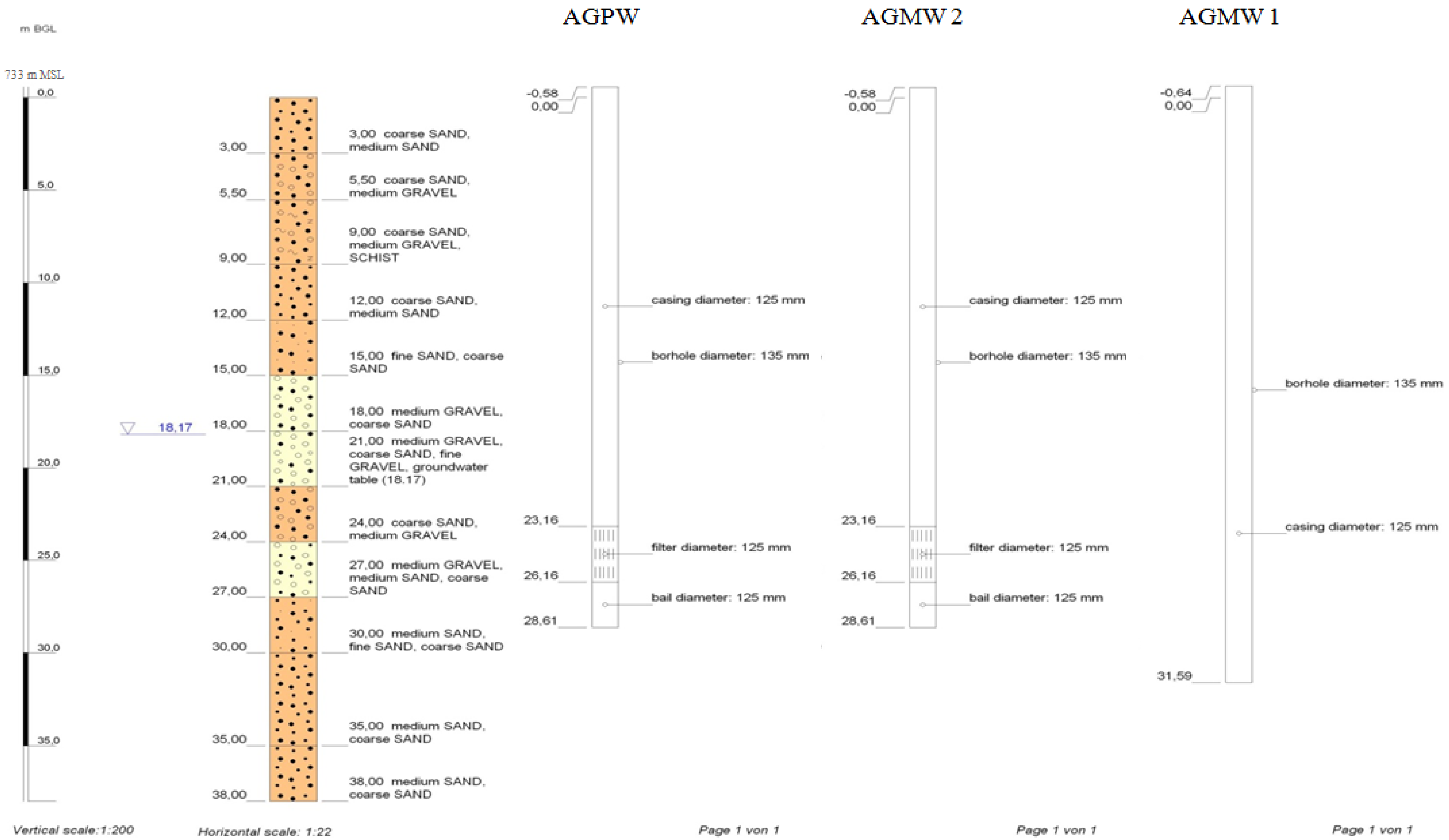

Figure 4.7 (d) Details of the bore log and the well assembly at Agastyamuni (Ronghang and Sandhu, 2011)

4.2.2. Pumping Tests

Pumping tests were carried out immediately after the wells were commissioned in 2010 and after a year in 2011. The hydrograph obtained from the monitoring well and production well is shown in Figure A7 (a)-(d) to A8 (a)-(d) of Appendix A. (Numerical values retrieved from data logger are given CD-ROM). The duration of pumping and the drawdown observed in the production wells and monitoring wells at all the sites are given in Table 4.3(a). The aquifer characteristics derived from the pumping tests data are tabulated in Table 4.3(b).

The hydraulic conductivity (k) is within the observed variation at existing RBF aquifers. Hydraulic conductivity at various RBF schemes in Germany and USA has been found to vary from 1×10^{-3} to 6×10^{-4} m/s (Grischeck et al., 2002 and Ray et al., 2002).

Table 4.3 (a) Observation from short and long-duration pumping tests

Pumping Test[1]	**Discharge (LPM)**	**Duration of pumping phase (minutes)**	**Steady-state drawdown (m)**		
Srinagar			**SNPW 1**	**SNMW**	**SNPW#**
1(May 16,2010)	90	283 (4.71 h.)	0.55	0.35	- Not built
2 (May 17,2010)	620	605 (10.08 h.)	4.30	2.54	
3 (Nov 4,2011)[1]	710	2819 (46.98 h.)	-	1.73 (1.28)*	1.59
Agastyamuni			**AGPW**	**AGMW 2**	**AGMW 1**
1(May 15,2010)	85	143.5 (2.39 h.)	1.24	0.34	-
2 (May 14,2010)	320	35 (0.58 h.)	5.35	1.35	
3 (Nov 17,2011)[1]	230	4227.5 (~70.5 h.)	-	1.36 (0.59)*	1.08
Karnaprayag			**KPPW**	**KPMW**	
(May 13,2010)	95	185 (3.1 h.)	0.66	0.23	
(May 13,2010)	450	157 (2.6 h.)	3.78	0.89	
(Nov 26,2011)	690	2945.5(49.09h.)	4.94	1.73 (1.33)*	
Satpuli			**SPPW**	**SPMW**	
1(May 17,2010)	650	53 (0.9h.)	1.55	0.61	
2(May 17,2010)	-	140 (2.3h.)	1.64	0.64	
3(Dec 4, 2011)[1]	630	4035.5 (67.25h.)	-	0.81(0.71)*	

*drawdown (to compare the value observed in 2010); # Production well, without submersible pump, 23 m from SNPW-1 (towards hinterland), and was used as observation well; [1]Well was connected to water supply network so water level could not be measured at the production well in 2011. In 2010, pumped water was discharged towards the river through a long drainage pipe

Table 4.3 (b) Aquifer characteristics from pumping test data

Parameter	16-17.May.10	4.Nov.11	14-15.May.10	17th Nov.11	13May.10	26Nov.11	29Apr.10	26Nov.11
	Srinagar		Agastyamuni		Karnaprayag		Satpuli	
H, Saturated thickness of aquifer (m)	28.3	-	38	-	22.8	-	30	
S, Storage coefficient	5.7×10^{-6}	-	1.7×10^{-3}	-	3.9×10^{-7}	-	-	-
S_s, Specific storage (m^{-1})	2.0×10^{-7}	-	7.8×10^{-5}	-	1.7×10^{-8}	-	-	-
Well bottom of PW (m)	18.0		30.61		21		23.9	
h_{GW}, Available saturated thickness for partially penetrating well (m)[1]	28.08	27.5	37.4	37.1	22.4	21.9	29.2	29.6
f_l, Filter length (m)	5.5		3.0		5.2		15.9	
Z_0, Saturated thickness of the aquifer above the hard rock after steady state drawdown.(m)	27.5	25.78	36.1	35.3	21.7	20.16	27.7	28.72
k, Hydraulic conductivity after Thiem Dupuit (m/s) [2]	5.3×10^{-4}	-	2.7×10^{-5}	-	9.4×10^{-5}	-	27×10^{-5}	-
k, Hydraulic conductivity (m/s) (Cooper-Jacob)	5.14×10^{-4}	4.0×10^{-3}	2.02×10^{-4}	2.2×10^{-4}	7.28×10^{-4}	6.8×10^{-4}	4.51×10^{-4}	6.5×10^{-4}
k, from grain size (m/s)	3.09×10^{-4}-1.29×10^{-3}		-		-		0.69	
T, Transmissivity(m^2/s)[3]	2.17×10^{-3}	110×10^{-3}	1.7×10^{-3}	8.2×10^{-3}	2.50×10^{-3}	14.8×10^{-3}	13.5×10^{-3}	19×10^{-3}
R_w, Radius of influence (m) (Sichardt's formula)[4]	14.6	326	26	78.8	26.0	135.3	104	65
R_w, Radius of influence (m) (Kusakin's formula)[5]	15	323	24	93.0	24.0	123.7	99	68
Q_A, Steady state flow rate[2](L/min)	88.2	8543	151	797	174	175	1085	937
Q_F, Well yield (L/min)[2]	604	4099	636	1318	728	728	1476	1841
Safe Yield[2] (L/min)[6]	510	4000	550	1255	490	1400	1450	1750

[1]$h_{GW}=H-0.5\times s$; s - steady state drawdown (Table 4.3a);[2]$Q_A=\frac{\pi k(h_{GW}^2-Z_0^2)}{\ln\frac{R_w}{r_o}}$;[3]$T=kh_{GW}$;[4]$R=3000\,s\sqrt{k}$;[5]$R=575s\sqrt{Hk}$; [6]$Q_F=\frac{2}{15}\pi r_o Z_0\sqrt{k}$;[7]from interception of the plot between Q_A and Q_f (Q_A and Q_f in m^3/s from the formulae are reported in L/m)

4.2.3. Safe Yield of the Well

Safe yield of the wells calculated from DIN: 2004 are given in Table A9 (a)-(d) of Appendix A. The production capacity of RBF wells at Srinagar and Satpuli is similar to Meissen-Siebeneichen, in Germany. The ability of the well from the long duration pumping suggest that well can safely draw water ranging from 1255-4000 L/min which is more than an average well yield of Tolkwitz, Germany and same order that of Somersnorth, New Hamsphire (Grischek et al., 2002). Examples from such utilities around the globe suggest that the site at RBF well in the hilly area of Srinagar, Satpuli Agastyamuni, and Karnaprayag has a potential of RBF scheme.

4.2.4. Double Ring Infiltration Test

In an RBF system, the risk of infiltrating flood and rain water from the top remain high during the monsoon. It was necessary to estimate the infiltration rate of the soil to prevent the well from rapid seepage of rainfall-runoff and flood water into the wells. Double ring infiltrometer was used to determine the infiltration capacity of the soil above the aquifer (section 3.6). Results are presented graphically in Figure 4.9.

The values of initial infiltration rate, the time to attain constant infiltration and nearly constant infiltration rate are given in Table 4.4. The infiltration depends on the depth of the vadose zone, aquifer characteristics and the moisture present in the soil. The rate of infiltration being less than the hydraulic conductivity indicates the fact that the time taken by the flood water to reach the water table will be more than the time taken by the bank filtrate to reach the production well. Under such a scenario, the infiltrating rain or flood water is not expected to have an adverse effect on the quality of the bank filtrate.

Table 4.4 Result of the infiltration test from infiltration test

Location	Initial infiltration f_o(m/s)	Constant infiltration, f_c(m/s)	Time to attain constant infiltration, t (h)
Srinagar	2.33×10^{-4}	1.33×10^{-5}	1.90
Agastyamuni	9.50×10^{-4}	2.33×10^{-5}	1.20
Karnaprayag	1.32×10^{-3}	9.92×10^{-5}	0.70
Satpuli	8.30×10^{-5}	1.11×10^{-5}	1.20

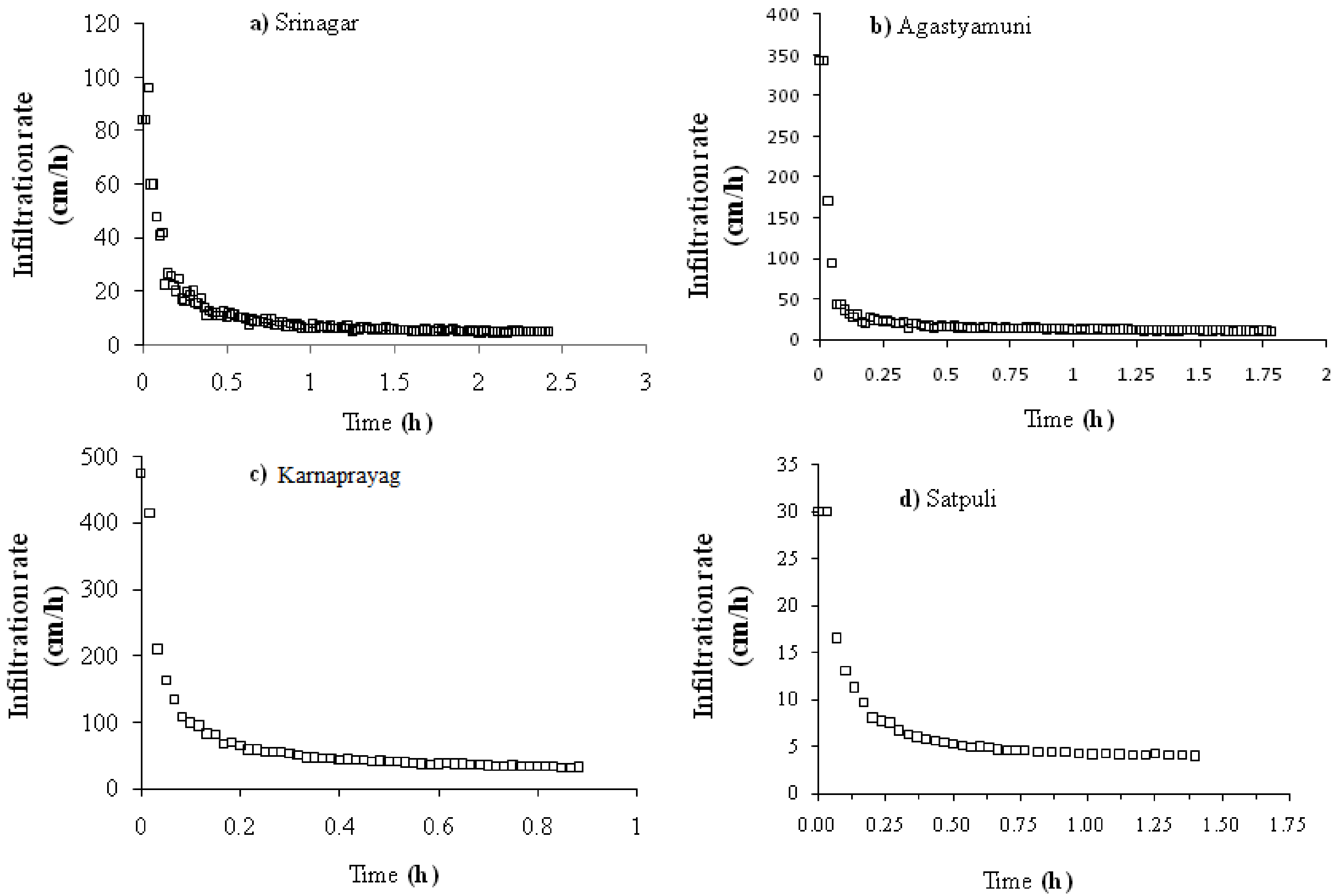

Figure 4.9 Infiltration capacity of the soil at the RBF site. (a) Srinagar (b) Agastyamuni(c) Karnaprayag and (d) Satpuli

4.3 TEMPERATURE PROFILE OF WATER IN MONITORING WELL

The use of heat (temperature) as a tracer for surface-water/ground-water interactions has been widely reported in natural environment by Slichter (1905), Lapham (1989), Constantz et al., (1998), (2002), (2003a&b), Stonestrom and Constantz. (2003) and Lorenzen et al., (2010). The difference in temperature between surface water and its surrounding water has been used to understand the movement of groundwater in the subsurface environment (Anderson 2003). Infiltration through heat is also investigated in hydrology (Barlow and Coupe, 2009; Constantz, 2008; Constantz et al., 2002; Cox et al., 2007; Schmidt et al., 2007). During sampling, the temperature as a measure of heat signal was recorded at a depth of every 0.5m from the water table to the bottom of the monitoring well. The numerical values of the temperature are given in Table B2 to B5 of Appendices B. The data obtained has been put under three categories namely pre-monsoon, monsoon and post-monsoon.

The temperature of the surficial zone is influenced by seasonal heating and cooling of the land surface.In pre and post monsoon, the aquifer in the surficial zone is compressed to around 2 m with a temperature variation of less than 1^0C i.e. the effect of temperature is more pronounced during monsoon. The amplitude of the temperature fluctuation decreases with the depth; below ~15 m temperature is not influenced by diurnal variation at the land surface (Silliman and Booth, 1993). Shallow groundwater temperature is ~1^0C higher or lower than the mean temperature of water in the geothermal zone. Temperature profiles in the surficial zone potentially provide information about seasonal recharge/discharge event from precipitation and interchange with surface water. The thickness of the aquifer in the surficial zone in monsoon is different at different sites. Also, the temperature profiles at four sites are different and, therefore, have been discussed separately.

4.3.1 Temperature Study: Srinagar Monitoring Well

The variation of temperature in the water is given in Table 4.5 and the plots are given in Figure 4.10. Well was drilled in 2010 and the first temperature profile was recorded in the monsoon in Aug 2011 before the well operation. At this time, the temperature varied from 23.5 to 22.9^0C (0.6^0C). It is to be observed that the monsoon profile of Aug. 2011 is different than the profile recorded in Aug. 2012, after the well operation. Without pumping, the temperature was under the influence of seasonal and diurnal heating and cooling of the land surface (Anderson 2005; Lorenzen et al., 2010). After the well was commissioned, and water was continuously abstracted, the effect of pumping on temperature profile is more noticeable in monsoon than in non-monsoon. The thickness of the aquifer in the surficial zone in monsoon is 8 to 9 m. It may be due to the withdrawal of infiltrated rainwater and/or river water (Figure 4.10).

According to Anderson (2005) and Larkin and Sharp (1992) the two observations namely (i) the relatively narrow surficial zone and (ii) the temperature gradient ranging from 0.01-0.08^{0}C/m up to 13 to19 m in monsoon and post-monsoon respectively, are indicative of gaining river scenario. However, in pre-monsoon there is not exchange (<10 m of surficial zone)

Table 4.5 Srinagar: Vertical temperature profile in the monitoring well

Month	Depths of top most and bottom most readings[1,] (length of the water column)(m)	Temperature of top most and bottom most layer (^{0}C)	Mixing zone below water table(length of surficial zone) (m)	Range of Temperature in surficial zone (difference),(^{0}C)
Pre-monsoon				
Feb.12	7.4-19.0 (11.6)	23.28-23.11	- (-)	23.28-23.40 (0.29)
Apr.12	7.2-19.5 (12.3)	23.89-23.18	7.1-11.0 (3.85)	23.89-23.39 (0.50)
May12	7.3-19.5 (12.2)	24.13-23.2	7.2-11.0 (3.72)	24.13-23.34 (0.91)
Mar.13	8.4-19.3 (10.9)	24.25-23.06	8.4-10.5 (2.08)	24.25-23.37 (0.88)
Monsoon				
Jun.12	7.4-20.0 (12.6)	24.32-22.45	7.4-17.0 (9.64)	24.32-23.12 (1.11)
Jul.12	7.9-20.0(12.1)	25.32-23.00	7.9-16.5 (8.63)	25.32-23(2.32)
Aug.12	7.3-19.5 (12.2)	25.62-23.00	7.3-15.5 (8.18)	25.62-23(2.62)
Sept.12	6.8-19.0 (12.2)	24.37-22.50	6.8-15.5 (8.66)	24.37-23(1.62)
Post-monsoon				
Nov.12	7.2-19.0 (11.8)	23.50-23.11	7.2-11.5 (4.32)	23.50-23.40 (0.10)
Dec.12	8.8-20.0 (11.2)	22.22-23.12	8.8-14.0 (2.65)	22.22-23.31(1.25)
Jan.13	8.2-19.5 (11.3)	22.50-23.06	8.2-9.5 (1.32)	22.50-23.12 (0.81)
[1]Depth of the water table is from the top of the casing);all reading are below the water table				

4.3.2. Temperature Study: Agastyamuni Monitoring Well

The temperature profile data of the Agastyamuni tabulated in Table 4.6 and presented in the Figure 4.11 cannot be clearly differentiated into pre-monsoon, monsoon and post-monsoon as in the case of Srinagar data

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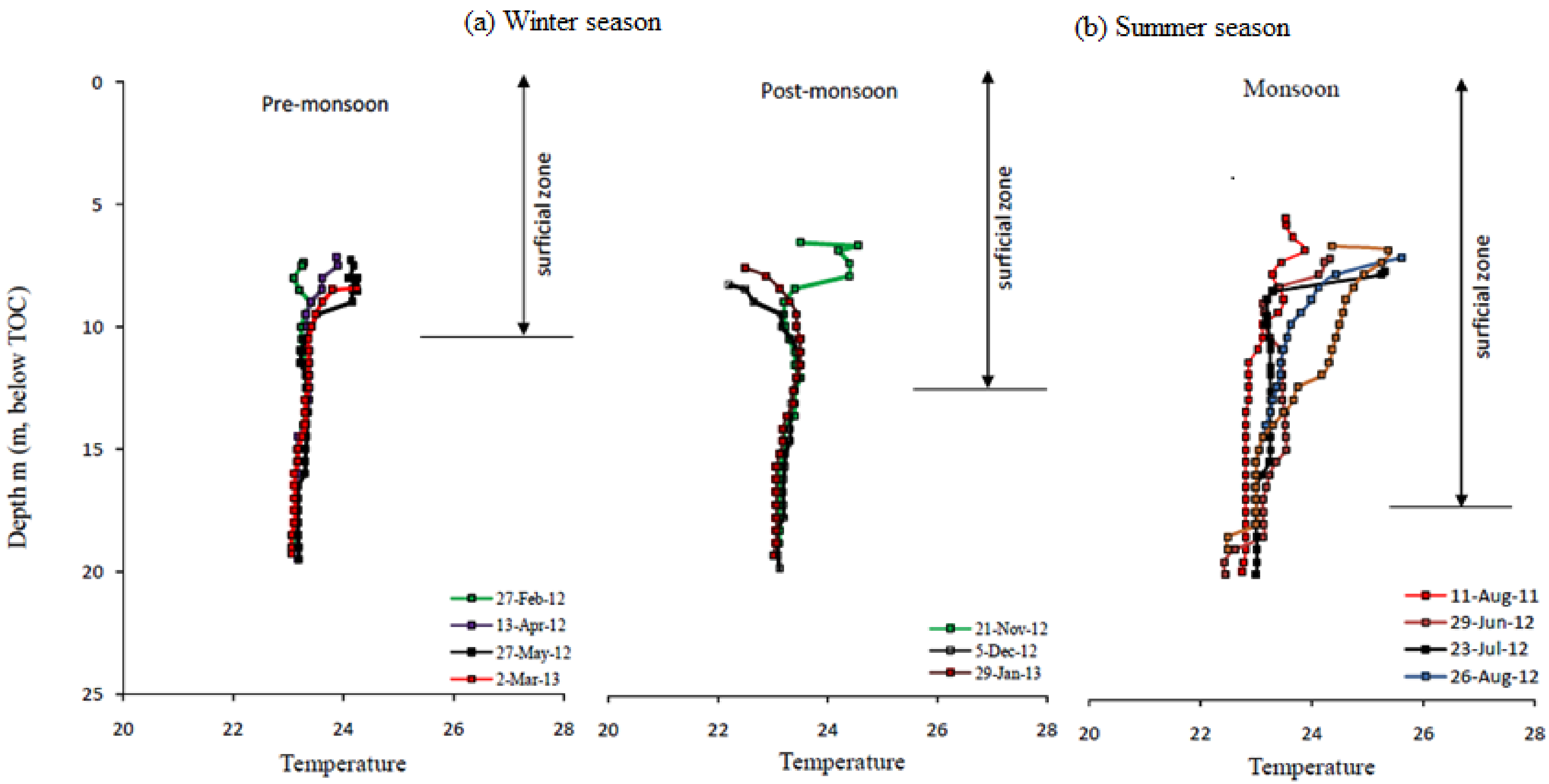

Figure 4.10 Srinagar: Temperature profile in the monitoring well (TOC- top of casing)

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Table 4.6 Agastyamuni: Vertical temperature profile in the monitoring well

Month	Depths of top most and bottom most readings[1], (length of the water column)(m)	Temperature of top most and bottom most layer (°C)	Mixing zone below water table(length of surficial zone) (m)	Range of Temperature in surficial zone (difference),(°C)
Pre-monsoon				
Feb.12 Apr.12	18.9-30.0(11.1) 17.2-23.5(6.3)	20.11-21.93 21.62-22.00	18.7-25.0 (6.3) 17.2-21.0 (3.8)	20.11-21.93(1.82) 21.64-22.00(0.19)
Mar.13	18.75-29.3(10.5)	21.93-22.31	21.9-22.3 (0.4)	21.93-22.31(0.38)
Monsoon				
Aug.12 Sept.12	15.25-22.50(7.25) 14.9-30.5(15.6)	24.81-22.00 23.00-21.93	15.25-20.0 (4.7) 14.9-25.0 (10.1)	22.00-24.81 (2.81) 21.93-23.00 (1.07)
Post-monsoon				
Jan.12 Nov.12 Dec.12 Jan.13	18.9-30.0(11.1) 17.2-29.3(12.1) 18.7-29.3(10.6) 19.0-29.3(10.3)	20.20-21.93 22.74-22.01 21.40-22.01 20.93-21.93	18.9-22.0 (3.1) 17.2-23.0 (5.8) 18.6-26.5 (7.9) 19.0-22.0(3.0)	20.20-21.93 (1.73) 22.01-22.10 (0.09) 21.40-22.01 (0.61) 20.93-21.93(1.00)

[1]Depth of the water table is from the top of the casing); all reading are below the water table

The depth of the surficial zone and the temperature gradient show the same degree of fluctuation. The water in the monitoring well is the mixture of the river water and ground water, and the ratio of the two waters apparently exhibits a narrow range of variation. This observation has been discussed along with the mixing ratio from the isotope data in Section 5.3.2

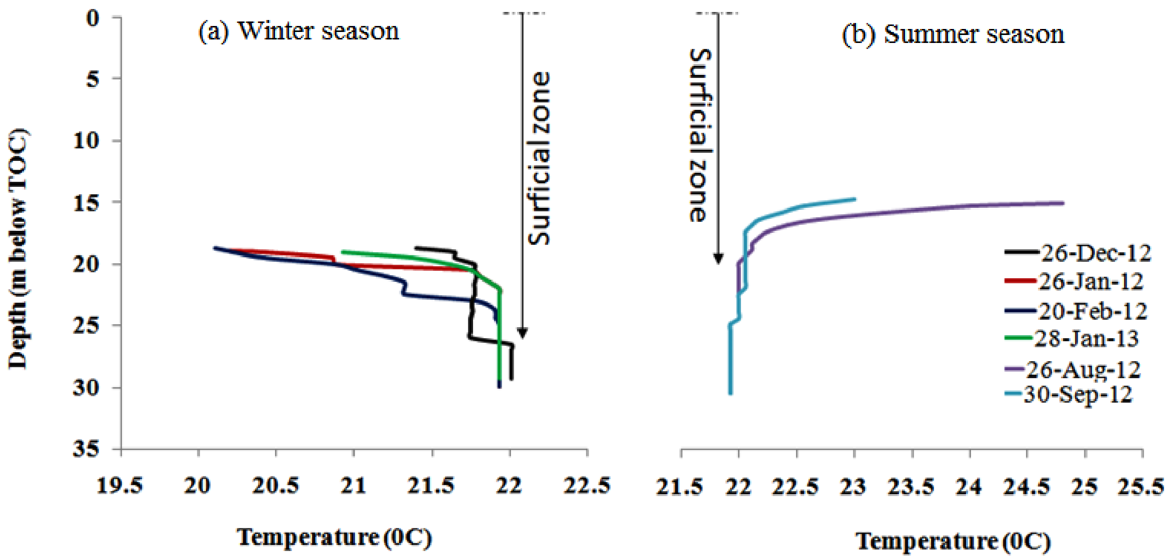

Figure 4.11 Agastyamuni: Temperature profile of the monitoring well (TOC- top of casing)

4.3.3. Temperature Study: Karnaprayag Monitoring Well

Perusals of data (Table 4.7) do not indicate mixing of the river water with the ground water during pre and post monsoon season. Influence of the river water has been noticed in the monsoon. The exchange occurred only during monsoon within the monsoon temperature envelope of around 4^{0}C (Figure 4.12) over a depth of 4 m. Indirect recharge to the sub-surface (groundwater) from the meandering at 700 m away at upstream cannot be ruled out.

Table 4.7 Karnaprayag: Vertical temperature profile in the monitoring well

Month	Depths of top most and bottom most readings[1], (length of the water column)(m)	Temperature of top most and bottom most layer (^{0}C)	Mixing zone below water table(length of surficial zone) (m)	Range of Temperature in surficial zone (difference),(^{0}C)
Pre-monsoon				
Apr.12 May12	8.38-17.3(8.92) 8.58-17.30 (8.72)	20.58-21.70 (1.12) 20.62-20.80 (0.18)	No mixing zone Average Temp. 21^{0}C (Isothermal)	
Monsoon				
Jun.12 Jul.12 Aug.12 Sept.12	8.50-17.30(8.8) 7.54-17.30 (9.76)) 7.0-16.50(5.50) 7.60-15.16(7.56)	24.60-20.88 (3.72) 25.24-20.88 (4.36) 25.18-20.86 (4.32) 24.31-20.56 (3.75)	≈ 4 m	≈4^{0}C
Post-monsoon				
Dec.12 Jan.12 Feb.12 Jan.13 Mar.13	8.46-17.30(8.84) 8.83-17.3 (8.47) 8.58-17.35 (8.77) 8.58-17.3 (8.72) 9-16 (7.0)	20.54-20.86 (0.32) 20.47-21.62 (1.15) 20.62-21.68 (1.06) 20.62-20.68 (0.06) 20.50-20.87 (0.73)	No mixing zone Average Temp. 21^{0}C (Isothermal)	

[1]Depth of the water table is from the top of the casing); all reading are below the water table

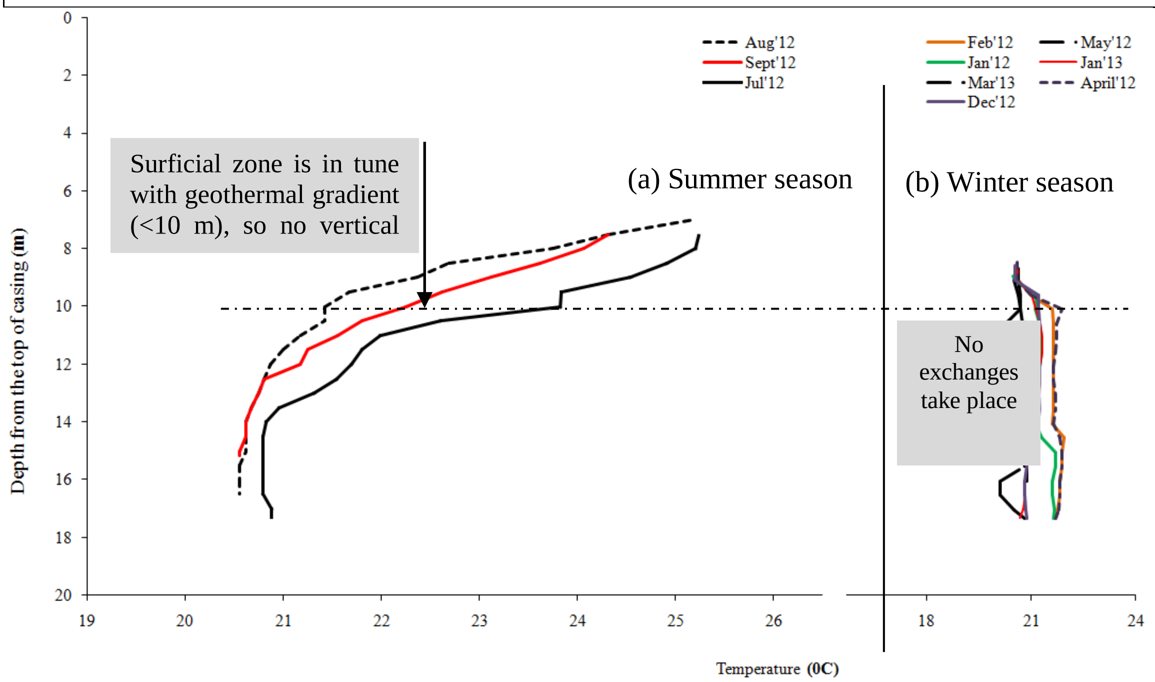

Figure 4.12 Karnaprayag: Temperature profile in the monitoring well

The effects of occasional pumping on temperature profile are not noticeable, as the well was not connected to the supply except in monsoon when the water level of the river is high (Figure 4.12). Karnaprayag, a shallow surficial zone (<10 m bgl) supports the supposition that there no or only very temporal seepage of negligible magnitude.

Furthermore, the gradient in the geothermal zone is very steep (~0.45^{0}C/m), which typically indicates a discharge zone corresponding to gaining river conditions. A concave upward deviation between 6 and 12 m bgl is visible in monsoon also suggest the infiltration of groundwater. No exchange occurs in the rest of the months (Oct.-Jun.) is confirmed by low gradient geothermal (0.006^{0}C/m)

4.3.4. Temperature Study: Satpuli Monitoring Well

The river water temperature varied from 24.3 to 28.1^{0}C in the monsoon and 13.2 to 24.6^{0}C in non-monsoon. It was observed that the average temperature difference between the river water and monitoring well water was 0.4^{0}C. This observation indicates the probable influence of river water on well water. In other words, such a narrow range of temperature difference suggests connectivity between the river and well water through subsurface flow (Constant, 1998; Ermakova and Lyukmanova, 2002). Further, it was observed that the surficial zone or depth of mixing is between 13.78 and 27.41 m below the piezometric ground water level (Table 4.8 and Figure 4.13).

Table 4.8 Satpuli: Temperature profile in the monitoring well

Month	Depths of top most and bottom most readings1, (length of the water column)(m)	Temperature of top most and bottom most layer (^{0}C)	Mixing zone below water table(length of surficial zone) (m)	Range of Temperature in surficial zone (difference),(^{0}C)
Pre-monsoon				
Jan.12	8.21-36.5 (28.3)	14.84-22.23	8.25-29.50(21.25)	15.4-22.12(6.75)
Feb.12	8.17-36.79 (28.62)	15.08-22.26	8.17-25.00 (16.82)	15.86-21.56 (5.7)
Jan.13	8.57-36.43 (27.86)	14.14-22.31	8.57-28.00 (19.43)	14.25-22.12 (7.87)
Mar.13	8.17-36.79 (28.62)	15.06-22.37	8.18-28.50 (20.32)	15.93-22.12 (6.19)
Monsoon				
Jun.12	7.35-37.27 (29.92)	21.18-26.4	7.35-34.00 (26.65)	25.9-21.96 (3.94)
Jul.12	7.59-37.27 (29.68)	20.31-26.43	7.59-35.00 (27.41)	26-22.13 (3.78)
Aug.12	7.28-37.50 (30.22)	22.12-26.37	7.28-29.00 (21.72)	26.37-22.12 (4.25)
Sept.12	8.14-36.24 (28.1)	22.18-26.00	8.14-22.50 (14.36)	26-22.25 (3.75)
Post-monsoon				
Nov.12	8.89-36.79 (27.9)	20.93-32.12	8.89-28.00 (19.11)	21.56-22.13 (0.56)
Dec.12	7.84-36 (28.16)	15.36-22.22	7.84-21.62 (13.78)	15.36-26.5 (11.14)
[1]Depth of the water table is from the top of the casing); all reading are below the water table				

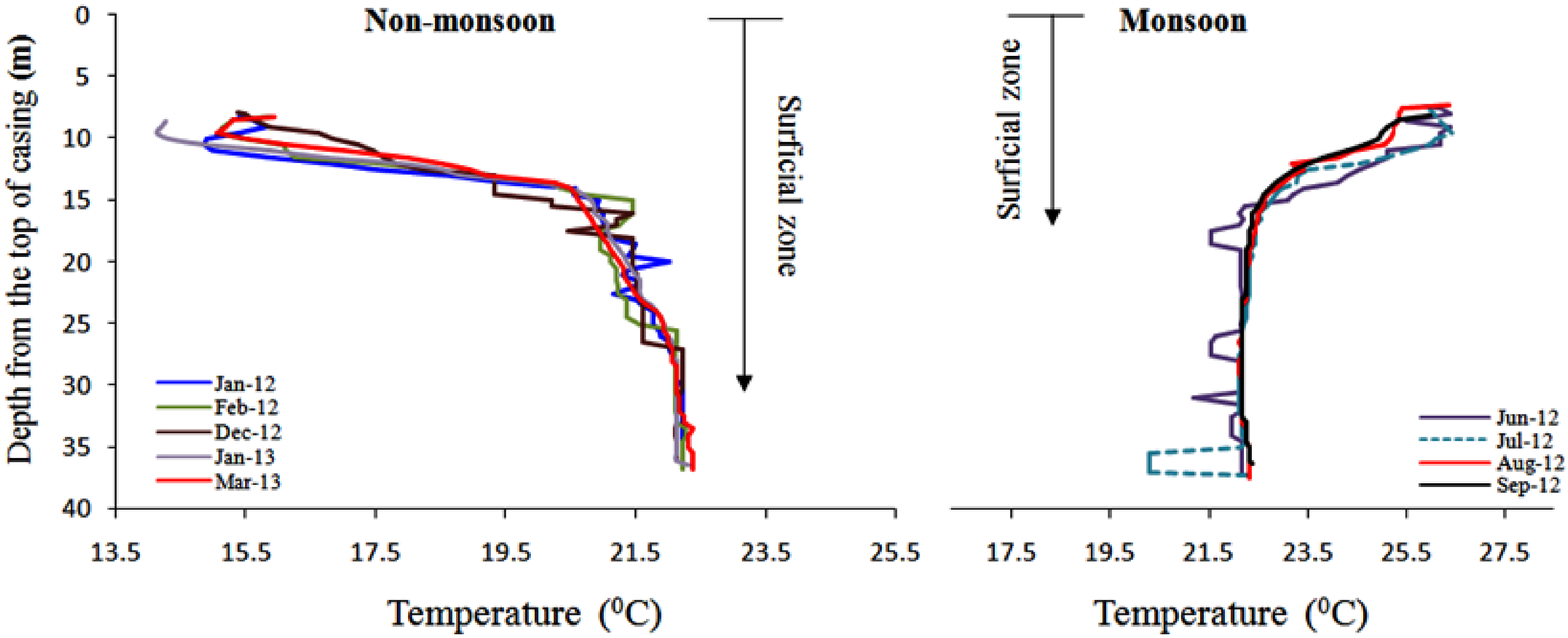

Figure 4.13 Satpuli: Temperature profile in the monitoring well

In pre and post monsoon the aquifer in the surficial zone is elongated up to 21.25 m with temperature variation of more than 5^0C i.e. the effect of temperature is pronounced throughout the year (Ermakova and Lyukmanova, 2002; Anderson, 2005; Lorenzen et al., 2010).

4.4. SUMMARY

The following observations emerged out from the hydrogeological investigations carried out at RBF sites in the mountainous regions:

- At all the sites, the effective grain size of riverbed material is found to be similar to that of the aquifer material. It, therefore, suggests that aquifers are the results of sediment deposition from the river
- The grain size of aquifers material at Satpuli is coarser than Srinagar RBF site.
- The aquifer thickness is around 21 m at Karnaprayag. At other sites thickness is more than 30 m.
- The hydraulic conductivity from the pumping test was found to range from 4.0×10^{-3} - 6.8×10^{-4} m/s, the highest being at Srinagar RBF site.
- The radius of influence that primarily depends on the saturated thickness and type of aquifer was estimated to be around 14 -326 m.
- The estimated maximum safe yield of 4000 L/min was estimated for Srinagar RBF site whereas the minimum of 1255 L/min was found at Agastyamuni RBF site.
- The steady state infiltration at Karnaprayag RBF site was 35.7 cm/h whereas at Satpuli the infiltration rate was as low as 4.0 cm/hr. At other two locations, the rates were between these two values.
- Temperature profiles data from the monitoring wells indicate the following:
    - At Srinagar, the monsoon and non-monsoon data are different. During non-monsoon, the river is classified as gaining river, whereas it is a losing river during monsoon
    - The effect of river water filtration through the subsurface flow is not observed at Karnaprayag. The well, however, was not connected to supply line. Continuous pumping is likely to change the interaction between the river and ground water.

There is no clear distinction between the monsoon and non-monsoon temperature profile at Agastyamuni and Satpuli. However, the effect of the river water is noticeable at Satpuli throughout the year. The well water temperature changes with the river water temperature. At Agastyamuni, the impact of the river water on the well water is not pronounced

CHAPTER-5
WATER QUALITY INVESTIGATIONS

Before starting the regular monitoring, water samples from ten hand pumps at Srinagar, eight hand pumps at Satpuli, fourteen hand pumps at Agastyamuni and four hand pumps at Karnaprayag were analyzed in May and August of 2010. Based on the water quality data, one hand pump at each site was selected as a ground water source. Subsequently, the river water (surface water, SW), RBF production well (PW) water and the water from one selected India Mark-II hand pump (groundwater, HP) at each of the four sites were regularly monitored from Jan 2012 to March 2013.

Srinagar site was found to be different than the other three locations. At Srinagar, production well water is isotopically similar to the river water and chemically similar to the ground water. Also, the nitrate concentration is more than the desired concentration of 45 mg/L. To understand this, additional water, soil, and rock samples were analyzed. Considering these facts, water samples from 19 hand pumps at Srinagar, were again examined in January, March and May of 2013. In May and September of 2013 water samples from four springs were also analyzed. Sampling locations are shown in Figure 4.2-4.5. In other words, Srinagar site was more extensively investigated compared to the other three sites. Therefore, results from the Srinagar site have been discussed separately, and the general observations from other three sites have been merged into a Table 5.7. Data from the isotopic analysis for each site has been separately presented. *(Findings from the RBF site at Srinagar have been published; Gupta et al. (2015) Nitrate Contamination of riverbank filtration at Srinagar, Uttarakhand, India: A Case of Geogenic Mineralization, Journal of Hydrology Vol. 531,Part 3,pp 626-637).*

5.1. SRINAGAR

5.1.1 Quality of Water from the River, Production Well and Hand Pumps

The production well at Srinagar was commissioned in May 2010. Subsequently two rounds of sampling were done in May and August 2010. Water samples from 10-hand pumps in the vicinity of the RBF site, production well, and the river were collected and analyzed. Results are presented in Figure 5.1. The objective of this exercise was to assess the groundwater quality of that region. On the basis of the EC values, the water in the area could be classified into three categories, e.g. (i) water having EC <500 µS/cm, (ii) water of EC between 500-800µS/cm, and (iii) water samples of EC ranging from 800-1000 µS/cm.

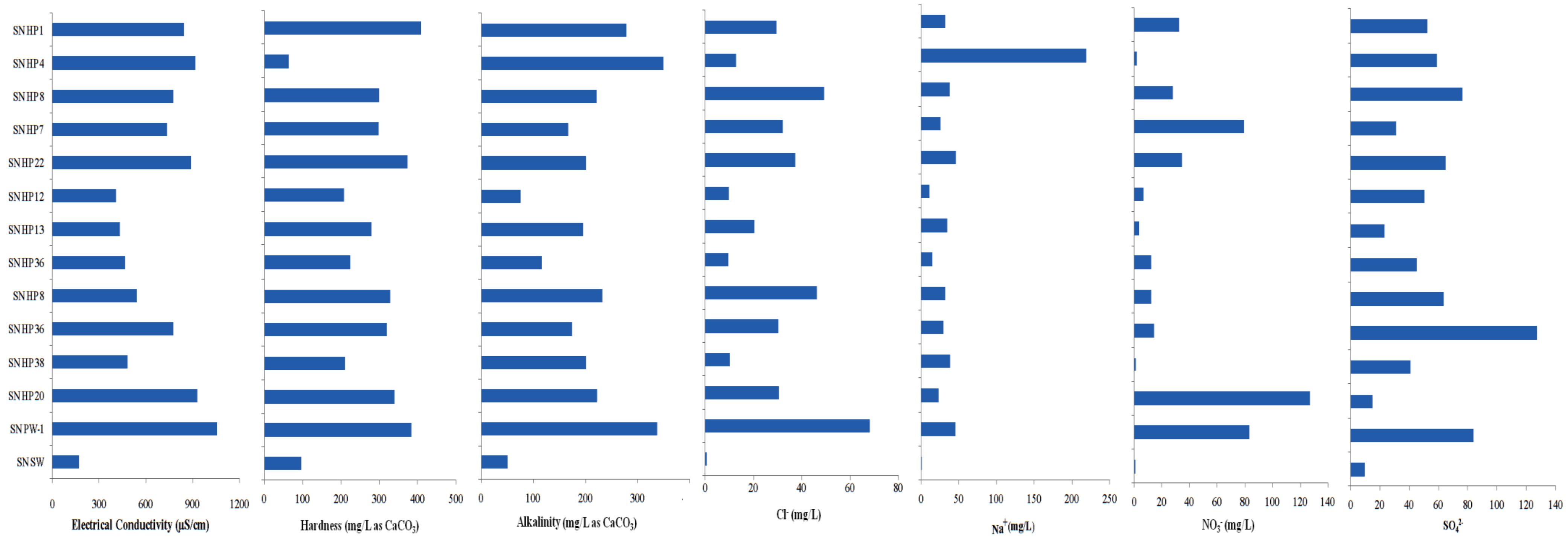

Figure 5.1 Variation of water quality parameters in the vicinity of the bank filtration site at Srinagar

EC of all the samples was more than the EC of the river water. The electrical conductivity of the four water samples i.e. SNHP-1, SNHP-4, SNHP-11, and SNHP-20 was found to be in the range from 840-930µS/cm. The EC of the production well (SNPW-1) was around 1000 µS/cm. All the samples except those from hand pumps SNHP-12 and SNHP-14 were found to have elevated bicarbonate concentration.

The concentration of the major ions in water from the SNHP-20 was the maximum. It was taken as groundwater. To assess the riverbank filtration at Srinagar, water samples from the river (SNSW), SNPW-1 and SNHP-20 were collected from January 2012 to May 2013 and analyzed for physicochemical (and biological too) water quality parameters as well as stable isotopes ^{18}O and ^{2}H.Water quality data also suggests that groundwater recharge zone is different for different hand pumps within a short distance.

5.1.1.1 On-site measurement:

(a) Temperature, pH, Electrical Conductivity and Dissolved Oxygen

Temperature, pH, conductivity and DO of samples were measured on site. The temperature of the river, well, and hand pump waters varied from 12.8 to 21.1, 21 to 26.3, and 17.5 to 25.6°C, respectively. The maximum temperatures were noticed in the monsoon during July-August, and minimum temperatures of 12.8, 17.5 and 21°C of the river water, hand pump water, and production well water were observed in January. The pH data depicts a narrow range of variation throughout the sampling schedule for the water samples from the three sources. Variation in the EC of the hand pump water was more than the production well water. The temporal variation in EC of the hand pump water suggests that the water is being abstracted from an unconfined aquifer. DO of the Alaknanda river water was close to 100% saturation value; whereas DO of the production well and hand pump water varied from 9 to 25% of the saturation values (Figure 5.2).

5.1.1.2 Laboratory analysis:

(a) Turbidity and Bacteriological Quality of Water

The most probable numbers (MPN) of total and fecal coliforms in the samples from the river, RBF production well, and hand pump are presented in Figure 5.3. Water from SNPW-1 did not have total coliform for the most part of the year except for a breakthrough during July-

September, 2012 after heavy rains. The same was true for the hand pump water. The breakthrough may be due to the short circuit or infiltration of the surface runoff from the monsoon rains (Weiss et al., 2005; Wett et al., 2002). Fecal coliform was absent both in the production well and hand pump water (Figure 5.3). The RBF well water had turbidity<2.0 NTU throughout the year (Figure 5.4), even when the river water had a high turbidity of >1700 NTU in monsoon. Hand pump had slightly higher turbidity than the well water but much lower than the river water.

(b) Ionic composition of Water

The concentration of ions in water samples is given in Table 5.1. The perusal of the data indicates high mineral contents of the production well and hand pump waters as compared to the river water. The ionic composition of water from SNPW-1 was comparable to the water from the hand pump (Figure 5.5). Maximum temporal variation in dissolved ions has been observed in the hand pump water. The river water had HCO_3^-, SO_4^{2-}, Ca^{2+}, and Mg^{2+} ions predominantly.

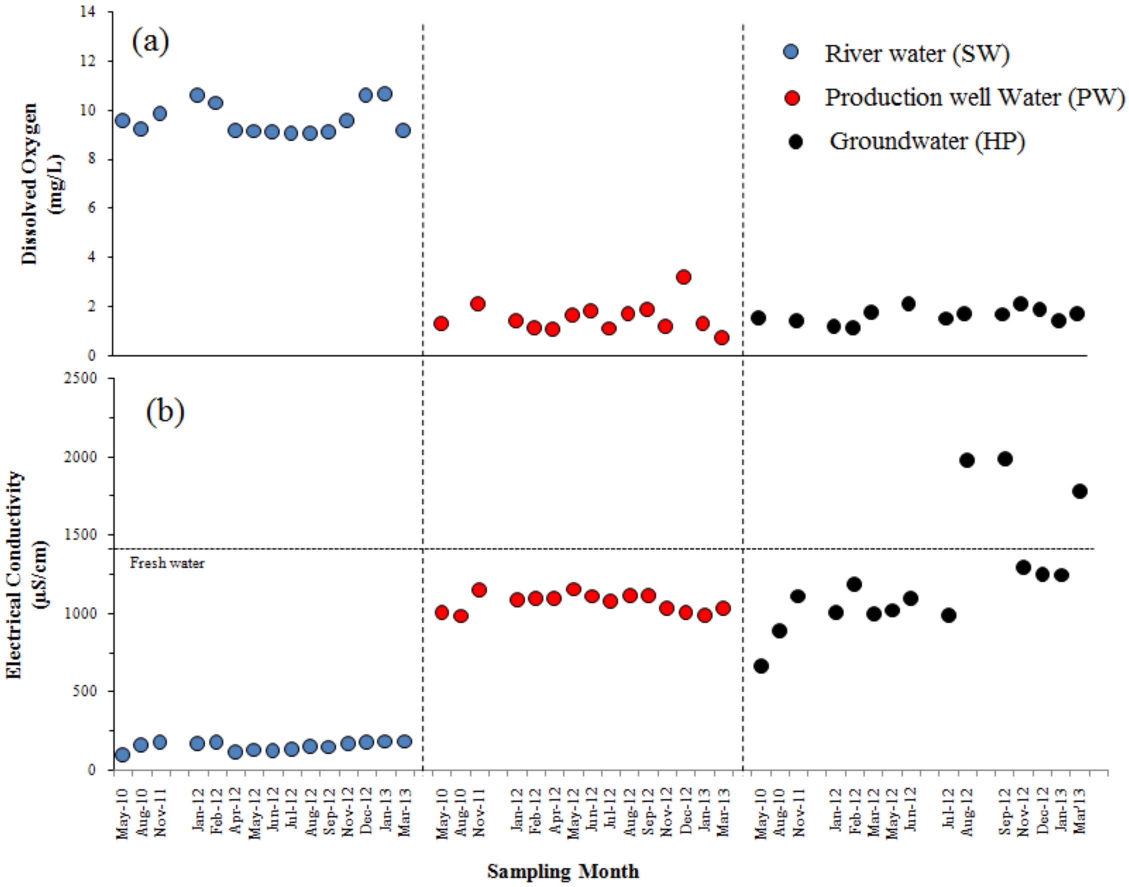

Figure 5.2 Srinagar: Temporal variation in the river (SNSW), production well (SNPW-1) and hand pump (SNHP-20) water **(a)** Dissolved oxygen **(b)** Electrical conductivity

while the other two sources had these ions along with NO_3^-, Cl^-, Na^+, and K^+ in significant concentration.

The ion balance shown in Figure 5.5 reveals ~5% or less error for all the samples analyzed. The quality of the SNPW-1water, except NO_3^-, is in agreement with the drinking water standards prescribed by theBIS-10500 (2012). Water samples from SNPW-1 had nitrate concentrations in the range from 53 to 138 mg/L, which is more than the permissible limit of 45 mg/L for drinking water in India (BIS-10500, 2012). The river water on the other hand consistently had less than 5 mg/L nitrate. Ammonium concentration in the river water was also negligible. The river is well mixed as it meanders through the valley (Figure 4.2). However, to check the possibility of any zone in the river having higher nitrate concentrations, 14 samples were collected from the river at various points across 3 locations ~3-4 km apart within 24 hours in May 2013. All samples had nitrate concentrations between 1.5 and 1.8 mg/L. This confirmed that the nitrate concentration in the river water was consistently low at all points.

Table 5.1 Srinagar: Average concentration and standard deviation of major ions in the water from the Alaknanda River (SNSW), Production well (SNPW-1) and Hand pump (SNHP-20)

Parameters	Alaknanda River (SNSW)		Production well (SNPW 1)		Groundwater (SNHP-20)	
	Average[1]	Standard deviation	Average[2]	Standard deviation	Average[2]	Standard deviation
EC (µS/cm)	156	28.9	1067	54.6	1245	402.1
TDS (mg/L)	93.5	17.4	640.2	32.8	746.7	241.3
Cl^- (mg/L)	1.0	0.3	54.70	12.4	106.3	36.7
NO_3^- (mg/L)	1.5	1.0	102.5	22.9	116.3	109.3
SO_4^{2-} (mg/L)	14.7	8.3	90.60	59.0	96.0	38.6
Alkalinity(mg/L $CaCO_3$)	68.1	12.5	336.5	17.5	322.3	48.2
Ca^{2+} (mg/L)	23.9	4.1	125.0	25.6	122.7	39.9
Mg^{2+} (mg/L)	5.3	2.3	38.80	4.0	44.8	11.6
Na^+ (mg/L)	3.1	1.5	63.20	11.8	92.3	35.2
K^+ (mg/L)	1.6	1.2	10.80	5.6	35.9	32.2
Hardness (mg/L $CaCO_3$)	81.5	18.5	471.7	69.8	490.5	137.2
Average based on [1]n=12,[2]n=14; all the values are in mg/L except EC						

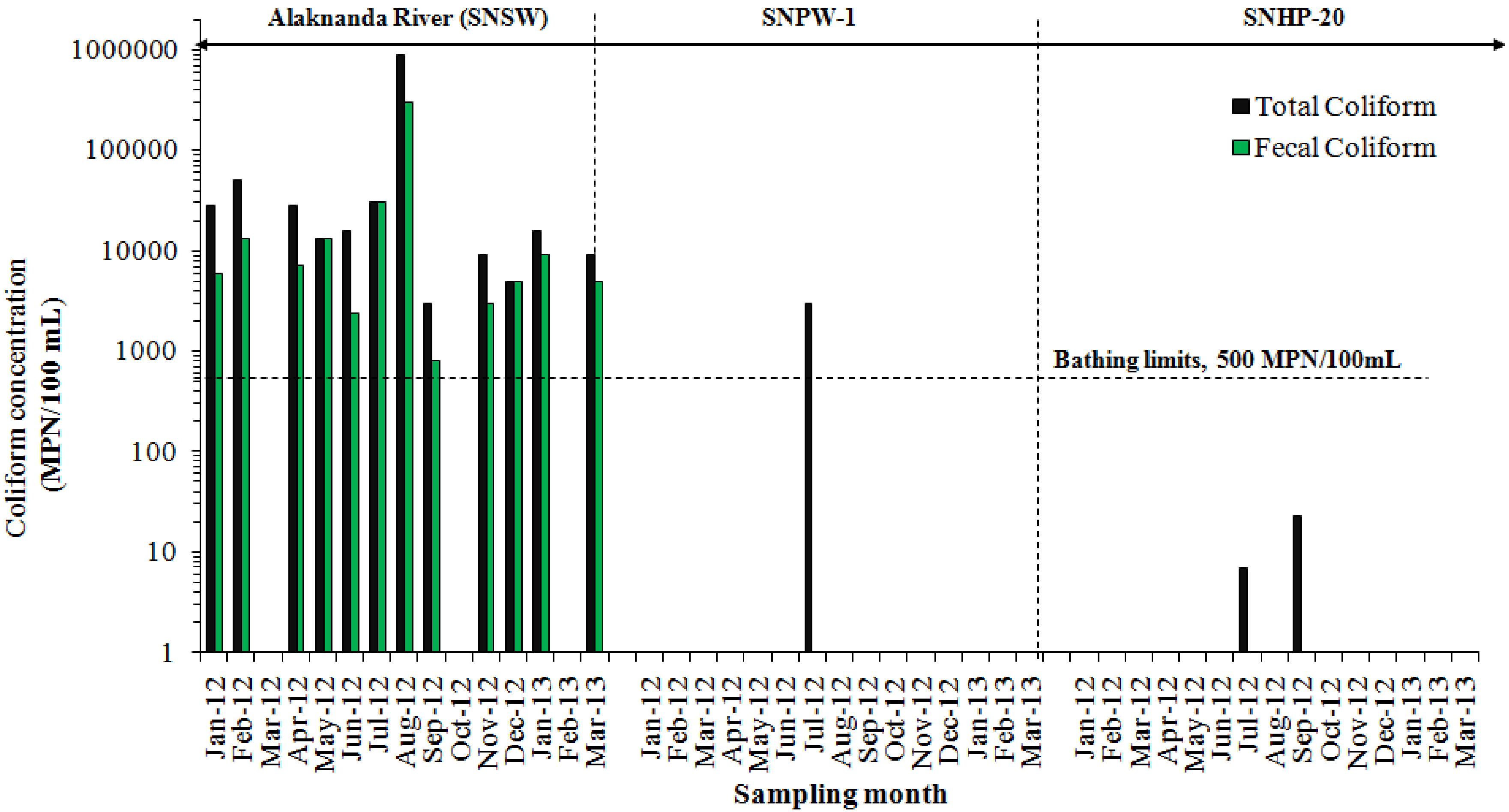

Figure 5.3 Srinagar: Total and fecal coliform in the river (SNSW), production well (SNPW-1) and hand pump (SNHP-20) water

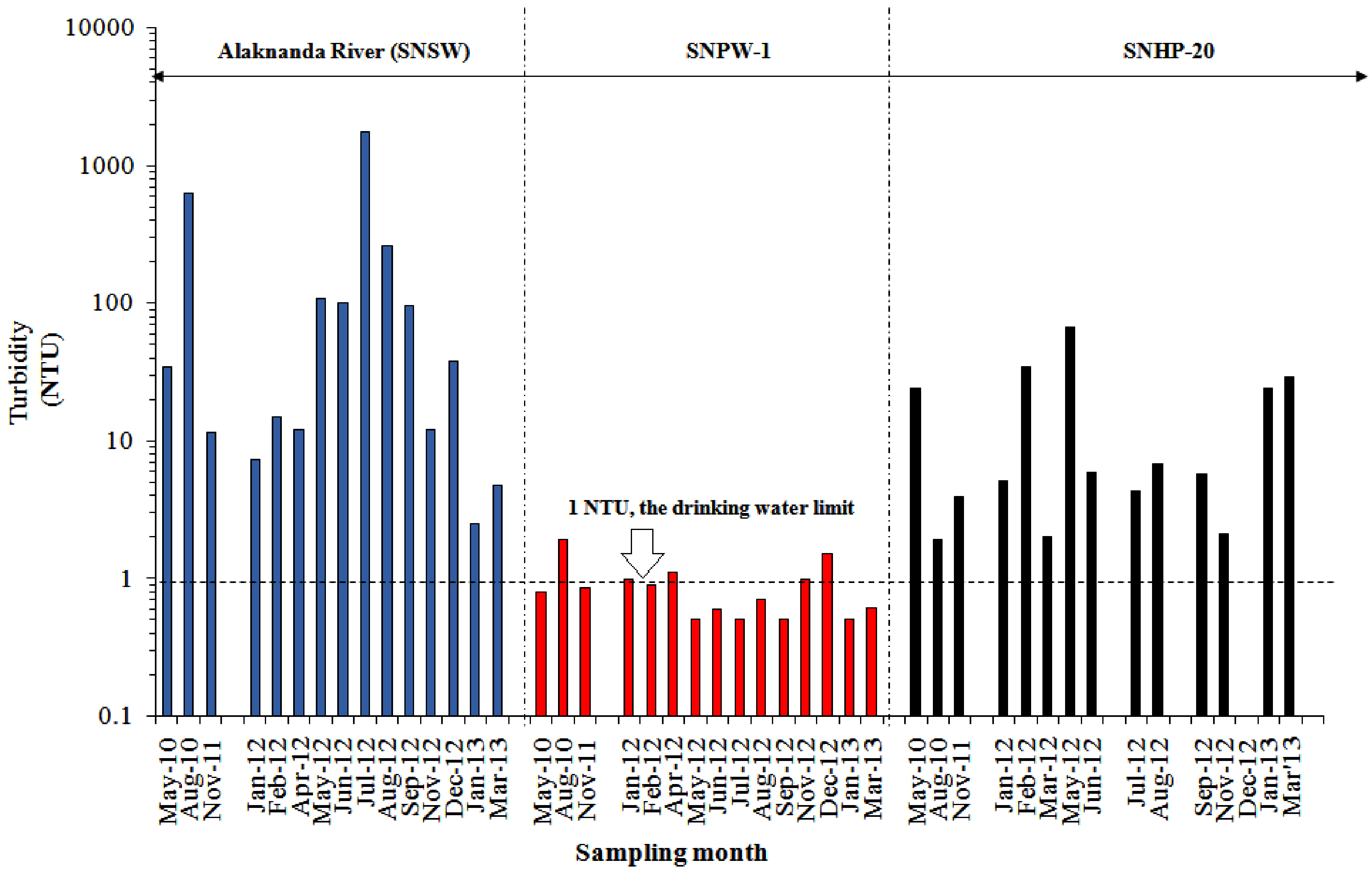

Figure 5.4 Srinagar**:** Temporal variation in turbidity of the river (SNSW), SNPW-1, and SNHP-20 water

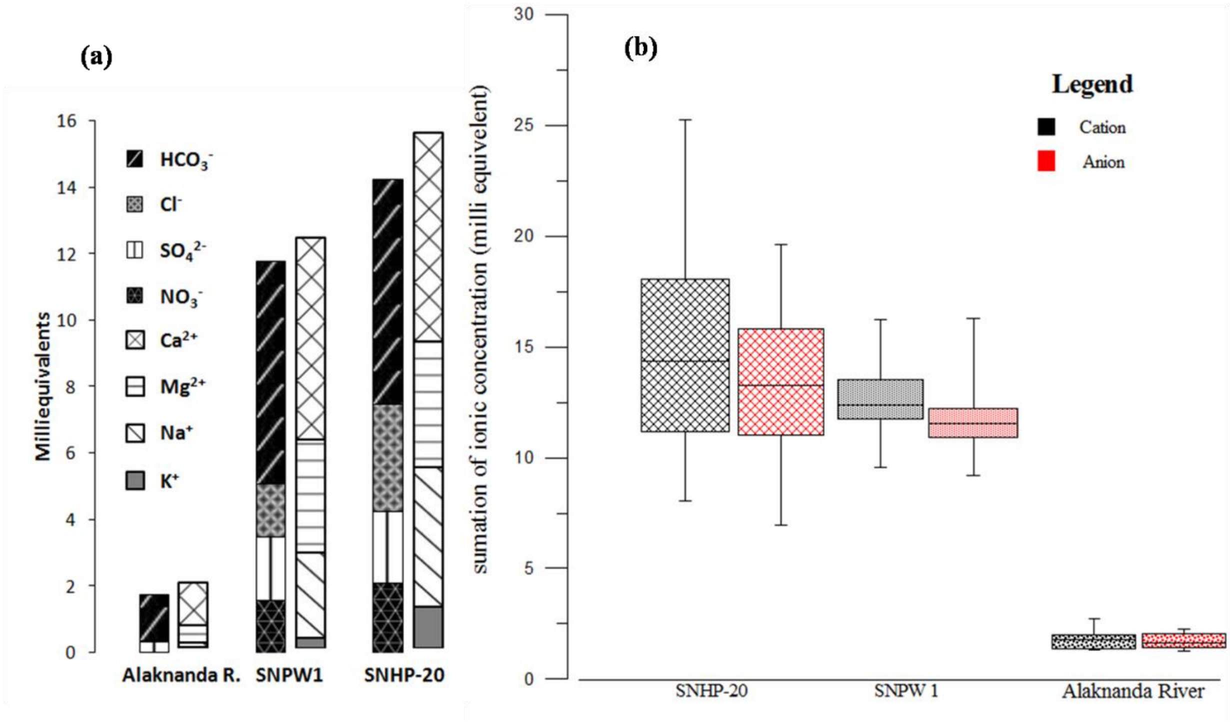

Figure 5.5 Srinagar: Major ions in the water from the Alaknanda River (SNSW), Production well (SNPW-1) and Hand pump (SNHP-20) **(a)** Ionic distribution **(b)** Ion balance for the average concentrations

Maximum temporal variation in major ions was observed in the samples of hand pump water. Nevertheless, the compositions of waters from the production well and hand pump are not significantly different (Figure 5.6). Apart from the difference in concentration of ions, a perceptible difference between the river water and other two waters is the increased concentrations of nitrates and chlorides in well and hand pump waters. Calcium and bicarbonates dominate these water samples. Average calcium in the river water was 66.6 % of the total cations whereas well and hand pump waters had 49.6 and 41.6 %. Bicarbonates in all the samples are more than the calcium but less than the calcium and magnesium together. The percent sodium, potassium, chlorides, and nitrates are more in well and hand pump waters than the river water. The river water during its course through the aquifer dissolves chlorides and nitrates of sodium and potassium. Alternatively, well water and hand pump waters are a mixture of ground water and surface water or waters from different aquifers. A sum of potassium and sodium correlates fairly well with the sum of chloride and nitrate (Figure 5.7). If this is the situation, then the sum of calcium and magnesium should also correlate well with sulfate and bicarbonate. However, data exhibits fluctuation and a good correlation could not be established. Around 60% of the data correlates very well (Figure 5.6). A few other observations regarding water quality are as under:

- Carbonate hardness is more than the non-carbonate hardness (Figure 5.8(a))

- The hardness of a few monsoon (September) water samples is more than the permissible level (Figure 5.8(b))
- Water from production well is safe as it is free from coliform bacteria. The nitrate however is high.

These results raised two important questions: Is the water abstracted from the RBF well bank filtrate or ground water? And what are the source(s) for nitrate and other minerals in the well and hand pump waters? Mineralization of water in riverbank aquifers can occur either by minerals present in the aquifers or by mixing with highly mineralized groundwater. SNPW-1 water is chemically similar to the SNHP-20 water. Spatio-temporal variations of the mineral concentrations and stable isotope δ^2H and δ^{18}O in the waters yielded further insight into these phenomena. Since ions other than nitrates in well water are in compliance with drinking water standards, the focus of further investigations here has been on nitrates.

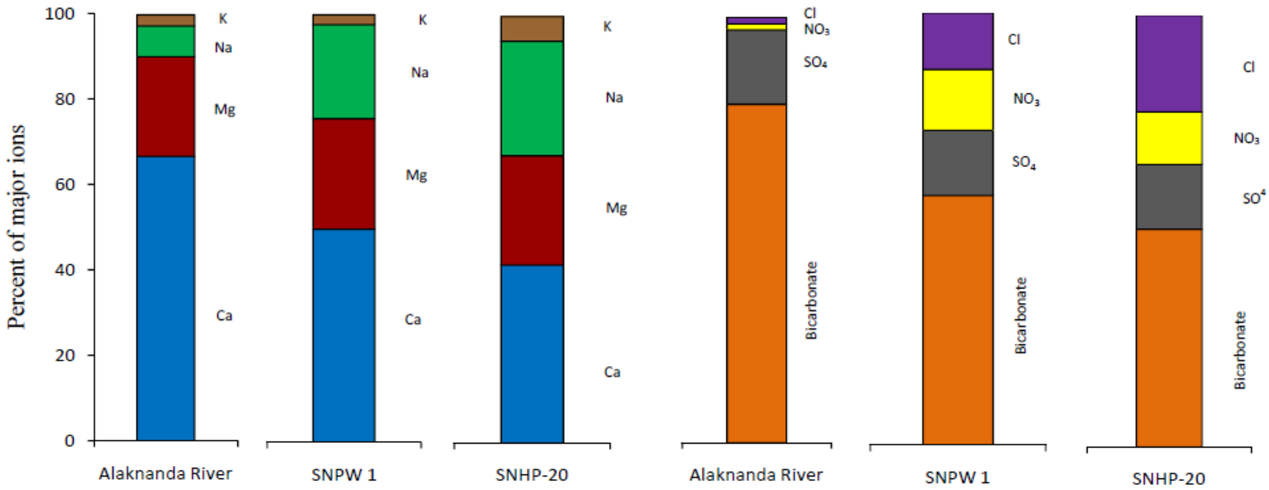

Figure 5.6 Srinagar: Average compositions of major ions in the Alaknanda River (SNSW), Production well (SNPW-1) and Hand pump (SNHP-20)

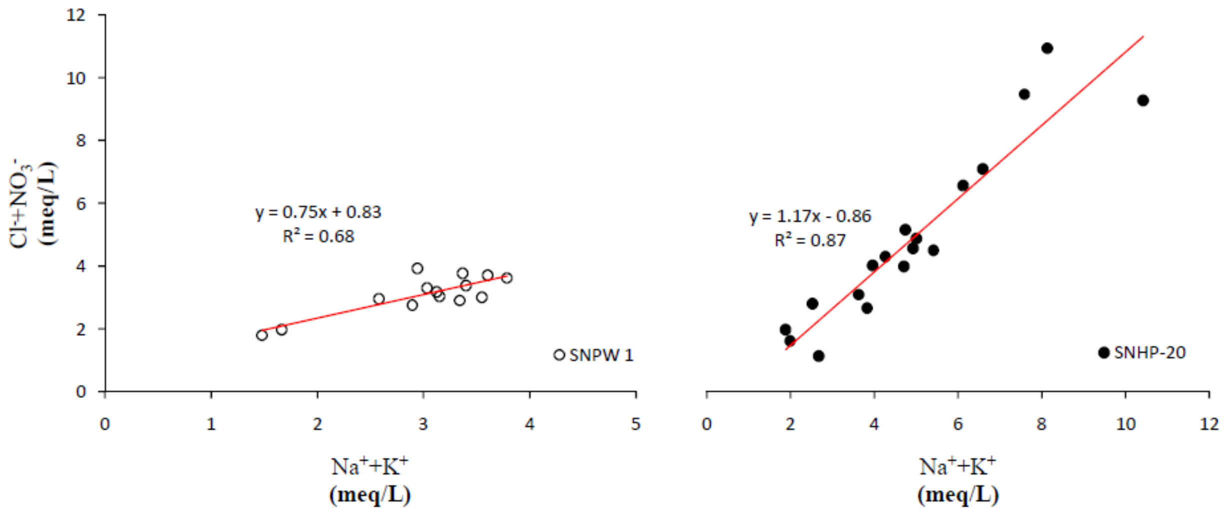

Figure 5.7 Correlation between four major ions in production well (SNPW 1) and ground water (SNHP-20)

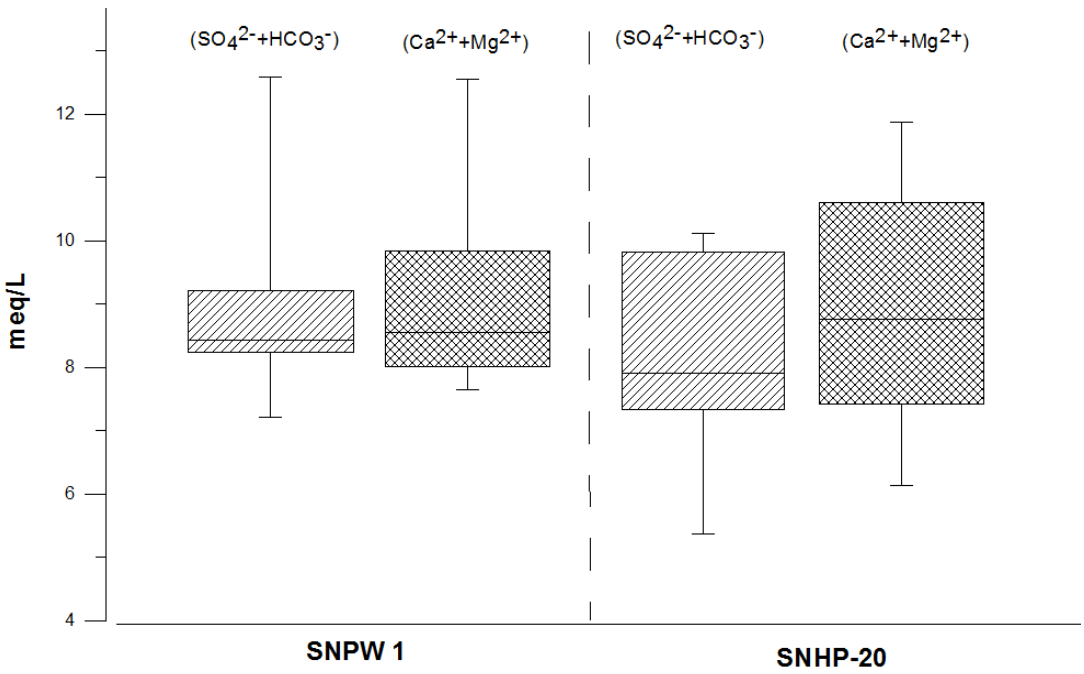

Figure 5.8 (a) Srinagar: Variations in four major ions of production well (SNPW 1) and hand pump (SNHP-20) water

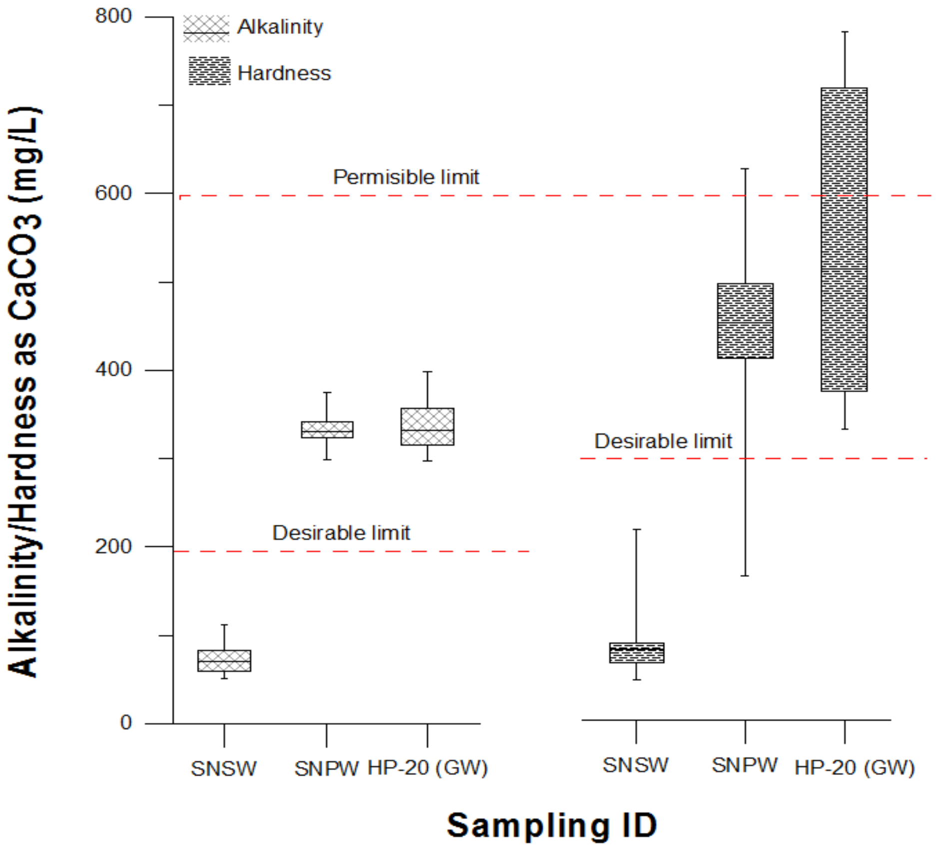

Figure 5.8(b) Srinagar: Distribution of alkalinity and hardness in the surface water, bank filtrate and ground water

5.1.2 Temporal Variations in Nitrate

The nitrates are usually associated with two origins: natural and anthropogenic. Several researchers have identified the increasing anthropogenic activities as the nitrate source(s) in natural waters. Intensive agriculture using large amounts of mineral fertilizers or animal waste, sewage seepage, drainage from farmhouses, and chemical industries producing or using nitrogen-containing compounds are a few nitrate sources (Holloway et al., 1998; Bolger and Stevens. 1999; Grischek et al., 1996 & 2002; Tredouxetal., 2009; Obrike et al., 2011).Sewage and landfill drainage samples had nitrate concentration <2 mg/L (Table 5.2) and ammonium concentrations around 20 mg/L and 9 mg/L, respectively. These values are typical for sewage and landfill. Even if ammonia is converted to nitrate, the composition and minerals in these samples are not comparable with the well water. Thus, the wastewaters from the small town population may be contributing but alone cannot be entirely responsible for the observed concentrations of nitrate and other ions in the well and hand pump water.

Natural sources include surface runoff from forests, grasslands, geological deposits of nitrate salts, etc. Surface runoff from forests typically contains ~0.1 - 20 mg/L nitrate (McDowell and Omernik, 1977; Feichtinger *et al*., 2002); however, in certain Sierra forests in USA, the runoff immediately after rains are found to contain ~150 - 400 mg/L nitrate for brief periods of time (Miller *et al*., 2005). High nitrate concentration in natural water over extended period of time can come from natural deposits of nitrate salts, such as in the Atacama deserts of Chile and various locations in the USA (Mansfield and Boardman, 1932). A review by Holloway and Dahlgren (2002) indicates that interaction with N-bearing bedrock can also be significant and often overlooked natural source of nitrate in groundwater. Temporal variations of ionic concentrations along with its spatial distribution in the region can help significantly in distinguishing the nitrate source in natural waters.

Small variation in EC of SNPW-1 water (Figure 5.9(a)) indicated that the well water was approximately in a state of equilibrium with the aquifer material even after heavy rains. The nitrate concentrations in SNPW-1 and SNHP-20 were comparable (Figure 5.9(a)) but monthly variations were much less in SNPW-1 water. Such stable nitrate levels indicate that **the nitrate input is not seasonal but perennial**. Lack of high correlation of nitrate concentrations with the rains during monsoon (July-September) indicates that the **surface runoff from the forest and the town are not the principal contributor of nitrate** in subsurface waters.

To understand the spatial variation of nitrate contamination in the aquifers in the region, water samples from seven hand pumps, five tube wells and four springs (total 16 samples) in the vicinity of the RBF well (SNPW-1) were collected and analyzed.

Table 5.2 Srinagar: Concentration of major ions in sewage samples in the region (n=1)

Location	NO_3^-	NO_2^-	PO_4^{3-}	SO_4^{2-}	F^-	Cl^-	HCO_3^-	NH_4^+	K^+	Na^+	Ca^{2+}	Mg^{2+}
	Milligram per liter											
T3	0.7	<0.2	7.0	10	0.4	19	232	20.5	7.7	22	56	9
T1 outlet	2.0	0.4	8.1	11	0.2	89	195	9.7	6.3	80	31	8
T2 drainage	0.6	<0.2	0.4	11	0.3	16	24.8	9.2	33.5	13	77	9

T_3- sewage from open drain; T_2-leachate from landfill;T_1-Oulet from wastewater treatment plant

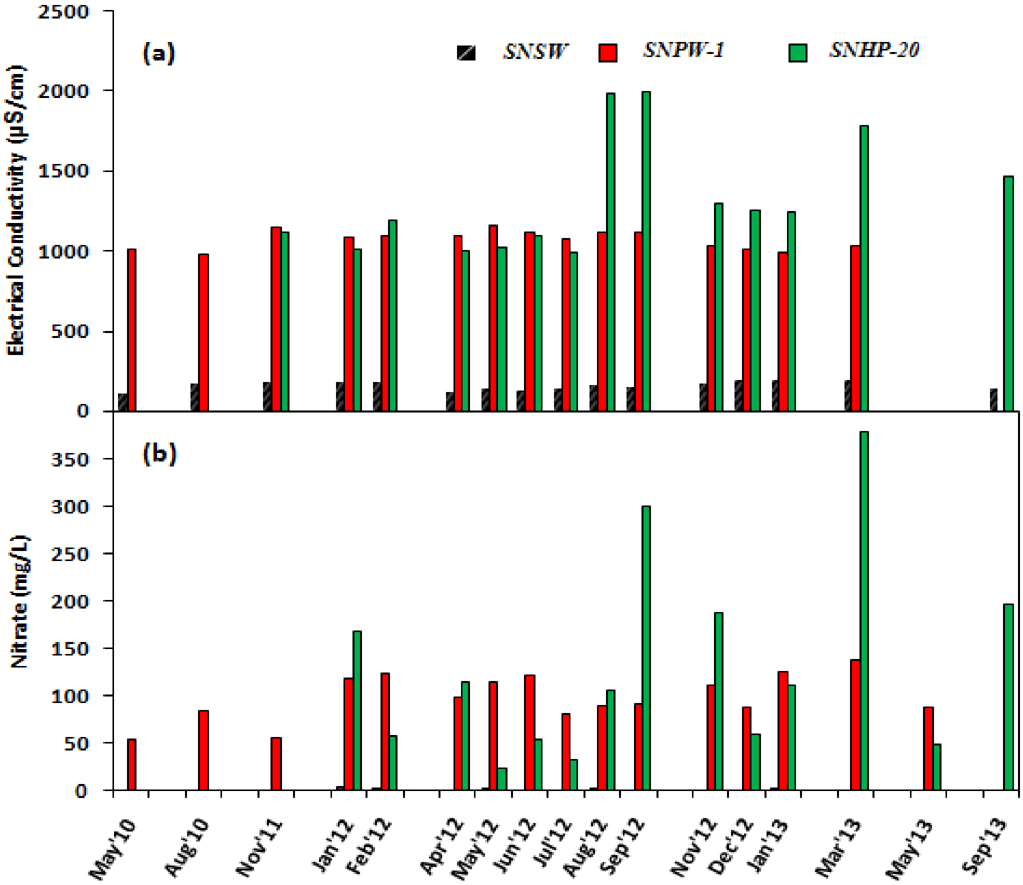

Figure 5.9 Srinagar: Temporal variation of **(a)** electrical conductivity and **(b)** nitrate concentration in the water from the Alaknanda River, SNPW-1, and SNHP-20.

5.1.3 Nitrate in Other Water Sources in the Region

Figure 5.10shows the spatial variation in nitrate concentration across some of the key water sources in the region. The average values of NO_3^- and EC along with the range are listed in Table 5.3. Among 16 water samples, only four samples from hand pumps SNHP-7, SNHP-31, SNHP-36, and SNHP-38 have nitrates less than 10 mg/L. The conductivity of SNHP-31 is comparable to the river water, but the other three samples have relatively high conductivity.

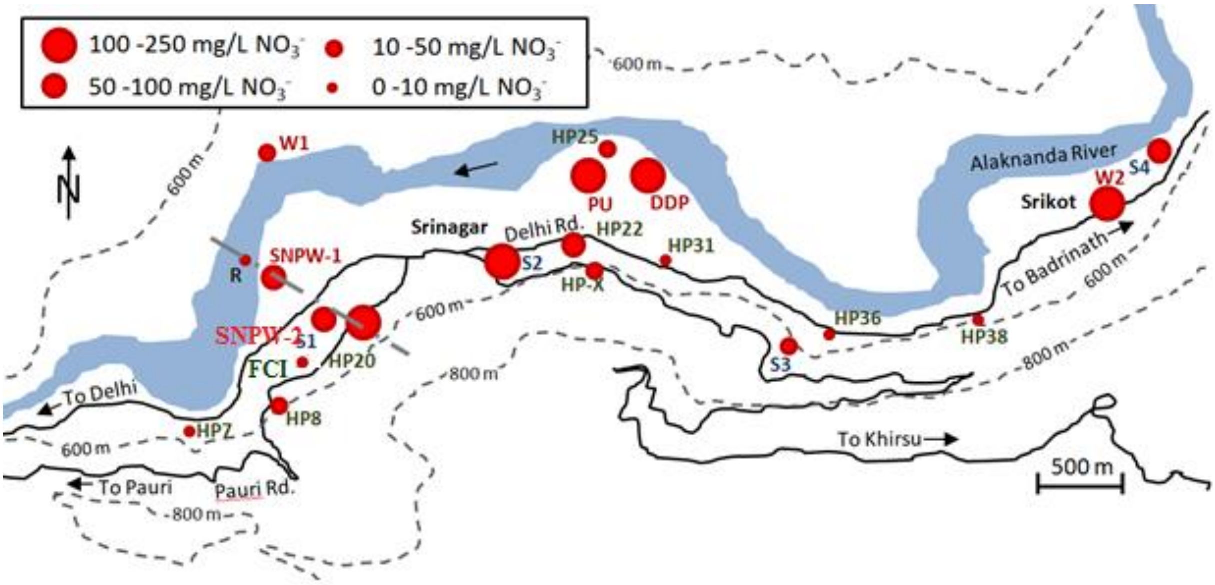

Figure 5.10 Variation of nitrate in some of the key water sources in the Srinagar-Srikot region

There was high nitrate concentration in the water from other hand pumps, tube wells, and springs. Nitrate concentrations in some of the deep tube wells (SNPW-1, SNPW-DDP, and W2 (Srikot) located close to the river bank were >100 mg/L (Table 5.3). In addition, spring S2 located away from the river had nitrate concentrations up to 150 mg/L; while S4 is located close to the river with very low population density region uphill had nitrate concentration ~100 mg/L. The inference drawn from this is that the nitrate is present in the aquifers at higher altitudes as well as close to the riverbank. However, the nitrate distribution is not homogeneous in the region.

Table 5.3 Srinagar: Average EC and nitrate concentrations of the water sources.

Water source[1]	N	EC (µS/cm)	NO_3^- (mg/L)
W1(SNPW-N)	1	624	42
SNPW 1	1	1012	205
SNPW-DDP	3	1105 (1055-1155)	162 (88-216)
W2 (Srikot)	2	841	113 (103- 123)
SNHP-7	2	949 (871 – 1027)	0.7 (<0.2-0.7)
SNHP-FCI	1	689	26
SNHP-X	3	454 (453-454)	32 (16-44)
SNHP-22	4	1140 (1030 – 1247)	68 (27-102)
SNHP-25	4	1688 (1396 – 1882)	44 (14-97)
SNHP-31	3	203 (189 – 227)	4.5 (3.6-5.4)
SNHP-36	3	481 (471-483)	6.0 (1.9-13.5)
SNHP-38	3	558 (536 – 574)	3.0 (1.2-4.0)
S1	2	623	75 (70-80)
S2	2	754	140 (134-146)
S3	2	500	41 (38-45)
S4	2	754	97 (93-101)
n-number of samples; W-bore well; SN-Srinagar; HP- Indian mark-II hand pump; PW-Production well; S-Spring; [1]For the location of these water sources refer Figure 5.10			

5.1.4. Srinagar: Isotopic Characterization of Water and Mixing Proportions

Results of isotope analysis are presented in Figure 5.11. The δ^2H and $\delta^{18}O$ values for hand pump, SNHP-20 are highest among all the sources. The δ^2H and $\delta^{18}O$ values for the waters of the Alaknanda River, SNPW-1, and SNHP-20 (Figure 5.11) indicate that (i) in the non- monsoon, SNPW-1 water samples are isotopically similar to the river water and (ii) the fraction of the bank filtrate in the PW water range from 23 to 88% (Table 5.4). The groundwater isotopic values are very close to the local meteoric water line (Eq. 5.3-5.4; Table 5.11) suggesting the source of groundwater to be local rainwater recharge. The observation is further substantiated by the temperature profile of the water in Srinagar monitoring well (Figure 4.10). The values for the river water, on the other hand, are closer to the meteoric water line at higher altitude zone of Gangotri (Eq.5.5; Table 5.11) which is representative of the source of the river Alaknanda near Badrinath (30°44'N, 79°29'E, 3414 m above MSL). The groundwater responds relatively fast to the rains, i.e. it is not an old groundwater.

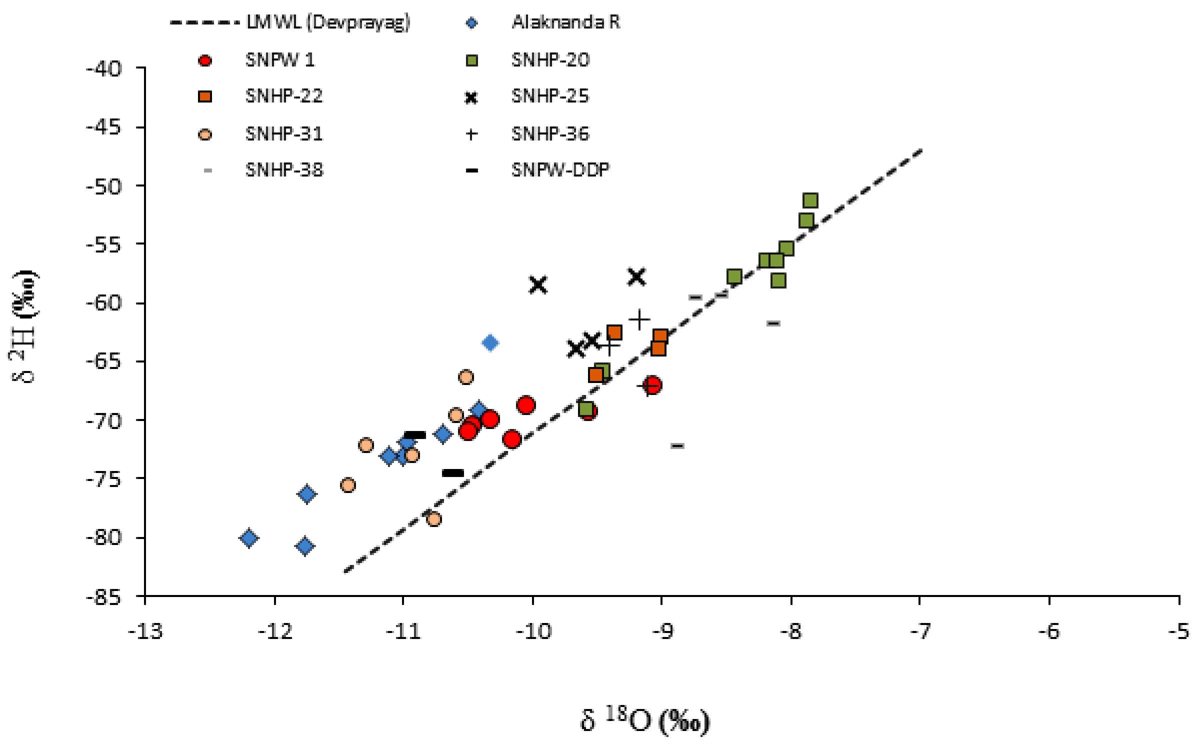

Figure 5.11 $\delta^{18}O$ *vs.* $\delta^{2}H$ of the waters from Srinagar; correlations are given through Eq.5.6-5.8 in Table 5.10

Variable mixing of highly mineralized groundwater with river water in the form of bank filtrate should change ion concentrations in the well, SNPW-1 according to the proportion of the mixture. However, the nitrate levels in SNPW-1 did not change appreciably during or after rains in spite of increased contribution from groundwater during the monsoon season. Nitrates in SNPW-1 remain in the range of 50 to 100 mg/L with or without a substantial contribution from the groundwater. The data suggests that the **nitrate in the RBF well water may be due to mixing of nitrate-bearing groundwater as well as mineralization from a source localized within the flow paths of the bank filtrate**.

The possible flow paths for the river water to the well, SNPW-1 are several including up to ~2 km long path from the eastern part of Srinagar. Isotopic values of other samples presented in Figure 5.11 show a complex pattern of groundwater mixing with bank filtrate and mineralization. Hand pump, SNHP-31 is located ~1 km away from the river. It has low conductivity (comparable to the river water) and is isotopically similar to river water. Well at Deen Dayal Park (SNPW-DDP) drilled in 2003, on the other hand, is much closer to the river and isotopically almost same as river water, representing negligible groundwater mixing and yet high mineralization. This well also has very high concentration of nitrate. Hand pumps SNHP-22 and SNHP-25 have almost equal proportions of river and groundwater, and yet these pumps have large amounts of nitrate, while hand pumps SNHP-36 and SNHP-38 have isotopic signatures of close to 100% groundwater but have much lower nitrate concentrations. The variations in mineralization and nitrate concentrations exist for water sources located in the densely populated parts of the town. It indicates that **nitrate source is not present uniformly over the town but varies from an aquifer to the aquifer, and the level of contamination in the water sources is independent of the proportion of groundwater in the sources**.

Considering SNHP–20 as ground water the percent of the bank filtrate in the SNPW water has been calculated from the general mass balance Equation 5.1.The percent of the bank filtrate ranging from 23.5 to 88.1% do not exhibit seasonal trend (Table 5.4). It may be due to long travel time taken by the bank filtrate to reach the PW. The annual average of the bank filtrate computed from the mean concentration of $\delta^{18}O$ is 69.5%.

$$C_{BF} = \frac{C_{PW} - C_{GW}}{C_{SW} - C_{GW}} \qquad \text{5.1}$$

C_{BF}–fraction of the filtrate in the production well water;
C_{PW}, C_{GW}, C_{SW} - tracer concentration in the production well water, ground water and river water respectively

Table 5.4 Srinagar: Percent of the bank filtrate in PW

Month	Concentration of stable isotope oxygen ($\delta^{18}O$)			% surface water
	SNSW	SNPW-1	SNHP-20	
29-5-12	-10.3	-10.0	-7.89	88.1
26-7-12	-11.0	-10.0	-8.04	66.2
26-8-12	-12.2	-9.07	-8.11	23.5
28-11-12	-11.3	-10.1	-9.10	45.9
29-12-12	-11.1	-10.5	-8.20	78.0
Average	-11.2	-9.90	-8.30	69.5

5.1.5 Leaching from Aquifer Materials and Rocks

Analysis of ions and isotopes in various water samples demonstrate mineralization of river water during its travel through the aquifer. To assess leaching of nitrate and other minerals, a few samples of the aquifer materials and rocks were tested for their leaching potential in distilled water. Results are presented in Table 5.5. Riverbank sand samples leached very small amount of nitrate in distilled water. Aquifer material obtained during drilling of the RBF well from the depth of 5 m leached about 10 mg/kg of nitrate, while the materials between 16-20 m leached <1 mg/kg of nitrate. The riverbank aquifer material therefore does not appear to be the dominant source of nitrate to the bank filtrate and groundwater. The aquifer samples, however, leached significant amount of other highly soluble ions such as Na^+ and K^+. The aquifer material thus was not completely washed off the soluble minerals and lack of nitrate was indeed a characteristic of the aquifer materials. Soil samples near the well from the farm at Pantnagar University (SNPW-PU) and exposed hill soil near hand pump-X (SNPW-X) also showed negligible amounts of nitrate (Figure 5.10). Soil from weathered bedrock near SNHP-38 was found to have 67 mg/kg of nitrate content. This area has no appreciable human habitation around it. It therefore suggests the possibility of nitrate leaching from phyllite bedrocks. Some of the rock samples collected from exposed bedrock leached very high amounts of nitrate (Table 5.6). Some of the phyllite rocks from the Pauri road leached nitrate as much as 500 – 2000 mg/kg of their mass. Besides, these rocks also contained Cl^-, Na^+, and Ca^{2+} in high concentrations of ~500 mg/kg. Loose rock samples collected from the area did not leach any appreciable amount of ions, likely due to washing effect by the rains. Aquifer profile at the RBF site has thick phyllite bedrock at a depth of about 20 m (Figure 5.10, Figure 4.8(a)). The bedrock could be a direct source of nitrate contamination in the bank filtrate and groundwater.

Leaching of salts was more from powdered rocks than with pebbles of nearly 1 cm size (Table 5.5). Also, leaching from the rock powder was very fast. More than 90% of the minerals were leached within 2 hours. Replacing the leachate with fresh distilled water did not further leach appreciable amount of minerals (Table 5.5). These two experiments showed that even though nitrate is present in the rocks in readily soluble form, these bedrocks as a whole will not release nitrate instantaneously. The release is probably diffusion controlled and depends on the contact area and travel time of water in the strata.

The phyllite bedrock in the region has significant folds and fractures (Shekhar et al., 2011). The rocks are not highly porous, and predominant interaction of water with these bedrocks is likely to be only through fractures and cracks in the bedrock. This can also explain if these rocks are really the source of nitrate and if nitrate is present in the rocks in readily soluble form, then why a decrease in the amount of nitrate in bank filtrate or groundwater has not been observed over a period of 2 years of study? Since the bedrock are partially exposed to water at crack and fracture zones, and even there the rocks do not release the nitrate instantaneously, complete washing away of nitrate from the bedrock will take a long time.

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Table 5.5 Concentrations of various ions leached into distilled water from soil/aquifer/riverbed materials.

Sample ID	NO_3^-	NO_2^-	SO_4^{2-}	F^-	Cl^-	PO_4^{3-}	HCO_3^-	NH_4^+	K^+	Na^+	Ca^{2+}	Mg^{2+}
	Milligram per litre											
G4	4.80	<0.2	46.4	0.90	4.50	<1	117	<0.5	8.40	14.4	51.2	2.70
G3	0.90	<0.2	92.7	0.90	6.10	<1	286	<0.5	9.60	10.2	111	4.80
G1	1.80	0.60	241	1.30	0.60	<1	337	<0.5	15.2	3.9	262	14.7
SNPW 1 (5 m)	10.5	0.60	8.4	1.20	6.90	<1	165	<0.5	5.70	14.7	47.1	6.60
SNPW 1 (16-20 m)	0.90	<0.2	50.0	6.90	5.10	<1	417	<0.5	9.30	144.6	60.9	23.1
Near SNPW-PU	0.70	<0.2	8.00	2.90	1.80	12.6	322	3.6	20.7	15.0	108	19.2
Near SNHP-38	67.0	4.8	3.30	3.30	32.7	<1	103	<0.5	<1	16.8	39	12.1
Near SNHP-X	0.70	<0.2	3.90	3.60	6.30	<1	286	<0.5	2.10	48.3	75	8.70
Concentration of ions in mg/kg rock leached from the powdered (unless otherwise mentioned) rock in distilled water.												
Phyllite@ SNHP-20	1947	14.4	602	1.50	747	-	212	<1.5	14.0	693	572	258
Phyllite@ SNHP-20	579	0.60	299	1.80	344	-	1190	<1.5	12.0	398	338	43.0
Phyllite@ G3	674	0.40	95.0	2.40	692	-	1336	<1.5	17.0	444	306	60.0
Quartzite@ G2	530	1.20	350	3.80	243	-	806	<1.5	33.0	219	261	89.0
Phyllite@ G2	50.0	0.40	54.0	0.90	16.4	-	732	<1.5	42.0	85.5	131	30.0
1 cm size stone from SNHP-20	302	0.20	39.0	0.90	186	-	567	<1.5	9.00	215	82.0	63.0
#Phyllite@ SNHP20 (sample a)[1]	649	4.80	201	0.50	249	-	71.0	<0.5	4.80	231	191	86
#Phyllite second batch[2]	57	1.70	22.0	0.20	23.0	-	112	<0.5	2.30	30.0	32	11

[1]After soaking for three days in distilled water
[2]After decanting sample a and re-soaking in fresh distilled water, #Concentration of ions in rock leachate in mg/L when 50 g of rock powder was soaked in 150 mL of distilled water; The soil from RBF well site was obtained and stored during drilling of the well.

Holloway et al. (1998) found that phyllite and schist bedrocks in a particular California watersheds contained ~1000 ppm of total nitrogen and leaching from these rocks leads to elevated nitrate concentrations in the water streams in the region. They have estimated that the N flux in the watershed area is ~10 kg N ha^{-1} yr^{-1}, while a 10 cm thick layer of these rocks would contain up to ~2500 kg N ha^{-1} of land area, resulting in high nitrate concentrations in waters for hundreds of years.

Holloway and Dahlgren (2002) have ascribed two origins of geogenic nitrogen species in rocks. One is the fixation of nitrogen species from the atmosphere in clays and deposition of organics in sediments during geological past of the region. Second is the active release of N-containing gasses from the deep earth, often found in hydrothermal systems. The form of nitrogen species in rock and its leaching potential depends on the thermal history of the rock. Recent investigations have also shown that the Main Boundary Thrust (MBT) zones in Kashmir have evaporite deposits in association with phyllite, schist and carbonate rocks in isolated pockets (Singh and Singh, 2010). The same MBT also passes close to the Srinagar region. Evaporite mineral pockets, if present in this area, can also explain such high mineralization of groundwater. This is corroborated by the presence of increased levels of calcium and magnesium salts along with chlorides and nitrates of sodium and potassium. Therefore, there is a need for further geological investigations to identify the source and nature of these minerals in the region.

In addition to the availability of mineral in an aquifer, mineralization of groundwater also depends on the groundwater dynamics due to seasonal cycles as well as due to anthropogenic interferences (Lorenzen et al., 2012). Construction activities and increased uptake of groundwater can increase the fluctuation in the groundwater flow and water level that can increase dissolution of minerals from the unsaturated zone as well as deeper regions.

Such high nitrate concentrations have been observed only at a few bank filtration sites worldwide. For example, high nitrate levels have been found in the landside groundwater at RBF sites in Dresden and Meissen along the Elbe River in Germany (Grischek et al., 1996 and 2002). There, nitrate concentrations between 50 and 170 mg/L were found in regions with greenhouses and beneath the city center. A particular pumping rate was defined at the RBF site in Dresden-Tolkewitz to limit the portion of landside groundwater (and thus the amount of nitrate) in the pumped water. This solution prevented the need for any special treatment to remove nitrate in the waterworks. Detailed flow modeling of groundwater in the region can suggest the appropriate measures to reduce the amounts of nitrate for the case of Srinagar RBF scheme.

5.1.6. ^{15}N Isotope Analysis

To assess if the nitrate observed in the waters was same as the nitrate leached from bedrock, the two groups of nitrates were analyzed for ^{15}N isotope content. Results for δ^{15}N in nitrates in some of the water samples and leachates from phyllite and quartzite rocks are given in Table 5.6. The δ^{15}N values for nitrate in water samples are comparable to the δ^{15}N values for nitrates leached from rocks. The δ^{15}N values of all the samples are significantly different from 0‰ (the value for atmospheric N), which suggests that the nitrate in waters is not from fertilizers or synthetic nitrates runoff because these have δ^{15}N values close to 0 ± 6‰. The observed δ^{15}N value for the phyllite sample is in the range of 1-10 ‰. Holloway and Dahlgren, (2002) have documented these values of the δ^{15}N for known phyllites. While this data is not confirmatory, it is consistent with the hypotheses that nitrate in bedrock is the predominant source of nitrate in RBF well and other groundwater sources in the region.

Table 5.6 Isotopic concentrations of $\delta\ ^{15}$N in nitrate in various sources in the region

Parameter analysis	NO_3^- (mg/L)	δ^{15}N (‰)
A) Water samples		
SNPW 1(Mar, 2013)	138	11.4
SNPW 1 (May, 2013)	84	12.2
Handpump next to SNPW 1(Mar, 2013)	137	12.8
SNPW-DDP (Jan, 2013)	139	12.4
S4 (May, 2013)	81	8.8
B) Rock leachates (6 mL water per 1 g rock)		
Phyllite rock (SNHP-20)	100	7.9
Quartzite rock (Near SNHP-FCI)	131	13.3

5.1.7 Travel Time at Srinagar

Heat carried by groundwater has been used as a tracer to estimate the travel times (Anderson, 2005, Becker et al., 2004, Cox et al., 2007). The travel time taken by the surface water (Alaknanda River) to the production well drilled on the bank was calculated using the thermal and isotope signatures of the water. The temperature has been successfully applied in many studies for stream-aquifer interactions (Constantz et al., 2006; Constantz and Stronestrom 2004; Sprenger et al., 2011).

The travel time taken by the surface water (Alaknanda River) to the production well drilled on the bank was calculated using the thermal and isotope signature of the water. The temperature of the river water was compared with the temperature of the production well and the monitoring well water for estimating the lags or lead in the thermograph. From the thermograph and isotope graph (Figure 5.12 a& b) the travel time of the filtrate to reach the PW (during pumping) is approximately 1.3 months in the monsoon and nearly 1 months in non-monsoon assuming retardation factor of 3 for glaciofluvial materials (Jäckli and Ryf, 1978; Bonnard et al., 1991).

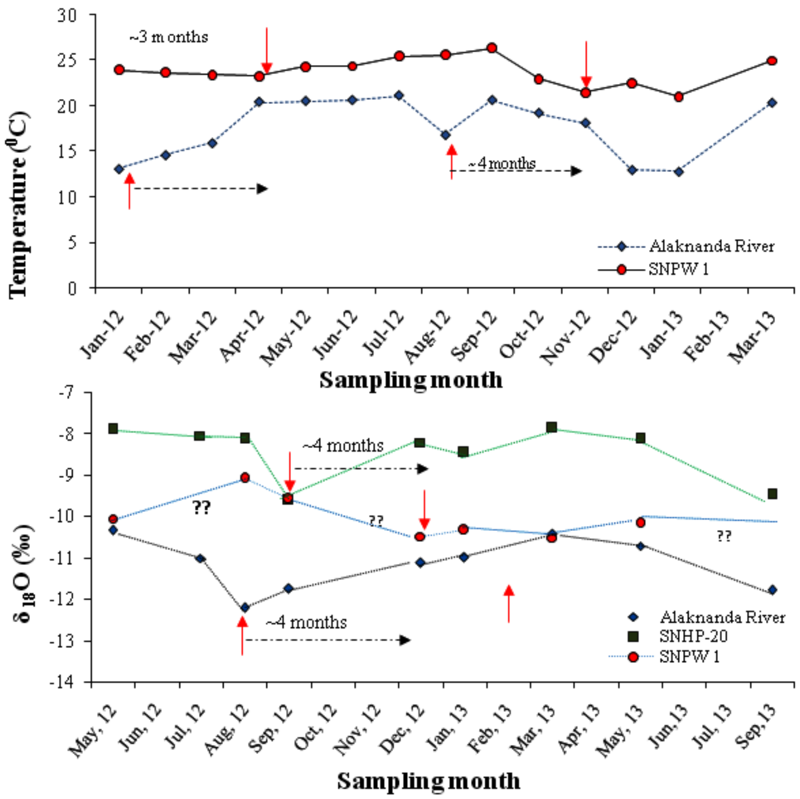


Figure 5.12 Travel time from natural tracers (a) temperature and (b) stable isotope

5.2 SUMMARY

The study showed that the water obtained from the RBF well in Srinagar is safe in terms of bacteriological quality and turbidity than the river water. However, it is highly mineralized with respect to the river water. The ionic concentrations in the production well water are comparable to the groundwater in the region. Stable isotope δ^2H and $\delta^{18}O$ values, however, show that the RBF well water is predominantly river water. All water quality parameters except nitrate concentrations of the RBF well water are within the drinking water standards, BIS: 10500 (2012).

Nitrate concentrations are high in the RBF well as well as groundwater in several zones in the Srinagar and Srikot area. There are areas of exposed bedrock in the region that were found to leach nitrate in water, suggesting these rocks to be the origin of nitrate in the bank filtrate and the groundwater. Isotope analysis of $\delta^{15}N$ in nitrates shows similarities in the isotopic composition of nitrate in water samples and leachates obtained from the rocks.

The occurrence of phyllites and quartzites and their release of nitrate underline the need for a pilot well or intensive sampling of available hand pumps before installation of a larger RBF scheme in the hills of Uttarakhand. As far as present scenario is concerned, there are two options: one to treat W2 water for nitrate removal and the other is to carry out flow modeling to make the RBF well at a site where nitrates in filtrate could be controlled.

5.3 WATER QUALITY AT SATPULI, AGASTYAMUNI AND KARNAPRAYAG

5.3.1. Quality of Water from Hand Pumps in the Vicinity of the RBF Sites

The production wells at Satpuli, Agastyamuni and Karnaprayag were commissioned in May 2010. Results of sampling and analysis done in May and August 2010 are shown in Figure 5.13 (a) to (c). The quality of the water does not depend on the distance from the river.

Groundwater samples from the hand pumps at Satpuli show a variation in the mineral content. The electrical conductivity of nearly 75% of the water samples is more than 500 µS/cm. Hand pump 6 (SPHP-6) water has maximum conductivity. Water samples from most of the hand pumps at Karnaprayag and Agastyamuni have a narrow range of variation in electrical conductivity. The EC of HP water at Agastyamuni is in the range from 400 to 500 µS/cm whereas at Karnaprayag EC of water samples from the HP were between 250 and 350 µS/cm. Hand pump 6 (SPHP-6) has maximum electrical conductivity and is located about 1 km away from the production well towards the hill. Similarly, water from AGHP-5 and KPHP-2 has maximum conductivity and are situated close to the RBF well.

Based on the chemical composition and distance from the RBF well, SPHP-6, KPHP-2 and AGHP-5 have been identified as probable sources of ground waters that mix with the river water in the production well during riverbank filtration. Subsequently, river water (SPSW, KPSW & AGSW), hand pump water (as groundwater) and production well water (SPPW, KPPW & AGPW) were collected monthly from Jan 2012 to March 2013 and analyzed. The quality of the water from the rivers, production wells and hand pumps at three sites are given in Figure 5.14 to 15.17 and in the Table B 6 given in Annexure B.

Table 5.7 summarizes water quality parameters of nine samples at three sites. On the basis of the data presented a few observations made on water quality are as below:

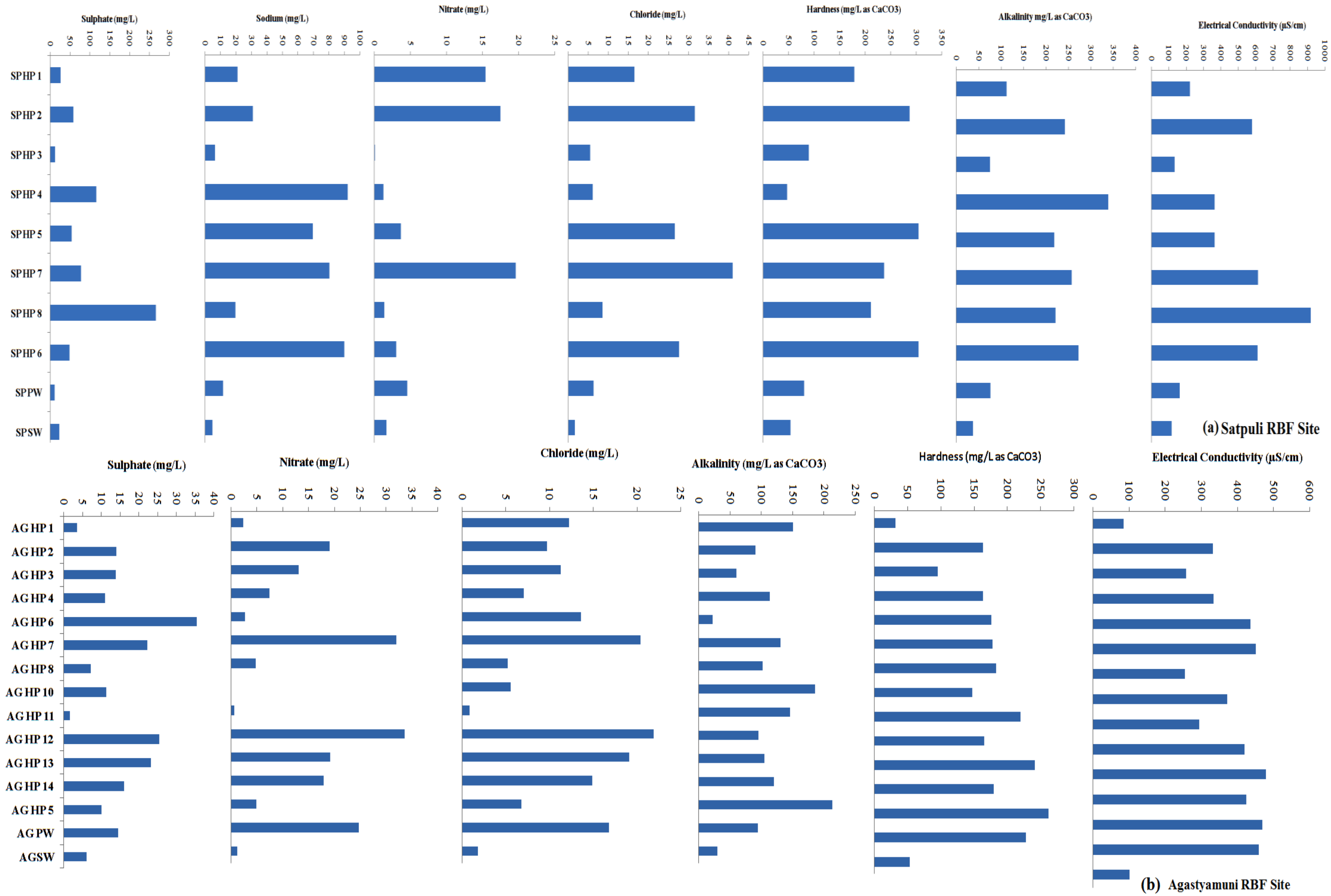
1. EC of PW water at Satpuli is comparable to the river water but less than the HP water. However, at Agastyamuni, PW water EC is between the EC of HP and the river water but more close to the HP water. The situation at Karnapryag is different. Here EC of KPPW is comparable to KPHP and occasionally more than the EC of KPHP water. Based on EC values it is inferred that water abstracted from the PW at Satpuli is mainly riverbank filtrate, at Agastyamuni, PW water is a mixture of the river and HP water and KPPW water is ground water (Table 5.14))

2. The bacteriological quality of the surface water at all the sites is found to be above the bathing limit BIS: 2296-1982 (CWC 2010). The concentration of both total and fecal coliforms in the production and groundwater were mostly below the detection limit (<2 MPN/100 mL). During monsoon, a breakthrough of total coliforms was observed in the hand pump as well as production well water, suggesting possible short circuit or infiltration from the surface runoff from the monsoon rains (Weiss et al., 2005; Wett et al., 2002). The fecal coliform, however, was not detected in any of the water samples from PW and HP (Figure 5.17)

3. Ionic Composition of Water:

- The ionic composition of the river water (SW), PW and HP water at Satpuli, Agastyamuni, and Karnaprayag is presented in Figure 5.18-5.20. For most of the samples, the percent error in cations and anions is less than 5%. The quality of the water from the HP and PW, except in monsoon, has been found to be in conformity with the drinking water standards, BIS:10500 (2012).

- The major ions in the river water and PW water are calcium and bicarbonates. The HP water at Satpuli and Agastyamuni, however, has sodium and bicarbonate as major ions. Also, the composition of the SPSW and SPPW water is similar (Figure 5.18 (a)-(C)). Thus, the EC values and composition suggest SPPW water to be mainly the bank filtrate.



Sulphate (mg/L)
Sodium (mg/L)
Nitrate (mg/L)
Chloride (mg/L)
Hardness (mg/L as CaCO3)
Alkalinity mg/L as CaCO3)
Electrical Conductivity (µS/cm)
SPHP 1
SPHP 2
SPHP 3
SPHP 4
SPHP 5
SPHP 7
SPHP 8
SPHP 6
SPPW
SPSW
(a) Satpuli RBF Site
Sulphate (mg/L)
Nitrate (mg/L)
Chloride (mg/L)
Alkalinity (mg/L as CaCO3)
Hardness (mg/L as CaCO3)
Electrical Conductivity (µS/cm)
AG HP 1
AG HP 2
AG HP 3
AG HP 4
AG HP 6
AG HP 7
AG HP 8
AG HP 10
AG HP 11
AG HP 12
AG HP 13
AG HP 14
AG HP 5
AG PW
AGSW
(b) Agastyamuni RBF Site

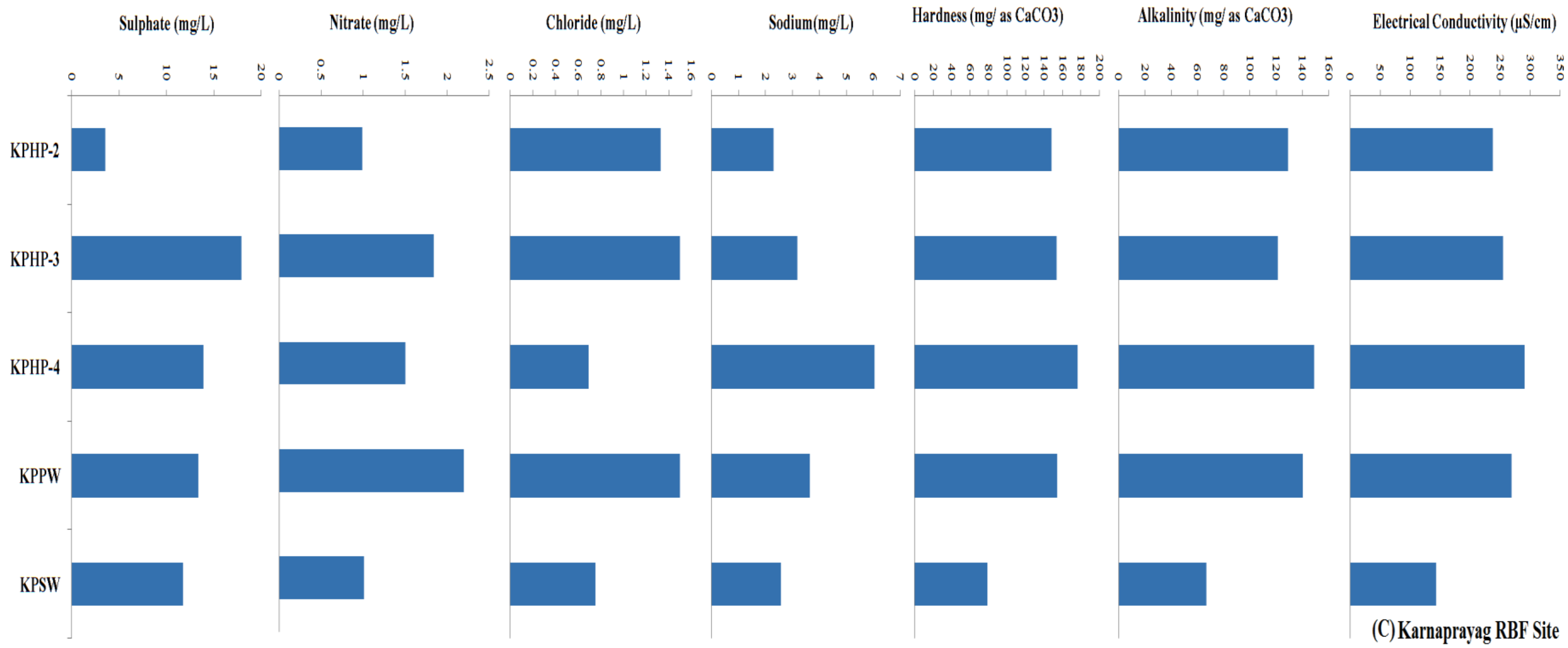


Figure 5.13 Spatial **v**ariation in water quality parameters in the vicinity of the bank filtrate site at **(a)** Satpuli;**(b)** Agastyamuni and **(c)** Karnaprayag

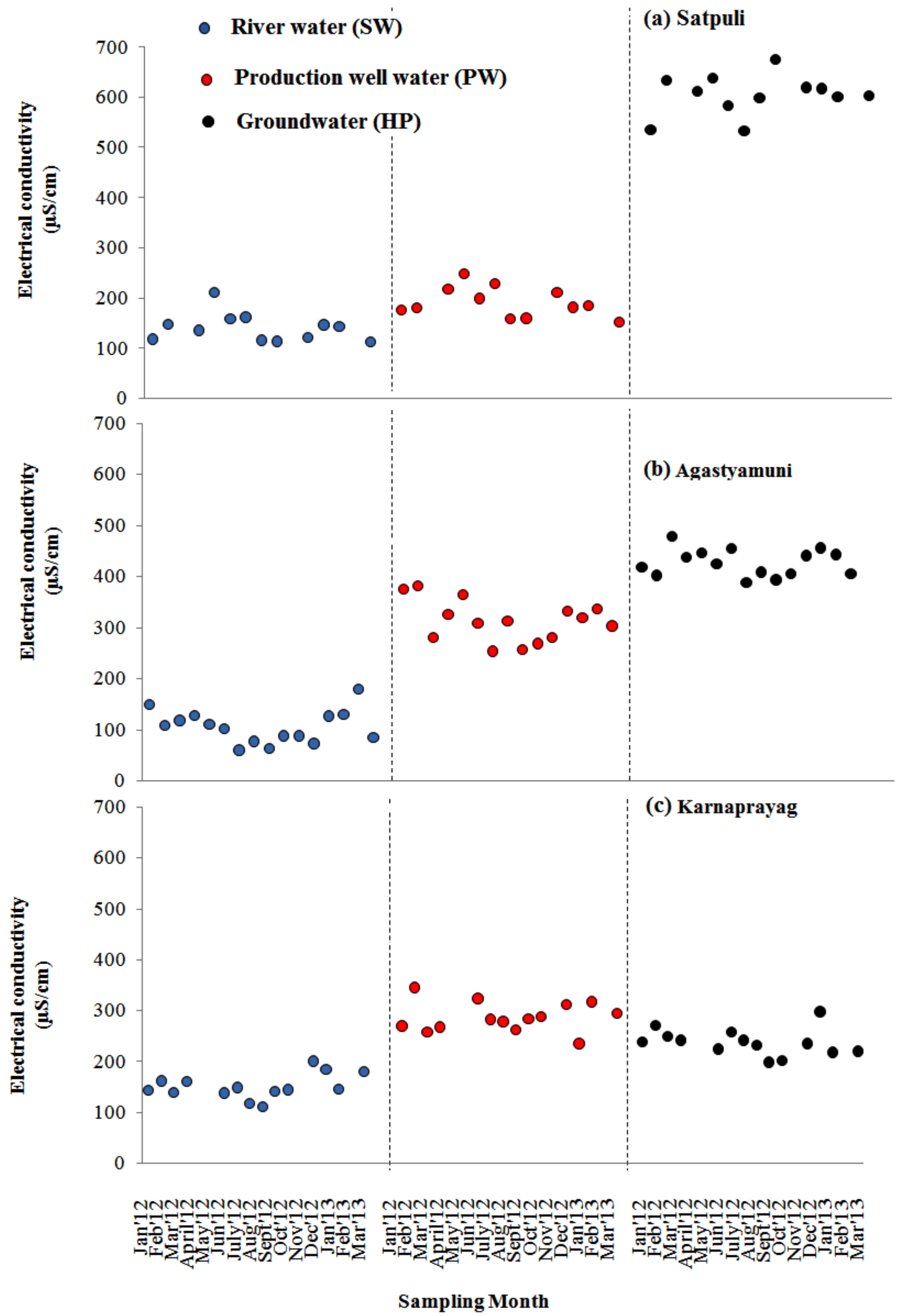


Figure 5.14 Temporal variation of electrical conductivity in the river water (SW), PW and HP water samples at **(a)** Satpuli **(b)** Agastyamuni and **(c)** Karnaprayag

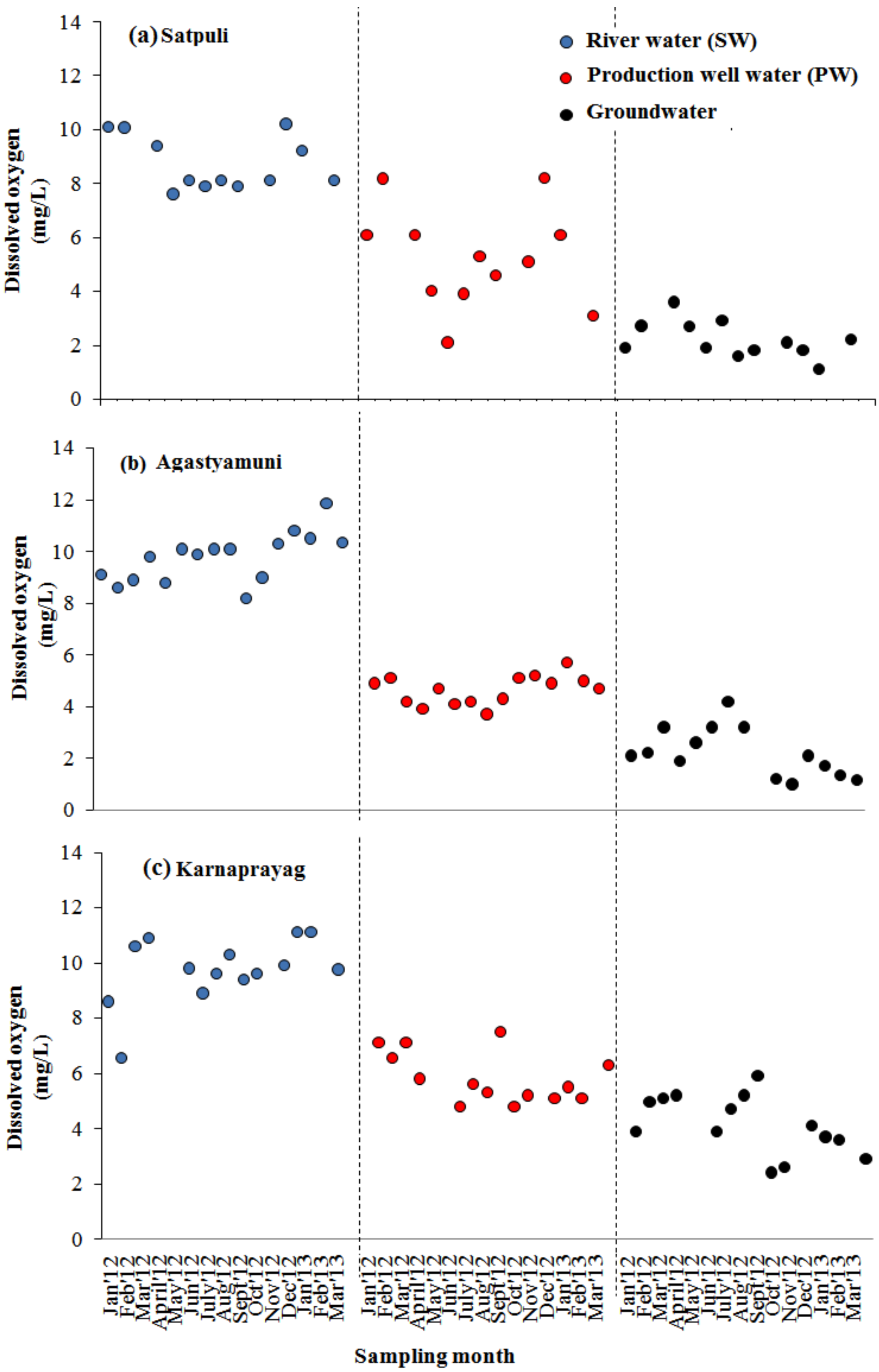


Figure 5.15 Temporal variation of dissolved oxygen in the river water (SW), PW and HP water samplesat **(a)** Satpuli **(b)** Agastyamuni and **(c)** Karnaprayag

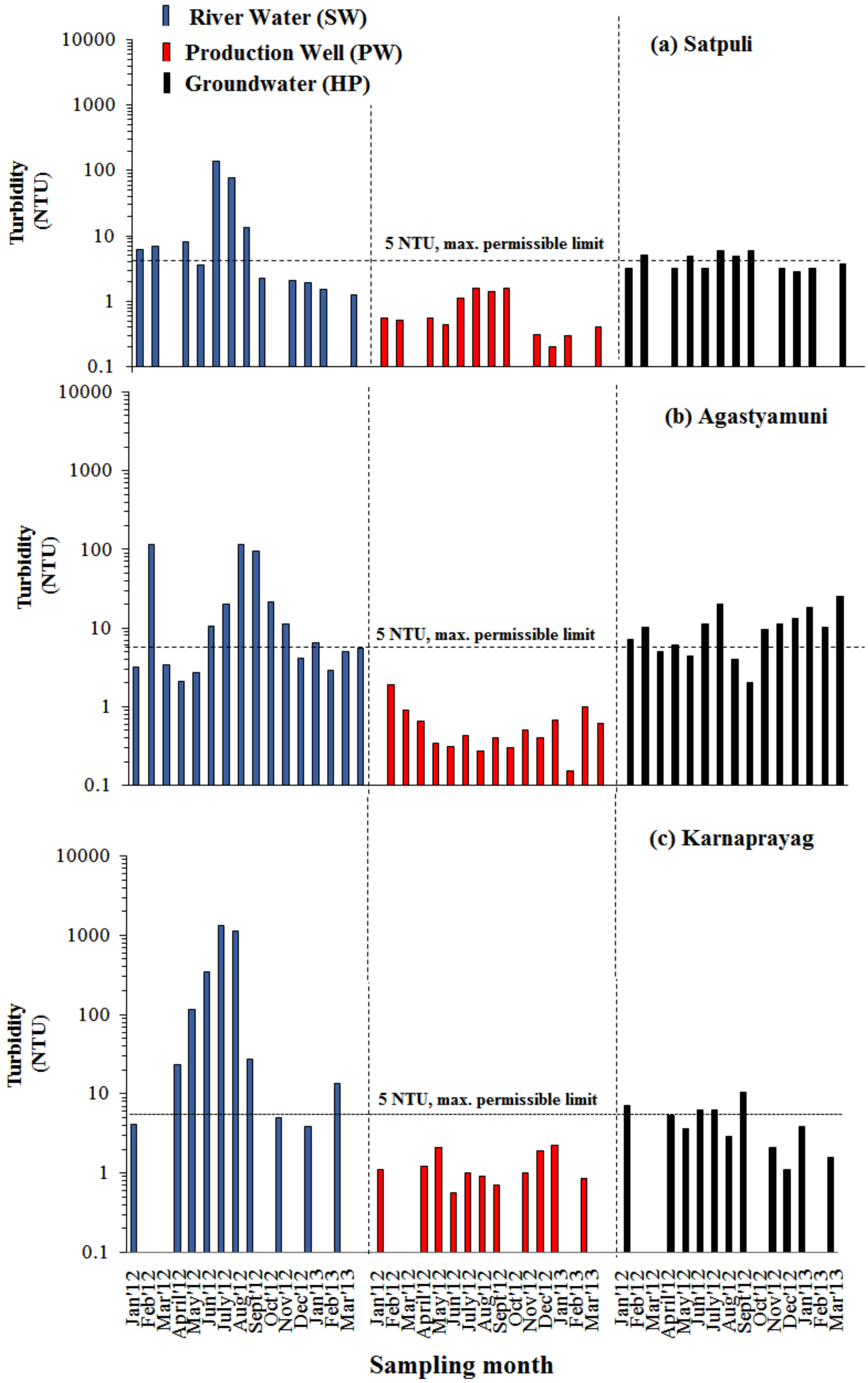


Figure 5.16 Temporal variations of turbidity in the river water (SW), PW and HP water samples at **(a)** Satpuli **(b)** Agastyamuni and **(c)** Karnaprayag

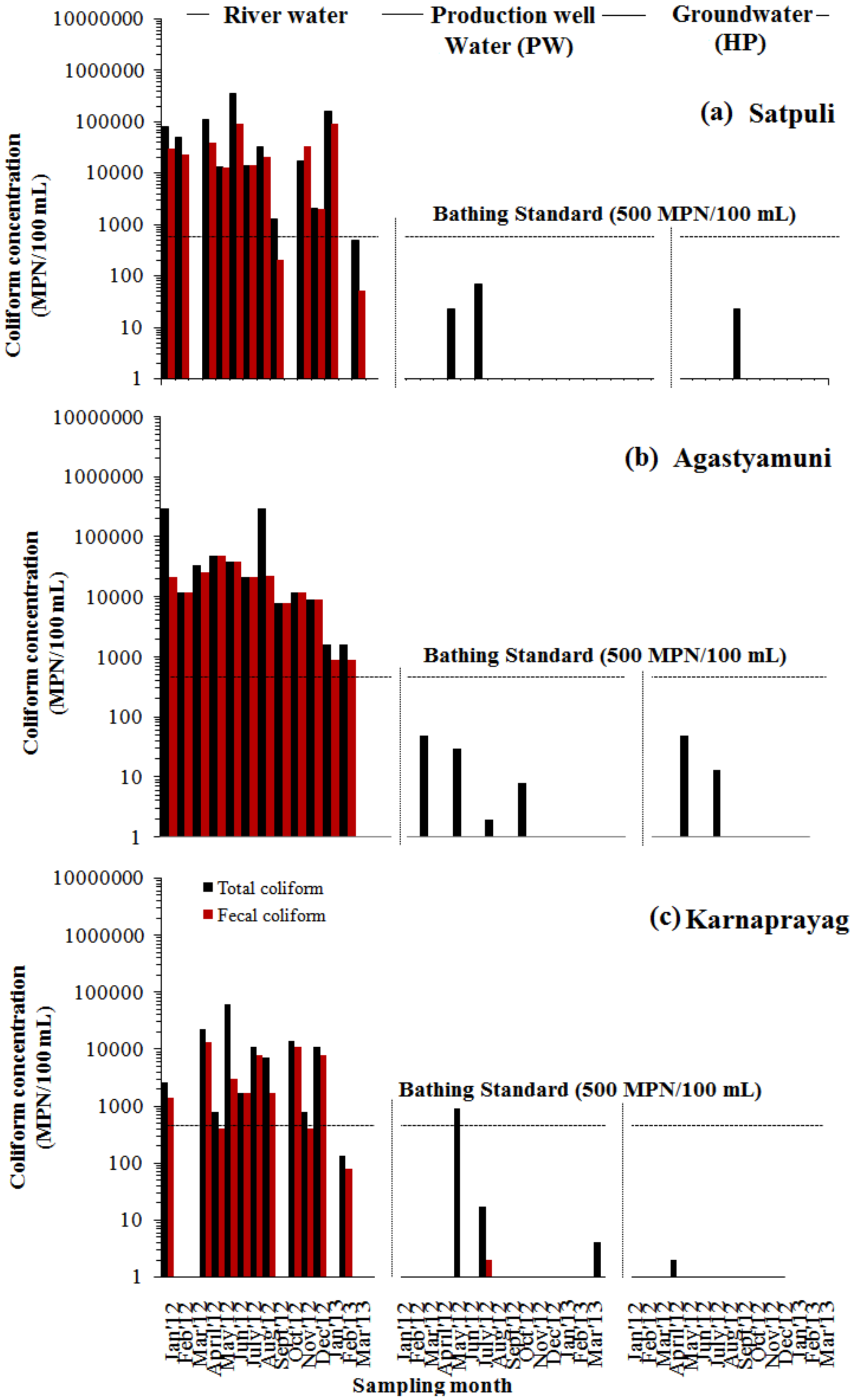


Figure 5.17 Total and fecal coliform distribution in the river water (SW), PW and HP water samples at **(a)** Satpuli **(b)** Agastyamuni and **(c)** Karnaprayag (vertical lines are missing, Also write SW, PW and GW)

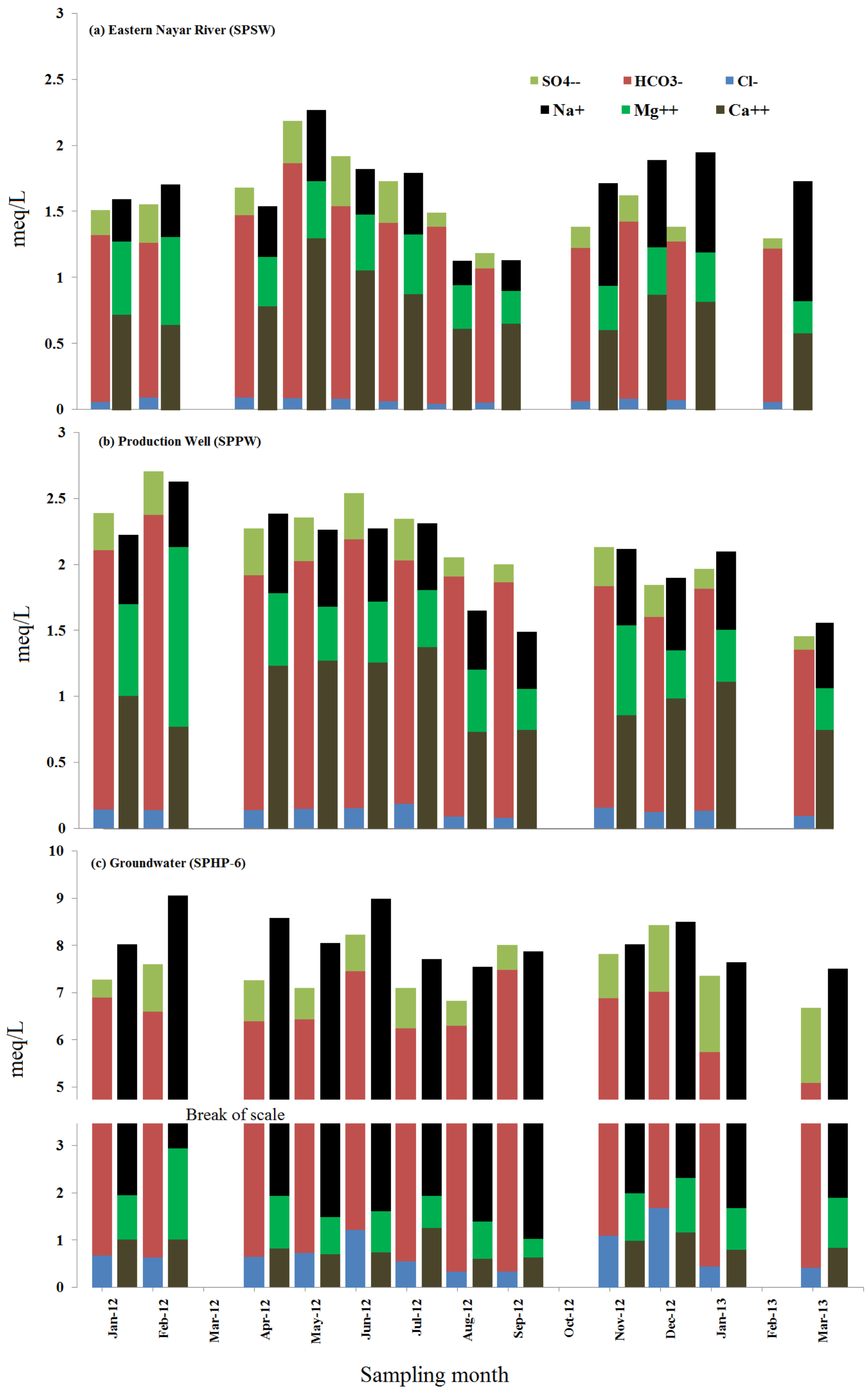


Figure 5.18 Satpuli: Distribution of major ions in water samples from the **(a)** Eastern Nayar River (SPSW), **(b)** Production well (SPPW) and **(c)** Hand pump (SPHP-6)

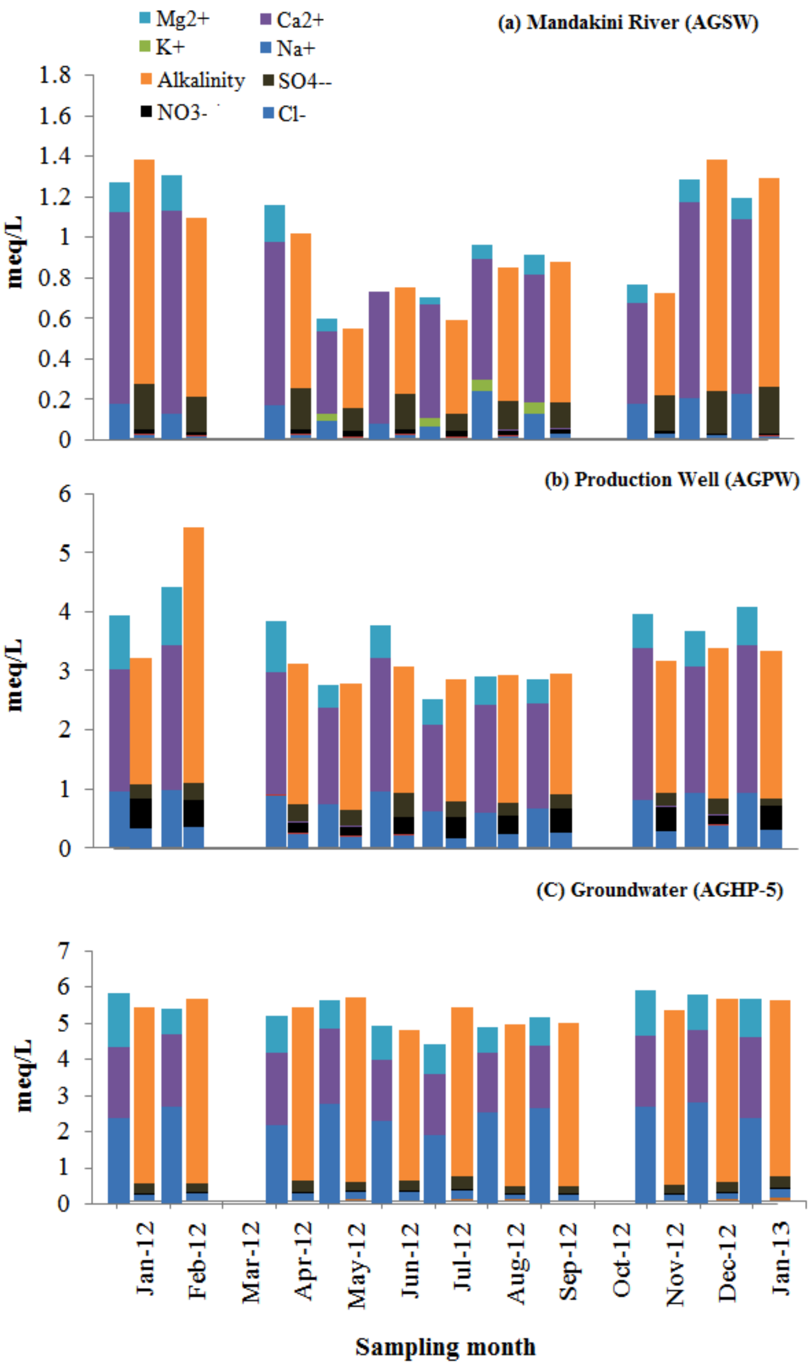


Figure 5.19 Agastyamuni: Distribution of major ions in water from **(a)** Mandakini River (AGSW), **(b)** Production well (AGPW) and **(c)** Hand pump (AGHP-5)

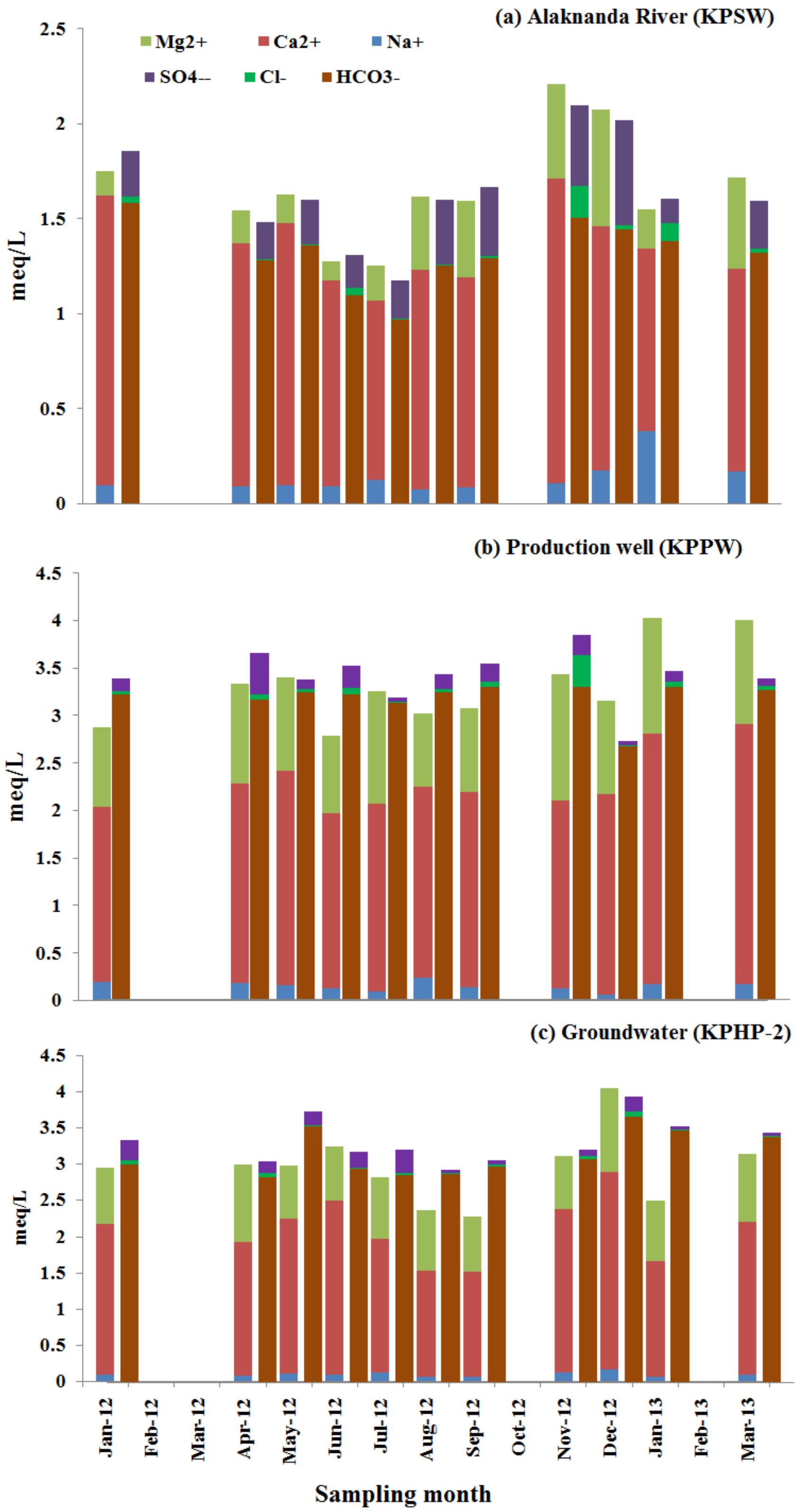


Figure 5.20 Karnaprayag: Distribution of major ions in water from the **(a)** Alaknanda River (KPSW), **(b)** Production well (KPPW) and **(c)** Hand pump (KPHP-2)

Table 5.7 Summary of water quality parameters from Satpuli, Agastyamuni and Karnaprayag

Location	Sample ID	Water Quality Parameter								Remarks
		Temp ^{0}C	Average pH	Coliform*($\times 10^3$)		EC (μS/cm)	Turbidity (NTU)	DO (% saturation)	Major Ions (% of meq/L; average)	
				TC	FC					
River	SPSW (East. Nayar)	13.2–31.0	8.4	0.5-350	0.05-90	112-211	1.2-134	100	Ca 53; HCO_3 87	-
	AGSW (Mandakini)	8.80-21.5	8.01	1.6-300	0.9-50	59-129	2.1-116	100	Ca 72; HCO_3 78	
	KPSW (Alaknanda)	9.00-16.9	8.3	0.130-60	0.08-13	110-200	3.8-1338	100	Ca 70; HCO_3 80	
Production Well	SPPW	14.0- 26.9	7.9	<2-.07	<2	151-247	<2	30-60	Ca 48 ; HCO_3 87	-
	AGPW	17.8-28.6	6.8	<2-.05	<2	253-363	<2	9-25	Ca 58; HCO_3 73	Na & Mg
	KPPW	17.4-24.3	7.8	<2-.9	<2	234-345	<5	52-80	Ca 64; HCO_3 91	-
Hand Pump	SPHP- 6	19.7-27.1	8.4	<2	<2	532-681	2.8-5.9	10-30	Na 75; HCO_3 86	Ca 13%
	AGHP-5	15.5-23.6	7.4	<2-.05	<2	387-455	2-25	13-42	Na 45; HCO_3 91	Ca 36%
	KPHP-2	16.6-35.2	7.5	<2 -.004	<2	198-297	1.1-10	33-73	Ca 68; HCO_3 94	-
* <2: All the tubes were negative										

- The AGPW water has calcium and bicarbonate ions predominantly; nevertheless the percent of calcium ions is less than the river water. The increased levels of sodium and magnesium that is present in PW water probably originates from the AGHP water (Figure 5.19).

- At Karnaprayag, the ionic composition of water from the three sources appears to be the same. However, EC and concentrations of the ions in PW water are occasionally more than the HP water that in turn is more than the river water. Therefore, it can be inferred that the PW water is not a mixture of the river and the KPHP-2 water. It could be a different ground water. From the available data the mineralization of the river water, however, cannot be ruled out. This could be understood from the isotopic data along with ionic composition. This aspect has been discussed in section 5.3.2.

5.3.2 Isotopic Characterization of Water Sample and Mixing Ratio

The chemical composition of the river water, PW, and HP water suggests the probability of the bank filtrate in the water abstracted from the PW. An insight into the river bank filtration and mixing is obtained through the stable isotopic characterization of the water samples. Since the mixing is site specific, it has been separately discussed at each location. The isotope values of different water samples have been compared with the local meteoric water line (LMWL). The slope of the plot of $\delta^{18}O$ and $\delta^{2}H$ and excess d values has been tabulated in Table 5.11.

5.3.2.1 Satpuli

Results of isotopic analysis for Satpuli samples are presented in Figure 5.21. The temporal variation in $\delta^{2}H$ and $\delta^{18}O$ values of waters from Eastern Nayar River and SPPW are similar. In other words, SPPW water is isotopically similar to the river water. The production well draws the bank filtrate largely for the most part of the year. The Same inference was drawn from the temperature profile (Figure 4.13), EC data and chemical composition of the water (Figure 5.15(a)).

The isotopic signatures of all the three samples collected in January are alike. The river and well water samples of May 2012 are heavier than the ground water. It could probably be due to the evaporative enrichment of the river and production well water. One of the limitations of such speculations is that these inferences are based on single observations. Nevertheless, the inference drawn from isotopic data is in agreement with the general effects of weather on rivers.

The isotopic values of all the sample are very close to the local meteoric water line, suggesting the local rain were responsible for the recharge of the water resources. The observed differences in $\delta^{18}O$ and δ^{2} H values may be due to the difference in temperature of the river water, PW and hand pump water (PW).

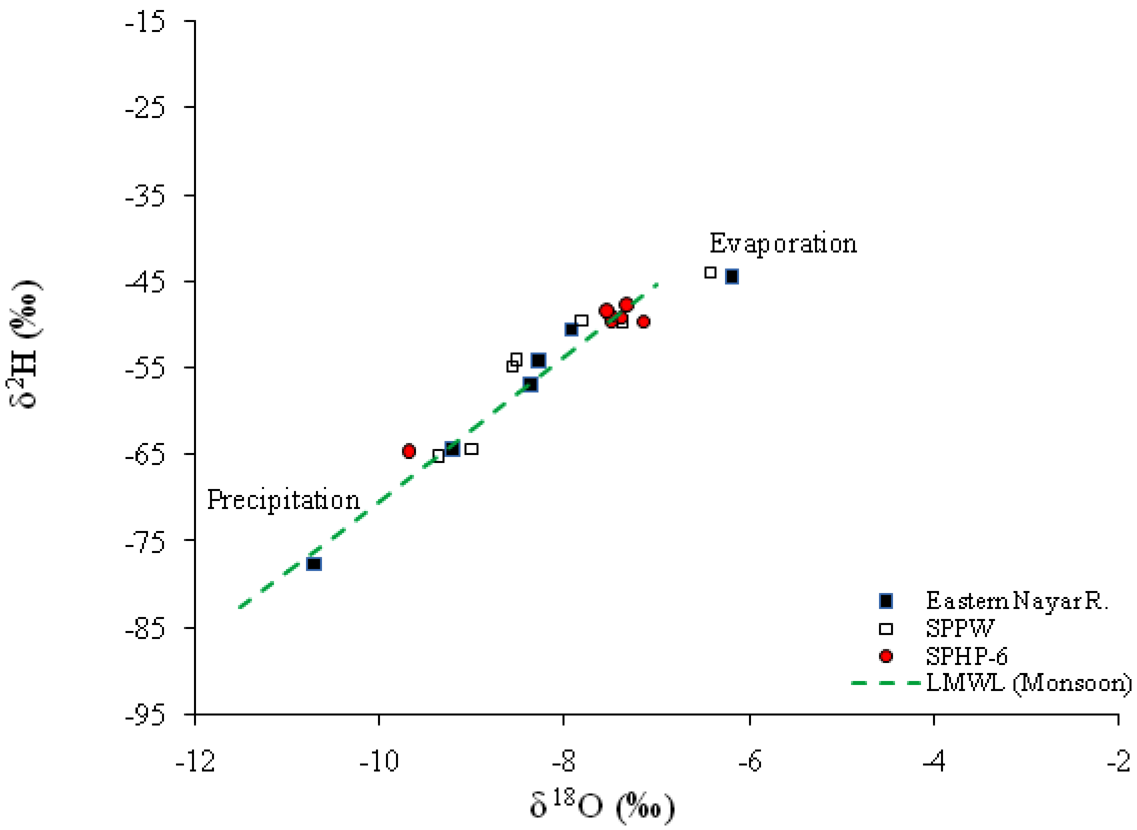


Figure 5.21 Satpuli: δ^{18}O vs. δ^{2}H of water samples at Satpuli; (Correlations: Eq.5.9-5.11; Table 5.11)

The concentration of the stable isotope oxygen (δ^{18}O) and chloride was used for calculating the mixing ratio of surface water to the ground water in the production well water using Equation 5.1. The computed bank filtrate and the concentration of stable isotope and chloride are given in Table 5.8. There are a few questions that need to be addressed here. What is meant by negative contribution (July data) and more than 100 % contribution of the river water (Sept., Dec., and March. data)? Such a discrepancy is due to production well water is either most enriched or most depleted. This can be explained by considering the travel time to the production well i.e. the signature of the production well water measured in a particular month is the river or ground water that has spent some time in the aquifer. The percent river water in the production well water calculated from the δ^{18}O and chloride do not exactly match. However, results from both indicate the same trend. Also, these corroborate the observations on the temperature profile (Figure 4.13).

Table 5.8 Satpuli: Percent of the bank filtrate in PW

Month	Concentration of stable isotope oxygen ($\delta^{18}O$)			% River water
	Surface water (SPSW)	Production well (SPPW)	Groundwater (SPHP-6)	
May-12	-6.2	-6.41	-7.31	81.1
Aug-12	-10.7	-9.00	-7.15	52.1
Sept-12	-9.2	-9.36	-7.39	109
Dec-12	-8.36	-8.55	-7.48	122
Jan-13	-7.93	-7.81	-7.53	70.0
Mar-13	-8.54	-8.52	-9.69	102
Average	**-8.49**	**-8.27**	**-7.76**	**70**
Concentration of chloride				
Jan-12	2.1	5.1	24.1	86
Feb-12	3.3	4.8	22.7	92
Apr-12	3.2	4.9	19.1	89
May-12	3.1	5.1	15.6	84
Jun-12	2.9	5.3	43.0	94
Jul-12	2.3	6.5	19.5	76
Sept-12	1.8	2.8	12	90
Nov-12	2.2	5.6	39.1	91
Jan-13	2.6	4.7	15.8	84
Mar-13	2.1	3.3	14.8	91
Average	**2.6**	**4.8**	**22.6**	**88**

(a) Travel time

The travel time of the river water (SPSW) to the production well during the bank filtration was calculated using a model developed by Davis et al., (1980), Edmunds and Gaye. (1994).The temperature has been successfully applied in many studies for stream-aquifer interactions (Constantz et al., 2002; Constantz and Stronestrom 2004; Sprenger et al., 2011).

The temperature, electrical conductivity, and isotope as tracers of the production well water were compared with the river water to estimating the lags or lead (Figure 5.22). The lags and lead appearing in the isotope data, temperature data and EC values of the river and production well water are matching. There is a slight difference in the values due to the mixing of ground water. Such a pattern reflects a very short travel time for the river water.

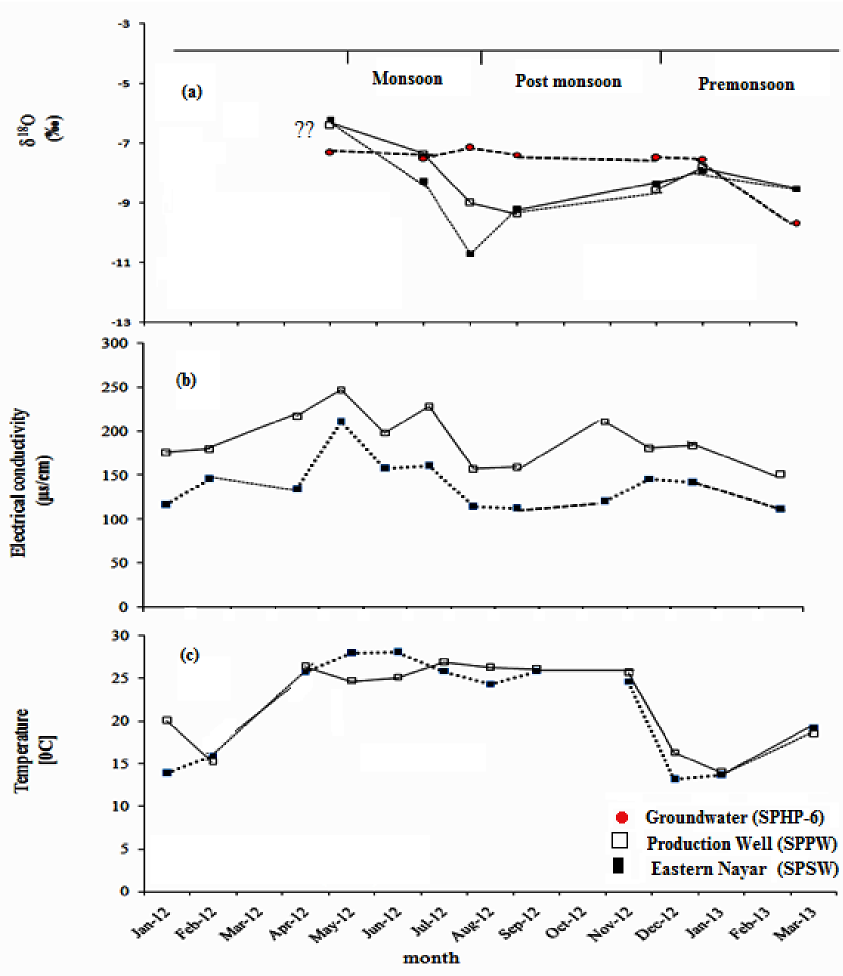


Figure 5.22 Satpuli: Temporal variation in **(a)** Stable isotope **(b)** Electrical conductivity **(c)** Temperature

The data depicting temporal variation in natural tracers $\delta^{18}O$, EC or temperature of the water samples is inadequate to confidently estimating the travel time. Based on the Darcy's law and the horizontal distance between river and SPPW of 7 m in the monsoon, and 45 m in the non-monsoon the estimated travel time is 0.3 day and 13 days respectively. As per the traces it should be ~10 days on considering the thermal retardation factor of 3, (Figure 5.22). However, there is no clear time shift. Considering this, the average annual contribution of the RBF water to the PW water is 88%

5.3.2.2 Agastyamuni

Results of stable isotope analysis are presented in Figure 5.23. The δ^2H and $\delta^{18}O$ values for the waters of the Mandakini River, AGPW, and AGHP-5 indicate that the (i) AGPW water and groundwater fall on LMWL. The values of the river water, on the other hand, are not matching with the meteoric water line. Kumar et al. (2010) have reported such an observation for the rivers at a higher altitude of Himalaya. (ii) The production well water is lighter than the ground water but heavier than the river water. Also, the δ^{18}O value of PW water ranges from – 8.47 to – 7.73‰ whereas for the river water variation is from -11.75 to-9.35‰. The HP water like PW water exhibits a narrow range of variation from -7.43 to -6.90 ‰. It may be due the effect of temperature.

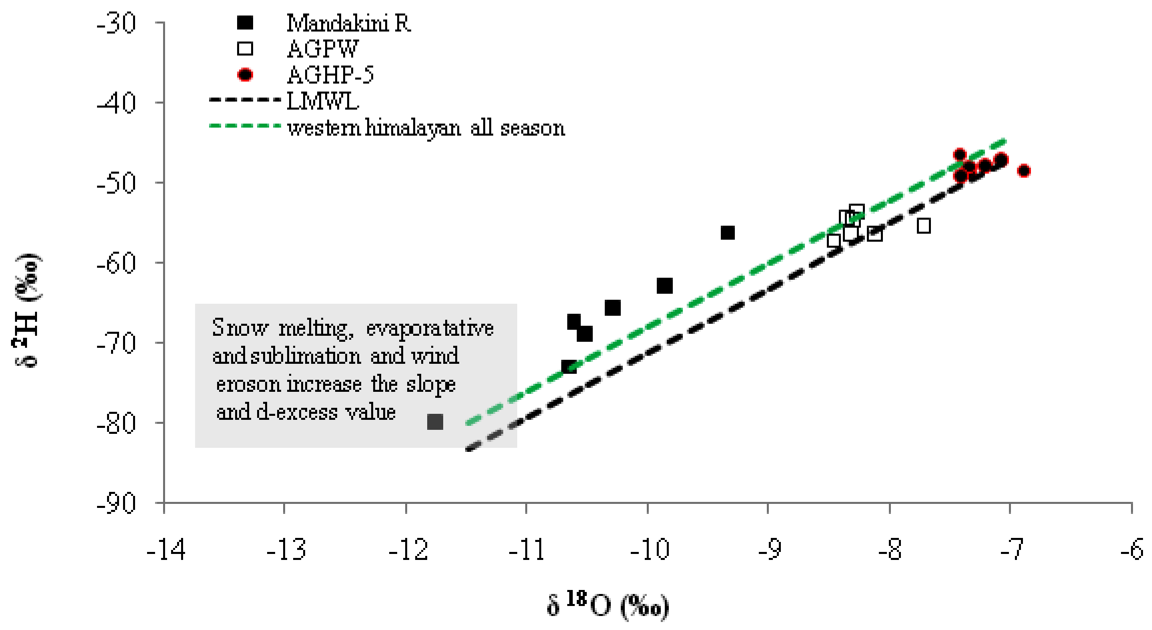


Figure 5.23 δ^{18}O *vs.* δ^{2}H of water samples at Agastyamuni; (Correlation: Eq.5.12; Table 5.11)

From EC as well as δ^{18}O values, the production well water appears to be the mixture of ground water and riverbank filtrate. Accordingly, the mixing ratios have been calculated from the mass balance Eq. 5.1 using δ^{18}O concentration (Table 5.9). The data reveals that the percent of bank filtrate in the production well water is less than 50 % except for May 2012. However, the percent of filtrate does not exhibit any trend that can be correlated to the season.

Since the EC data is relatively stable, it has also been used to estimating the percent of the bank filtrate in the PW water. Results are presented in Table 5.9. The bank filtrate in the production well water varies between 24 to around 40 %. In May 2012, however, the bank filtrate is ~ 51%. One of the reasons for the maximum percent of the bank filtrates in PW in May water could be the travel time. The data is inadequate to comment further on this. Nevertheless, the annual average of the bank filtrate in the production well water is around 38 %. From the stable isotope data, the contribution of the bank filtrate averages around 31 %. The annual average mixing ratio from isotope data and EC is in fair agreement.

Table 5.9 Stable isotope and EC concentration and percent of bank filtrate at Agastyamuni

Month	**Concentration of stable isotope oxygen ($\delta^{18}O$)**			**% bank filtrate#**
	Mandakini R. (AGSW)	**Production well (AGPW)**	**Groundwater (AGHP-5)**	
May-12	-9.35	-8.47	-7.08	61.2
Jul-12	-9.85	-8.31	-7.34	38.6
Aug-12	-11.8	-7.73	-6.90	17.1
Sept-12	-10.7	-8.12	-7.21	26.4
Dec-12	-10.5	-8.30	-7.34	30.3
Jan-13	-10.6	-8.27	-7.43	26.3
Mar-13	-10.3	-8.35	-7.41	32.7
Average	-10.4	-8.22	-7.24	31.0
Electrical conductivity (μS/cm)				
May-12	59	253	454	50.9
Jun-12	76	312	387	24.1
Jul-12	62	256	408	43.9
Aug-12	87	268	393	40.8
Sep-12	87	280	405	39.3
Dec-12	126	318	455	41.6
Jan-13	129	336	442	33.9
Mar-13	84	302	404	31.9
Average	89	291	419	38.8

(a) Travel time

The travel time for the surface water (Mandakini River) and groundwater to reach the production well located on the bank was calculated using isotope signature $\delta^{18}O$ of the river water and production well water (Davis et al., 1980; Edmunds and Gaye, 1994).The data presented in Figure 5.24 appears to be inadequate to draw any inference regarding travel time.

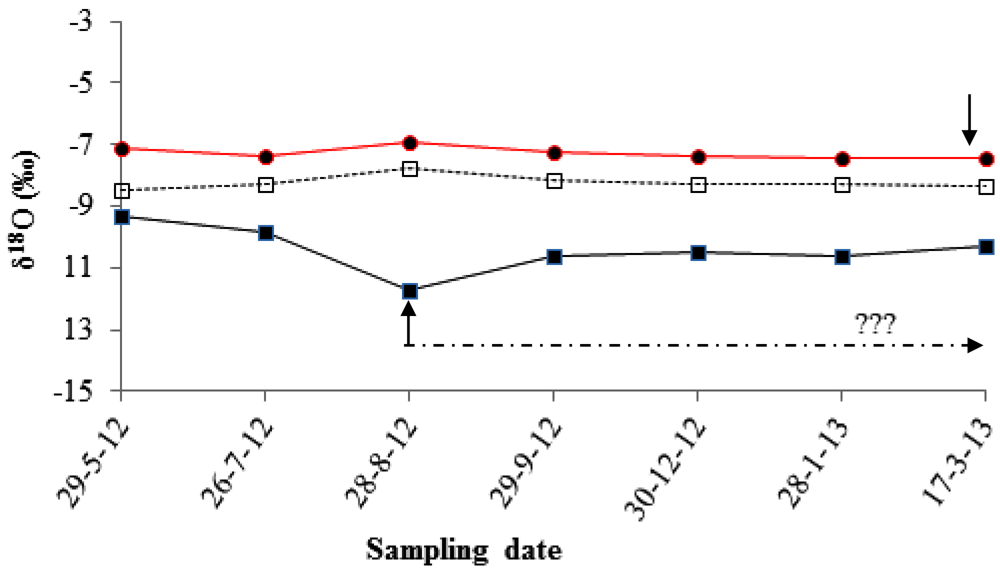


Figure 5.24 Agastyamuni: Temporal variation in $\delta\ ^{18}O$ (‰) signature

5.3.2.3 Karnaprayag

Values of stable isotopes presented in Figure 5.25 (a&b) indicate that the (i) KPPW water and groundwater (KPHP-2) fall on LMWL. (ii) The production well water is heavier than the river water and lighter than the KPHP-2 water. The mixing ratios calculated from stable isotope oxygen ($\delta^{18}O$) using mass balance Eq.5.1 are given in Table 5.11.

The data in Table 5.10 reveals that the percent of bank filtrate in the production well water is less than 16 % except July 12. The EC of the production well water is occasionally more than the EC of the HP water. Higher EC of the PW water due to mineralization of the river water during bank filtration is also ruled out as the two waters are isotopically different.

The Alaknanda river water at Srinagar is slightly heavier than the river at Karnaprayag. It may be due to the difference in altitude and weather conditions at two sites. Several tributaries join the Alaknanda River at Srinagar as it is downstream of Karnaprayag. This may also change the isotopic signature of the river.

(a) Travel time

Travel time couldn't be calculated as the ground water is feeding the production well and the river. The production well needs to operate continuously to ascertain any changes in flow pattern.

Table 5.10 Karnaprayag**:** Stable isotope concentration and percent of bank filtration

Month	Concentration of stable isotope oxygen ($\delta^{18}O$)			% bank filtrate
	Alaknand R (KPSW).	**Production well (KPPW)**	**Groundwater (KPHP-2)**	
Jul.12	-11.07	-9.78	-9.33	25.9
Aug.12	-13.36	-9.07	-8.66	8.7
Sept.12	-11.98	-9.18	-8.78	12.5
Dec.12	-11.47	-9.38	-9.60	-
Jan.13	-11.53	-9.61	-9.25	15.8
Mar.13	-11.15	-9.25	-8.91	15.1
Average	-11.76	-9.38	-9.09	11.0

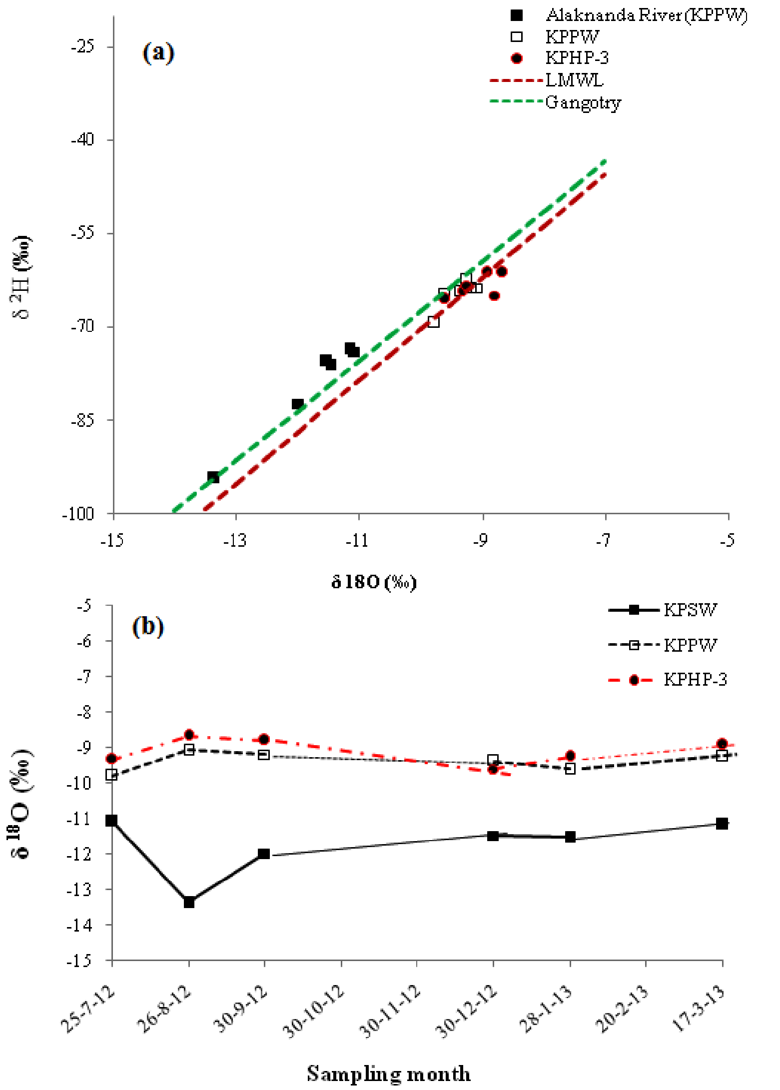


Figure 5.25 Karnaprayag **(a)** δ^{18}O *vs.* δ^{2}H of water samples; (Correlation: Eq.5.13; Table 5.11) **(b)** Temporal variation inδ^{18}O.

Table 5.11 Correlation between δ^2H and $\delta^{18}O$ for water samples

Site	Sample	Equation	Eq. No.	R^2	Remarks
From the literature	Devaprayag LMWL (30⁰08'26"N, 78⁰35'48"E)				
	(all season)	δ^2H=8.07 $\delta^{18}O$+9.940	5.2	1	Kumar et al., 2010
	(monsoon)	δ^2H =8.27 $\delta^{18}O$ +12.43	5.3	1	
	Western Himalaya (all season)	δ^2H =7.95 $\delta^{18}O$ +11.51	5.4	1	
	Gangotry	δ^2H =8.01 $\delta^{18}O$ +12.69	5.5	1	
Srinagar	SNHP-20	δ^2H =8.52 $\delta^{18}O$ +13.60	5.6	0.94	Experimental observations; Figure 5.11
	SNSW	δ^2H =8.06 $\delta^{18}O$ +13.80	5.7	0.97	
	SNPW-1*	δ^2H =2.39 $\delta^{18}O$ +45.50	5.8	0.67	
Satpuli	SPHP-6	δ^2H =6.73 $\delta^{18}O$ +0.765	5.9	0.96	Experimental observations; Figure. 5.21
	SPSW	δ^2H =7.24 $\delta^{18}O$ +4.408	5.10	0.88	
	SPPW	δ^2H =7.61 $\delta^{18}O$ +6.176	5.11	0.99	
Agastyamuni	AGSW	δ^2H =9.81 $\delta^{18}O$ +43.61	5.12	0.95	Figure. 5.23;
	AGPW	-	-	-	Data on LMWL (Eq 5.3)
	AGHP-5	-	-	-	
Karnaprayag	KPSW	δ^2H =9.33 $\delta^{18}O$ +30.44	5.13	0.98	Figure 5.25
	KPPW	-	-	-	Data on LMWL (Eq 5.3)
	KPHP-2	-	-	-	
*Poor correlation is due to temporal variation in the fraction of the bank filtrate in PW water					

5.4 SUMMARY

The assessment of the river bank filtration at four sites on the basis of water quality can be summarized as under

- The river bank filtration at Satpuli and Srinagar is effective. The average (annual) bank filtrate contribution to the production well water is more than more than 65%. The seasonal variation in the input of the bank filtrate to the PW water from tracers could not be precisely determined due to inadequate data.
- The water from the production well at Srinagar is the mineralized river water. Mineralization takes place during travel of the river water through the aquifer to the production well.
- Well water is isotopically similar to the river water and chemically similar to the ground water. The water quality except nitrate is in conformity with the drinking water standard (BIS 10500:2012).
- Nitrate in water has been found to be geogenic in nature. Leaching from phyllite rock is one of the sources of nitrate in water.
- Nitrate >45 mg/L has been found in springs as well as in several hand pump waters.
- The production well water quality at Satpuli is not much different from the river water. The travel time estimated from the Darcy's Law is around 13 days during non-monsoon and less than a day in monsoon. The water quality is in conformity with the drinking water standards.
- Production well at Agastyamuni has around 34% of the bank filtrate whereas at Karnaprayag the bank filtrate was <16%. The travel time, however, could not be determined due to inadequate temporal data.

CHAPTER-6
EFFECT OF GRAIN SIZE AND FLOW RATES ON THE QUALITY OF FILTERED WATER

Two sets of experiments were performed in the laboratory to evaluate the effect of (i) flow rates and (ii) filter materials on the quality of the water filtered through the column. These sets of experiment were conducted in the Environmental Engineering Laboratory of Indian Institute of Roorkee, Roorkee, India and Water Sciences Laboratory, HTW, Dresden, Germany respectively.

6.1 EFFECT OF FLOW RATE ON QUALITY OF FILTERED WATER

Four stainless steel columns were packed with the aquifer material collected at a depth of 16-20 m from the RBF well that was being drilled at Srinagar. These columns were fed with canal water maintained at linear velocities of 2.02, 10.2, 16.3 and 32.7m/d.

6.1.1 Grain –size Analysis of Filter Materials

Grain size analysis was carried out as per BIS 1607-1977 and results are given in Table 4.3 of section 4.5.1. The size of the aquifer materials that was used to pack the columns ranged from 0.33-6.1mm. Average grain size (d_{50}) of the filter materials was 0.37 mm with 20 % gravel, 72 % sand and 8 % fine sand and silt. The hydraulic conductivity was ~ 1.14 x 10^{-4} m/s. The uniformity coefficient (C_u) was 3.8. The gain size finer than 0.212 mm and larger than 0.425 mm was discarded to avoid low hydraulic conductivity and wall effects (Nsir, 2009; Sentenac et al., 2001; Lewis and Sjöstrom, 2010).

6.1.2 Experimental Setup

The specification of the columns that were used for the laboratory experiments and characteristic of aquifer materials are given in Table 3.2 of section 3.13.1. The schematics of the experimental set up indicating operation of single column is shown in Figure 3.18 of section 3.13.1. Details regarding experimental procedures are given in section 3.13.

6.1.3 Tracer Test

Tracer tests were conducted to find out effective porosity of the aquifer materials in columns. Conductivity of the filtered water was measured at regular interval. Breakthrough curves were obtained by plotting fractions (C/C_0) of the input concentrations (C_0) as a function of time (t) Effective porosity was estimated from equation 3.5 (Section 3.13.1). The t_{50} values of different columns along with other observations and operational parameters are given in

Table 6.1. The midpoint (C/C_0=0.5) of the sigmoidal curve corresponding to one pore volume is indicative of plug flow through packed porous media (Figure A10 in appendices A; Marlow et al., (1991).

Table 6.1 Summary of tracer test results

Characteristics \ Design flow rate	Column A (1cm^3/min)		Column B (5cm^3/min)		Column C (10cm^3/min		Column D (20 cm^3/min)	
	Before[1]	**After**[2]	**Before**[1]	**After**[2]	**Before**[1]	**After**[2]	**Before**[1]	**After**[2]
(Q), Flow rate[3] (cm^3/min)	1.1	0.7	5.1	2.6	10	4.7	20.6	1.8
(v), Specific discharge; cm/min (m/d)	0.14 (2.02)	0.09 (1.29)	0.71 (10.2)	0.38 (5.47)	1.10 (16.3)	0.69 (9.93)	2.27 (32.7)	0.23 (3.31)
t_{50}Effective contact time(min) (computed from Eq. 6.1)	324 (327)	468 (461)	66 (65.4)	120(126)	42 (32.7)	66 (69.6)	18 (15.9)	195 (182)
Effective porosity (%)	49.2	45.4	45.4	43.1	38.6	29.9	39.7	33.9
Decrease in porosity (%)	7.7		5.1		22.5		14.6	
Decrease in discharge (%)	35.2		48.6		73		91.2	

[1] at start of the experiment; [2] before terminating the experiment i.e. after 72 days; [3] flow rate at which the tracer test was conducted.

The perusal of data in Table 6.1 suggests the effect of flow rate (i.e. pumping rate) on breakthrough of the solute. The effective porosity from the tracer test of the material in columns operating at low flow rates and the porosity calculated from the bulk density before the start of the experiment was found to be nearly the same (Table 3.2 of section 3.9.1). Both initial porosity and flow rate reduced during operation by 5-22 % and 35-91% respectively in the four columns. The reduction in porosity and flow rate, increased with increase in operating flow rate from 1 to 20 cm3/min or flow velocities from 0.1 to 2.3 cm/min. The time (t_{50}) for 50% solute response (C/C0 =0.5) to the liner velocity is shown in Figure 6.1.

The Effective contact time decreases with the increase in liner velocity. The time, t_{50} conformed to Equation. 6.1.

$$t_{50} = \frac{45.4}{v} or \frac{327}{Q} \qquad \ldots\ldots 6.1$$

Where $t_{50}$is the effective contact time (C/Co =0.5)
v is the linear velocity at which the tracer test is conducted (cm/min) and Q is the discharge (cm^3/min)

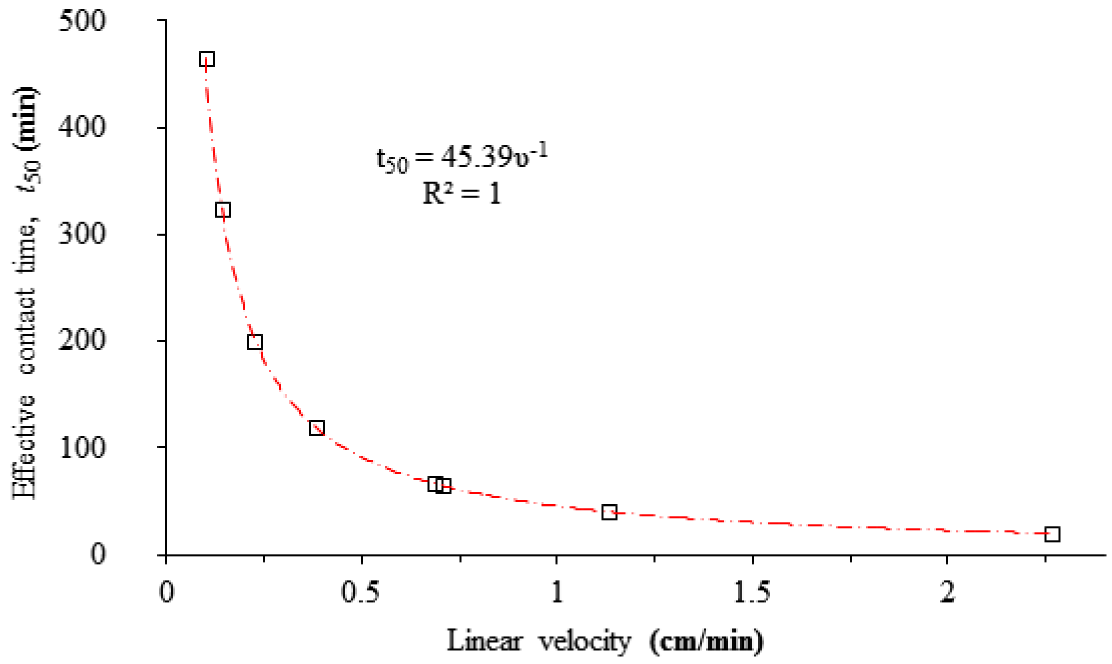


Figure 6.1 Correlation between velocity (v) and effective contact time (t_{50})

6.1.4 Discharge Rate

Temporal variation in discharge of all the columns for 72 day is shown through Figure 6.2(a) to (d).

Initial discharge of 1.05 cm^3/min in column-A was reduced to 0.7 cm^3/min on day 72. In all the columns, the discharge was significantly reduced. The reduction in flow given in Table 6.1 increased with increase in flow rate. In column A the flow gradually reduced and reduction in flow conformed to linear relation given by Eq. 6.2

$$v = \frac{(1 - t_{50} \times 10^{-3})}{A} \quad \ldots\ldots \quad (6.2)$$

Where v (cm/min) is the predicted linear velocity at time t (day) for an initial flow of 1 cm^3/min

The percent reduction in discharge and porosity in other columns after 72 days of operation is given in Table 6.1. The decreased flow rate or reduced porosity of the columns operating at higher flow rate is due to deposition of SS at the filter water interface, and/or particle intrusion into the aquifer material (Mauclaire et al., 2004). These observations; therefore suggest that water abstraction from a RBF well induced by pumping is likely to clog the aquifer. Ideally, water abstraction should be compatible with the water recharge into the well.

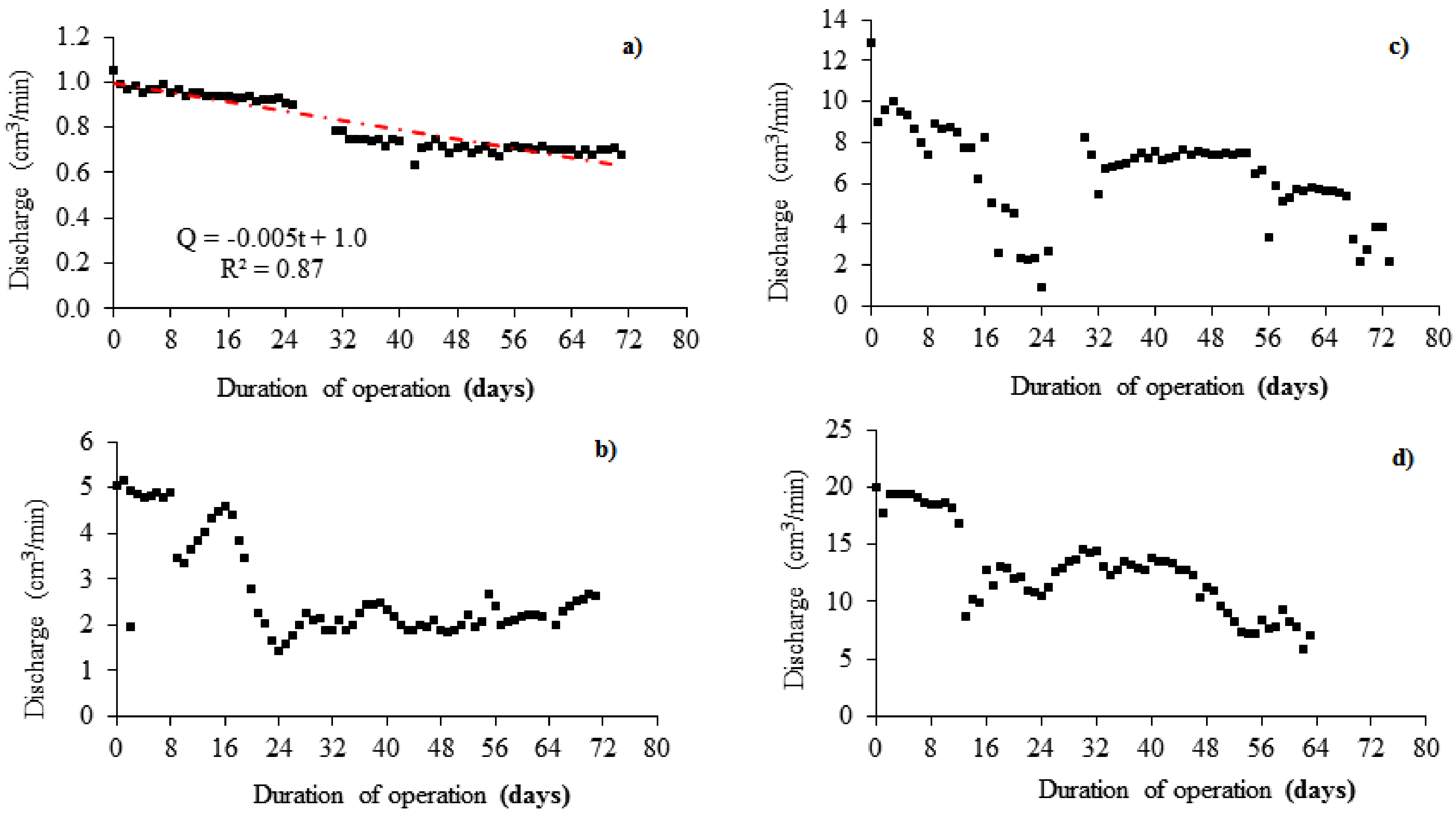


Figure 6.2 Temporal variations in flow rate (**(a)-(d)** represent column A – column D)).

6.1.5 Water Quality

EC, pH, UV-A, turbidity, total coliform and fecal coliform of the source water and filtered water were monitored to assess the performance of the laboratory filters. Results are summarized in Table 6.2.

Table 6.2 Column performance: Quality of inlet and outlet water

Column		pH (mean±σ[a])	EC, (μS/cm) (mean±σ[a])	UV-A, (cm^{-1}) mean±σ[a]	Range of Turbidity (NTU)	Coliform (log removal) max- min[b]	
						Total	Fecal
A	Inlet	7.9±0.08	266±30	0.04±0.030	0.90-107	5.0-1.4	4.6-2.4
	Outlet	7.8±0.09	278±27	0.02±0.010	0.24-3.56		
B	Inlet	7.9±0.09	257±44	0.02±0.005	2.10-80.0	5.7-1.9	5.4-1.3
	Outlet	7.8±0.08	267±41	0.02±0.006	0.22-9.46		
C	Inlet	7.9±0.08	237±35	0.02±0.030	1.50-165	4.6-0.6	4.4-0
	Outlet	7.8±0.23	243±30	0.01±0.010	0.26-8.35		
D	Inlet	7.9±0.09	238±36	0.02±0.006	1.40-104	3.8-1.5	4.2-1.0
	Outlet	7.8±0.08	243±34	0.02±0.005	0.22-0.29		
Number of samples; a-128; b-22; σ-standard deviation							

The perusal of data in Table 6.2 does not indicate any significant change in pH of the inlet and outlet water. Electrical conductivity of outlet water was 3-4 % more than that of the inlet water. Though it is a marginal increase but the increase is consistent in all the columns. Mineralization of inlet water during column operation has been reported by Dash et al. (2010).

Change in UV-A, an indicator of natural organic matter (NOM), is not consistent in the four columns. The mean value of UV-A of outlet water from column-A and C is 50 % of the inlet water where as there is no change in absorbance in water from other two columns. This discrepancy may be due to very low UV-A of the feed water. Reduction in NOM during column operation and RBF has been reported by Worch et al. (2002) and Kolehmainen et al. (2009). Turbidity of inlet water was considerably reduced after filtration irrespective of the flow rates and initial turbidity. All the outlet water samples from all the columns had turbidity <2 NTU. Similar observations have been recorded by Mahvi et al. (2003), Jenkins et al. (2011). Profiles of total and fecal coliforms are presented in Figure 6.3 (a&b).

The outlet water from column-A was always observed to be devoid of fecal coliform bacteria. The total coliforms were noticed initially for about 10 days. Subsequently, samples did not respond to most probable number (MPN) test. Initial deposition of SS at water soil interface combined with low water velocity (0.14 cm/min) does not facilitate bacterial transport through the column-A (Syngouna and Chrysikopoulos. 2011). The performance of column-B was satisfactory for a short duration between 10-40 days i.e. the column yielded safe water for a few days. The removal of total coliform and fecal coliform in column C was ~ 2.1-3log and 1.6-1.9log respectively. The outlet water without total coliform was rarely observed in column D. Maximum removal of total coliform and fecal coliform was observed in column A. The probability of response to MPN test is shown in Figure 6.4. About 26% of the outlet water samples were positive to MPN test and none of the samples were positive to the fecal coliform test. The elimination of fecal coliform in column A is 100 % whereas the reduction in flow over a period of 72 days is only 35%. The improvement of the water quality in column A is the combined effect of filtration or straining of the particles and to high retention time (~ 5.5 h) because of low flow rate (Mahvi et al., 2003; Foppen and Schijven, 2006).

The filtered water from columns-B to D, always showed the presence of coliforms. It is reported that bacterial travel through the aquifer depends on groundwater flow velocity, survival rate, initial concentration, dilution and dispersion of groundwater, and the sensitivity of the method used to detect bacteria (Matthess and Pekeger 1988; Bitton, and Harvey. 1992; Sharma et al., 1985; Smith et al., 1985 Stevik et al., 1999). In the present scenario the flow velocity is only variable effecting coliform transport. Thus suggesting that high abstraction rate can cause the breakthrough of coliform bacteria into the well.

The suspended solid loading in columns-B, C and D was more than the column-A and the output water from all the columns had the same clarity (i.e. turbidity <2). Also discharge through the columns reduced from A to D. These observations, therefore, suggests that column-D is more clogged than column-C, B and A. Despite increased clogging, the flow velocity through columns-B, C and D is more than the velocity in column-A. The breakthrough in column-A did not take place even after 72 days of operation or 319 pore-volume of water (calculated on the basis of initial flow and initial porosity). Velocity as low as 0.23 cm/min in a clogged column-D was not able to completely immobilize bacteria by any of the mechanisms suggested by Tan et al. (1994) and Lawrence and Hendry (1996).

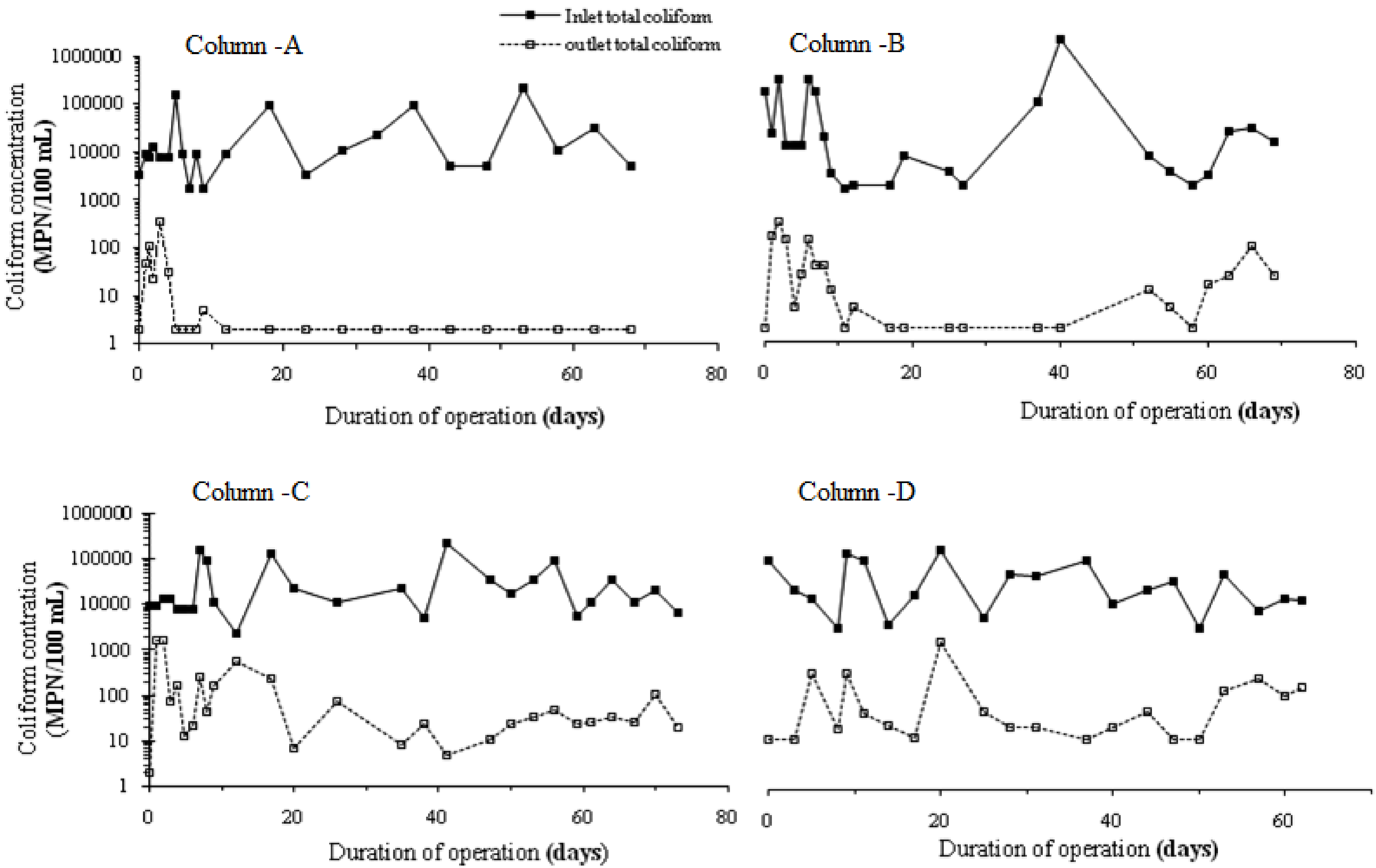


Figure 6.3 (a) Total coliform variation in columns A-D

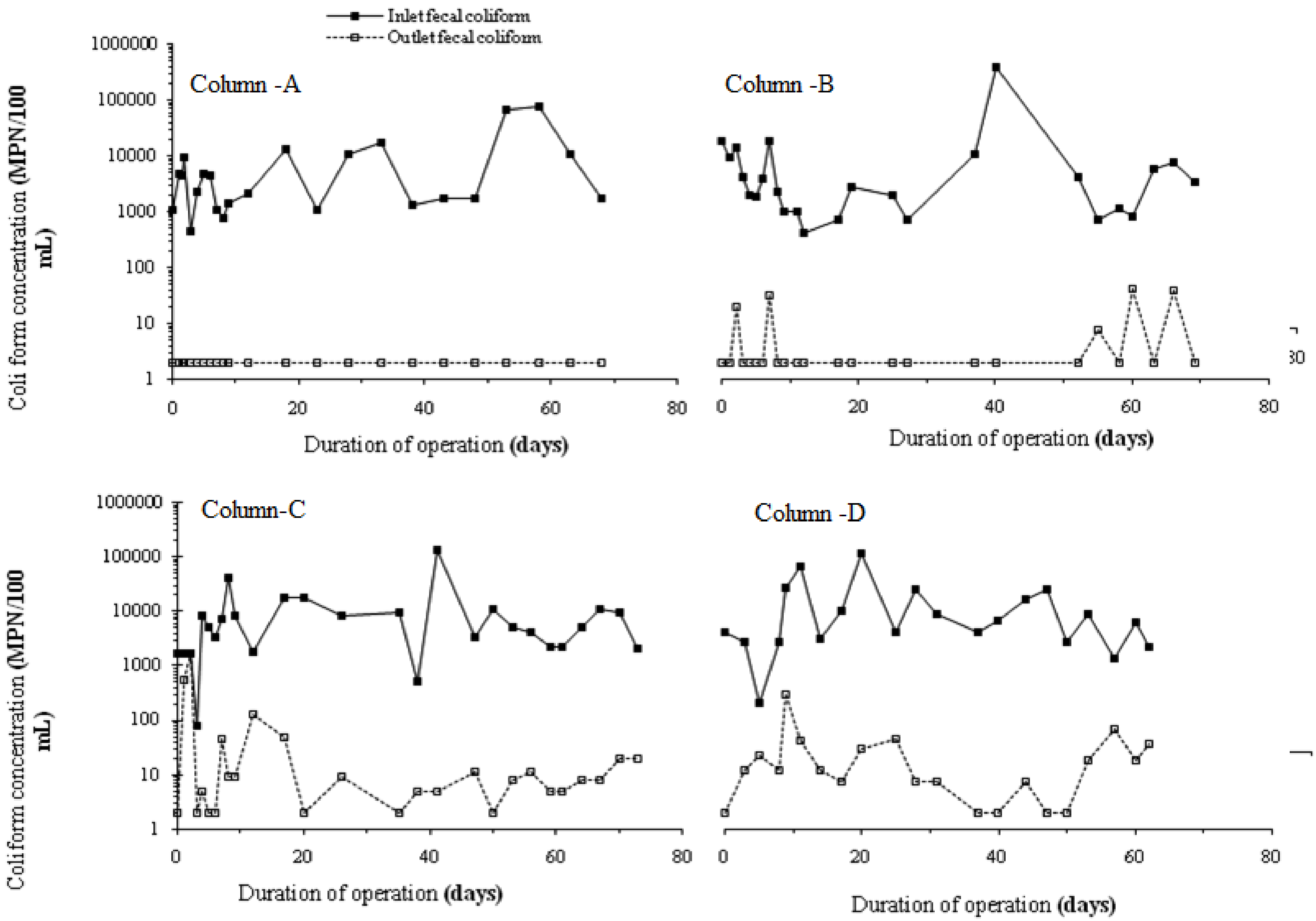


Figure 6.3(b) Fecal coliform variation in columns A-D

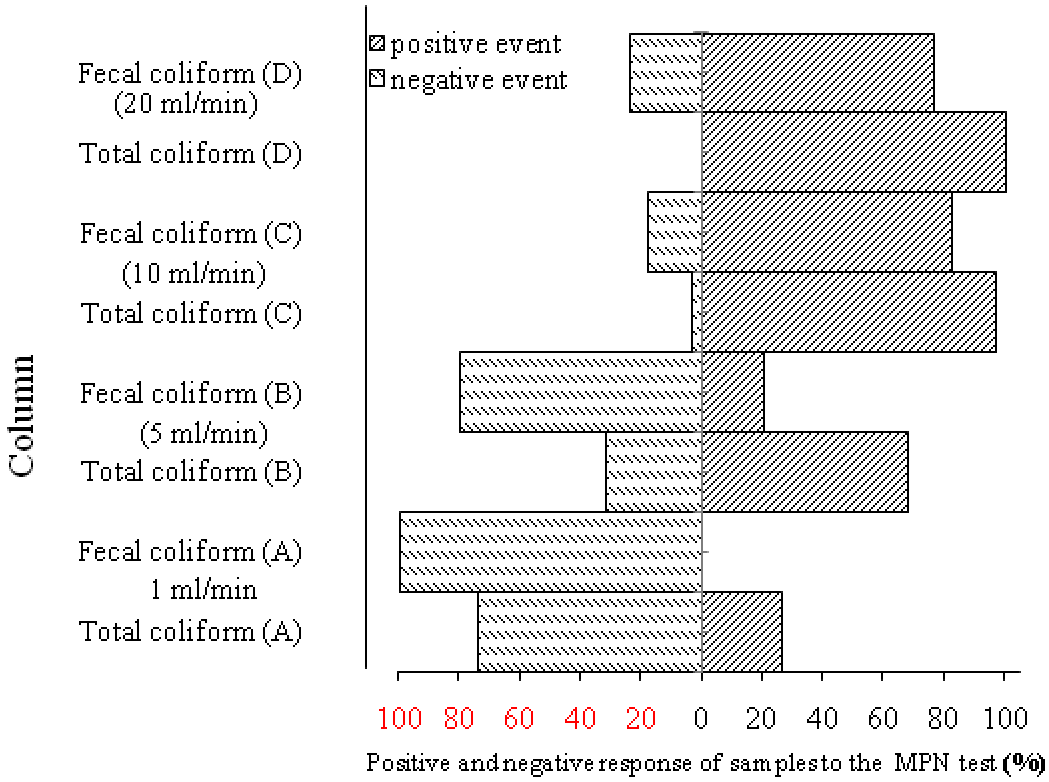


Figure 6.4 Distribution of coliform

The frequency of occurrence of total coliform in column-B was about 68% where as in column-C and D it increased up to 96-100% (Figure 6.4). The inference drawn from this study is that a flow velocity up to 0.14 cm/min is able to immobilize coliform through an aquifer of hydraulic conductivity of 0.68 cm/min. Stevik et al. (1999) found that chemical factors such as pH, cation exchange capacity and ionic strength, do not have significant effect on the transport of E. coli.

6.1.6 Mechanism of Bacterial Transport

The convective diffusion equation suggested by Yao et al., (1971) for the filtration of colloids in saturated media has been used to predicting the transport of microorganisms by Harvey and Garabedian (1991) and Murphy and Ginn (2000). This colloid filtration theory was also applied by Schijven et al. (2002) to calculate the removal of coliforms in and artificial recharge dune. Accordingly, the coliform removal at steady state with no dispersion, die off and negligible growth can be given by Eq. (6.3 & 6.3a).

$$v\left(\frac{dc}{dx}\right) + K_C = 0 \quad \text{..........} \quad 6.3$$

$$\frac{C}{C_o} = \exp(-\frac{K_C L}{v}) \quad \text{6.3a}$$

Where, C and C_0 are the concentrations of coliform in the outlet and inlet water respectively

K_c is the deposition coefficient,

v is the interstitial pore velocity,

L is the length of the column.

The deposition coefficient depends on the diameter of the collector (mean grain size), porosity, attachment efficiency and single-collector efficiency (Tien et al., 1979). Physical factors such as gravitational effect, van der Waals effect, peclet number, aspect ratio, Hamaker constant etc affect the single collector efficiency or bacterial deposition (Martin et al., 1992; Hijnen et al., 2005 and Schijven et al., 2002). Bacterial deposition coefficient, K_c for columns-A, B, C & D has been computed at the start and at the end of the experiment. Values are given in Table 6.3.

The deposition coefficient has been found to linearly vary with velocity (Figure 6). Accordingly, the removal should increase with increase in velocity. However removal is a cumulative effect of K_c and L/v (Eq.6.3). From the data (Table 6.3) removal factor decreases

Table 6.3 Deposition constant, K_c and Removal factor of bacteria

Particular		**Deposition coefficient, K_c x10^{-3} (sec^{-1})**		**Removal factor, ($\frac{K_C L}{v}$)**	
		Bacteria coliforms		**Bacteria coliforms**	
		Before[1]	After[2]	Before[1]	After[2]
Column	A	0.33	0.37	9.31	7.20
	B	0.48	1	5.67	7.21
	C	1.3	1.9	5.12	7.29
	D	2.2	4.5	5.27	5.55
1 at start of the experiment; 2 before terminating the experiment i.e. after 72 days; Matrix for calculating deposition coefficient is given in appendix in CD-ROM					

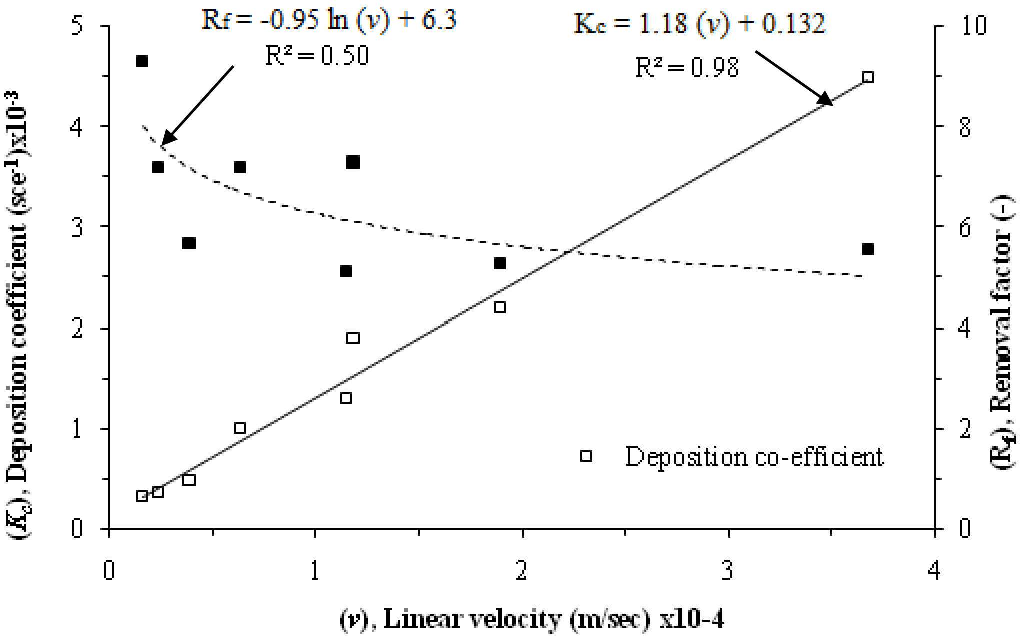


Figure 6.5 Correlation between linear velocity (v) and (i) deposition coefficient (K_c) (ii) removal factor (R_f)

with increase in velocity. The model (Eq.6.3a) has primarily been developed on the basis of average concentration of coliform in the inlet and outlet water. Therefore the temporal fluctuation, are not accounted. The mean size of the single collector changes with duration of operation due to deposition of the suspended solids in the inlet water and the effect of this has also not been considered in the model.

6.1.7 Summary

Based on the variable flow rates laboratory experiment, it is concluded that the column operated at high flow rate has high risk of pathogen breakthrough although it is heavily clogged. The following are noteworthy:

- High abstraction rate will clog the filter and reduce the discharge up to 91%. Whereas in low flow rate system the reduction in flow is only 35%. Possibility of bacterial breakthrough is likely to increase during flood condition. However shear stress and self-cleaning during high flow is not considered.
- All the outlet water samples from all the columns had turbidity <2 NTU
- The elimination of fecal coliform in low flow rate is 100 %; the improvement in water quality is due to the combined effect of filtration or straining of the particles and to high retention time (~ 5.5 h).

- High abstraction rate (similar to column-D) may not be able to completely immobilize bacteria by any of the mechanisms suggested by Marlow et al. (1991), Lawrence and Hendry, (1996).

6.2 EFFECT OF FILTER MATERIALS ON THE QUALITY OF FILTERED WATER

In this set of experiments four columns (C-I to C-IV) were packed with different filter materials such as glass beads, sand from artificial recharge basin, aquifer material from the Elbe river bed etc. The experimental set up was placed at the premises of the port company *Sächsische Binnenhäfen Oberelbe Gmbh*, Flügelweg, Dresden, Germany (Figure 6.6 and Figure A11 of appendices A). The procedures related to the preparation of the experiment are given in section 3.13.2. Column studies were performed over a period of 31 days under ambient conditions.

6.2.1 Grain size analysis and Column Packing

The results of grain size analysis along with uniformity coefficient for the materials used in the columns are given in Table 6.4. The sieve test results showed that the sand from the artificial recharge basin has <1% silt. The sand was coarser than the other two materials (except the glass beads). The material in column-III has 12% medium sand, 24% gravel, 50% coarse sand, and remaining 14% cobbles of size larger than 10 mm. An attempt was made to simulate river bed conditions in column-IV. The packing of columns with different filter media is pictorially presented in Table 6.4.

Column-III, filled with mixed fine sand to medium gravel represents the monsoon situation (erosive conditions) where the scouring of the riverbed has taken place. Column-IV (river bed with fine loamy sediment) represents the situation of natural riverbed during post-monsoon (depositing conditions), where all the fine are deposited on the riverbed. The grain size distribution is similar to many RBF sites in Haridwar (Dash et al., 2010) upper Rhine valley (Schubert. 2002 & 2006) and at Satpuli (Ronghang et al., 2014).

6.2.2. Column Operation

The columns packed with four different sizes of filter materials were fed with the Elbe river water. These columns were operated in two phases. In the first phase feed water level was maintained at 7.2 m above the river water level. After thirteen days of continuous operation columns C-III and C-IV were clogged. At this point of time the feed tank was raised (0.56 m higher from previous level) to allow water to flow through the clogged columns.

During column operation the observed increase in head loss and decrease in hydraulic conductivity are due to the deposition of fine suspended solids in the feed water. In phase II the flow increased in all the columns. The head loss, however, increased with column operation irrespective of phase.

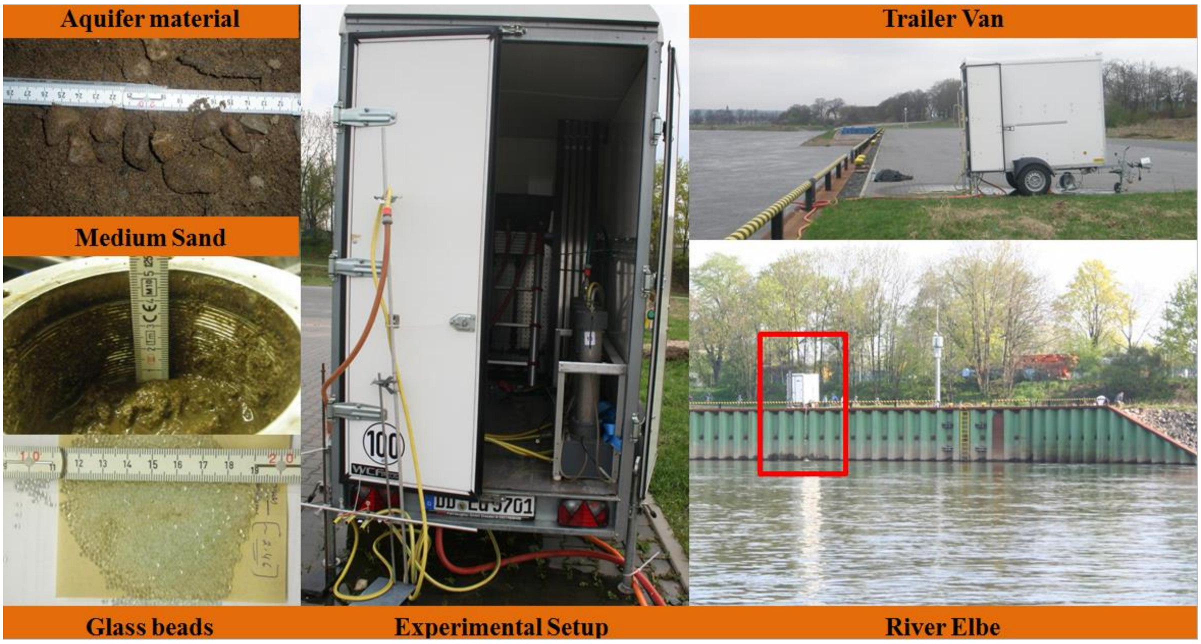


Figure 6.6 Experimental set up of the column test at Dresden

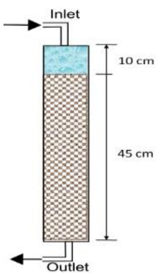
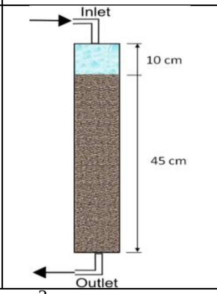
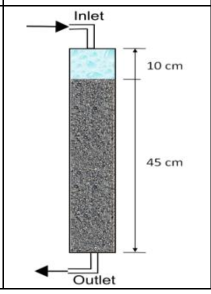
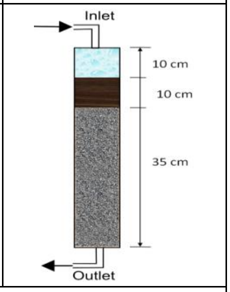
6.2.3 Variation of Hydraulic Conductivity

Manometer reading at constant water head was used for calculating the hydraulic gradient (ΔH/L) and saturated hydraulic conductivity (K) of the filter material by Darcy's laws (Eq.3.6). Variation in hydraulic conductivity with days of column operation is presented in Figure 6.8. Initial and final values in both the phases are tabulated in Table 6.5. The perusal of conductivity data in Figure 6.6 reveals the following:

- Hydraulic conductivity (k) of glass beads filled (C-I) was reduced by about 95% in the first phase. Reduction in K of the material in other columns was less than the C-I
- In the beginning of the second phase hydraulic conductivity was increased in columns C-I, C-III and C-IV.

The change in hydraulic conductivity is due to clogging of the filter media or deposition of fine suspended solids at the water-solid interphase (Mays and Hunt, 2005, Siriwardene, 2007). The change in K and head loss is characteristics of the material inside the columns. C-I and C-II are packed with coarse material. The solids are likely to penetrate. The difference in response of these two columns to the increasing head is due to the difference in the effective size, uniformity coefficient of the material in C-I and C-II (Table 6.4).

Table 6.4 Summary of grain size distribution of filter materials

Parameters	Column I	Column II	Column III	Column IV
Type of materials	Glass beads	Sand from artificial recharge site	Sub surface river bed material	Sub surface at the bottom and fines above[1,2]
Grain size distribution range (mm)	1.7-2.1	0.2-2.0	0.06-20	0.06-20
Characteristic of the material[3]				
Effective size, d_{10}	1.74	0.45	0.28	0.26
d_{30}	1.80	0.64	0.45	0.43
d_{50}	1.90	0.70	0.65	0.50
d_{60}	2.01	0.80	0.85	0.82
d_{90}	2.09	1.40	10.5	10.4
Uniformity coefficient, C_u	1.15	1.78	2.83	2.98
Coefficient of gradation, C_c	0.93	1.14	0.79	0.94
% Medium gravel (8-10mm)	-	-	20	19.1
% Fine gravel (2-8 mm)	-	-	10	11.0
% Coarse sand (0.4-2 mm)	45	90	44	41.3
% Fine sand (0.08-0.4 mm)	55	10	26	27.8
% Silt (0.005-0.08)	-	-	-	0.89
Schematic presentation of columns				

[1]Value are obtained based on weighted average;[2]the column has a layer of 10 cm black color fine loamy deposit from the river shore; [3]Grain sizes distribution are given in CD-ROM

The uniformity coefficient of spherical glass beads of nearly uniform size packed in column, C-I, is close to one. The aquifer material in other columns-C-II to C-IV is irregular in shape and non-uniform in size (Figure 6.7).

The effective size of the material in C-II to C-IV is less than that in C-I. The fine solids in the feed water are removed by straining at the interface in columns II to IV whereas in C-I these may be entrapped in the pores in the column. On increasing the flow rate in the second phase of operation, entangled particles are dislodged to increase k (Figure 6.8). The increase in conductivity in C-III and C-IV is due to the removal of fines from the column.

Table 6.5 Operation of columns packed with different filter media

Operational phase*	**Type of material used**	**Operational Conditions**	**Discharge (cm^3/min)**	**Head loss(m)**	**Hydraulic conductivity(m/s)**
Phase –I	Glass beads (C-I)	S	1036	0.09	1.1×10^{-2}
		E	102.9	0.22	4.0×10^{-4}
Phase –II		S	1200	0.57	2.0×10^{-3}
		E	46.5	1.6	2.7×10^{-5}
Phase –I	Sand from Artificial Recharge (C-II)	S	54.5	1.29	4.0×10^{-5}
		E	31.1	1.39	2.1×10^{-5}
Phase –II		S	18.9	1.50	1.8×10^{-5}
		E	3.2	1.87	1.6×10^{-6}
Phase –I	Aquifer materials (C-III)	S	2.2	0.93	2.6×10^{-6}
		E	1.3	1.12	1.0×10^{-6}
Phase –II		S	7.1	1.20	5.4×10^{-6}
		E	1.7	1.80	9.2×10^{-7}
Phase –I	Aquifer material + Fine loamy sediment (C-IV)	S	0.75	0.95	7.6×10^{-7}
		E	0.31	1.29	2.3×10^{-7}
Phase –II		S	22.6	1.76	1.2×10^{-5}
		E	0.79	1.86	3.5×10^{-7}

* Phase-I from day 0 to 13 and Phase- II from day 14 to 31; S-Start and E- End

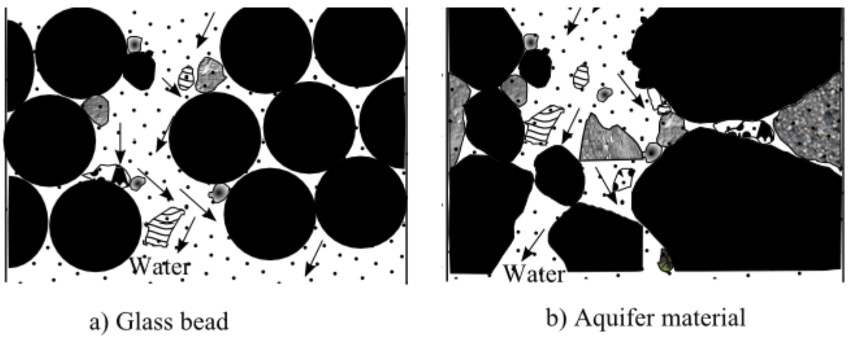


Figure 6.7 Schematics of media (a) Glass beads (b) Aquifer material

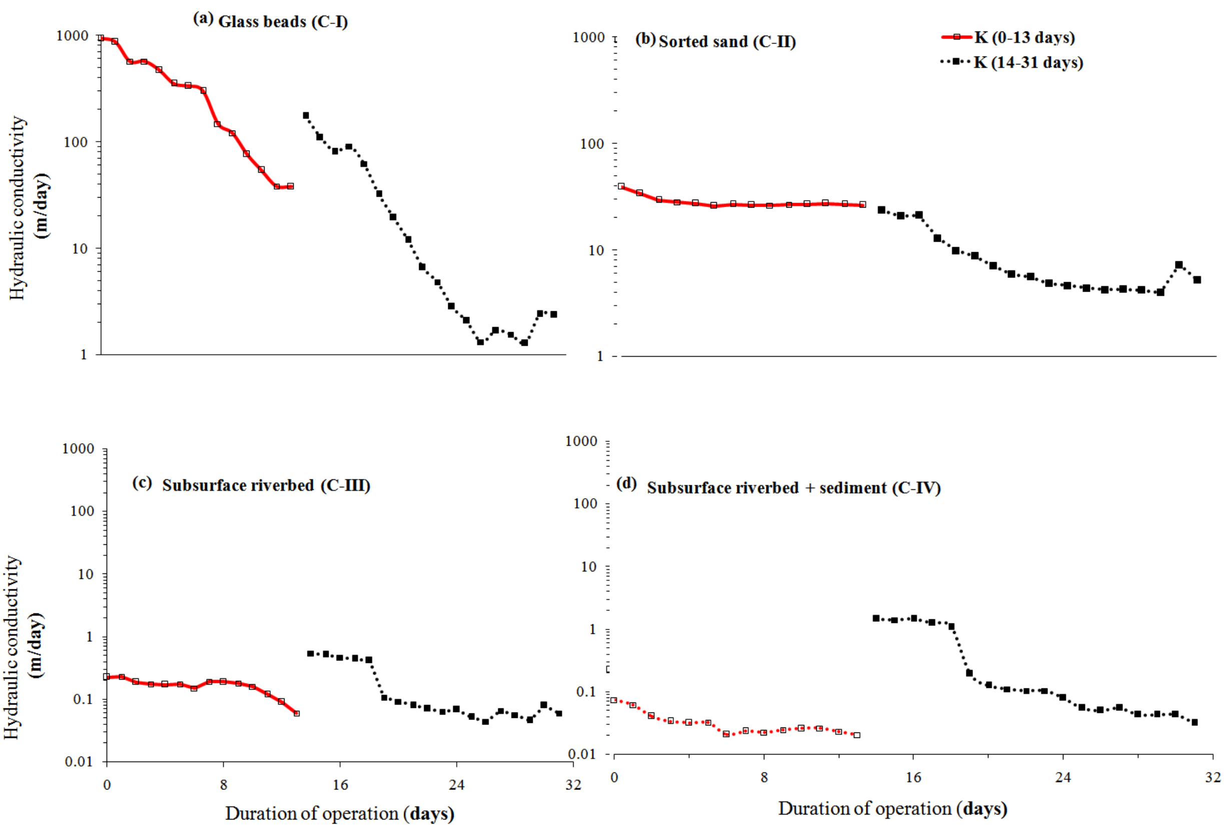


Figure 6.8 Change in hydraulic conductivity in columns packed with different materials.

6.2.4 Change in water quality

The initial effective size of the material in these columns is less than the C-II and C-I. The observations therefore demonstrate that filters of coarse material are clogged and de-clogged with ease as compared to the filters with fine material. Initially the head loss in C-I was 9 cm and flow rate is 1036 mL/min. Similar observation has been recorded in another set of column experiments at IIT Roorkee (Section 6.1). The maximum clogging in Column-D operated at 20 mL/min was noticed and minimum in the Column-A operated at 1 mL/min.

The electrical conductivity, turbidity and coliform (MPN/100 mL) of the feed water and filtered water were daily monitored.

6.2.4.1 Electrical conductivity

The daily variations in electrical conductivity (EC) of the inlet (*Elbe* river) water and outlet (filtrate) water from the columns are shown in Figure 6.9. The conductivity of the water filtered from C-I and C-II did not change during first phase of operation and in the second phase there was a marginal increase. It may be due to the leaching from the material deposited in Phase–I. The initial high EC of the filtrate from C-IV may be due to mineral dissolution present in the riverbed material. Towards the end of the column operation initially increased EC stabilized to the EC of inlet water.

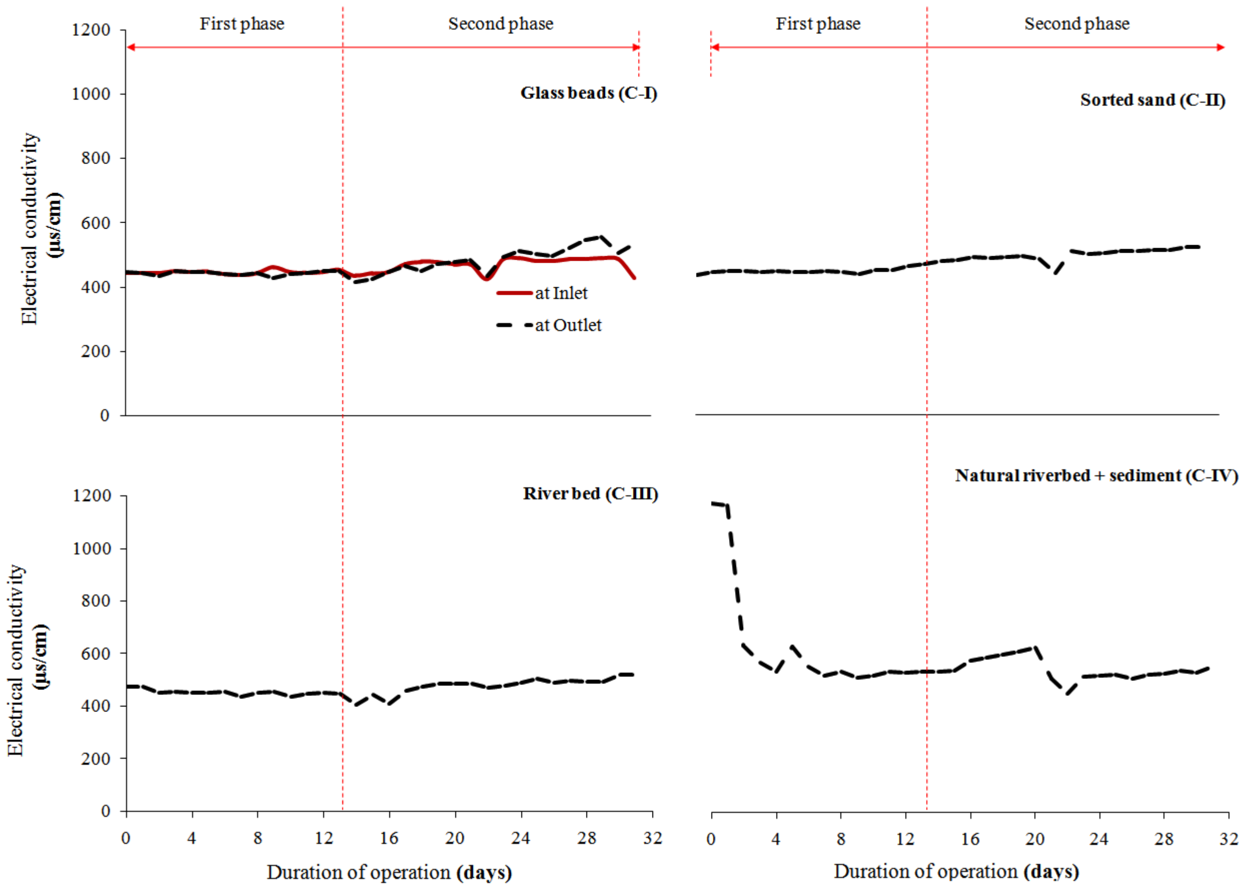


Figure 6.9 Variation in electrical conductivity

6.2.4.2 Turbidity

The variation in turbidity of the water filtered from C-II, C-III and C-IV is the same (Figure 6.10) the different behaviour of C-I is due the difference in discharge or difference in hydraulic conductivity After 10 days, the turbidity of filtered water from all the columns was same. The turbidity of the C-I water again increased in Phase-II due to the increased discharge. These irregular patterns of turbidity are due to the clogging and de-clogging processes. In other columns increase in discharge was not sufficient enough to dislodge initially deposited suspended solids or de-clog the clogged filter. Such an event was also reported by Kretzschmar et al. (1977). After a sudden increase, the turbidity thereafter consistently decreased (Gao et al. (2012). Thus, by changing the flow condition, the pseudo-equilibrium condition may be disturbed in coarser and homogeneous material like glass beads. The perusal of data on k in

Figure 6.8 indicates increase in hydraulic conductivity in C-III and C-IV in the beginning of the second phase of operation. This could be due to the removal of fines on increasing the flow rate to around 7 and 22 mL/min (Table 6.5). The turbidity of the filtered water however did not increase.

Apparently, it means that the flood like situation can collapse the clogging layer formed in the riverbed and breakthrough of pollutants may occur in coarser materials like glass beads (representing the bed material of a river in its upper course, e.g. in mountainous areas) but in riverbed system of the lower course of the river can withstand the effect of high infiltration rates.

6.2.4.3 Total coliform and *E.coli*

The range of total coliform and *E. coli* and their average values in the inflow (Elbe River water) and outflow of the columns along with their removal efficiency are given in Table 6.6. Experimental observations made over the duration of 31-days period are given in Figure 6.11.

The average removal efficiency of *E. coli* in columns C-I, C-II, C-III and C-IV was around 83.6%, 98.9%, 96.9%, and 99.9%, respectively. The flow rates through the columns that depend on the media are important for the elimination of both total coliform and *E.coli* from the inlet water. The coarser and homogenous material like glass beads and sand from artificial recharge basin has a removal efficiency less than the natural material like in a riverbed system (riverbed + loamy with fine sediment)

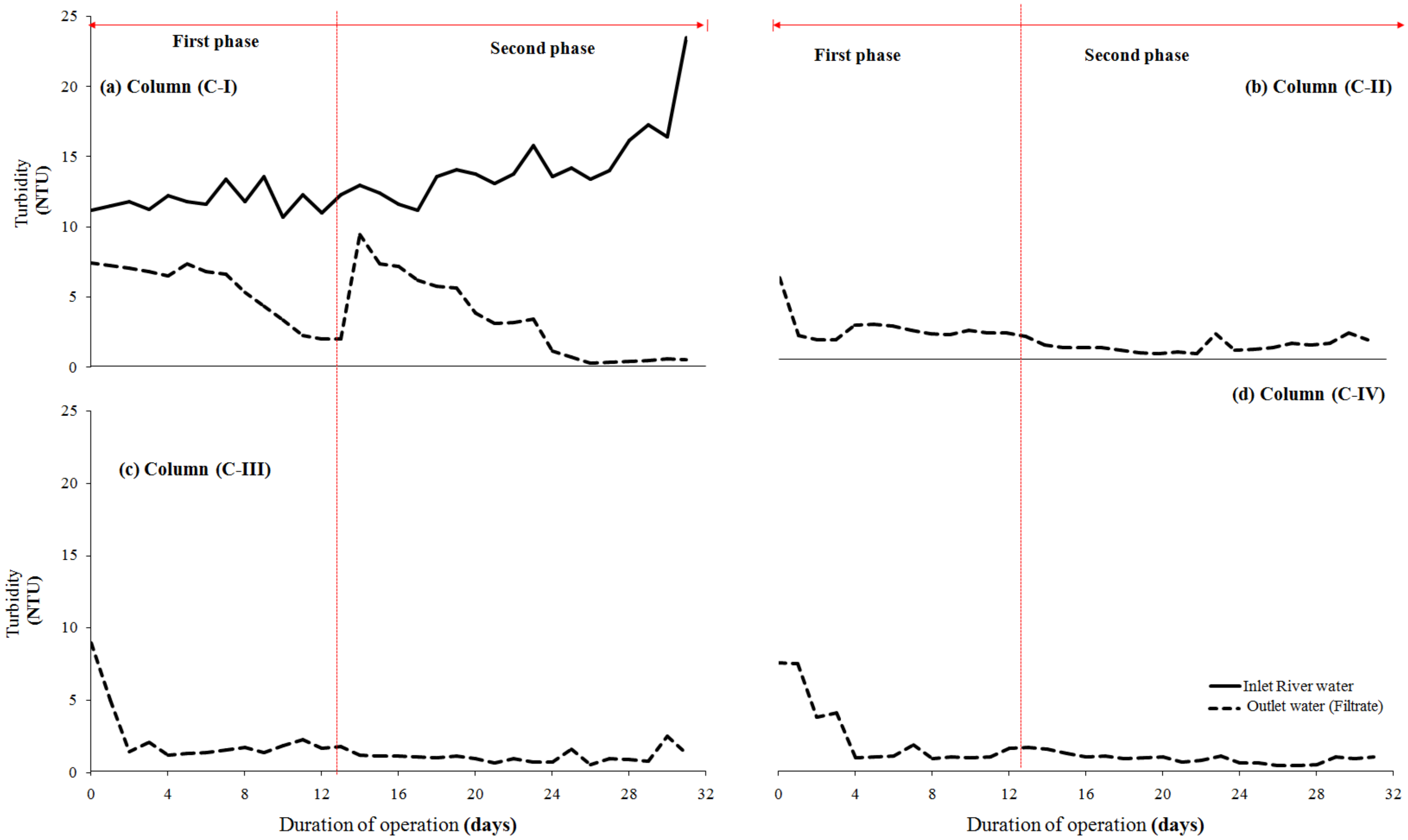


Figure 6.10 Variation in turbidity of various filter materials

Table 6.6 Removal of coliform and *E.coli* during filtration.

Parameter	Elbe river	Glass beads (Column I)	Sorted sand (Column II)	River bed (column III)	Riverbed+ fine sediment (Column IV)
Total coliform (MPN/100mL)	1112-14163 -5803	86.2-4884 -1017	62.4-866.4 -295	<1-200.5 -24	<1-323 -64
Log removal of TC with reference to Elbe river water	-	0.3-2.1 -0.9	0.2-1.9 -1.3	1.2->3.7 (>3.5)	0.9->4.2 -2.9
E. coli counts (MPN/100 ml)	175-3654 (1087)	4.1-845 -208	1-228 -52	<1- 88.5 -13	<1- 5.3 (<1)
Log removal of *E. coli* with reference to Elbe river water	-	0.03-1.9 -1	0.9-2.9 -1.8	0.6 – >4.2 (>2.5)	2.3 – >3.6 (>2.9)
n = 11 for each column and Elbe river water					

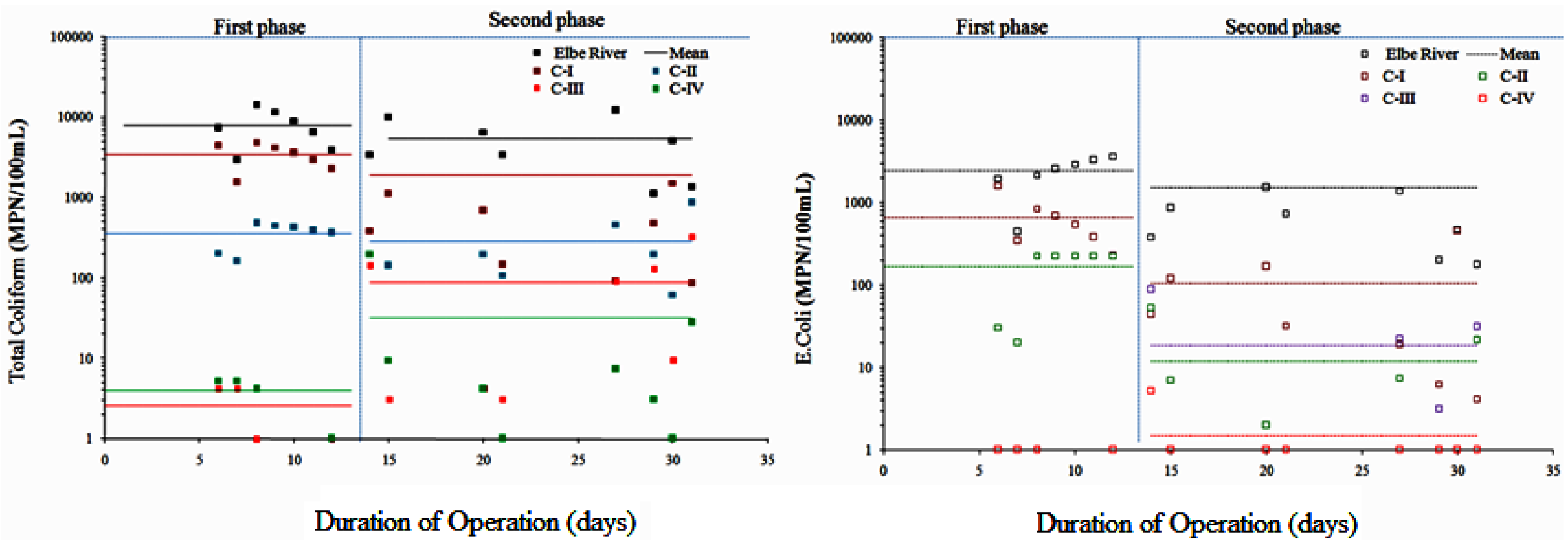


Figure 6.11 Coliform removals in different filter materials

The clogging layer in C-III and C-IV protects against the breakthrough and increases the residence time thereby enhancing the removal of coliforms. Columns packed with fine aquifer material operated at low flow rate or long residence time results in a better bacterial removal due to straining, attachment, decay or inactivation caused by eventual entrapment in dead-end pores (Baumgarten et al., 2011). *E. coli* quite often was less than the detection limit of 1MPN/100 mL. Total coliform and *E.coli* in the filtered water from C-I and C-II continue to decrease even in the second phase of operation. However, in the initial stages of the second phase of column operation, breakthrough of bacteria is noticed in C-III and C-IV. This is probably due to the removal of fines and increase in flow rate to 7 and 22 mL/min from 1.7 and 0.31 mL/min respectively. The residence time of 1-2 days was considerably reduced and bacterial entrapment was adversely affected.

6.2.5 Summary

These investigations suggest that significant log removal of total coliforms and *E. coli* can be achieved within a short flow path of 0.45 m and residence times of 1-2 days and even less. Also, the riverbed after high flooding (scour riverbed) can reduce coliform by up to 4.2 log and *E.Coli* by 3.9 log. The information on the removal of turbidity and bacteria indicate the potential of RBF as a shield against diseases caused by pathogens in drinking water. Breakthrough of bacteria in the initial stages of the flood, however, cannot be ruled out. Wett et al., 2002 have reported that the riverbed acts as a barrier to the flood wave that transports pathogens from the river to a RBF well. Significant removal of coliforms and *E.Coli* was observed within the first few meters of the flow path.

The hydraulic conductivity and infiltration rate decrease with the time of column operation due to clogging, which eventually improves bacterial removal efficiency. Clogging increases with increase in flow rate due to high loading of solids. Clogging depends on the size and shape of the material used.

It is recommended to use flow rate/infiltration rate as a tool to predict the clogging processes, if the grain size and shape factor is known. It also suggests that there is a benefit of having a two layered system instead of one layer. Also, filtration is more sustainable at low flow rate i.e. at a velocity around 0.1 cm/min (C-IV).

CHAPTER 7
CONCLUSION AND RECOMMENDATIONS

7.1 CONCLUSION

The objective of the research was to assess riverbank filtration in the hilly areas of Uttarakhand. Investigations were carried out at four sites located at an altitude of 551-769 m above the MSL in Uttarakhand. The production wells at these sites were at a distance of 50-165 m from the river in non-monsoon whereas wells were close to seven meters from the river in the monsoon. Out of four sites, the production wells (PW) at two locations namely Srinagar (551m above MSL) and Satpuli (580 m above MSL) yielded about 70-88% bank filtrate. The production well at Karnaprayag (769 m above MSL) mostly produced ground water. The production well water at Agastyamuni (AGPW; 733 m above MSL) was more than 65% handpump or groundwater. The percent of the bank filtrate in the PW water is the average of the monthly data collected during the study period. The aquifer characteristics at four sites are nearly the same. Altitude appears to be one of the factors that influence the RBF capacity to deliver bank filtrate. The observation is in agreement with the statement made by Grischek and Ray (2009). Also, at higher altitude due to moderate to steep gradient, the recharge water disperses down gradient and results in lower recovery efficiency of the aquifer recharge (Dillon and Jimenez 2008). The yield of the production wells at Agastyamuni and Karnaprayag is less than the yield at Srinagar and Satpuli.

The quality of the water from the hand pumps (ground water) varies widely in the vicinity of the production wells. The aquifer characteristics in Srinagar were also found to change at a short distance of about 100 m. The hand pump water identified as groundwater is the water from the unconfined aquifer. At Srinagar water from one of the hand pumps (SNHP-31) was similar to the river water. Also, the water from the SNPW-1 was chemically similar to the hand pump water but isotopically more close the river water. A few leaching experiments were done with soil and rocks samples. The results obtained suggest the mineralization of the river water as it travels through the aquifer.

The quality of the PW water except at Srinagar is in conformity with the drinking water quality standards (BIS 10500:2012). Nitrate in Srinagar is more than the prescribed value of 45 mg/L.

Besides the field investigations, a few column runs were carried out to understand the process and criteria for sustainable bank filtration. The inferences drawn from the column experiments are as under:

- High abstraction rate (i.e. 20 mL/min) clogs the filter and reduces the discharge up to 91%. However, the reduction in discharge is ~ 35% in case of low flow system of 1 mL/min.
- The column operated at high flow rate has a high risk of pathogen breakthrough although it is heavily clogged.
- Clogging increases with increase in flow rate due to high loading of solids.
- Clogging depends on the size and shape of the material used as well as on the source water quality.
- The elimination of fecal coliform at low flow (0.65 m/d) is 100 %.
- Flow rate/infiltration rate can be used as a tool to predict the clogging processes if the grain size and shape factor is known.
- From the column experiments it was found that the two or multilayered aquifer is more efficient in removing turbidity and coliform than the mono layer aquifer.
- Filtration is sustainable at low flow rate i.e. at a velocity around 0.1 cm/min.
- The high abstraction rate (similar to column-D) is not able to completely immobilize bacteria by any of the suggested mechanisms such as gravitational effect, van der Waals effect, peclet number, aspect ratio, Hamaker constant, etc.

The high flow conditions refer to the flood conditions. Observations from the column experiment suggest that the (i) riverbed after high flooding (scoured riverbed) can reduce coliform and (ii) RBF has a potential to act as a shield against diseases in drinking water. The breakthrough of bacteria in the initial stages of the flood, however, cannot be ruled out.

7.2 LIMITATIONS AND FUTURE RESEARCH

Monitoring of RBF schemes at different sites was done for fourteen months. The stable isotope data was not sufficient to highlight the seasonal variation in the proportion of the bank filtrate in the production well water. The data was also inadequate to determine the travel time. More work is required to understand hydro-geochemistry of the location at Srinagar especially in reference to nitrate in water. A few application and research that can be taken up are given below:

i. A battery of wells along the river will not only cater for future increases in demand but will also increase the proportion of bank filtrate abstracted by the wells.

ii. More frequent monitoring especially of the river conditions (discharge), drawdown and water quality of the RBF wells is necessary to study the behavior of the wells with river stage.
iii. It would be beneficial to analyze stable isotopes for more than a year to determine the seasonal variation in the proportion of the bank filtrate as well as travel time.
iv. Development of the groundwater flow and transport model for the RBF site in the hilly region can strengthen the speculation.

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APPENDICES (A): FIGURES

Figure A1 Site exploration (**a)** Satpuli **(b)** Karnaprayag **(c)** Agastyamuni (**d)** Water level measuring **(e)** On-site measurement of water quality from HP

Figure A2 Activities in the RBF site **(a)** Aquifer material collection from bore hole **(b)** Filter assemble with pea gravel **(c)** Riverbed material collection (**d)** Peizometric water level measuring **(e)** Preparation of pumping test

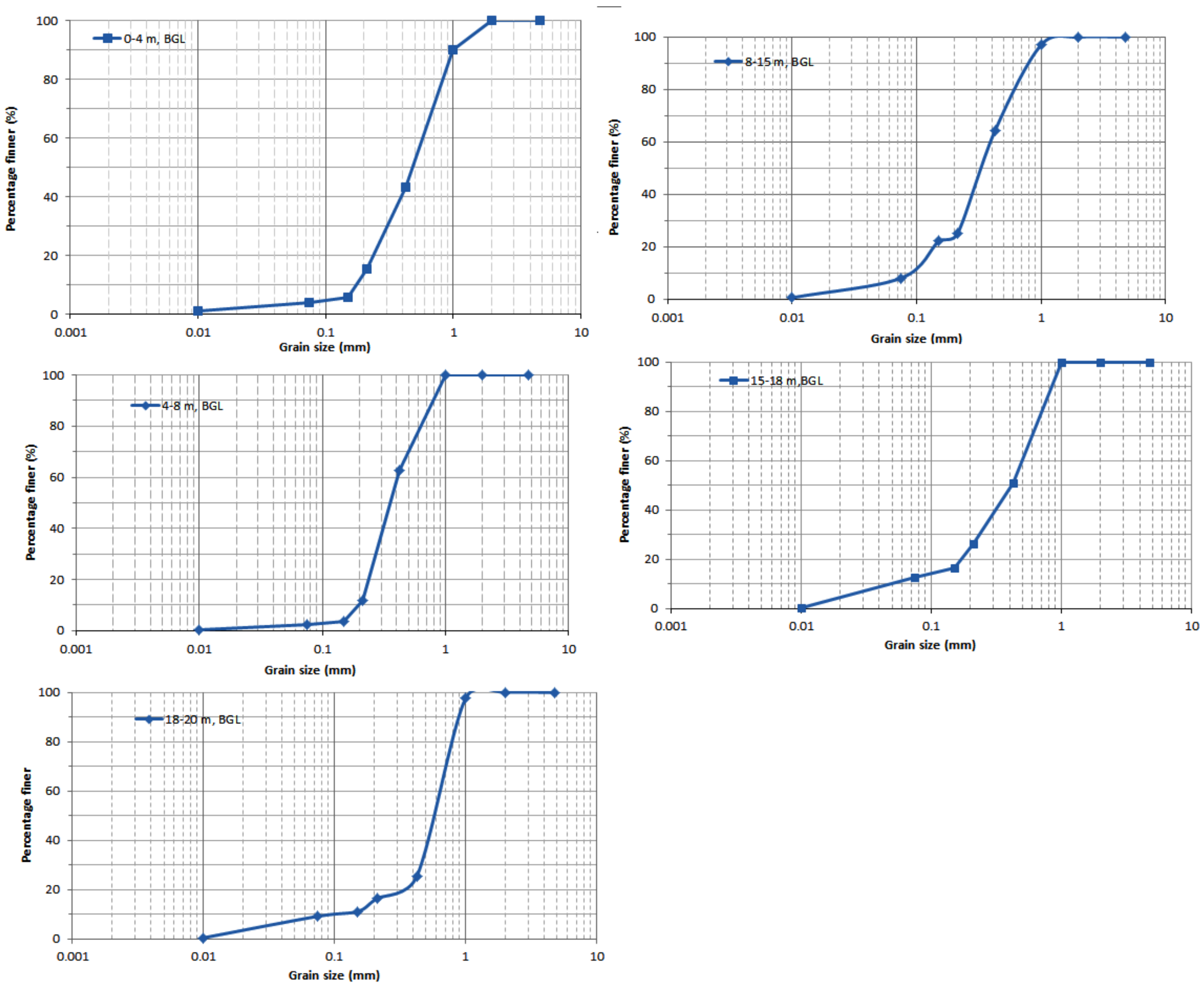


Figure A3 Grain sizes distribution of SNPW-2

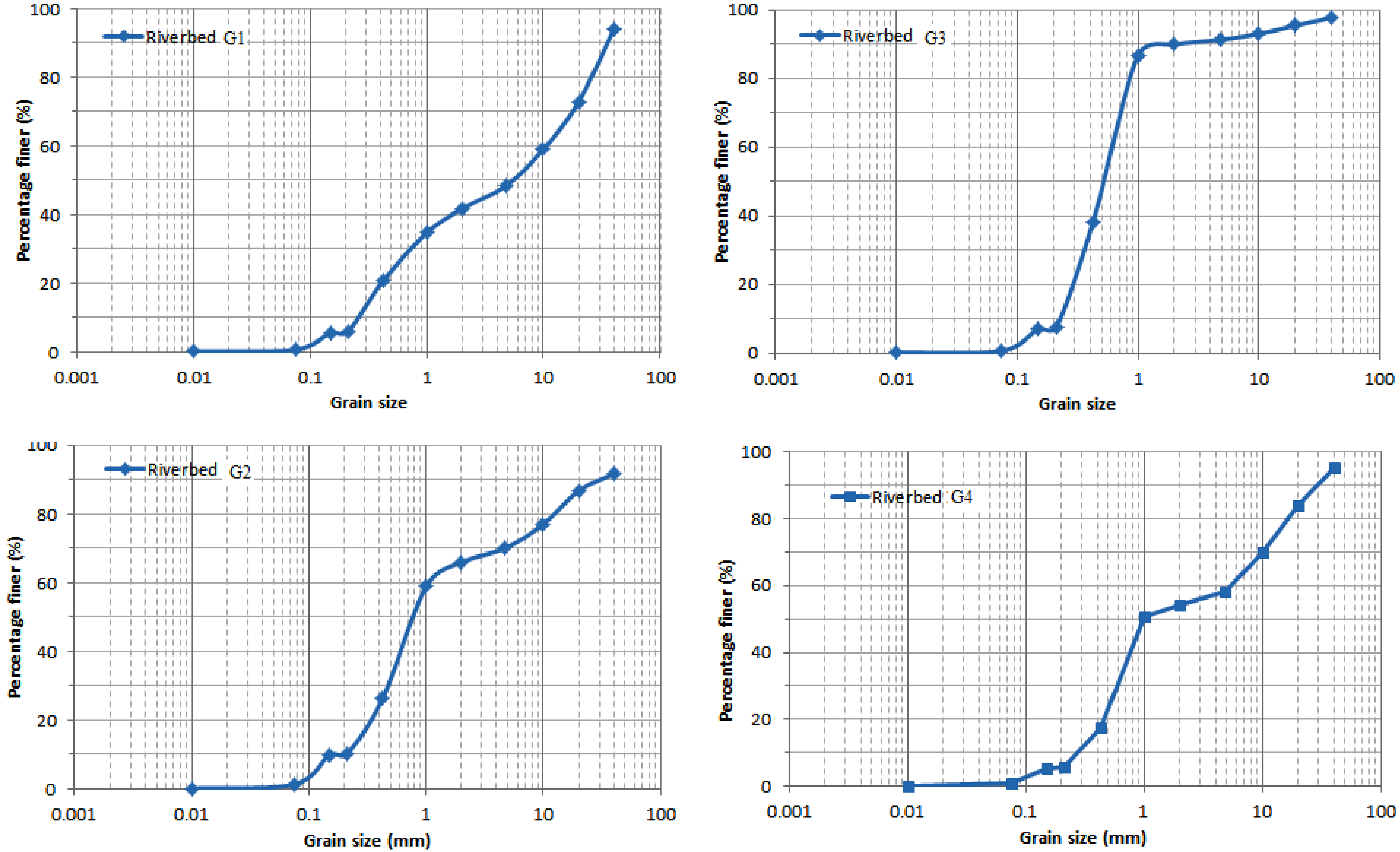
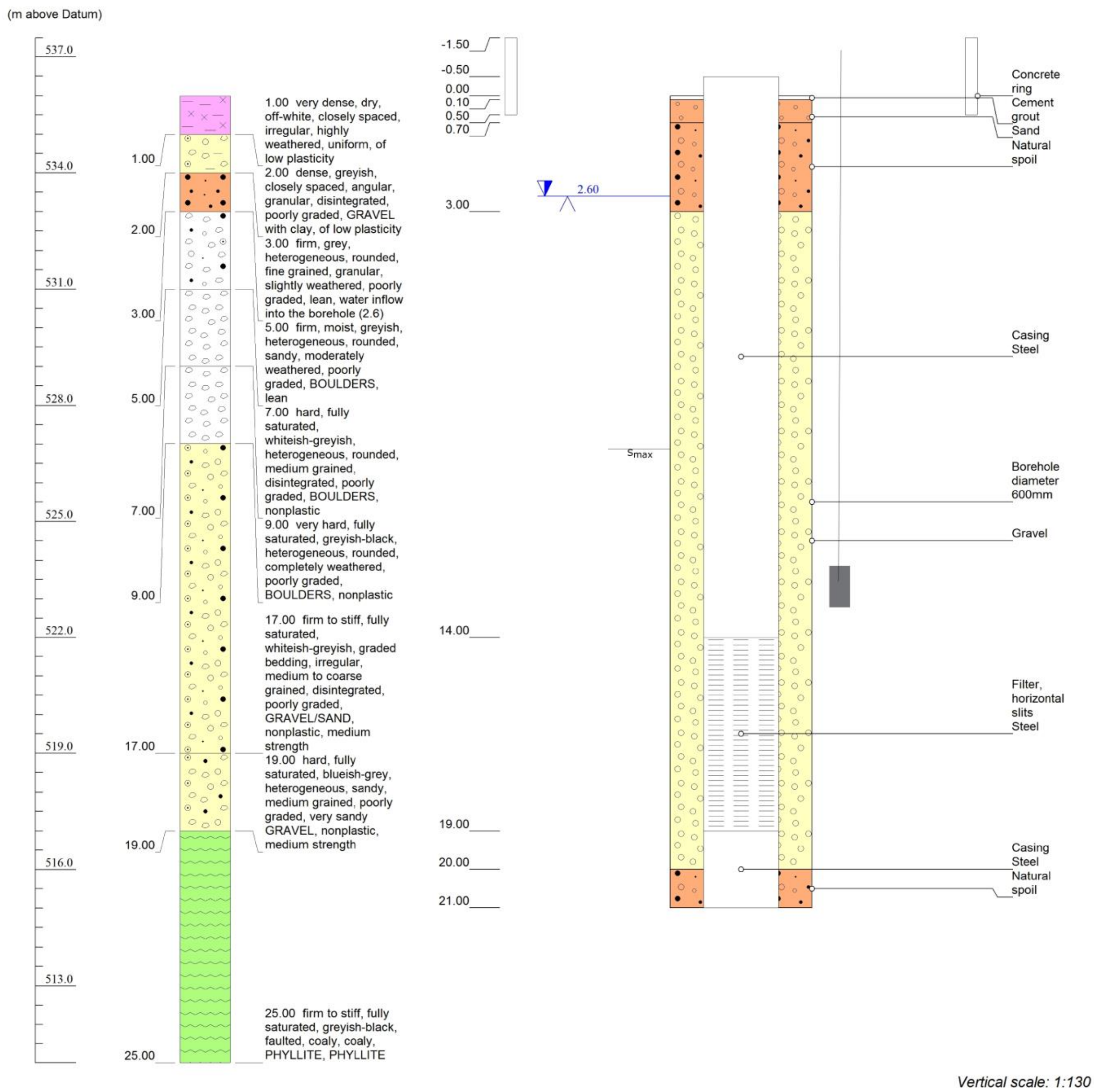


Figure A4 Grain sizes distribution of Alaknanda Riverbed materials (SNRB)



Project:	**New RBF well field site**		
Location point:	**Srinagar Nagar Pallika, Srinagar (UK)**		
Client:	Uttarakhand Jal Santhan	Easting (X):	78
Author:	Balaji Drilling	Northing (Y):	30
Checked by:	Er.L.C.Adalakha	Ground level:	536.00 m above Datum
Date:	08/31/2011	End depth:	22.00 m below ground

Figure A5 Bore log and well assembly of production well (SNPW-2) at Srinagar

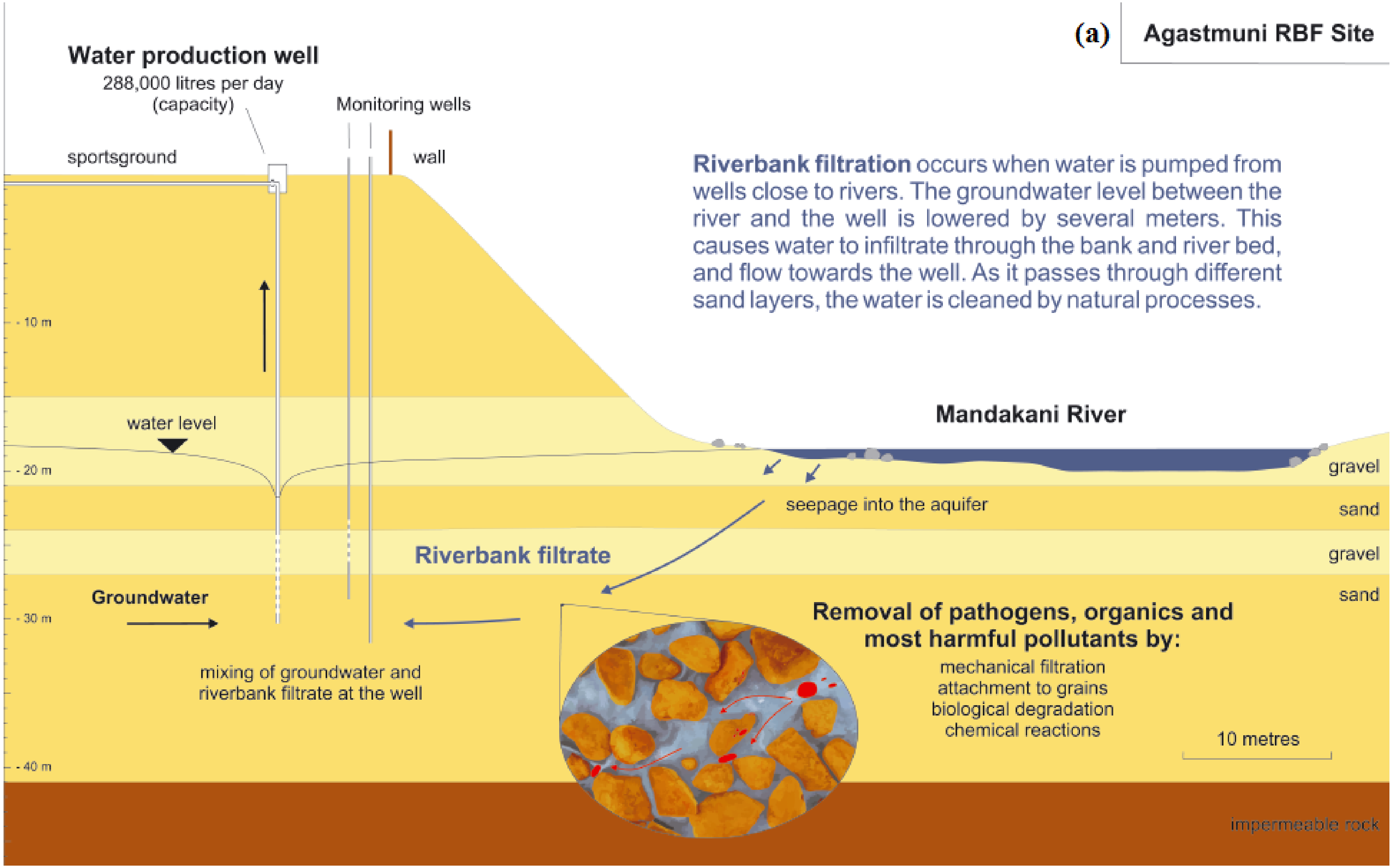


Figure A6 Aquifer profile of the RBF site at **(a)** Agastyamuni

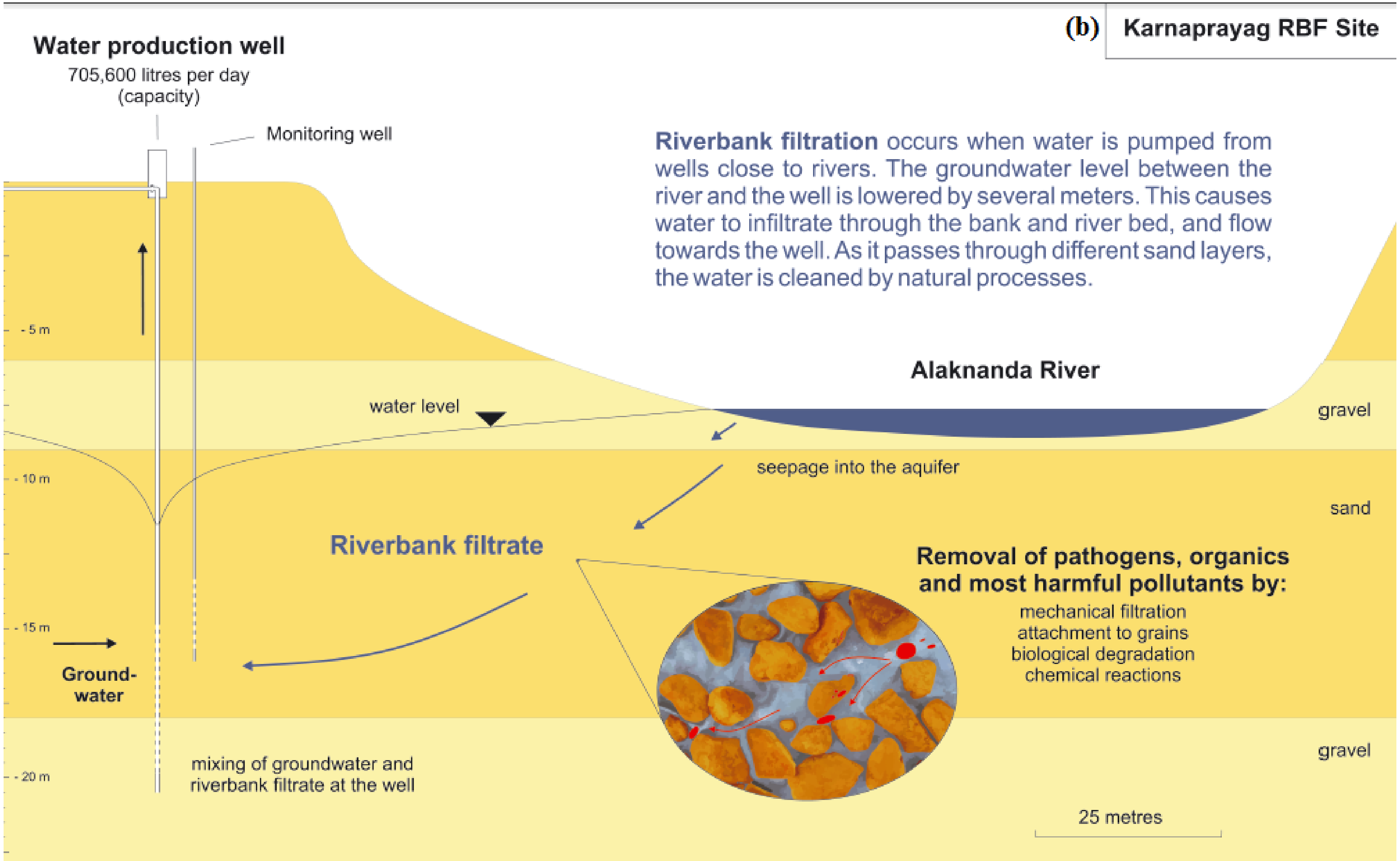


Figure A6 Aquifer profile of the RBF site at **(b)** Karnaprayag

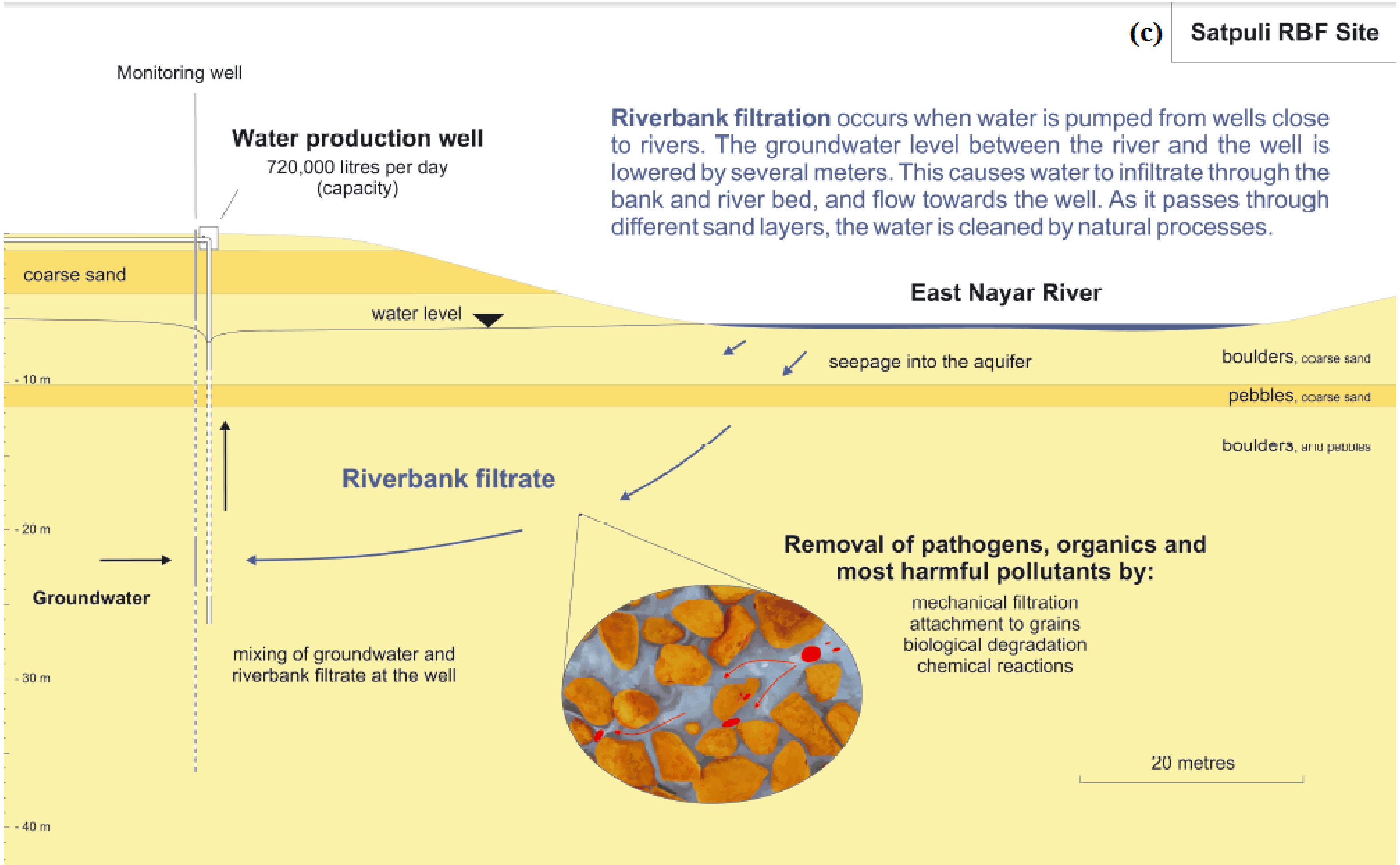


Figure A6 Aquifer profile of the RBF site at **(c)** Satpuli

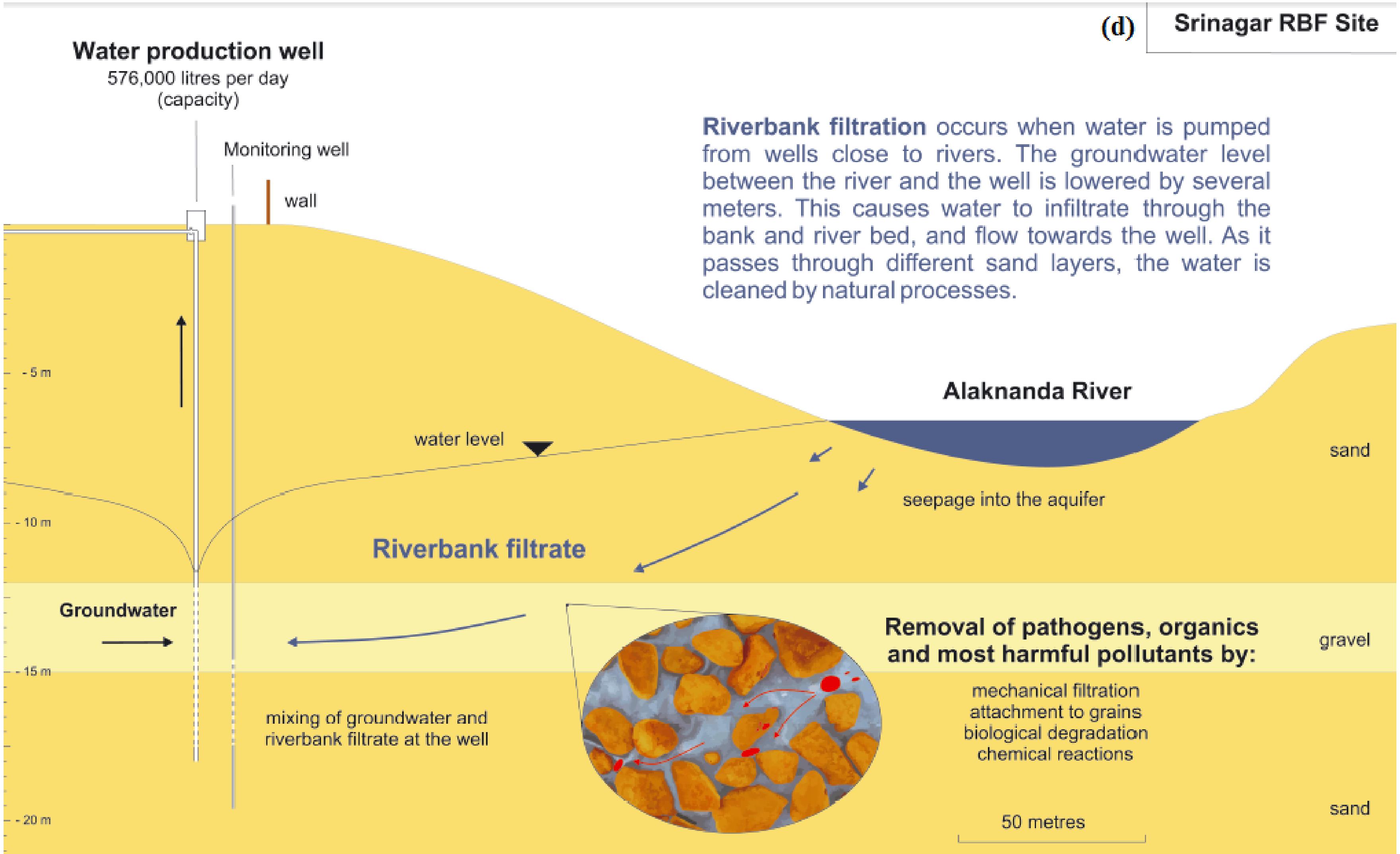


Figure A6 Aquifer profile of the RBF site at **(d)** Srinagar

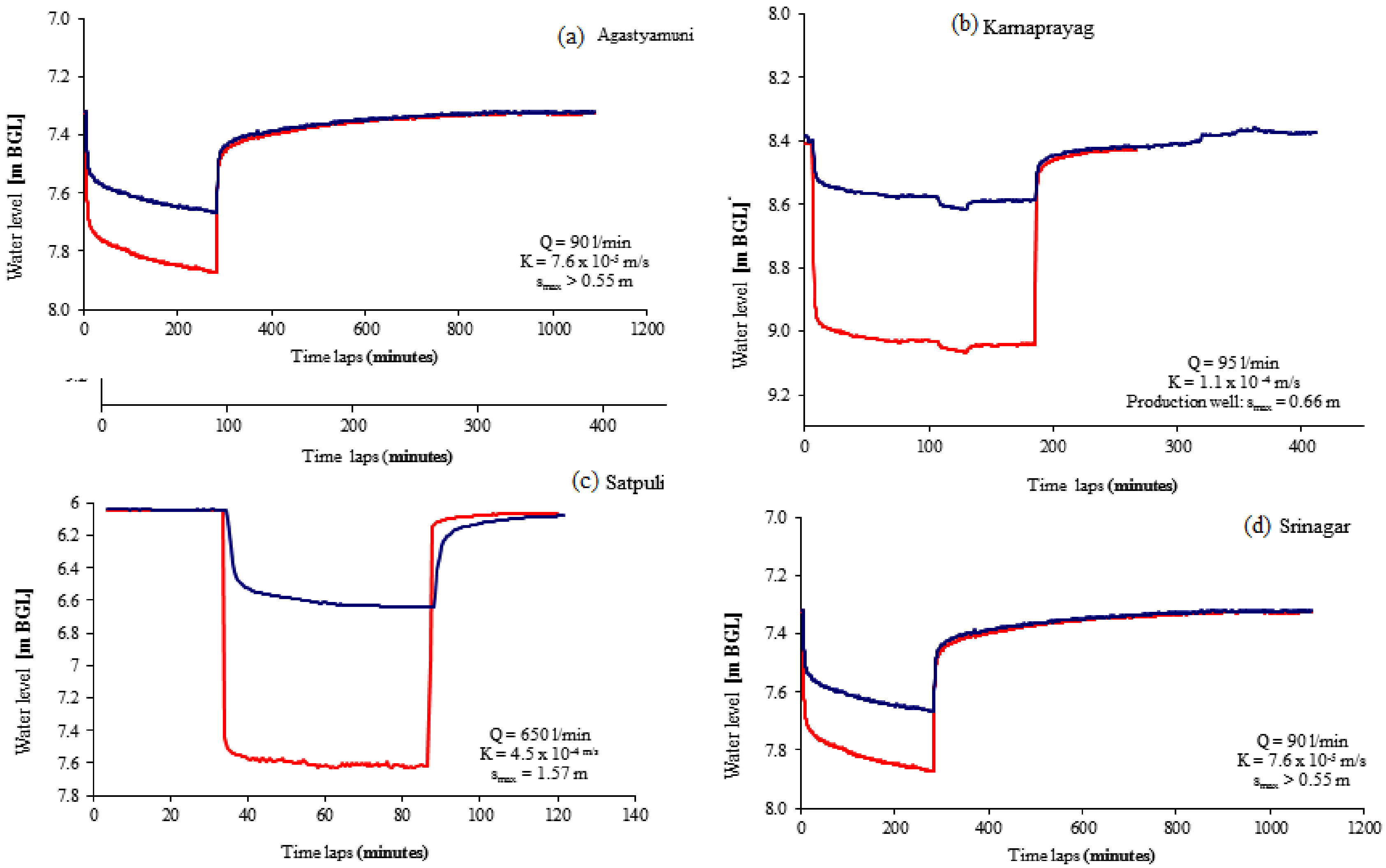


Figure A7 Hydrograph of pumping test conducted in 2010 at various RBF well (a) Agastyamuni (b) Karnaprayag (c) Satpuli and (d) Srinagar (Continue….)

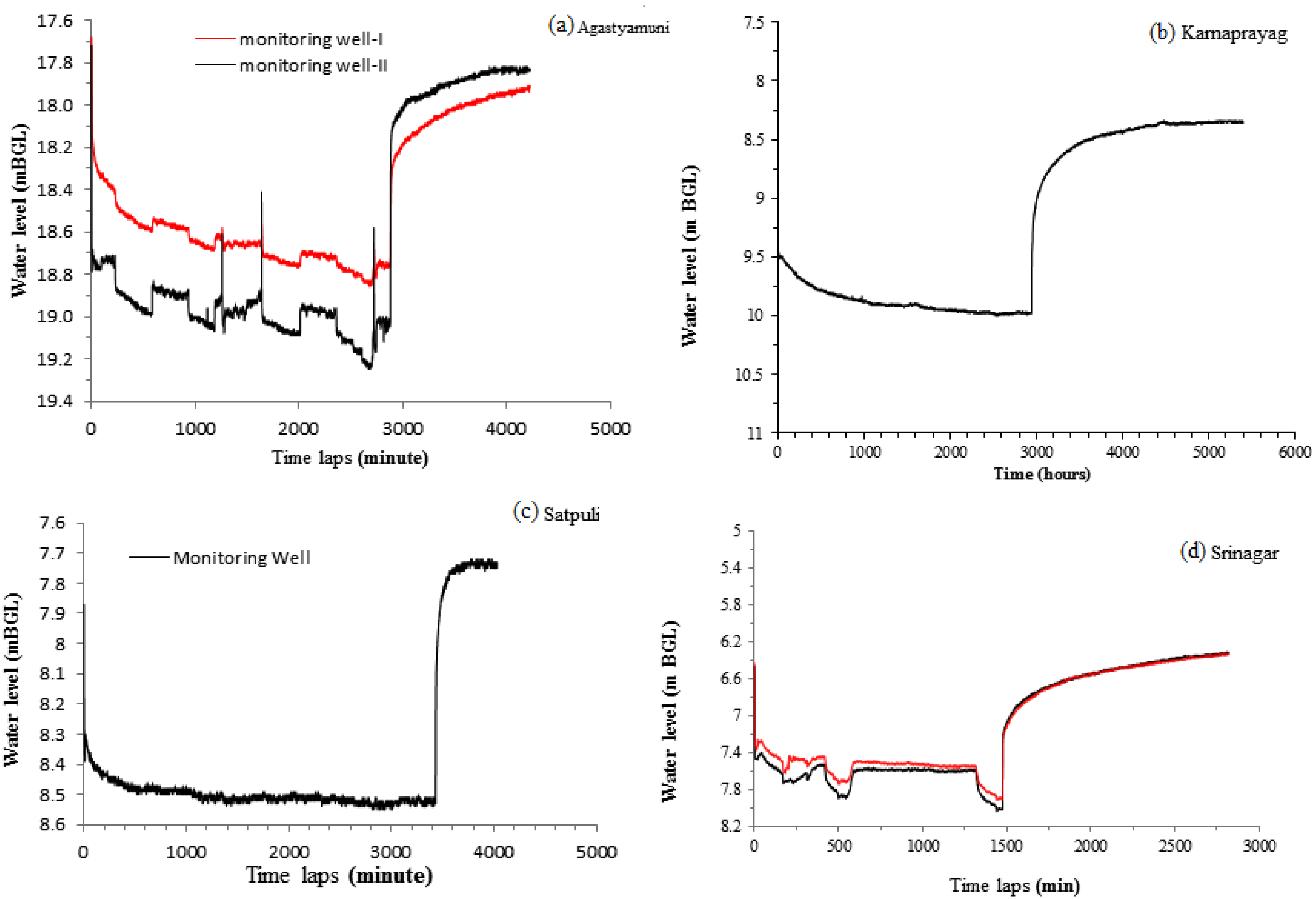


Figure A8 Hydrograph of pumping tests conducted in 2011 at various RBF well (a) Agastyamuni (b) Karnaprayag (c) Satpuli and (d) Srinagar

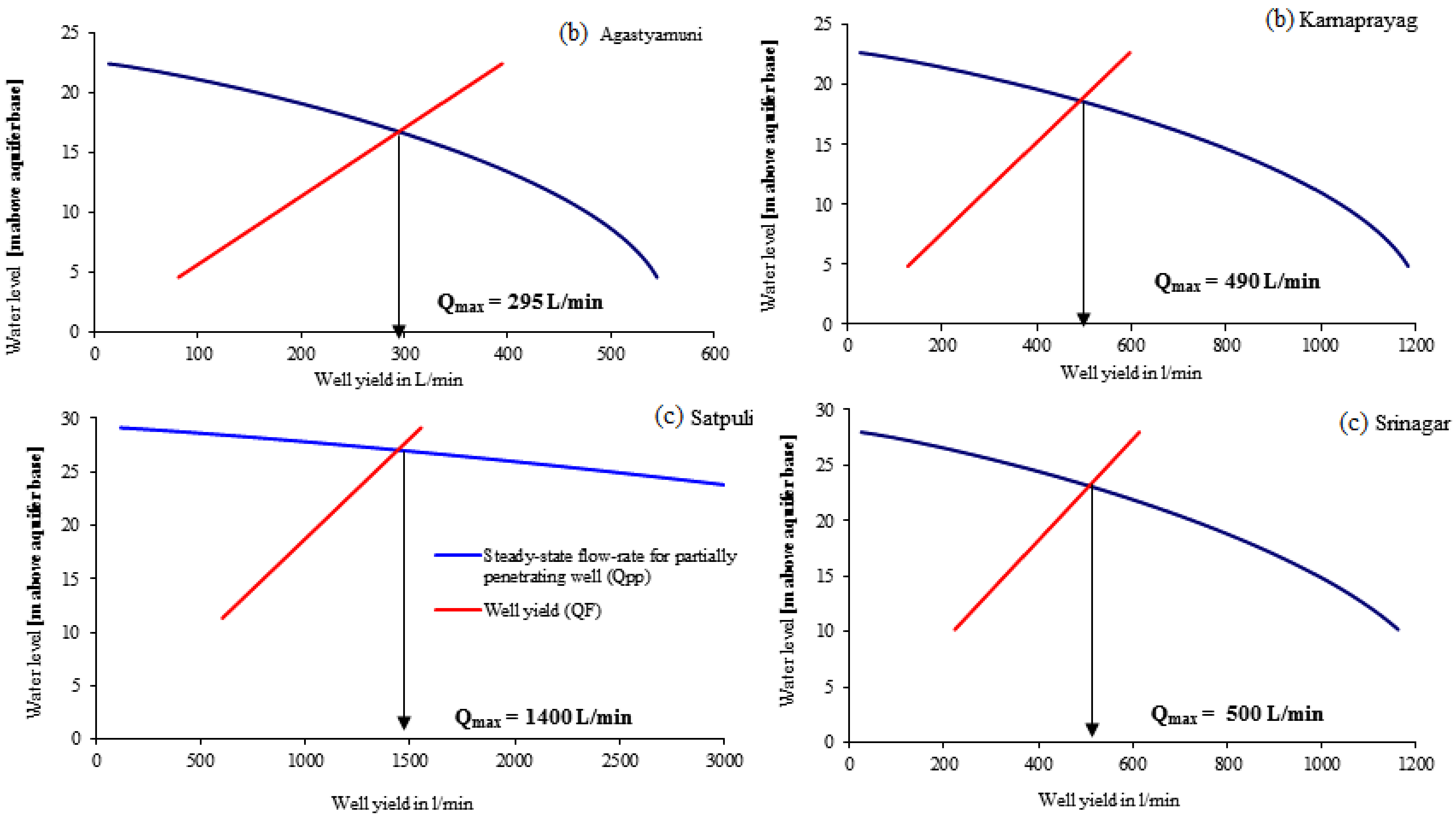


Figure A9 Plot between steady state flow rates vs well yield for estimating safe yield as on 2010 (a) Agastyamuni (b) Karnaprayag (c) Satpuli and (d) Srinagar

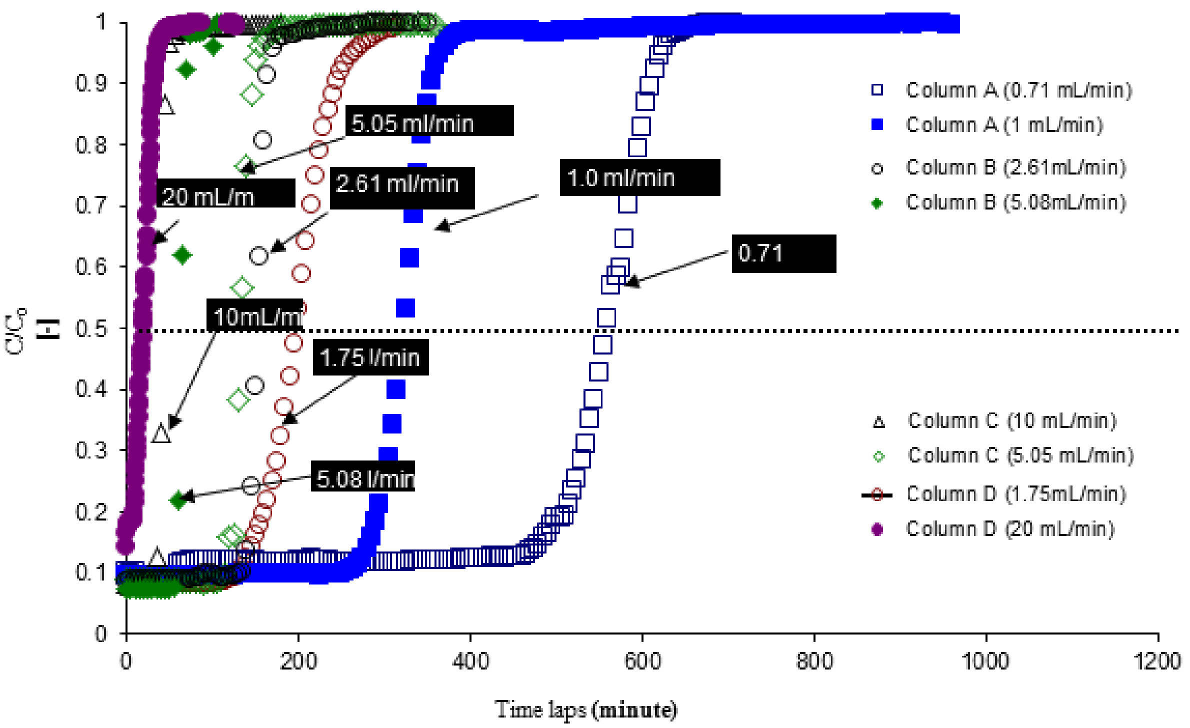


Figure A10 Break through curve from tracer test at different flow rates

Figure A11 Preparation of columns setup at Dresden **(a)** Filter material collection at artificial recharge basin **(a)** Recording manometer reading

Table B1 Sampling locations at RBF sites

Location ID	**Location**	**Latitude, Longitude**	**Elevation above mean sea level**	Distance from the river (m)
R	River Sampling point	30°13’16.2”N, 78°45’56”E	535 m	0
W1	ChaurasTubewell (experimental)	30°13’38.8”N, 78°45’54.1”E	548 m	-
SNPW-1	RBF tube well	30°13’14.2”N, 78°45’58.3”E	547 m	118
SNPW-PU	Tubewell, Pantnagar University Orchard	30°13’36.4”N, 78°47’7.2”E	547 m	56
DDP	DeenDayal Park tubewell	30°13’39.7”N, 78°47’15.5”E	548 m	
W2	Srikot GMVN Guest house tube well	30°13’26.8”N, 78°48’57.0”E	569 m	303
SNHP-7	Handpump 7	30°12’47.2”N, 78°45’45.8”E	557 m	
SNHP-FCI	Handpump(Pauri Rd. –FCI)	30°13’4.9”N, 78°46’16.8”E;	574 m	607
SNHP-20	Handpump 20 (Bhaktiyana)	30°13’17.3”N, 78°46’29.2”E	572 m	
SNHP-X	Handpump X (Bughani Rd.)	30°13’14.2”N, 78°46’56.0”E	604 m	344
SNHP-22	Handpump 22 (hospital)	30°13’19.2”N, 78°47’9.6”E	572 m	37
SNHP-25	Handpump 25	30°13’38.5”N, 78°47’8.3”E	547 m	318
SNHP-31	Handpump 31 (Samrat Hotel)	30°13’16.9”N, 78°47’27.4”E	579 m	256
SNHP-36	Handpump 36	30°13’5.5”N, 78°47’59.6”E	573 m	74
SNHP-38	Handpump 38 (Near Bhagwati Memorial school)	30°13’7.2”N, 78°48’34.2”E	575 m	437
S1	Bhaktiyana Spring	30°13’12.3”N, 78°46’19.2”E	556 m	291
S2	KamleshwarDhara (Spring)	30°13’19.8”N, 78°46’43.3”E	557 m	245
S3	KotharDhara	30°13’8.7”N, 78°47’47.7”E	602 m	32
S4	Srikot Shiv Temple Spring	30°13’38.2”N, 78°49’10.0”E	552 m	-
T1	Sewage Treatment Plant	30°13’36.7”N, 78°47’3.4”E	547 m	-
T2	Landfill	30°13’37.9”N, 78°47’3.5”E	547 m	-
T3	Open sewage flowing to river	30°13’41.3”N, 78°47’13.1”E	544 m	-
G1	Soil Sampling points at riverbank	30°13’18.1”N, 78°45’56.4”E;	541 m	-
G3		30°13’40.5”N, 78°47’11.2”E;		
G4		30°13’45.1”N, 78°46’43.7”E		
G2	Exposed bedrocks on Pauri Rd.	30°12’55.7”N, 78°46’7.4”E	574 m	
AGHP-1	Hand pump 01	30°22'57.64"N;79° 0'31.54"E	784.55	40
AGHP-2	Hand pump 02	30°23'4.96"N;79° 0'47.65"E	778.15	60
AGHP-3	Hand pump 03	30°23'8.07"N;79° 0'57.95"E	801.32	90
AGHP-4	Hand pump 04	30°23'24.50"N;79° 1'19.20"E	790.3	180
AGHP-5	Hand pump 05	30°23'22.97"N;79° 1'20.95"E	795.83	250
AGHP-12	Hand pump 12	30°23'26.19"N;79° 1'18.54"E	787.91	120

AGHP-14	Hand pump 14	30°23'21.06"N;79° 1'11.76"E	790.3	170
AGHP-13	Hand pump 13	30°23'27.16"N;79° 1'16.14"E	785.77	60
AGHP-6	Hand pump 06	30°23'30.10"N;79° 1'25.52"E	790.65	70
AGHP-7	Hand pump 07	30°23'34.79"N;79° 1'42.07"E	785.16	50
AGHP-8	Hand pump 08	30°23'35.91"N;79° 1'46.57"E	788.52	70
AGHP-9	Hand pump 09	30°23'37.79"N;79° 1'51.95"E	797.36	60
AGHP-10	Hand pump 10	30°23'44.37"N;79° 2'0.04"E	805.59	40
AGHP-11	Hand pump 11	30°23'49.31"N;79° 2'2.31"E	804.67	60
Ukhimath (ST)	Mahadev temple	30°31'6.51"N;79° 5'43.85"E	1301.19	Not measured (Very far)
Ukhimath (S)	Primary School	30°29'56.91"N; 79° 5'43.53"E	1401.77	
KPHP-01	Hand pump 01	30°16'59.74"N;79°14'56.23"E	808	260
KPHP-02	Hand pump 02	30°17'11.12"N;79°14'59.98"E	779	130
KPHP-03	Hand pump 03	30°17'12.87"N;79°15'03.06"E	777	120
KPHP-04	Hand pump 04	30°17'25.44"N;79°15'35.99"E	784	70
SPPW	Production well	29°55'8.62"N, 78°42'42.27"E	576	40
SPHP-1	SPHP-1	29°55'26.21"N, 78°42'42.28"E	772.7	240
SPHP-2	near Tahsildar office	29°55'22.75"N, 78°42'36.91"E	671.5	160
SPHP-3	Primary School	29°55'6.94"N, 78°42'43.37"E	578.5	20
SPHP-4	SPHP-4	29°55'5.76"N, 78°42'26.75"E	645.6	70
SPHP-5	SPHP-5	29°55'23.76"N, 78°42'24.76"E	605.9	60
SPHP-6	Groundwater	29°55'4.90"N, 78°42'28.23"E	601	60
SPHP-7	SPHP-7	29°55'3.00"N, 78°42'35.12"E	608.1	100
SPHP-8	near Dangleshwar Mahadev Temple	29°54'33.34"N, 78°42'57.37"E	607.2	110

Table B2 Depth-wise temperature profile of the water in the monitoring well of Srinagar (Continue……..)

11th Aug.2011		27th Feb.2012		13th Apr.2012		27th May. 2012		29th Jun.2012		23rd Jul.2012	
Temp (^{0}C)	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**
23.534	5.75	26.534	7.37	23.28	7.15	23.89	7.28	24.136	7.36	24.32	7.87
23.54	6	26.54	7.5	23.25	7.5	23.91	7.5	24.19	7.51	24.22	8
23.66	6.5	26.66	8	23.1	8	23.62	8	24.123	8	24.12	8.67
23.88	7	26.88	8.5	23.2	8.5	23.61	8.55	24.26	8.5	23.42	9
23.45	7.5	27.45	9	23.41	9	23.41	8	24.26	9.16	23.12	9.67
23.3	8	27.3	9.5	23.31	9.5	23.33	8.5	24.16	9.5	23.15	10
23.4	8.5	27.4	10	23.23	10	23.35	9	24.16	10	23.16	10.67
23.5	9	23.5	10.5	23.25	10.5	23.35	9.5	23.52	10.5	23.25	11

23.4	9.5	23.4	11	23.25	11	23.39	10	23.42	11	23.45	11.67
23.12	10	23.12	11.5	23.32	11.5	23.39	10.5	23.32	11.5	23.46	12
23.123	10.5	23.123	12	23.32	12	23.39	11	23.23	12	23.47	12.67
23.03	11	23.03	12.5	23.33	12.5	23.39	11.5	23.23	12.5	23.47	13
22.87	11.5	22.87	13	23.32	13	23.38	12	23.34	13	23.47	13.5
22.87	12	22.87	13.5	23.315	13.5	23.36	12.5	23.34	13.5	23.52	14
22.87	12.5	22.87	14	23.28	14	23.31	13	23.34	14	23.52	14.5
22.87	13	22.87	14.5	23.21	14.5	23.18	13.5	23.34	14.5	23.53	15
22.81	13.5	22.81	15	23.16	15	23.18	14	23.34	15	23.54	15.5
22.81	14	22.81	15.5	23.16	15.5	23.18	14.5	23.34	15.5	23.36	16
22.81	14.5	22.81	16	23.16	16	23.18	15	23.32	16	23.24	16.5
22.81	15	22.81	16.5	23.16	16.5	23.18	15.5	23.31	16.5	23.19	17
22.81	15.5	22.81	17	23.16	17	23.18	16	23.31	17	23.12	17.5
22.81	16	22.81	17.5	23.16	17.5	23.18	16.5	23.18	17.5	23.13	18
22.81	16.5	22.81	18	23.16	18	23.18	17	23.18	18	23.13	18.5
22.81	17	22.81	18.5	23.1	18.5	23.18	17.5	23.18	18.5	23.12	19
22.81	17.5	22.81	19	23.11	19	23.18	18	23.18	19	22.62	19.5
22.81	18	22.81	-	-	19.5	23.18	18.5	23.18	19.5	22.43	20
22.81	18.5	22.81	-	-	7.15	23.18	19	23.2	20	22.45	-
22.81	19	22.81	-	-	-	-	19.5	23.2	-	-	-
22.78	19.5	22.78	-	-	-	-	-	-	-	-	-
22.75	19.895	22.75	-	-	-	-	-	-	-	-	-

Table B2 Depth-wise temperature profile of the water in the monitoring well of Srinagar

26th Aug.2012		24th Sept.2012		21st Nov. 2012		05th Dec.2012		29th Jan.2013		02nd Mar.2013	
Depth (m)	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**
25.32	7.315	-	6.84	24.37	7.18	8.85	22.2	8.18	22.5	8.42	24.25
25.25	7.5	25.62	7	25.37	7.3	9	22.5	8.5	22.87	8.5	23.81
23.31	8	25.25	7.5	25.25	7.5	9.5	22.64	9	23.12	9	23.62
23.21	8.5	24.43	8	24.93	8	10	23.15	9.5	23.31	9.5	23.5
23.21	9	24.12	8.5	24.75	8.5	10.5	23.16	10	23.43	10	23.43
23.21	9.5	24	9	24.62	9	11	23.35	10.5	23.43	10.5	23.37
23.26	10	23.81	9.5	24.56	9.5	11.5	23.46	11	23.5	11	23.37
23.26	10.5	23.62	10	24.5	10	12	23.46	11.5	23.5	11.5	23.37
23.26	11	23.56	10.5	24.43	10.5	12.5	23.46	12	23.5	12	23.37
23.26	11.5	23.5	11	24.37	11	13	23.36	12.5	23.43	12.5	23.37
23.26	12	23.43	11.5	24.31	11.5	13.5	23.34	13	23.37	13	23.31
23.26	12.5	23.43	12	24.18	12	14	23.31	13.5	23.37	13.5	23.31
23.26	13	23.37	12.5	23.75	12.5	14.5	23.31	14	23.25	14	23.31
23.26	13.5	23.31	13	23.68	13	15	23.31	14.5	23.18	14.5	23.25
23.26	14	23.25	13.5	23.5	13.5	15.5	23.22	15	23.18	15	23.18
23.26	14.5	23.18	14	23.31	14	16	23.22	15.5	23.12	15.5	23.18
23.24	15	23.12	14.5	23.12	14.5	16.5	23.19	16	23.06	16	23.12
23.1	15.5	23.06	15	23.05	15	17	23.18	16.5	23.06	16.5	23.12
23	16	23	15.5	23	15.5	17.5	23.19	17	23.06	17	23.12
23	16.5	23	16	23	16	18	23.2	17.5	23.06	17.5	23.12
23	17	23	16.5	23	16.5	18.5	23.06	18	23.06	18	23.12
23	17.5	23	17	19	23.09	19.5	23.09	18.5	23.06	18.5	23.06
23.01	-	23	17.5	23	17.5	20	23.12	19	23.06	19	23.06
23.01	-	-	18	23	18	8.85	22.2	19.5	23	19.28	23.06
23.01	-	-	18.5	22.5	18.5					8.42	24.25
23	-	-	19	22.5	19					8.5	23.81
-	-	-	-	-	-					9	23.62

Table B3 Depth-wise temperature profile of the water in the monitoring well of Agastyamuni (Continue)

26th Jan.2012		20th Feb. 2012		26th Apr. 2012		26th Aug.2012		30th Sept. 2012		29th Nov.2012	
Depth (m)	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**
18.89	20.2	18.72	20.11	17.23	21.64	15.25	24.81	14.92	23	17.21	22.1
19	20.43	19	20.23	17.5	22.21	15.5	24	15.5	22.56	18	22.4
19.5	20.86	19.5	20.42	18	22.43	16	23.25	16	22.37	18.5	22.34
20	20.88	20	20.88	18.5	22.25	16.5	22.68	16.5	22.18	19	22.43
20.5	21.75	20.5	21.01	19	22.18	17.0	22.43	17	22.12	19.5	22.64
21	21.81	21	21.21	19.5	22.12	17.5	22.25	17.5	22.06	20	22.68
21.5	21.87	21.5	21.32	20	22.12	18.0	22.18	18	22.06	20.5	22.74
22	21.93	22	21.32	20.5	22.06	18.5	22.12	18.5	22.06	21	22.4
22.5	21.93	22.5	21.32	21	22	19.0	22.12	19	22.06	21.5	22.24
23	21.93	23	21.78	21.5	22	19.5	22.06	19.5	22.06	22	22.22
23.5	21.93	23.5	21.88	22	22	20.0	22.00	20	22.06	22.5	22.2
24	21.93	24	21.91	22.5	22	20.5	22.00	20.5	22.06	23	22.01
24.5	21.93	24.5	21.91	23	22	21.0	22.00	21	22.06	23.5	22.01
25	21.93	25	21.93	23.5	22	21.5	22.00	21.5	22.06	24	22.01
25.5	21.93	25.5	21.93	-	-	22.0	22.00	22	22.06	24.5	22.01
26	21.93	26	21.93	-	-	-	22.00	22.5	22.00	25	22.01
26.5	21.93	26.5	21.93	-	-	-	-	23	22.00	25.5	22.01
27	21.93	27	21.93	-	-	-	-	23.5	22.00	26	22.01
27.5	21.93	27.5	21.93	-	-	-	-	24	22.00	26.5	22.01
28	21.93	28	21.93	-	-	-	-	24.5	22.00	27	22.01
28.5	21.93	28.5	21.93	-	-	-	-	25	21.93	27.5	22.01
29	21.93	29	21.93	-	-	-	-	25.5	21.93	28	22.01
29.5	21.93	29.5	21.93	-	-	-	-	26	21.93	28.5	22.01
30	21.93	30	21.93	-	-	-	-	26.5	21.93	29	22.01
30	21.93	30	21.93	-	-	-	-	27	21.93	29.275	22.01
18.89	20.2	18.72	20.11	-	-	-	-	27.5	21.93		

Table B3 Depth-wise temperature profile of the water in the monitoring well of Agastyamuni

26th Dec.2012		28th Jan.2013		03th Mar.2013	
Depth (m)	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**
18.67	21.4	19	20.93	18.75	22.31
19	21.64	19.5	21.37	19	22.25
19.5	21.64	20	21.62	19.5	22.18
20	21.77	20.5	21.75	20	22.12
20.5	21.77	21	21.81	20.5	22.06
21	21.78	21.5	21.87	21	22.06
21.5	21.77	22	21.93	21.5	22.06
22	21.77	22.5	21.93	22	22.06
22.5	21.77	23	21.93	22.5	22.00
23	21.76	23.5	21.93	23	22.00
23.5	21.76	24	21.93	23.5	22.00
24	21.76	24.5	21.93	24	22.00
24.5	21.75	25	21.93	24.5	22.00
25	21.75	25.5	21.93	25	21.93
25.5	21.75	26	21.93	25.5	21.93
26	21.75	26.5	21.93	26	21.93
26.5	22.01	27	21.93	26.5	21.93
27	22.01	27.5	21.93	27	21.93
27.5	22.01	28	21.93	27.5	21.93
28	22.01	28.5	21.93	28	21.93
28.5	22.01	29	21.93	28.5	21.93
29	22.01	29.275	21.93	29	21.93
29.275	22.01	-	-	29.3	21.93

Table B4 Depth-wise temperature profile of the water in the monitoring well of Karnaprayag

26th Feb.2012		26th May 2012		26th June 2012		26th Aug.2015		30th Sept.2012		27th Jan.2013		03rd Mar.2013	
Depth (m)	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C)**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**
8.58	20.62	8.58	20.62	8.11	24.6	7	31.7^{0}C	7.505	24.31	8.58	20.62	9	20.5
9	20.62	9	20.62	8.5	24.71	7.5	25.18	8	24.06	9	20.62	9.5	20.62
9.5	21	9.5	20.7	9	23.54	8	24.31	8.5	23.62	9.5	21	10	20.68
10	21.612	10	20.7	9.5	23.42	8.5	23.75	9	23.12	10	21.12	10.5	20.75
10.5	21.625	10.5	20.25	10	23.21	9	22.68	9.5	22.62	10.5	21.25	11	20.75
11	21.631	11	20.31	10.5	22.11	9.5	22.37	10	22.25	11	21.31	11.5	20.81
11.5	21.631	11.5	20.31	11	21.99	10	21.68	10.5	21.81	11.5	21.31	12	20.87
12	21.625	12	20.25	11.5	21.78	10.5	21.43	11	21.56	12	21.25	12.5	20.87
12.5	21.625	12.5	20.25	12	21.67	11	21.43	11.5	21.25	12.5	21.25	13	20.87
13	21.618	13	20.18	12.5	21.42	11.5	21.18	12	21.18	13	21.18	13.5	20.87
13.5	21.618	13.5	20.18	13	21.22	12	21	12.5	20.81	13.5	21.18	14	20.87
14	21.612	14	20.12	13.5	20.91	12.5	20.87	13	20.75	14	21.12	14.5	20.87
14.5	21.93	14.5	20.3	14	20.78	13	20.81	13.5	20.68	14.5	20.93	15	20.81
15	21.87	15	20.8	14.5	20.78	13.5	20.75	14	20.62	15	20.87	15.5	20.87
15.5	21.87	15.5	20.8	15	20.78	14	20.68	14.5	20.62	15.5	20.87	16	20.87
16	21.81	16	20.1	15.5	20.78	14.5	20.62	15	20.56	16	20.81	9	20.5
16.5	21.81	16.5	20.1	16	20.78	15	20.62	15.16	20.56	16.5	20.81	9.5	20.62
17	21.75	17	20.5	16.5	20.78	15.5	20.62	-	-	17	20.75	10	20.68
17.3	21.68	17.3	20.8	17	20.88	16	20.56	-	-	17.3	20.68	10.5	20.75

Table B5 Depth-wise temperature profile of the water in the monitoring well of Satpuli (continue…)

26th Jan 2012		26th Feb. 2012		26th May 2012		26th Jun 2012		30th Jul 2012		26th August	
Depth (m)	Temp (^{0}C).	Depth (m)	Temp (^{0}C).	Depth (m)	Temp (^{0}C).	Depth (m)	Temp (^{0}C).	Depth (m)	Temp (^{0}C).	Depth (m)	Temp (^{0}C).
8.21	15.4	8.175	15.86	7.175	21.51	7.35	25.9	7.59	26	7.285	26.37
8.5	15.6	8.5	15.29	7.52	22.19	7.5	26.2	8.56	26.18	7.5	25.43
9	15.8	9	15.15	8.5	22.95	8	26.4	9	26.32	8	25.37
9.5	15.4	9.5	15.08	9	23.21	8.56	25.5	9.56	26.43	8.5	25.37
10	14.9	10	15.45	9.5	23.46	9	26.4	10	26.12	9	25.25
10.5	14.84	10.5	16.07	10	23.65	9.56	26.2	10.5	26	9.5	25.25
11	14.99	11	16.12	10.5	24.26	10	26.2	11	25.56	10	25.18
11.5	15.9	11.5	16.26	11	23.1	10.5	26.2	11.5	25.06	10.5	25.06
12	16.8	12	17.56	11.5	22.16	11	25.11	12	24.56	11	24.43
12.5	17.5	12.5	18.35	12	22.11	11.5	25.11	12.5	23.5	11.5	24.12
13	18.6	13	18.95	12.5	22.12	12	24.86	13	23.32	12	23.18
13.5	19.5	13.5	20.12	13	21.62	12.5	24.56	13.5	23.28	12.5	23.43
14	20.56	14	20.36	13.5	21.64	13	24.32	14	22.97	13	23.18
14.5	20.54	14.5	20.65	14	21.56	13.5	24.12	14.5	22.87	13.5	23
15	20.94	15	21.45	14.5	21.52	14	23.41	15	22.78	14	22.87
15.5	20.89	15.5	21.45	15	21.44	14.5	23.22	15.5	22.68	14.5	22.68
16	20.99	16	21.45	15.5	21.44	15	23.1	16	22.51	15	22.62
16.5	20.98	16.5	21.34	16	21.44	15.5	22.22	16.5	22.56	15.5	22.62
17	21.02	17	21.25	16.5	21.44	16	22.12	17	22.45	16	22.5
17.5	21.05	17.5	20.96	17	21.4	16.5	22.21	17.5	22.43	16.5	22.5
18	21.11	18	20.96	17.5	21.38	17	22.12	18	22.43	17	22.43
18.5	21.5	18.5	20.96	18	21.38	17.5	21.56	18.5	22.43	17.5	22.43
19	21.46	19	20.96	18.5	21.38	18	21.56	19	22.31	18	22.37
19.5	21.39	19.5	21.12	19	21.38	18.5	21.56	19.5	22.37	18.5	22.37
20	22.01	20	21.12	19.5	21.36	19	22.13	20	22.31	19	22.31
20.5	21.43	20.5	21.21	20	21.36	19.5	22.13	20.5	22.31	19.5	22.31
21	21.3	21	21.21	20.5	21.36	20	22.13	21	22.31	20	22.31
21.5	21.52	21.5	21.21	21	21.36	20.5	22.13	21.5	22.31	20.5	22.25
22	21.5	22	21.23	21.5	21.35	21	22.13	22	22.31	21	22.25
22.5	21.15	22.5	21.23	22	21.35	21.5	22.13	22.5	22.31	21.5	22.25
23	21.5	23	21.36	22.5	21.35	22	22.13	23	22.28	22	22.25
23.5	21.61	23.5	21.36	23	21.35	22.5	22.16	23.5	22.25	22.5	22.25
24	21.76	24	21.36	23.5	21.36	23	22.16	24	22.25	23	22.25

24.5	21.76	24.5	21.36	24	21.36	23.5	22.16	24.5	22.25	23.5	22.18
25	21.76	25	21.56	24.5	21.21	24	22.16	25	22.2	24	22.18
25.5	21.85	25.5	22.12	25	21.12	24.5	22.16	25.5	22.18	24.5	22.18
26	21.89	26	22.12	25.5	21.12	25	22.15	26	22.18	25	22.18
26.5	22.01	26.5	22.12	26	21.12	25.5	22.16	26.5	22.18	25.5	22.18
27	22.02	27	22.11	26.5	20.96	26	21.65	27	22.16	26	22.18
27.5	22.06	27.5	22.11	27	20.96	26.5	21.56	27.5	22.12	26.5	22.12
28	22.09	28	22.11	27.5	20.96	27	21.56	28	22.12	27	22.18
28.5	22.13	28.5	22.11	28	21.96	27.5	21.56	28.5	22.12	27.5	22.18
29	22.12	29	22.11	28.5	21.96	28	22.13	29	22.12	28	22.12
29.5	22.12	29.5	22.112	29	21.96	28.5	22.16	29.5	22.12	28.5	22.12
30	22.21	30	22.11	29.5	21.78	29	22.16	30	22.12	29	22.12
30.5	22.21	30.5	22.11	30	21.78	29.5	22.16	30.5	22.12	29.5	22.18
31	22.21	31	22.11	30.5	21.67	30	22.16	31	22.12	30	22.18
31.5	22.21	31.5	22.11	31	21.67	30.5	22.18	31.5	22.12	30.5	22.18
32	22.21	32	22.11	31.5	21.49	31	21.18	32	22.12	31	22.18
32.5	22.21	32.5	22.13	32	21.49	31.5	22.18	32.5	22.18	31.5	22.18
33	22.21	33	22.12	32.5	21.49	32	22.18	33	22.18	32	22.18
33.5	22.21	33.5	22.26	33	21.38	32.5	21.96	33.5	22.18	32.5	22.18
34	22.21	34	22.26	33.5	21.38	33	21.96	34	22.18	33	22.18
34.5	22.23	34.5	22.22	34	21.38	33.5	21.96	34.5	22.25	33.5	22.25
35	22.23	35	22.22	34.5	21.38	34	21.96	35	22.13	34	22.25
35.5	22.23	35.5	22.22	35	21.42	34.5	22.16	35.5	20.31	34.5	22.25
36	22.23	36	22.22	35.5	21.42	35	22.16	36	20.31	35	22.31
36.5	22.23	36.5	22.22	36	21.31	35.5	22.16	36.5	20.31	35.5	22.31
-	-	36.79	22.22	36.5	21.31	36	22.16	37	20.31	36	22.31
-	-	-	-	36.79	21.33	36.5	22.16	37.27	22.37	36.5	22.31
-	-	-	-	-	-	37	22.16	-	-	37	22.31
-	-	-	-	-	-	37.27	22.16	-	-	37.5	22.31

Table B5 Depth-wise temperature profile of the water in the monitoring well of Satpuli

Sept. 2012		29th Nov.2012		26th Dec.2012		27th Jan.2013		03rd Mar.2013	
Depth (m)	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**	**Depth (m)**	**Temp (^{0}C).**
8.14	26	8.89	21.56	7.84	15.36	8.566	14.25	8.175	15.93
8.5	25.37	9	22.13	8	15.49	9	14.18	8.5	15.31
9	25.12	9.5	22.23	8.5	15.62	9.5	14.12	9	15.18
9.5	25	10	22.35	9	15.86	10	14.31	9.5	15.06
10	24.93	10.5	22.56	9.5	16.6	10.5	14.87	10	15.5
10.5	24.68	11	22.56	10	16.83	11	15.87	10.5	16.12
11	24.31	11.5	22.46	10.5	17.23	11.5	16.75	11	17
11.5	23.81	12	22.46	11	17.44	12	17.87	11.5	18
12	23.5	12.5	22.36	11.5	17.62	12.5	18.5	12	18.5
12.5	23.25	13	22.66	12	17.82	13	18.81	12.5	18.93
13	23.06	13.5	22.84	12.5	18.22	13.5	19.93	13	19.18
13.5	22.87	14	22.96	13	19.32	14	20.5	13.5	20.25
14	22.75	14.5	22.98	13.5	19.32	14.5	20.68	14	20.5
14.5	22.62	15	23.12	14	19.32	15	20.81	14.5	20.56
15	22.56	15.5	23.12	14.5	19.32	15.5	20.87	15	20.62
15.5	22.5	16	23.12	15	20.21	16	20.87	15.5	20.68
16	22.37	16.5	22.65	15.5	20.21	16.5	21	16	20.75
16.5	22.37	17	22.65	16	21.46	17	21.06	16.5	20.81
17	22.37	17.5	20.93	16.5	21.21	17.5	21.06	17	20.87
17.5	22.31	18	21.6	17	21.21	18	21.12	17.5	20.93
18	22.31	18.5	21.62	17.5	20.46	18.5	21.18	18	21
18.5	22.31	19	21.23	18	21.46	19	21.25	18.5	21.06
19	22.25	19.5	21.22	18.5	21.46	19.5	21.31	19	21.12
19.5	22.25	20	21.23	19	21.46	20	21.37	19.5	21.18
20	22.25	20.5	21.23	19.5	21.46	20.5	21.43	20	21.25
20.5	22.25	21	21.23	20	21.46	21	21.5	20.5	21.31
21	22.25	21.5	21.23	20.5	21.46	21.5	21.56	21	21.31
21.5	22.25	22	21.23	21	21.52	22	21.56	21.5	21.37
22	22.25	22.5	21.24	21.5	21.52	22.5	21.56	22	21.43
22.5	22.25	23	21.36	22	21.52	23	21.62	22.5	21.5
23	22.18	23.5	21.46	22.5	21.52	23.5	21.75	23	21.56
23.5	22.18	24	21.46	23	21.56	24	21.81	23.5	21.68
24	22.18	24.5	21.44	23.5	21.62	24.5	21.87	24	21.81

24.5	22.18	25	21.32	24	21.62	25	21.93	24.5	21.87
25	22.18	25.5	21.33	24.5	21.62	25.5	21.93	25	21.93
25.5	22.18	26	21.22	25	21.62	26	22	25.5	21.93
26	22.18	26.5	21.22	25.5	21.62	26.5	22.06	26	22
26.5	22.18	27	21.22	26	21.62	27	22.06	26.5	22
27	22.18	27.5	22.13	26.5	21.62	27.5	22.06	27	22.06
27.5	22.18	28	22.16	27	22.22	28	22.12	27.5	22.06
28	22.18	28.5	22.16	27.5	22.22	28.5	22.12	28	22.06
28.5	22.18	29	22.16	28	22.22	29	22.12	28.5	22.12
29	22.18	29.5	22.16	28.5	22.21	29.5	22.12	29	22.12
29.5	22.18	30	21.16	29	22.21	30	22.12	29.5	22.12
30	22.18	30.5	22.13	29.5	22.22	30.5	22.12	30	22.12
30.5	22.18	31	21.13	30	22.22	31	22.12	30.5	22.12
31	22.18	31.5	21.13	30.5	22.19	31.5	22.12	31	22.18
31.5	22.18	32	21.13	31	22.16	32	22.12	31.5	22.18
32	22.18	32.5	21.13	31.5	22.13	32.5	22.12	32	22.18
32.5	22.18	33	21.13	32	22.12	33	22.12	32.5	22.25
33	22.25	33.5	21.13	32.5	22.12	33.5	22.12	33	22.25
33.5	22.25	34	21.22	33	22.12	34	22.12	33.5	22.37
34	22.25	34.5	21.22	33.5	22.11	34.5	22.12	34	22.31
34.5	22.25	35	21.23	34	22.1	35	22.12	34.5	22.31
35	22.31	35.5	21.23	34.5	22.14	35.5	22.12	35	22.31
35.5	22.31	36	21.23	35	22.12	36	22.12	35.5	22.37
36	22.31	36.5	21.23	35.5	22.12	36.43	22.31	36	22.37
36.24	22.37	36.79	21.23	36	22.12	-	-	36.5	22.37
-	-	-	-	-	-	-	-	36.79	22.37

Table B6 Average concentration and standard deviation of major ions in the River water, Production well water and groundwater collected from Hand pump (Continue…….).

	Satpuli						Agastyamuni	
Parameters	**Eastern Nayar River (SPSW)**		**Production well (SPPW)**		**Groundwater (SPHP-6)**		**Mandakini River (AGSW)**	
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Avg.	STDEV	Avg.	Avg.	STDEV	STDEV	Avg.	STDEV
EC (μS/cm)	139.6	25.3	192.6	104.5	32.7	28.8	610.7	42
TDS (mg/L)	83.8	15.2	115.5	62.7	19.62	17.3	366.4	25.2
Cl- (mg/L)	3.2	1.6	5.4	1.7	2	2.2	24.3	13.4
NO3-(mg/L)	1.5	1.4	2.8	2.9	5.9	2.6	1	0.8
SO42-(mg/L)	9.8	4.2	11.9	9.2	2.4	4.1	39.9	24.4
Alkalinity (mg/L as CaCO3)	64.8	9.7	87.6	50.9	29.6	12.7	291.5	29.3
F-(mg/L)	0.3	0.5	1			2.3	0.4	0.5
Ca2+(mg/L)	19.2	6.9	22.6	18.2	8.9	5	25.1	20.5
Mg2+ (mg/L)	5.6	3.7	6.8	2.1	1.9	3.4	13.7	8.6
Na+ (mg/L)	7.9	2.7	12.8	3.8	1.6	2.9	152.7	20
K+ (mg/L)	0.7	0.8	0.5	1	1.5	0.9	0.6	1.4
Hardness (mg/L as CaCO3)	66.7	34.7	79.3	53.6	29.4	27.1	105.1	86

Table B6 Average concentration and standard deviation of major ions in the water from the River water, Production well water and groundwater collected from Hand pump

Parameters	Agastyamuni				Karanprayag					
	Production well (AGPW)		**Groundwater (AGHP-5)**		**Alaknanda River (KPSW)**		**Production well (KPPW)**		**Groundwater (KPHP-2)**	
1	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
	Avg.	STDEV	Avg.	STDEV	Avg.	STDEV	Avg.	STDEV	Avg.	STDEV
EC (μS/cm)	312.5	41	426	26.6	151.5	24.7	286.9	29.5	238.6	26.2
TDS (mg/L)	187.5	24	255.6	15.96	90.9	14.82	172.14	17.7	143.16	15.72
Cl^- (mg/L)	10.7	2.9	6.3	1.3	1.4	1.6	2.7	2.9	1.1	0.6
NO_3^-(mg/L)	21.7	6.5	1.1	0.8	1.8	1.1	3.6	2.4	1.2	0.6
SO_4^{2-}(mg/L)	12.3	2.9	10.8	2.2	12.8	5.9	9.2	5.3	6.5	4.1
Alkalinity (mg/L as $CaCO_3$)	124.2	29	209.4	32.2	65.8	8.1	156.9	12.2	135.1	11.7
F^-(mg/L)	Below detectable limit									
Ca^{2+}(mg/L)	42.1	8	39.5	4.3	26.1	5.2	43.9	6.4	41.4	8.4
Mg^{2+} (mg/L)	8.4	2.9	11.9	3.8	3.8	2.5	12.3	2.3	10.4	1.9
Na^+ (mg/L)	18.4	3.5	56.5	5.7	3.3	1.8	3.6	1	2.2	0.6
K^+ (mg/L)	1.9	2.1	0.7	1.6	1	0.9	2.3	1.2	0.5	0.7
Hardness (mg/L as $CaCO_3$)	139.6	29	147.6	21.5	80.6	15.6	160.4	22.1	146.5	22

END OF THE THESIS

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