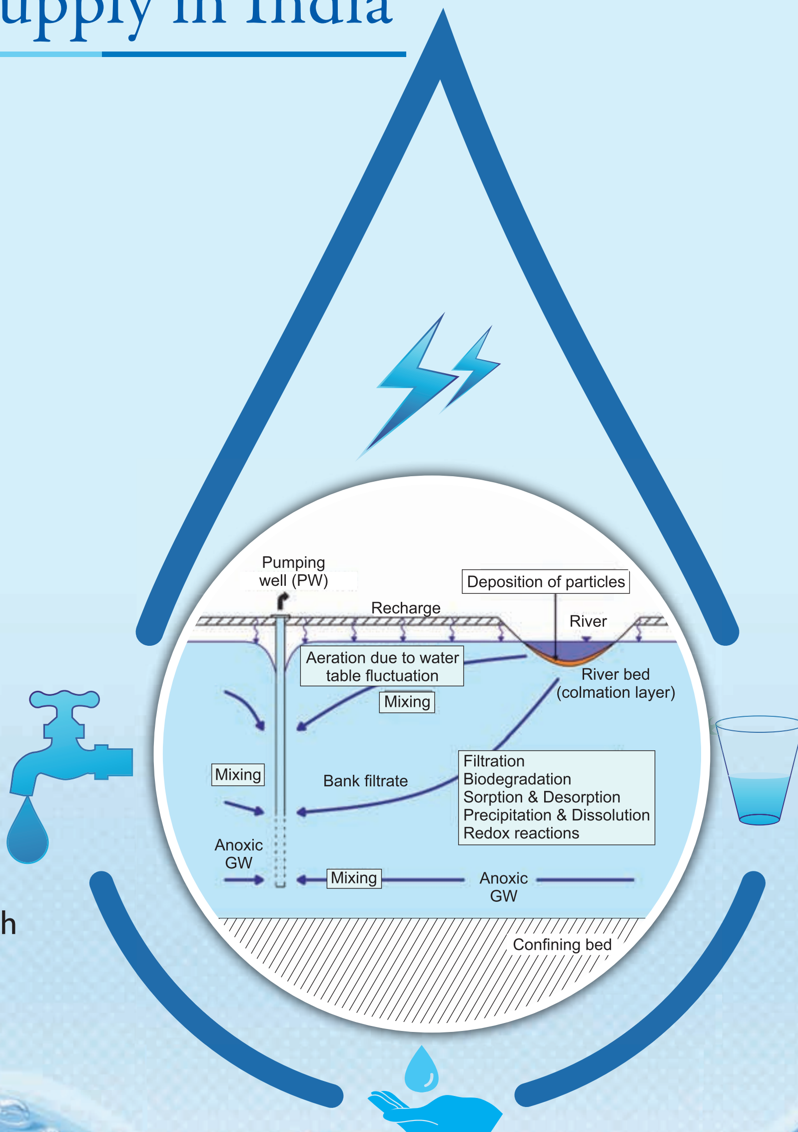
Guidelines on Bank Filtration for Water Supply in India



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GUIDELINES ON BANK FILTRATION FOR WATER SUPPLY IN INDIA

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FOREWORD

Department of Science and Technology (DST) is the nodal department of the Government of India for promoting Science and technology activities in the country. Several planned programmes have been implemented which has enabled in meeting the technological demands for the Indian Society. Water technology Initiative (WTI) of DST is a flagship initiative to promote technological advancements aimed towards providing safe water at affordable cost using appropriate Science and Technology interventions.

It is a matter of immense pleasure to me that DST supported the Uttarakhand State Council for Science and Technology (UCOST), Dehradun in collaboration with National Institute of Hydrology (NIH), Roorkee for developing and bringing out this Book on "Guidelines on Bank Filtration for Water Supply in India" through its flagship initiative (WTI) to address the water related issues.

RBF is a unique and cost effective technology which provides quality drinking water. Successful models have been demonstrated at 6 different sites in Uttarakhand benefiting a population of more than 60,000 people in state of Uttarakhand though initiative of UCOST, Uttarakhand Jal Sansthan (UJS) Dehradun and facilitation by DST. DST has provided consistent support for nurturing and establishing this technology. I am glad that this technology is now being taken up for replication and up scaling in different parts of the country and many states are now coming forward.

I would like to congratulate all the authors, editors and reviewers for their painstaking efforts for preparing such a knowledgeable compilation. I am also happy to note that DST, Scientists Dr. Neelima Alam & Dr. Sanjay Bajpai, associated with WTI have facilitated these interventions through all possible efforts and contributed by providing qualitative feedbacks for its improvement.

The efforts of the partner agencies UCOST Dehradun, NIH Roorkee, UJS Dehradun, IIT Roorkee and SWD, HTW University of Dresden, Germany are commendable. I am sure this publication will be useful to all the stakeholders in understanding, initiating, promoting and establishing this unique technology.

(Ashutosh Sharma)

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PREFACE

Earth's freshwater resources are facing tremendous pressure, both quantitatively and qualitatively. Many people do not have consistent access to safe drinking water. Unsustainable groundwater abstractions, deterioration of the quality of surface and groundwater and extremely reduced flow of rivers are just a few amongst the multitude of water problems that is plaguing India and the world.

Riverbank Filtration (RBF) or simply Bank Filtration (BF, a unified term for river and lake bank or bed filtration) is a proven natural and sustainable water treatment technique that is recognised as a potentially useful tool in every integrated water resources management toolbox. BF is a process wherein surface water from rivers, channels and lakes is induced by pumping from nearby production wells to flow through the natural aquifer sediments, undergoing many positive changes in water quality before finally mixing with local groundwater from the land side and being abstracted for direct use or further treatment. In human history, large cities and industrial centres have often developed at locations where surface water was available. As the quality of surface water in many places gradually declined, treatment costs increased. Here, BF may be used as an alternative water abstraction providing natural pre-treatment and higher safety during floods and spills. Often groundwater is being used as an alternative or supplementary source. However, if groundwater resources near the cities are insufficient or of poor quality (for instance contaminated with nitrate, iron, manganese, arsenic or fluoride), implementing BF may help to ensure a stable and high-quality drinking water supply. BF has therefore been used for several decades, especially in Europe, to provide drinking water to communities located near surface water bodies, typically rivers.

In this context, nearly 15 years of research and numerous scientific works in the form of journal articles, conferences, workshop proceedings and other information, education and communication (IEC) events such as training courses on BF and presentations at exhibitions and industry trade fairs on BF in India has shown that it has a large potential to enhance the quality of water for drinking, however, concerted efforts are still required to fully realise the potential of BF through its widespread and conscious application. Interactions between researchers working on BF in India and policymakers, water supply organisations, authorities and stakeholders has revealed the need for a document on BF relevant for Indian conditions to help them to understand and how to implement it. The nine chapters of these guidelines synthesise the information contained in some of the scientific works and the field experiences of some of the authors and engineers who contributed to the preparation of these guidelines.

The structure of these guidelines follows the sequential phases of a general methodology that can be used from planning, implementation to monitoring a prospective BF scheme in India. While chapter 1 provides an introduction to BF and describes the motivation to use it in India, chapters 2 and 3 are dedicated to the technical aspects of planning and implementing a BF scheme. Subsequently, water quality, health risk assessment and post-treatment aspects are described in chapters 4 and 5. Chapter 6 is dedicated to the numerical flow modelling of a BF scheme. Chapter 7 discusses tried and tested strategies that can be used to propagate BF in other parts of India based on the example deployed in Uttarakhand. Considering that these guidelines are also the result of a 15-year continuous Indo-German collaboration, chapters 8 and 9 accordingly discuss case studies from both these countries.

At this point, it is pertinent to mention how these guidelines came into existence. Being a prominent state of the central Indian Himalayan region, Uttarakhand encompasses diverse geographical features and accordingly complex are its problems, especially for water supply. The adoption subsequent effective implementation of suitable science and technology interventions is necessary to achieve safe and sustainable water supply in the state. In this context, some of the most important rivers, namely Ganga and Yamuna, and prominent landmarks of hydraulic engineering such as the headworks of the Upper and Lower Ganga Canals are also located in Uttarakhand. The Roorkee College (in Roorkee, Uttar Pradesh and now Uttarakhand) was established in 1847 by the Upper Ganga Canal to train engineers for canal construction; this was later named as the Indian Institute of Technology Roorkee in 2001. Here the first "International Workshop on Riverbank Filtration" was organised in March 2004 by Prof Chittaranjan Ray and Prof C.S.P. Ojha in culmination to the former's fact-finding reconnaissance of locations in the Gangetic plains with an unexplored potential for RBF.

Consequently, under the coordination of the Division of Water Sciences at the University of Applied Sciences Dresden (HTW Dresden), the two-year project "EU-India Riverbank Filtration Network" (EU-India RBFN) commenced in 2005 (with funding from the European Commission's Economic Cross Cultural Programme). Together with the partners IIT Roorkee, Uttarakhand State Water Supply Organisation – Uttarakhand Jal Sansthan (UJS), the water supply division of the utility works of the city of Düsseldorf in Germany "Stadtwerke Düsseldorf AG" (SWD) and other European and Indian partners, the application of RBF at the case study sites of Haridwar, Patna, Nainital and Srinagar and some other locations were scientifically investigated.

To continue the systematic investigation and application of RBF, at different sites especially in Uttarakhand, a series of research and pilot projects and information and education communication (IEC) events were conducted spanning a decade (until 2014) that led to several milestones. Notable amongst them are the establishment of the Cooperation Centre for RBF (CCRBF, since 2007); the Indo-German RBF Network (RBFN by HTW Dresden, 2008–2011, funded by the German Federal Ministry of Education and Research / BMBF); the Workshop on Source, Treatment and Distribution of Drinking Water (2009, organised by Uttarakhand State Council for Science & Technology/ UCOST); the recognition of the RBF scheme in Haridwar operated by UJS as a demonstration site for RBF in India by the Managed Aquifer Recharge Network (MAR-NET) of the International Association of Hydrogeologists (IAH) in 2010; the project on "Development of RBF in hilly regions for sustainable solution for qualitative and quantitative issues related to drinking water in Uttarakhand" (2010–2013, UJS & UCOST and funded by the Water Technology Initiative of the Department of Science and Technology/ DST-WTI, Government of India); the Indo-German Workshop on Bank Filtration for Sustainable Drinking Water Supply (2011, UCOST & HTW Dresden); the establishment of the Indo-German Competence Centre on RBF at the National Institute of Hydrology (NIH) in Roorkee in collaboration with HTW Dresden in 2011; the EU-funded the project Saph Pani comprising mainly of European and Indian partners (2011–2014; coordinated by the University of Applied Sciences and Arts Northwestern Switzerland) and the "Indo-German Workshop on Science-based Master Planning for Bank Filtration Water Supply in India" organised by HTW Dresden and NIH Roorkee in Dresden in 2014 (funded by the Indo-German Science and Technology Centre/IGSTC).

Uttarakhand State Council for Science and Technology, Dehradun and National Institute of Hydrology, Roorkee jointly undertook the task of preparing the River Bank Filtration Guidelines to document a baseline data and standard procedures to set the foundation for implementing the RBF/BF schemes in different parts of the globe especially in India. The Department of Science and Technology, Water Technology Initiative (WTI) Division, Government of India realises the importance of this natural technique and agreed to fund the project to compile this work. This is the result of a series of meetings with DST and authors to finalize the chapters and content. We are thankful to the official of WTI Division, DST (Government of India), New Delhi, Dr Sanjay Bajpai, Head, Technology Mission Division (Energy & Water) and Dr Neelma Alam Scientist 'E' and committee members for their

encouragement and time-to-time feedback, which helped us in compiling this book. We are also thankful to the reviewers, Prof Rajendra Prasad, Andhra University, Andhra Pradesh, Prof Indu Mehrotra, IIT, Roorkee, Prof Govind Mishra, IIT Roorkee and Er. H. P. Uniyal, Former Chief General Manager and Advisor Planning Commission Uttarakhand for reviewing the chapters and to Dr B.P. Purohit, Joint Director, UCOST for suggestions.

The above research projects proved that BF is a sustainable and effective water treatment technology, especially for turbidity and pathogens that are crucial parameters of concern in Uttarakhand. The IGSTC-funded workshop and the conclusion of the Saph Pani Project in 2014 made policy recommendations for BF in India. In line with these recommendations the projects NIRWINDU (2015–2018; HTW Dresden) and Peya Jal Suraksha (2015–2019; NIH Roorkee), funded by the BMBF and Indian Ministry of Water Resources, River Development and Ganga Rejuvenation respectively, were implemented. NIRWINDU was complimented in Uttarakhand by the project "Flood-protection, capacity enhancement and redevelopment of drinking water supply infrastructure" (UJS; 2014–2017, funded by Asian Development Bank). Consequent to the Saph Pani Project's recommendation to prepare and distribute a guideline for the implementation of BF in India (section 2.5.3 in Saph Pani "Final Publishable Summary Report"), UCOST and NIH Roorkee initiated the preparation of these guidelines within the project "Country-wide capacity building program on bank filtration for sustainable drinking water supply in India" (NIH and UCOST; 2016–2018), funded by the DST, Government of India.

Like most scientific works, these guidelines have their limitations. Consequently, they contain limited information on BF from other parts of India (other than North India). However, where available, data and information on these BF sites have been included and references have been provided. While these guidelines are also not a means to an end but they form the basis for a master plan on BF in India, a potential project for the future.

These guidelines could not have been prepared had it not been for the continued and unwavering support of the engineers, researchers, staff and students, both past and present, from UCOST, UJS, IIT Roorkee, NIH Roorkee and its regional centres and CCRBF from India and SWD, HTW Dresden and its partners, especially the Institute for Water Chemistry at the TU Dresden and the Dresden-branch of the DVGW-Water Technology Centre (TZW).

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ABBREVIATIONS

AA	amino acids
AOX	adsorbable organic halides
BDOC	biologically degradable dissolved organic carbon
BF/RBF	bank filtration/riverbank filtration
BFGs	boulder filled galleries
DALYs	disability adjusted life years
DBP	disinfection by-products
DOC	dissolved organic carbon
DTH	down the hole drilling
GC	gas chromatography
GHB	general head boundaries
GW	groundwater
HPLC	high-performance liquid chromatography
IWRM	integrated water resources management
LC	liquid chromatography
LPCD	liters per capita per day
MAR	managed aquifer recharge
MS	mass spectrometry
NOM	natural organic matter
ODEX	overburden drilling with eccentric bit
OMP	organic micropollutants
PAH	polycyclic aromatic hydrocarbons
PW	production well
RCW	radial collector well

SPE	solid phase extraction
SS	suspended solids
SW	surface water
THM	trihalomethanes
TOC	total organic carbon
UFW	unaccounted for water
WQI	water quality index
WSP	water safety plan
WTP	water treatment plant
WWTP	wastewater treatment plant

CONTENTS

1

Chapter

INTRODUCTION TO RIVERBANK FILTRATION AND NEED FOR IT IN INDIA

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This chapter introduces riverbank filtration (RBF) as a viable natural treatment of water mainly for drinking water production but also for industrial purposes and irrigation. The processes are illustrated, its advantages and limitations are highlighted and an overview of the application and potential of RBF in India is provided.

KEYWORDS: Riverbank filtration, natural treatment, drinking water, India

INTRODUCTION

It is widely accepted that India, with more than 1.21 billion people[1], face significant challenges in meeting the growing water supply needs of an increasing population. The problem is particularly acute for the urban population that comprises around 31.2% of the total population. Furthermore, the expansion of the water supply and sanitation infrastructure in Indian urban areas has not been able to keep pace with the growing population. Consequently, the substantial discharge of untreated to partially treated industrial and domestic wastewater into surface water leading to exceptionally high pathogen counts and organic pollution[2,3] and very high monsoonal turbidity are major problems. These cause frequent interruption of drinking water production by plants that directly abstract SW and conventionally treat it (flocculation, sedimentation, rapid sand filtration and disinfection). This is an ubiquitous issue experienced in many regions in India, which can and is being addressed by the application of riverbank filtration (RBF) at some locations.

RBF is used as a means of primary and pre-treatment by water utilities throughout the world, especially in Europe and North America. In Europe, more than 145 years of experience exist in the operation and maintenance of large bank filtration schemes. At many sites, RBF schemes have been successfully operated for several decades. By using wells installed in / near the banks of rivers, RBF combines the advantage of easy access to large volumes of SW with the benefit of natural filtration during subsurface (aquifer) passage. Consequently RBF is used where groundwater resources are limited; the direct abstraction of surface water followed by conventional treatment is costlier than treating bank filtrate and/or the fluctuations of surface water quality require enhanced treatment to meet the desired quality. The aim of this chapter is to introduce the process of RBF, highlight its advantages and give an overview of its application in India. The chapter concludes with a discussion on the need to develop RBF in India.

Riverbank filtration

Processes

Riverbank filtration (RBF) or simply bank filtration (BF, a unified term for river and lake bank / bed filtration)is a process in which the subsurface at a river or lake bank serves as a natural filter and physically and biochemically removes potential contaminants present in the surface water (Fig. 1-1). BF is initiated by the lowering of the groundwater (GW) table below that of an adjoining surface water (SW) table which

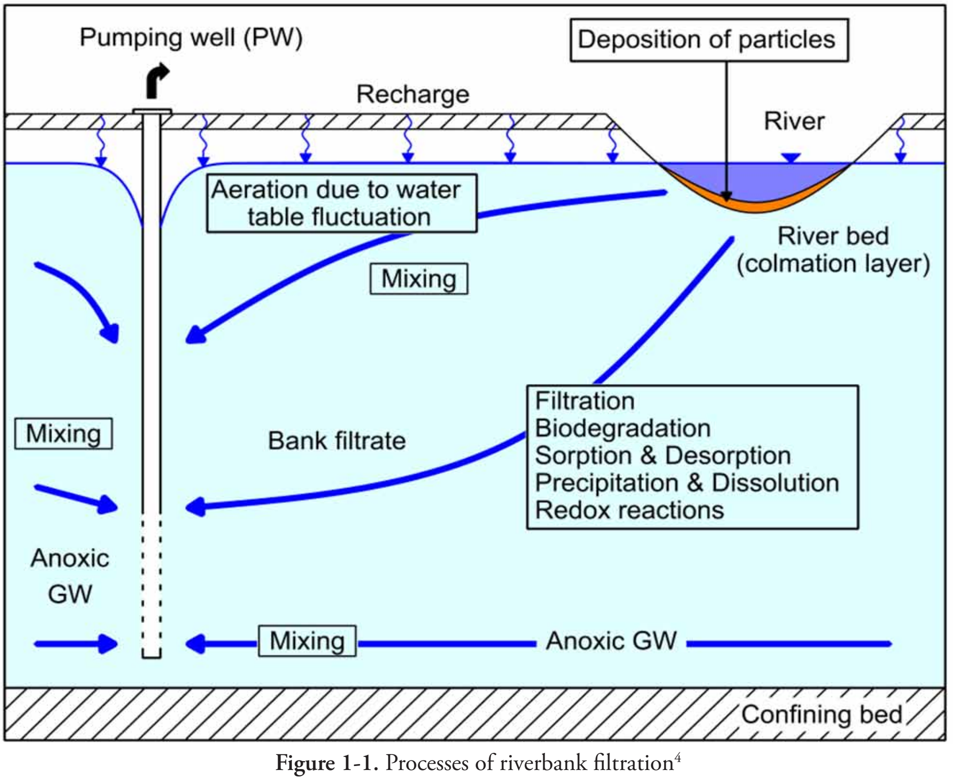

Figure 1-1. Processes of riverbank filtration[4]

induces SW to infiltrate through the permeable river bed and bank (or lake bank) into the aquifer as a result of the hydraulic gradient. The infiltration may be the direct result of an influent river under natural conditions or be induced by GW abstraction wells

The success of RBF schemes is dependent on the microbial activity and chemical transformations that are commonly enhanced in the clogging layer within the river bed compared to those that take place in surface or groundwaters. The biogeochemical interactions that sustain the quality of the pumped bank filtrate depend on numerous factors including riverbed and aquifer structure and mineralogy, SW quality, particle content and composition, oxygen and nitrate concentrations in the SW, types of organic matter in the surface and groundwater environments and land use in the local catchment area[5].

Hydraulic controls

For the quantitative and qualitative management of bank filtration systems, the catchment zones, infiltration zones, mixing proportions in the pumped raw water, flow paths and flow velocities of the bank filtrate need to be known. Flow conditions during bank filtration are commonly described using interpretations of water level measurements and groundwater flow modelling. An important factor is the formation of the colmation layer within the river bed (Fig. 1-1) that has a reduced hydraulic conductivity due to clogging from the input and precipitation of sediment particles, micro-organisms and organic colloids, precipitation of iron and manganese hydroxides and eventually calcium carbonate as well as gas bubbles. The hydraulic conductivity of the river bed varies with the dynamic hydrology and therefore cannot be regarded as constant.

During floods that have sufficient hydraulic transport energy, the river bed can be reworked and the colmation layer eroded. In general, a higher portion of infiltrated water in the pumped rawwater is expected due to removal of the clogging layer and the greater hydraulic gradient from the river to the wells. Severe floods can also have a detrimental effect by eroding the river bank and thus affecting the installedproduction wells and the GW flow regime; e.g. flow path lengths in the aquifer and retention times of the bank filtrate.

Attenuation of contaminants and pathogens by bank filtration

The beneficial attenuation processes listed subsequently result mainly from mixing, biodegradation and sorption processes within two main zones (Fig. 1-1): the biologically active colmation layer, where intensive degradation and adsorption processes occur within a short residence time; and along the main flow path between the river and abstraction well where degradation rates and sorption capacities are lower and mixing processes greater.RBF with its natural attenuation processes has the following advantages:

1. equilibration of temperature changes and concentrations of dissolved constituents in the bank filtrate;
2. removal of particles, turbidity, heavy metals, biodegradable compounds,algae and cyanobacteria, pathogenic bacteria, viruses and parasites, partial attenuation of absorbableorganic compounds, oil products and pesticides, pharmaceutical wastes and other trace organics, and decline of mutagenic activity.

Given sufficient flow path length and time and sufficient filtration capacity of the river bed and aquifer, microbial contaminants will be removed or inactivated to levels that help protect public health. The active attenuation processes during RBF, even in a sub-optimal setting or time, are likely to mitigate the public health impact[6]. Studies at RBF sites in the United States confirmed the results from studies in Europe concerning the substantial removal of natural organic matter after subsurface passage, thus reducing the potential for the formation of disinfection by-products after chlorination[7].

However, undesirable effects of bank filtration on water quality can include increases in dissolved iron, manganese and arsenic concentrations,ammonium andhardness.

Environmental and socio-economic benefits

From a sustainability point of view, RBF systems make better sense than full-scale treatment plants that directly abstract SW, since the energy and resource use in RBF will be lower and little to no chemical residues will be produced. RBF systems will require less energy to operate and to deliver a unit amount of water than conventional SW treatment systems. Furthermore,RBF has socio-economic values (Table- 1-1). In this context, the development of new RBF systems since 2010 in the mountainous state of Uttarakhandhas increased the per-capita availability of drinking water and resilience of these schemes against droughts and floods[8]

Table 1-1. Socio-economic value of bank filtration[9]

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

Overview of riverbank filtration in India

As of 2018, data-collection field surveys and scientific studies from 2003 onwards have revealed the presence of at least 26RBF systems across India[10-12](Fig. 1-2). These systems, with an aggregate production of more than 400,000 m^3/day,are located in different hydro-climatic and geological settings that accordingly have distinct advantages.Most RBF sites are located in regions having a substantial vertical and horizontal extent of alluvium, most prominently in the Indo Gangetic Plain. However, some RBF sites are also located in hilly, hard rock and coastal areas, such as in the states of Uttarakhand, Jharkhand and coastal Andhra Pradesh. In these areas the alluvium is mainly confined to the river course and nearby areas and is of limited thickness (3–7 m in Jharkhand; up to 20 m in Uttarakhand). Thus the existing RBF schemes are a suitable means for production of drinking water, and in some areas the only viable means of obtaining water compared to direct surface water or even GW.

In this context, RBF buffers the quantity of water required through bank- / bed-storage and can thus be considered as an element of managed aquifer recharge (MAR) and integrated water resources management (IWRM). Thus, RBF supplements existing surface and GW abstraction for drinking water supply in Ahmedabad, Delhi, Mathura, Dehradun and Srinagar (Uttarakhand) and serves as an alternative to SW and supplements GW abstraction in Haridwar, Patna, Medinipur, Kharagpur and parts of Jharkhand, Andhra Pradesh and Uttarakhand.

Field investigations have confirmed that there is a large potential to use RBF as an alternative to directly abstracted SW for drinking water production, primarily because RBF effectively removes pathogens and turbidity especially in monsoon. A significant removal of Total Coliforms, E. coli and turbidity by up to 90–99.99 % (≥4 Log_{10} removal) during RBF has been observed at various sites in Uttarakhandand similar high removals for adenoviruses and noroviruses in Delhi[13-19]. Other key water quality benefits of RBF are the removal of color, dissolved organic carbon and organic contaminants that require high doses of chlorine and thereby create a greater risk for formation of carcinogenic disinfection by-products (DBP), as reported for the RBF site in Mathura[20,21]. The removal of endocrine disruptor compounds and organochlorine pesticides by RBF wells along the Yamuna River between Delhi and Mathura has also been observed[22,23]. Overall, RBF produces water of a superior aesthetic quality than that derived directly from SW, as observed from investigations in Muzaffarnagar (rural Uttar Pradesh)[24], Delhi and Mathura.

The need for riverbank filtration in India

Although in Europe new RBF site developments are rare due to decreasing water demand, there is a renaissance of RBF technology in the USA, South Korea, Egypt and other countries[25]. Consequently, the main aspects favouring the use of RBF in India are summarised as[26]

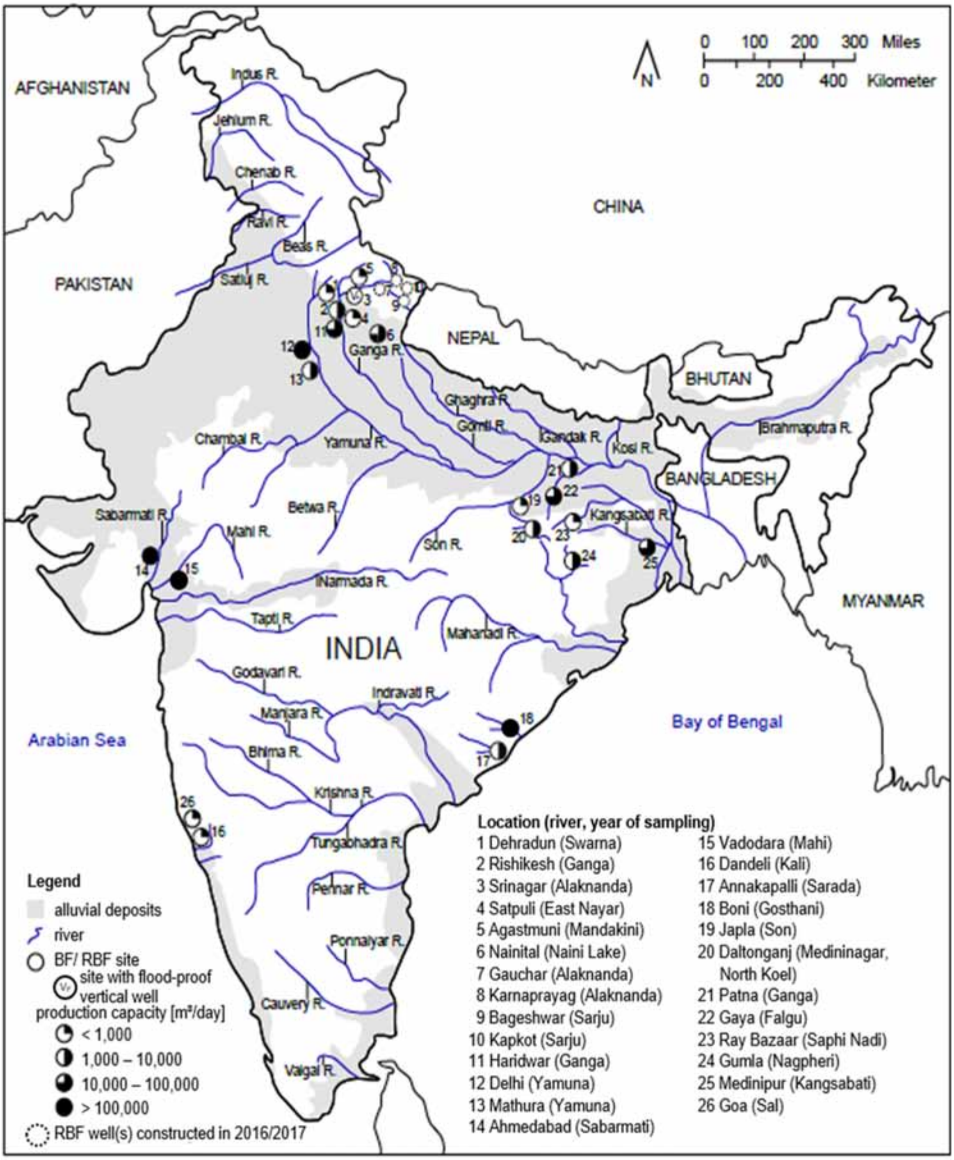

Figure 1-2. Operational RBF sites in India[12]

1. A sharp increase in India's urban population has resulted in rapidly increasing quantities of domestic sewage and industrial wastewater being discharged into river systems. Thus, in India the removal of microbial pathogens is considered crucial produce drinking water from surface water. RBF offers effective removal of microbial pathogens and is thus also recognised as a natural drinking water treatment method by the World Health Organisation[27].

2. Conventional water treatment systems in India are not designed to remove most dissolved chemicals (organics, organic micropollutants) so the removal efficiency of these systems for various dissolved contaminants is very low and could be increased in combination with RBF.
3. Many drinking water utilities in India prefer to comply with a Government of India directive to opt for direct surface abstraction instead of groundwater abstraction, especially when groundwater is insufficient and of inadequate quality[28]. The compliance can be problematic if the conventionally treated water does not meet prescribed standards[27,29].

Despite the advantages of being a sustainable natural process, an element of IWRM and a component of MAR, RBF is intentionally used only at some places in India resulting in a low portion of less than 0.1% of drinking water produced thereof.Considering the many existing but undocumented and unexplored RBF systems, the potential for RBF in India and taking into account the advantages of using RBF, there is a need for the organized and scientific development of RBF in India. The need for guidelines to systematically plan, investigate and design RBF systems has often come to light through interactions with practitioners in Indian water supply organizations, researchers and bureaucrats and is considered important for the development of RBF in India.

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REFERENCES

1. COI Rural Urban Distribution of Population. Provisional Population Totals, Census of India (COI) 2011. Office of the Registrar General and Census Commissioner, India, Ministry of Home Affairs, Government of India. *Available: http://censusindia.gov.in/2011-prov-results/paper2/data_files/india/Rural_ Urban_2011.pdf;* Accessed: 25.02.2015
2. CPCB Status of water supply, wastewater generation and treatment in class-I cities and class-II towns of India - Control of Urban Pollution Series: CUPS/ 70 / 2009 - 10. Central Pollution Control Board (CPCB), Ministry of Environment and Forests, Government of India, New Delhi, India.
3. Kumar D., Sharma S.K., Asolekar S.R., Constructed Wetlands and Other Engineered Natural Treatment Systems: India Status Report. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context – SaphPani.IWA Publishing, London,* UK, 2016, 127-148. ISBN13: 9781780407104.

4. Grischek T., Paufler S., Prediction of iron release during riverbank filtration. *J. Water*, 2017,**9(5)**, 317, 1-13. doi 10.3390/w9050317.

5. Grischek T., Schoenheinz D., Ray C., Siting and design issues for riverbank filtration schemes. In: Ray C., Melin G., Linsky R. B. (eds.) Riverbank Filtration – Improving source-water quality. *Water Science & Technology Library, Kluwer Academic Publishers,Dordrecht,* 2002, **43**, 291-302.

6. Schijven J., Berger P., Miettinen I., Removal of pathogens, surrogates, indicators, and toxins using riverbank filtration. In: Ray C., Melin G., Linsky R. B. (eds.) Riverbank Filtration – Improving source-water quality. *Water Science & Technology Library, Kluwer Academic Publishers, Dordrecht,* 2002, **43**, 73-116.

7. Weiss W.J., Bouwer E.J., Ball W.P., O´Melia C.R., Lechevallier M.W., Arora H., Speth T.F., Riverbank filtration – fate of DBP precursors and selected microorganisms. *Journal American WaterWorks Association,* 2003, **95(10),** 68-80.

8. Kimothi P C., Dimri D.D., Adlakha L. K., Kumar S., Rawat O.P., Patwal P.S., Grischek T., Sandhu C., EbermannJ., Ruppert M., Dobhal R., Ronghang M., Kumar P., Mehrotra I., Uniyal H.P., Development of Riverbank Filtration in Uttarakhand. Journal of Indian Water Works Association, *Special Issue on RiverBank Filtration,* December 2012, ISSN 0970-275X, 13-18.

9. Ray C., Schubert J., Linsky R.B., Melin G., Introduction. In: Ray C., Melin G., Linsky R.B. (eds.) Riverbank Filtration – Improving source-water quality. *WaterScience & Technology Library, Kluwer Academic Publishers, Dordrecht,* 2002**, 43,** 1-15.

10. Ray C., Drinking water supply in India and future potential for riverbank filtration. In: Ray C., Ojha C. S. P. (eds.) Riverbank Filtration – Theory, Practice and Potential for India. *Proceedings of the International Workshop on RBF*, Indian Institute of Technology Roorkee, India, 1-2 March 2004, Report CR-2005-01, 3-8.

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

12. Sandhu C., Grischek T., Ronghang M., Mehrotra I., Kumar P., Ghosh N.C., Rao Y.R.S., Chakraborty B., Patwal P.S., Kimothi P.C., Overview of bank filtration in India and the need for flood-proof RBF systems. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context – SaphPani*. *IWAPublishing*, London, UK, 2016, 17-38. *Open access at https://zenodo.org/record/61088#.V_Oqvcl65Ng.*

13. Dash R.R., Bhanu Prakash E.V.P, Kumar P., Mehrotra I., Sandhu C., Grischek T., River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. *Hydrogeology Journal*, 2010, **18(4),** 973-983.

14. Dash R.R., Mehrotra I., Kumar P., Grischek T., Study of water quality improvements at a riverbank filtration site along the upper course of the River Ganga, India. *Desalination and Water Treatment*, 2015**, 54(9),** 2422-2431.

15. Gupta A., Singh H., Ahmed F., Mehrotra I., Kumar P., Kumar S., Grischek T., Sandhu C., Lake bank filtration in landslide debris: irregular hydrology with effective filtration. *Sustainable Water Resources Management*, 2015, **1(1),** 15-26.

16. Ronghang M., Kumar P., Mehrotra I., Kimothi P.C., Adlakha L. K., Sandhu C., Grischek T., Voltz T.J., Application of riverbank filtration for year-round drinking water production in a small town in the hills of Uttarakhand. *Journal of Indian Water Works Association, Special Issue on RiverBank Filtration,* December 2012, ISSN 0970-275X,19-24.

17. Sandhu C., Grischek T., Riverbank filtration in India – using ecosystem services to safeguard human health. *Water ScienceTechnology,* 2012, **12(6),** 783-790.

18. Sprenger C., Lorenzen G., Grunert A., Ronghang M., Dizer H., Selinka H. C., Girones R., Lopez-Pila J.M., Mittal A.K., Szewzyk R., Removal of indigenous coliphages and enteric viruses during riverbank filtration from highly polluted river water in Delhi (India). *Journal ofWater and Health,* 2014, **12(2),** 332-342.

19. Bartak R., Page D., Sandhu C., Grischek T., Saini B., Mehrotra I., Jain C.K., Ghosh N.C., Application of risk-based assessment and management to riverbank filtration sites in India. *Journal of Water and Health*, 2015, **13(1),** 174-189.

20. Kumar P., Mehrotra I., Boernick H., Schmalz V.,Worch E., Schmidt W., Grischek T., Riverbank Filtration: An Alternative toPre-chlorination. *Journal of Indian Water Works Association,Special Issue on RiverBank Filtration,* December 2012, ISSN 0970-275X,50-58.

21. Singh P., Kumar P., Mehrotra I., Grischek T., Impact of riverbank filtration on treatment of polluted river water. *Journal of Environmental Management*, 2010, **91(5),** 1055-1062.

22. Mutiyar P.K., Mittal A.K., Pekdeger A., Status of organochlorine pesticides in the drinking water well-field located in the Delhi region of the flood plains of river Yamuna. *Drinking Water EngineeringScience*, 2011, **4(1),** 51-60.

23. Sprenger C., Lorenzen G., Hülshoff I., Grützmacher G., Ronghang M., Pekdeger A., Vulnerability of bank filtration systems to climate change. *Science of the TotalEnvironment,* 2011, **409(4),** 655-663.

24. Thakur A.K., Ojha C.S.P., Grischek T., Ray C., Sandhu C., Water Quality Improvement through River Bank Filtration in Extreme Environmental Conditions. *Journal of Indian Water Works Association,* 2010, **42(2),** 106-115.

25. Grischek T., Sandhu C., Ghosh N.C., Kimothi P.C., A conceptual master plan for RBF water supply in India - science, policy and implementation aspects. *Proceedings of the Indo-*

German Conference on Sustainability - Exploring planetary boundaries and their challenges and opportunities, Chennai (India), 2016, **27**, 54-55.

26. Sandhu C., A Concept for the Investigation of Riverbank Filtration Sites for Potable Water Supply in India. Ph. D. thesis. Dresden University of Applied Sciences, Faculty of Civil Engineering and Architecture, Division of Water Sciences and TU Dresden, Faculty of Environmental Sciences, Institute of Waste Management., 2015, *Available: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-208460.*
27. WHO Guidelines for drinking-water quality – 4th ed. incorporating 1st addendum. *World Health Organization*, Geneva, Switzerland, 2011, **4**, ISBN 978-9241548151.
28. CPHEEO Manual on Water Supply and Treatment, Central Public Health and Environmental Engineering Organisation (CPHEEO), *Ministry of UrbanDevelopment, Government of India,* New Delhi, India, 1999, 3rd ed.
29. IS 10500 Drinking Water – Specification. Indian Standard (second revision), *Bureau of Indian Standards*, New Delhi, 2012.

2
Chapter

PLANNING A BANK FILTRATION SCHEME

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This chapter highlights all aspects related to planning a RBF scheme in specific context to India. Policy and technical frameworks, methodologies to identify and investigate potential and existing sites are presented.

KEYWORDS: Feasibility assessment, site identification, advanced techniques

INTRODUCTION

Policy and technical frameworks for planning RBF schemes in different countries

Due to the site-specific nature of RBF no common universally applicable guidelines exist for the planning and investigation of RBF sites. Based on prevailing circumstances (water demand / need, climatic, environmental and hydrogeological factors), different countries have developed different approaches, collectively aimed towards the overall development of managed aquifer recharge (MAR) in general or in some cases RBF in particular. For example, Thailand has developed and implemented a top-down RBF site selection criterion that considers geology, hydrology, hydrogeology, land use and water supply and demand[1]. It is based on the availability of the necessary data in electronic format thereby enabling the use of GIS at national and regional scales but necessitating detailed field investigations at a local and site scale. Wide-ranging experiences on the design, operation and management of RBF systems from the United States, Germany, The Netherlands and Finland have been documented[2,3].

Furthermore in the United States, the water supply industry has adopted the broadly-defined regulatory concept "groundwater under the direct influence of surface water"[4].

Policy and technical frameworks for planning RBF sites in India

As of 2018 in India, there is no uniform policy or a specific technical framework for planning a RBF site. However, there are various framework and scientific works that support (directly or indirectly) the use of RBF in India and to which the development of RBF can be anchored. These include, but are not limited to, the National Water Policy[5], Indian Standard Guideline for Artificial Recharge to Groundwater[6] and the Master Plan for Artificial Recharge[7].In context to development of RBF in India at a state-level, the Department of Drinking Water of the Government ofUttarakhand issued a government order (GO) in March 2006 wherein specific natural treatment technologies for drinking water supply such as RBF and the use Koop wells for small-scale RBF schemes specifically designed for rural water supply should be encouraged by water supply organizations working in Uttarakhand. From a policy and an administrative perspective, the issuance of such a GO significantly simplifies planning aspects of RBF schemes for the water supply organization. As the provision of drinking water is a subject of state governments under the Constitution of India, a suitable approach can be selected to integrate or anchor RBF into various water supply infrastructure development projects at a state level.

Pre-requisites for RBF

Favourable hydrogeological conditions

The first step is for the water supply organization or the planner of a new water supply scheme to take an informed decision to opt for RBF and what the benefits of its application compared to direct surface water and / or groundwater abstraction are expected to be. This decision is coupled to the availability of suitable hydrogeological conditions because the latter must be met in order for RBF to occur. In general, the key characteristics of a potentially successful RBF site based on the review[8] of numerous RBF operations and site characteristics concluded that:

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

These parameters should be used as indicative because RBF can be used for a wide variety of conditions. On the other hand there might be conditions such as insufficient dissolved oxygen concentration available in the river water together with a high load of biodegradable organic compounds which could limit the application of RBF technique at a particular location.

Determining the need for RBF

Before investigating a potential site for RBF, the need for RBF should be clearly defined for the rural or urban communities that are to be supplied with water. This includes determining local demand for drinking water and deficits in quantity and/or quality and evaluating problems with the existing drinking water source, identifying benefits of using RBF over existing source, identifying presence of suitable surface water body and approximate location of RBF site. For this, existing manuals and guidelines on water supply and treatment and drinking water quality can be considered e.g. CPHEEO[9-12].

In general RBF is preferred for drinking water production when groundwater resources are insufficient or surface water quality fluctuations require increased efforts in water treatment to reach the desired quality.Thus the water supplier will usually choose from amongst the following objectives:

- Abstraction of a significant portion of bank filtrate (e.g. > 50 % bank filtrate in the abstracted water from the well),
- Removal of pathogens, especially in terms of log removal rates of bacteriological indicators (E. coli) that are comparatively easier to determine than protozoa and viruses,
- Maximum use of naturally occurring processes in the aquifer to attenuate organic and inorganic contaminants.

Achieving these objectives depends on the local geomorphological, hydrogeological and hydrogeochemical conditions at the proposed RBF site. Furthermore the location along the river, distance between the well and river, travel time of bankfiltrate and SW and ambient GW quality are important factors that have to be considered.Although a detailed and quantitative assessment of the risk to the environment and human health by using RBF at the proposed location may be difficult at an early stage, such as during the feasibility study, any potential risks that may be apparent should at least be considered at this stage. Existing RBF systems in India (Fig. 1-2) demonstrate certain advantages and also highlight issues that can be taken into account when determining the need for and planning a RBF scheme (Table-2-1).

Table 2-1. Hydrogeological features, advantages and issues of bank filtration sites in India[13]

BF site inFig. 1-2	General features of BF site location	Aquifers	Wells	Advantages of BF	Main issues for BF
1–11	Hilly or foothill regions by perennial SW bodies (snow-melt and spring-fed)	– Mostly shallow (up to 20 m) – Medium to coarse sand & gravel – Presence of large fluvial boulders common (influences drilling technique)	– Large-diameter caisson wells (7–10 m) – Vertical filter wells – Koop wells	– Removal of pathogens & turbidity – Year-round abstraction of water during monsoon & dry non-monsoon periods	– Construction of flood-proof wells – High sediment transport and turbidity in rivers during monsoon
12–13, 21	Middle-lower courses of rivers in Indo-Gangetic Plain	– Mostly shallow to deep (> 20 m) – Medium to fine alluvium	– Vertical filter wells typically 200–400 mm diameter – Radial collector wells located on riverbank and in riverbed	– Removal of pathogens, turbidity & organics – Year-round abstraction of water during monsoon & dry non-monsoon periods	– Partly extremely polluted SW (sites 12, 13) – Regulated river flow (sites 12,13) – Landward GW cont-amination – Fine sediments in lower courses of rivers may impede SW–GW interaction*
14–26 (except 21)	Peninsular India, east& west coast, semi-arid western India (Gujarat) and parts of South Ganga Plain	– Mainly hard rock aquifers in peninsular India. Limited alluvium deposits, partly confined to river courses – Medium to coarse sand and gravel riverbeds with thickness 3–20 m	– Radial collector wells in riverbed – Vertical wells (site 22, 400 mm diameter) – Caisson well (site 25)	– Removal of pathogens & turbidity – Year-round abstraction of water during monsoon & dry non-monsoon periods – Abstraction during monsoon and post-monsoon is generally higher compared to dry pre-monsoon	– Construction of flood-proof wells – Short travel time of bank filtrate to radial collector wells located in riverbeds, thereby possibility of breakthrough of turbidity and pathogens

* Possibility of presence of low-hydraulic conductivity layer which only partly cuts through the riverbed, local deposition of fines (e.g. site 21 in Patna[14])

Overview of methodology for planning and investigating a RBF scheme

Based on field investigations and scientific studies since 2005 at existing and potential RBF sites along the Ganga River and the development of new sites in Uttarakhand along tributaries of the Ganga, an overview of an overall general methodology is presented in Fig. 2-1.

Although it is recommendedto incorporate quantitative microbial risk assessments in the overall strategy[15,16] (Fig. 2-1), these can normally be performed only once sufficient water samples have been analysed for pathogens and after the RBF scheme actually begins abstracting bank filtrate or the induced surface water begins to arrive at the RBF well and is abstracted by it. While the analysis for bacteriological indicators (E. coli) can be performed easily in India, the limitations of many laboratories to analyse water samples for viruses and protozoa should be taken into consideration. Nevertheless, provisions should be made during the planning phaseto analyse these if the project is approved.

The associated tasks and aspects to be considered with the stages shown in Fig. 2-1 are visualized in Fig. 2-2 for the detailed investigation of a RBF site. Accordingly the stages 1 and 2 (Fig. 2-1) can be condensed into an initial site-assessment stage, as shown in Fig. 2-2. The relevant aspects of the investigation stages are discussed hereafter.

Feasibility assessment

Aim

In this stage, it is important to determine (mostly with the help of existing and available data and information) whether there is a local demand or a clearly defined environmental or health benefit of using RBF for drinking water supply (Fig. 2-1, stages 1 & 2). Additionally hydrogeological conditions and policy and local environmental legal aspects should be considered as the development of water production and supply systems depend on the local economy, including various stakeholders ranging from the regulator (administration or local government body) to the water supply organization and the consumer.In India, the state / local water supply organization is usually aware of the existing water quantity and quality issues affecting drinking water production.

Water quantity aspects

Piped water supplies to communities have to provide an adequate quantity and quality for domestic personal and household needs, institutional needs (offices, administration, public services), public purposes (street washing/ watering, flushing of sewers, watering of public parks), industrial and commercial uses, firefighting, livestock requirements and the minimum permissible unaccounted for water (UFW)[9]. The per capita recommended water supplies in communities include requirements of water for commercial, institutional and minor industries, but the bulk quantity to such establishments should be assessed separately with proper justification (Table 2-1).

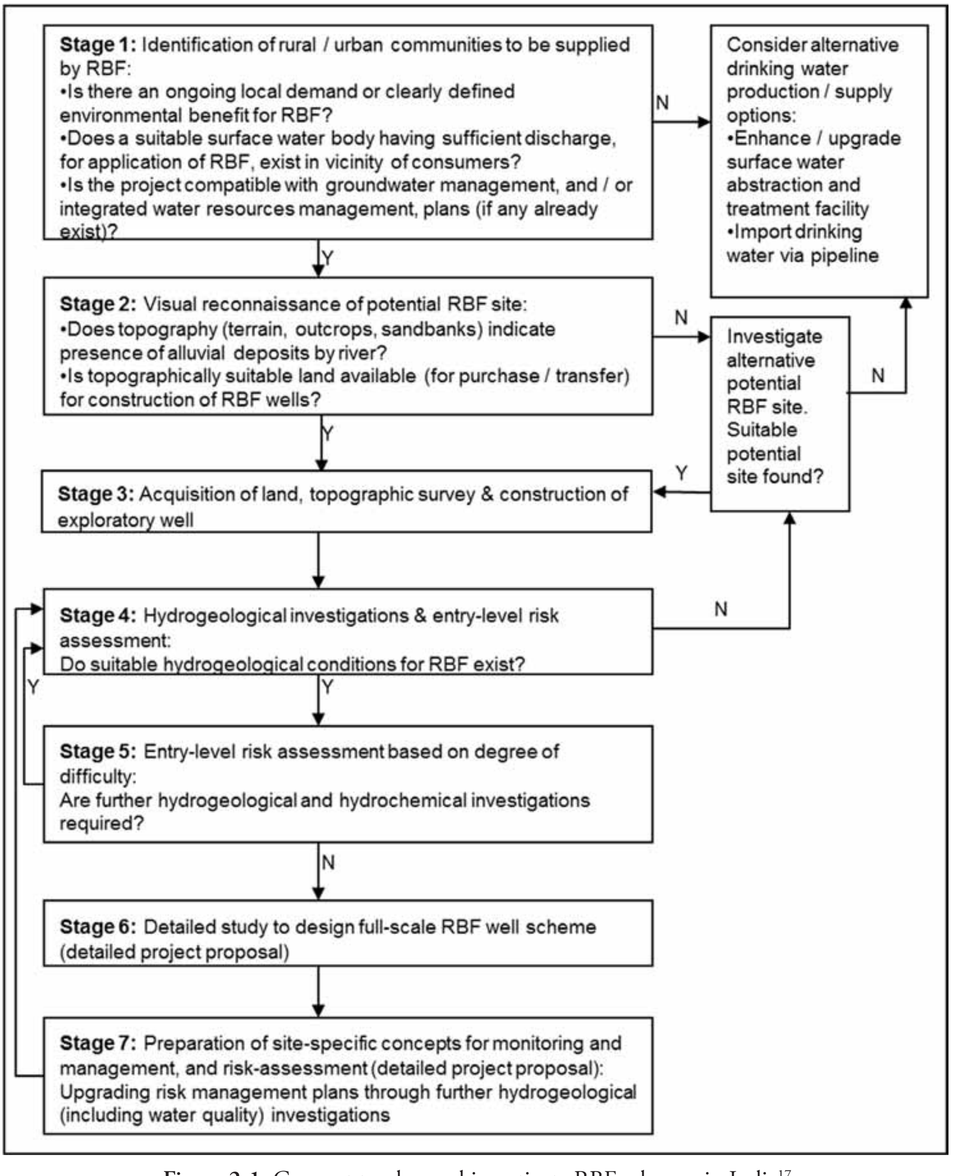

Figure 2-1. Concept to plan and investigate RBF schemes in India[17]

Table 2-1. Recommended per capita water quantity for designing schemes[9]

Type of water supply and sewerage system	Recommended water supply level (litre per capita per day / LPCD)
Towns provided with piped water supply but without sewerage system	70+15% (UFW)
Cities provided with piped water supply and existing or planned sewerage	135+15% (UFW)
Metropolitan and mega cities with piped water supply and existing or planned sewerage system	150+15% (UFW)

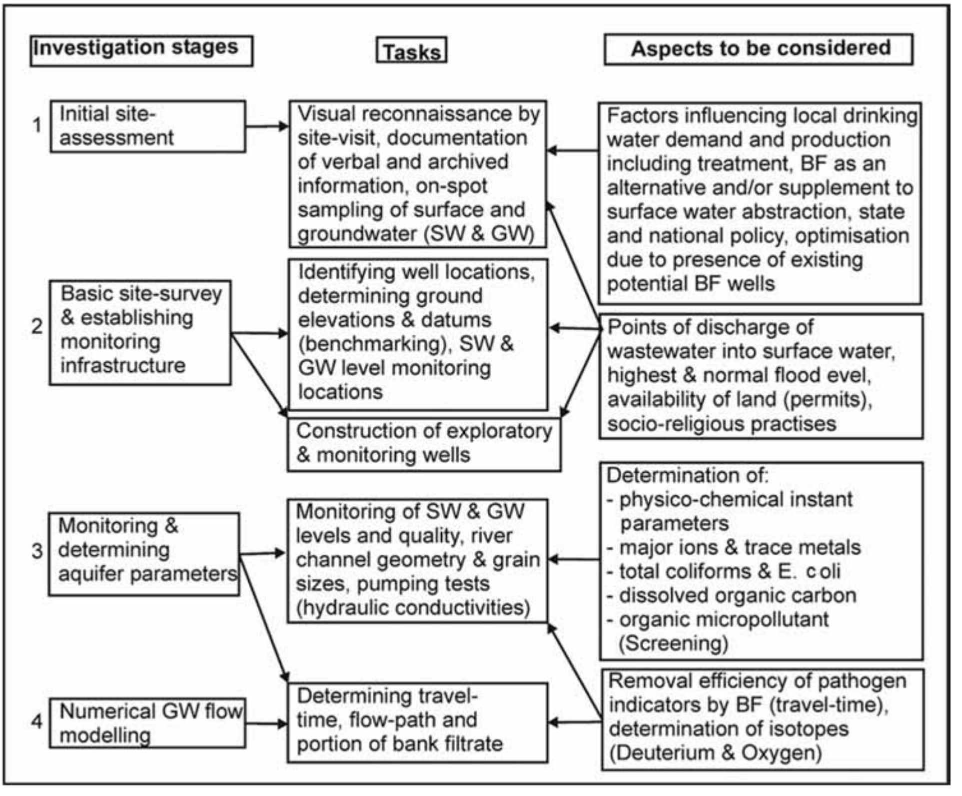

Figure 2-2. Methodology for the detailed investigation of a RBF site[17]

To obtain an assessment of the expected improvement in quantity of drinking water supplied, the real case of development of RBF in four towns in Uttarakhand is highlighted as an example (Table- 2-2)[18]. An analysis of drinking water production data of conventional surface water abstraction schemes showed a significant shortfall in production in 2010 to match the existing demand of 135 litres per capita per day (LPCD) as well as an additional 15 % (total 155 LPCD).

The main reasons for the shortfall were:

- Rapid increase in water consumption compared to existing capacity and
- Decrease in discharge of the riversand the shifting course away from the water abstraction structures resulting in a reduced volume of raw water for abstraction.

This also highlights the need to obtain a realistic prognosis of demographic factors such as population growth projections and migration trends, for which data can be obtained from the Registrar General and Census Commissioner of India.

Table 2-2. Status in 2010 of drinking water supply schemes in Uttarakhand that were subsequently supplemented with RBF systems[18]

Parameter	Srinagar	Karnaprayag	Agastmuni	Satpuli
Population in 2001 (Census of India, 2001)	19,658	6,955	3,359	5,200
Estimated population including pilgrims in 2010	31,500	8,700	5,700	7,900
Mean altitude [m above mean sea level]	551	769	733	580
Adjacent river	Alaknanda	Alaknanda	Mandakini	East Nayar
Main raw water source in 2010	Alaknanda	Ghat Gad &3 other streams	Sau Gaun Stream	Redul Stream
Distance [km] from surface water source to water treatment plant (WTP)	WTP located at source	1–6	7 & 25	9
Minimum discharge of existing raw water source in summer 2009 [m^3/day]	910^6–21×10^6 *	5251	86	345
Average production in 2010 [m^3/day]	3,750	640	70	310
Demand in 2010 [m^3/day]	4,880	1,340	880	1,070
Deficit in 2010 [m^3/day]	1,130	700	810	760
Per capita availability in 2010 [LPCD]	119	74	12	39

* Based on mean monthly discharge from March–May 2005[19]

Water quality aspects

The environmental and health benefit of using RBF can be determined by examining the water quality problems experienced with the existing conventional surface water abstraction system in context to the expected or desired improvements to be obtained from the eventual application of RBF. The main objective of long-term water quality monitoring is to get an overall understanding of the surface and groundwater quality, identify parameters of concern and assess their removal by RBF and eventual risks, determine the applicability of natural tracers and quantify the portion of bank filtrate in the water abstracted from the production wells.

Thus, to start with and in case no existing water quality data is available, a snap-shot sampling or screening that coversat least thequality parameters shown in Fig. 2-2 ("Monitoring & determining aquifer parameters") should be conducted and compared to the Indian Standard for Drinking Water[12]. Thereafter and if the initial assessment indicates that RBF is a potentially feasible alternative, a more elaborate water quality monitoring concept can be implemented, wherein a broader spectrum of parameters comprising physical-chemical instant field parameters, pathogen indicators, organic and inorganic chemicals and nutrients is included (Fig. 2-3).

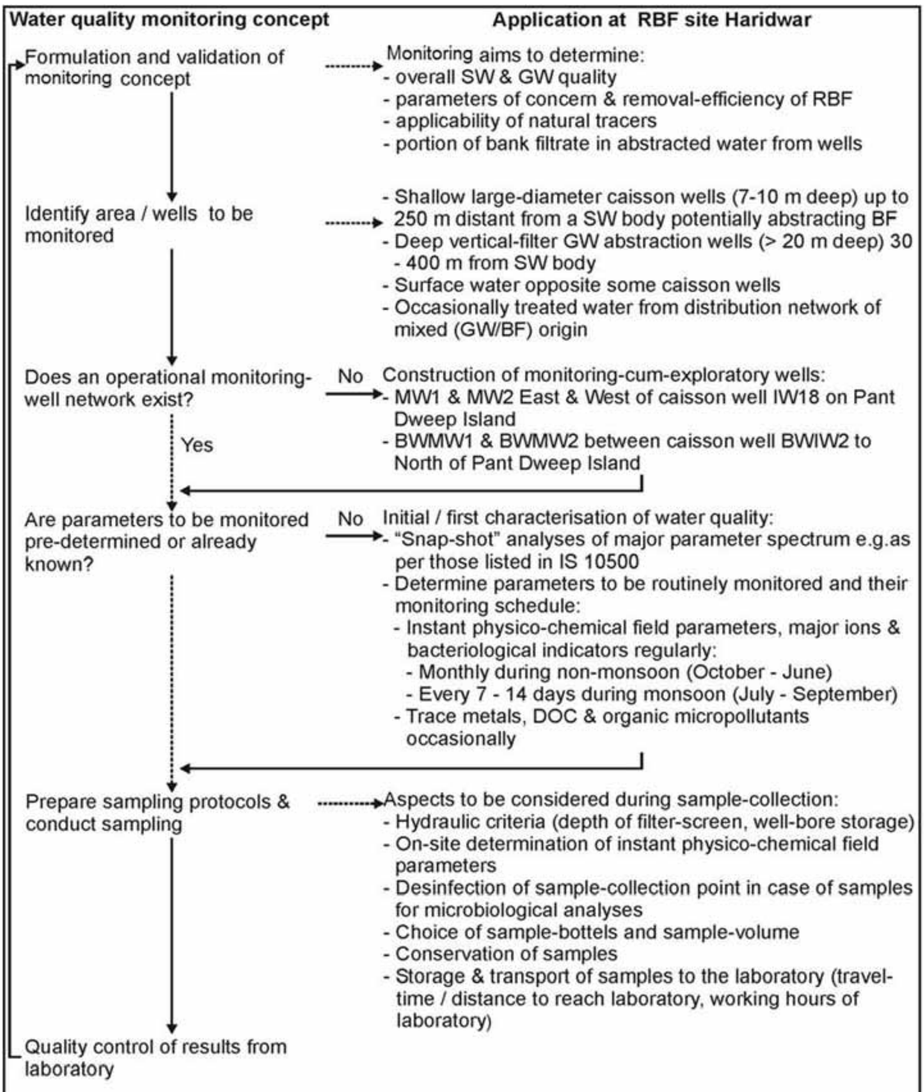

Figure 2-3. Water quality monitoring concept based on example of RBF site in Haridwar[17,21]

Non-invasive techniques for the identification of a RBF site

The identification of suitable RBF sites in hilly, alpine and hard rock regions is problematic due to limited vertical and horizontal extent of alluvial deposits, unsuitable exploratory well drilling techniques, steep terrain and lack of access for drilling equipment.For the identification of potential RBF sites using non-invasive techniques, an example of a site-suitability analysis can be cited[20]. This approach uses geographical information systems (ArcGIS v10.2), remote sensing data and groundwater flow modelling thatwas developed for a study area comprising a 100 km long mountainous stretch of the Alaknanda River in the state of Uttarakhand (Fig. 2-4). Different thematic maps of land use, watershed, river network, terrain and geology were generated with the help of remote sensing data. The potential locations of alluvial deposits were identified by reclassified thematic maps, using a weight-age factor in GIS domain. The sites thus identified were characterized using numerical groundwater flow modelling for their optimal abstraction rate, travel time and flow field of the induced bank filtrate.

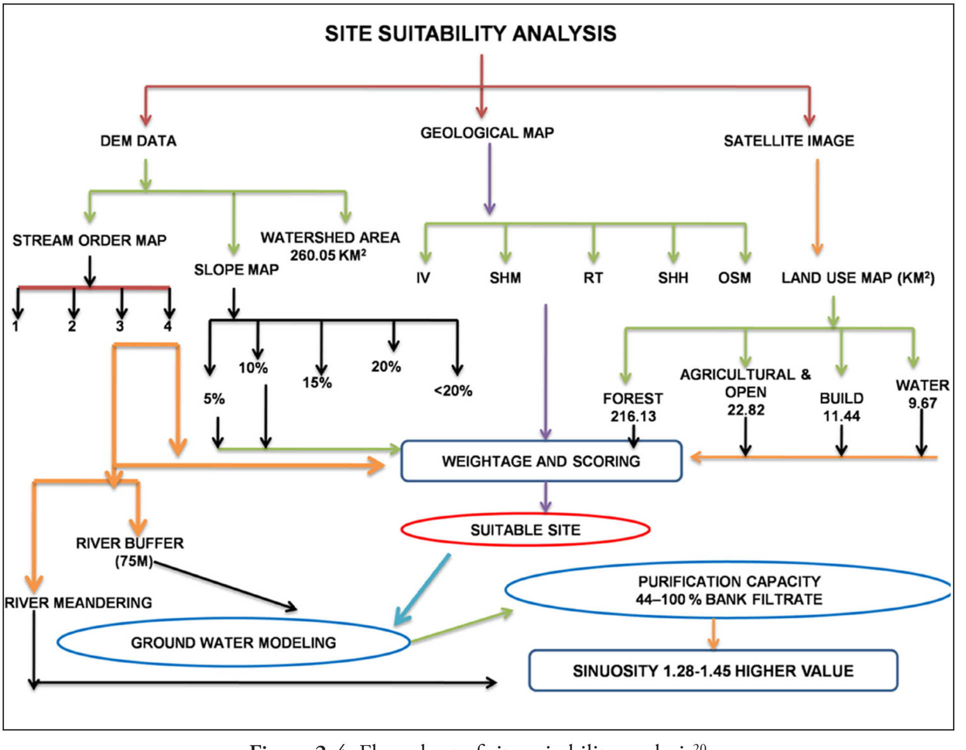

Figure 2-4. Flow chart of site suitability analysis[20]

Other non-invasive techniques include geophysical tools such as seismics, geoelectrics, self-potential, electromagnetics, ground penetration radar, gravity and magnetics. These can be applied to obtain information on the structural settings of the subsurface geology, hydrogeological settings and dynamic processes (Table-2-3)[22]. However, an optimal and reliable interpretation of data is more likely attainable using a multi-parameter approach by applying a combination of methods. Therefore, the criteria for selection of a specific method depends on the expected physical contrasts between the measured parameters, the spatial resolution of the method and organizational and logistical factors such as duration of the geophysical measurements, area to be investigated and cost and manpower involved. The cost, manpower and time involved for all types of non-invasive techniques are important to consider during investigations of a potential RBF site because while each method offers certain advantages, these can only be performed by experienced personnel. Furthermore the information obtained from these techniques must be supported with information from at least one invasive technique, ideally from an exploratory well.

Table 2-3. Geophysical tools for the exploration of potential RBF sites[22]

Method	Parameter measured (symbol)	Indicator for
seismics	velocity (v)	mineral content, porosity, density
geoelectrics	resistivity (p)	porosity, water content, salinity of fluids (water)
self-potential	natural potentials (U)	fluid flow, temperature gradients, ion concentra-tions
electromagnetics	conductivity (σ), permittivity (ε)	porosity, water content, water salinity
ground penetration radar	permittivity (ε), conductivity (σ)	porosity, water content, water salinity
gravity	density (ρ)	density of minerals, porosity
magnetics	magnetic permeability (κ)	content of magnetic minerals(e.g. magnetite)

Visual survey of a potential RBF site, collection and synthesis of data

It is advisable to have a physical visit to the potential site and conduct a visual inspection. This can usually be performed easily with support from the local water supply organization or other related organizations that are well-informed about the local area. As an example, visual site inspections in 2005-2006 along the Ganga indicated favourable conditions for RBF (Table- 2-4).

During the visual reconnaissance, favourable conditions for RBF are indicated by the presence of alluvial deposits, topographically relatively level land, perennial river flow and aesthetically good water quality. Other factors to take into account are the presence of any existing wells near or on the riverbank which may eventually already abstract some bank filtrate or can otherwise be used for monitoring water quality, landside wells to determine the quality of ambient groundwater, points of discharge of wastewater into the rivers as a RBF site should ideally be located upstream and site-access as highlighted in Table- 2-5.

Table 2-4. Results of initial site-assessment for the potential application of RBF[17]

Parameter	Haridwar	Patna	Srinagar
Characteristics of city / town			
Population	Large (>100,000)	Large (>1,000,000)	Medium (≥31,500)
Water supply	– Centralized (state government) – No data – Groundwater and possibly bank filtrate	– Centralized (municipal and state government) – No data – Groundwater and possibly bank filtrate	– Centralized (state government) – Only surface water abstraction until 2006
Well design and operation			
Type of existing wells	– Large diameter (~10 m) caisson – Shallow (≤10 m) – Intermittent operation – Vertical line shaft pump	– Vertical filter – Deep (150–200 m) – Intermittent operation – Vertical line shaft pump	– 2 vertical filter exploratory wells with submersible pumps built in August 2006
Relative proximity of wells to river	≤100 m	<300 m	<450 m
Production/ quality data	Non-existent	Non-existent	Non-existent
River characteristics			
Width of river channel	50 (UGC) – 600 m (river)	1–2 km	80–400 m
Riverbank material	Medium sand to boulders	Silt to fine sand	Medium sand–boulders
Aesthetic appearance	Good	Moderate	Good

Table 2-5. Criteria for potential RBF site selection in Srinagar, Uttarakhand[17]

Favourable factors	Limiting factors
– Topographically relatively levelled site, visual presence of alluvial deposits by the river towards the middle and downstream portion of Srinagar town.	– The river becomes narrower upstream of Srinagar town indicating insufficient areal extent and thickness of alluvium confirmed by visibly exposed bedrock of the river, hydrogeological map (NRSC, 2008) and geological investigations.

– Sufficient year-round river flow. However, during the period from the peak-monsoon (August–October) to the post-monsoon (January–February), the waterline can recede up to 190 m from the southern bank.	– Diversion of river flow through a tunnel (for electricity generation) upstream of Srinagar town and consequent regulation of natural surface flow.
– Availability of undeveloped bare land at a distance of 170 m from the river channel in the downstream portion of Srinagar town. No permanent human dwelling within 50 m radius, a few human dwellings within 100–200 m.	– Srinagar town is primarily spread over riverside areas with a low slope. Consequently, availability of land for a RBF site that should ideally be located upstream of a habitation and/or point(s) of discharge of wastewater into the river, is limited or expensive.
– Existing access to the proposed RBF site by a permanent road for transport of heavy equipment and construction materials (drilling rig, electricity generator, pipes, construction materials etc.).	– Construction of an access road specifically for the investigation and development of a RBF site may be required (land constraints). In such cases, permission needs to be obtained from the responsible authority.

General approach

The described methodology for planning and investigation of potential RBF sites has proven useful to characterize some sites in detail in Uttarakhand and conduct an initial site-assessment of RBF sites in other parts of India.Before investigating a potential site for RBF, the need for RBF should be clearly defined for the rural or urban communities. This in turn helps to site and design the RBF wells. The initial site-assessment can commence by identification of existing wells that could possibly abstract bank filtrate. Normal yearly monsoon flood levels and flood return periods should be considered so that the new RBF site is not inundated by the flood. The snap-shot water quality analysis is a good method to obtain an initial overview of the ambient groundwater, surface water and potential bank filtrate quality. Information on local geological, hydrogeological and hydrological conditions should be extensively researched via available national public domain journals, databases and maps as well as documented and verbal information with various water-related organizations. Often they contain valuable information for a local and regional scale that may not be available in international journals. Then, as far as possible, a preliminary numerical groundwater flow modelling study to obtain an initial assessment of the RBF system configuration should be performed to determine whether the selected site can fulfil the requirements (distance of wells, travel time, well-spacing, extractable water quantity from aquifer). If the initial site-assessment is inconclusive about the thickness of alluvium and depth to bedrock (determined from existing near-site borehole logs of drinking water and irrigation wells, exploratory wells for road and railway bridge piers, tunnels, dams etc., local and regional literature including maps) especially in mountainous and hard rock areas, then a geophysical exploration should be considered provided it is more cost-effective compared to drilling an exploratory well.The preference of using rotary drilling methods without drilling fluids like bentonite to drill borehole for exploratory well instead of using the "overburden drilling with eccentric bit (ODEX)" technique[23] should be given.

ACKNOWLEDGEMENTS

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REFERENCES

1. Archwichai L., Srisuk K., Chusanatus S., Pholkern K., Munyou S., Saraphirom P., Development of the Site Selection Criteria for Riverbank Filtration Project, Thailand. *Proceedings of the International Conference on Geology, Geotechnology & Mineral Resources of Indochina(GEOINDO 2011),* Khon Kaen, Thailand, 2011, 1-3 Dec. 2011, 352-361.
2. Ray C., Melin G., Linsky R.B., (eds.) Riverbank Filtration – Improving source-water quality. *Water Science &Technology Library*, Kluwer Academic Publishers, Dordrecht, 2002, **43**, 364 pages.
3. Ray C., Schubert J., Linsky R.B., Melin G., Introduction. In: Ray C., Melin G., Linsky R.B. (eds.) Riverbank Filtration – Improving source-water quality. *WaterScience & Technology Library*, Kluwer Academic Publishers, Dordrecht, 2002, **43**, 1-15.
4. EPA Ground water under the direct influence of surface water (GWUDISW). *United States Environmental Protection Agency*, 1989.
5. GOI National Water Policy. *Government of India,Ministry ofWater Resources*, New Delhi, 2012.
6. IS 15792 Artificial Recharge to Ground Water – Guidelines. *Bureau of IndianStandards,* New Delhi, India, 2008.
7. CGWB Master Plan for artificial recharge to ground water in India. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi. Available: *http://www.cgwb.gov.in/documents/MasterPlan-2013*.pdf, 2013.
8. Grischek T., Schubert J., Jasperse J.L., Stowe S.M., Collins M.R., What is the appropriate site for RBF? Management of aquifer recharge for sustainability. *Proceedings of the 6th International Symposium on Managed Aquifer Recharge* (I*SMAR6*), Acacia, Phoenix, 2007, 466-474.

9. CPHEEO Manual on Water Supply and Treatment, Central Public Health and Environmental Engineering Organisation (CPHEEO), *Ministry of UrbanDevelopment, Government of India,* New Delhi, India, 1999, 3rd ed.

10. CPHEEO & WHO Manual on Operation and Maintenance of Water Supply Systems. Central Public Health and Environmental Engineering Organisation*, Ministry of Urban Development, Government of India and World Health Organisation,* 2005.

11. WHO Guidelines for drinking-water quality – 4th ed. incorporating 1st addendum.*World Health Organization*, Geneva, Switzerland, 2011, **4**, ISBN 978-9241548151.

12. IS 10500 Drinking Water - Specification. Indian Standard (second revision), *Bureau of Indian Standards,* New Delhi, India, 2012.

13. Sandhu C., Grischek T., Ronghang M., Mehrotra I., Kumar P., Ghosh N.C., Rao Y.R.S., Chakraborty B., Patwal P.S., Kimothi P.C., Overview of bank filtration in India and the need for flood-proof RBF systems. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context – SaphPani*. IWA Publishing, London, UK, 2016, 17-38. ISBN13: 9781780407104.

14. Sandhu C., Grischek T., Schoenheinz D., Prasad T., Thakur A.K., Evaluation of bank filtration for drinking water supply in Patna by the Ganga River, India. In: Ray C., Shamrukh M. (eds.) Riverbank Filtration for Water Security in Desert Countries, *NATO Science for Peace and Security Series, Springer*, 2011, 203-222.

15. Page D., Dillon P., Vanderzalm J., Toze S., Sidhu S., Barry K., Levett K., Kremer S., Regel R., Risk assessment of aquifer storage transfer and recovery with urban stormwater for producing water of a potable quality. *J. Environ.Quality*, 2010, **39(6),** 2029-2039.

16. Bartak R., Page D., Sandhu C., Grischek T., Saini B., Mehrotra I., Jain C.K., Ghosh N.C., Application of risk-based assessment and management to riverbank filtration sites in India. *Journal of Waterand Health*, 2015, **13(1),** 174-189.

17. Sandhu C., A Concept for the Investigation of Riverbank Filtration Sites for Potable Water Supply in India. Ph. D. thesis. Dresden University of Applied Sciences, Faculty of Civil Engineering and Architecture, Division of Water Sciences and TU Dresden, Faculty of Environmental Sciences, Institute of Waste Management., 2015, *Available: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-208460.*

18. Kimothi P C., Dimri D.D., Adlakha L. K., Kumar S., Rawat O.P., Patwal P.S., Grischek T., Sandhu C., EbermannJ., Ruppert M., Dobhal R., Ronghang M., Kumar P., Mehrotra I., Uniyal H.P., Development of Riverbank Filtration in Uttarakhand. Journal of Indian Water Works Association, *Special Issue on RiverBank Filtration,* December 2012, ISSN 0970-275X, 13-18.

19. Chakrapani G.J., Saini R.K., Temporal and spatial variations in water discharge and sediment load in theAlaknanda and Bhagirathi Rivers in Himalaya, India. *Journal of Asian Earth Sciences*, 2009,**35(6)**, 545-553.

20. Patwal P.S., Integrated water resources management of a river stretch using GIS and Groundwater flow modeling. Master thesis, Indian Institute of Technology Roorkee, AHEC and University of Applied Sciences Dresden, Division of Water Sciences, 2015.

21. DVGW W 112(A), Fundamentals of groundwater sampling from groundwater monitoring wells (in German). DVGW (*German Technical and Scientific Association for Gas and Water*, technical norms – process sheet), Bonn, October 2011.

22. Schütze C., Flechsig C., Geophysical exploration of potential bank filtration sites. Indo-German Workshop on Science-based Master Planning for Bank Filtration Water Supply in India, University of Applied Sciences Dresden and National Institute of Hydrology Roorkee, 8-10 April 2014, Dresden, Germany.

23. Murphy J., Application of ODEX / TUBEX drilling method in a variably fractured volcanic / igneous environment. *Ground Water Management*, 1991, **5**, 799 - 814.

3

Chapter

DESIGN, OPERATION AND MAINTENANCE OF A BANK FILTRATION SCHEME

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This chapter highlights aspects related to the design, operation and maintenance of a RBF scheme in specific context to India. A summary of design parameters of some existing RBF schemes in India is provided. Different well types are discussed in context to the country's diverse hydrogeological formations. Methods to design RBF wells are described. New concepts for flood proof measures for wells in India are highlighted.

KEYWORDS: Well type, drilling techniques, geohydraulic parameters, flood proof wells

INTRODUCTION

While the investigation of the geology and determination of geohydraulic parameters forms the basis for assessing the suitability of a particular site for RBF (chap. 2), these and the following typical aspects should be considered during the design and operation of a RBF scheme[1,2]:

- hydraulic contact between river and aquifer and consequently the available river water that can be induced to flow into the aquifer,
- aims and quantity of RBF water abstraction,
- quality of river and groundwater,
- commercial river traffic (potential source of pollution; dredging of river bed),
- river flow velocity and bed load characteristics,
- seasonality of river flow (high flow / flood and low flow / drought conditions),
- stability of river channel (bank erosion and shifting of channel).

Although RBF sites generally have a few commonalities, each site has unique (site-specific) characteristics, because of which it is only possible to present conceptual RBF well designs and a general methodology to design wells. An overview of the hydrogeology and design parametersof at least 24 known RBF sites in India is provided in Table- 3-1. Based on the example of Uttarakhand and after conducting field research, three types of RBF systems were developed in the state: Koop well for low discharges (300–500 L/minute), vertical or tube wells for medium discharges (800–1200 L/minute) and caisson / large diameter wells for higher discharges (1500–3700 L/minute).

A feasibility assessment is necessary prior to construction of a RBF scheme (chap. 2), which will vary depending on the particular abstraction problem under consideration. In general, the following points ought to be given due consideration and should address the more frequently encountered difficulties: What is the daily volume of water to be abstracted? Can bank filtration meet the volume of water required? Are there any viable alternatives, cheaper methods available for water abstraction? Will the installation have a detrimental impact on the environment? Does the river water quality prevent the use of a RBF scheme e.g. is the water very turbid or polluted? Do geotechnical problems prevent the use of RBF? What would the consequences of a flood event be on the installation?

Overview of well types and geohydraulic parameters at RBF sites

Typical well types

The type of the well depends on the amount of water to be abstracted (well discharge), site-specific geology and planned travel time of the bank filtrate to the well. Experiences from older RBF schemes in operation in India indicate that safeguarding RBF wells from flood and health risks (due to direct contamination from the surface / above ground and poor surface water quality) is easier on certain types of wells (e.g. vertical wells) compared to other types (e.g. large-diameter caisson wells and radial collector wells/ RCW).

Most of the older RBF systems constructed in India prior to2000(Table- 3-1) have been designed primarily to fulfil the target of obtaining water of improved quality (compared to direct surface water abstraction) in sufficiently high volumes. Considering this and the local hydrogeological conditions, the wells of the RBF systems have been accordingly designed. Typically, these are classical vertical production wells, large-diameter caisson wells, RCW and one or more RCW with shorter radials at shallower depths connected to a single collector well (Fig. 3-1 to 3-4).

Table 3-1: Summary of design parameters of RBF systems in India listed in ascending order of abstraction rates[3,adapted]

Location (state)	Source water body	Well type (no. of wells)	Production capacity in m^3/day	Depth in m	Distance from source water in m	Travel-time of bank filtrate
Muzaffar Nagar* (UP)	Kali	V (1)	29–300	8–15	68	n. d.
Dandeli (Karnataka) **	Kali	V	55–220	20–23.7	52	~9 days
Sahaspur (Ddn. UK)	Swarna	R(s)	210–570	laterals 3–4 m beneath river bed		>150 min
Ray Bazaar (JH)	Saphi (n.p.)	C (1)	225	3–6	within river bed	minutes–hours
Agastmuni*** (UK)	Mandakini	V (1)	>280	30	33	n. d.
Bhimtal (UK)	Lake Bhimtal	V (1)	>320	48	16	n. d.
Satpuli*** (UK)	East Nayar	V (1)	756	26	43–45	2 days–2 weeks
Japla, Hussainabad (JH)	Son	R (1)	900	laterals 1 m beneath river bed		minutes–hours
Srinagar**** (UK)	Alaknanda	V (7)	1,300–8,000	18–44	10–102	$1^{M} – \geq 90^{NM}$ days
Gumla (JH)	Nagpheri (n.p.)	C (2)	>1,800 (max. 12,000)	3–6	within river bed	minutes–hours
Bageshwar[2016/17] (UK)	Sarju	C (1)	2,020	14.40	14	n. d.
Kapkot[2016/17] (UK)	Sarju	C (1)	2,020	12.50	32	n. d.
Mathura (UP)	Yamuna	R (1)	2,400	laterals 15.5 & 18 m beneath river bed		1.5–3 days
Patna (Bihar)	Ganga	V (6)	>3,500	150–300	9–236	n. d.
Anakapalli (AP)	Sarada	R (4)	>4,000	10	within river bed	minutes–hours
Gauchar**** (UK)	Alaknanda	V (1) & C (1)	4,320	14.7	61	n. d.
Daltonganj (JH)	North Koel (n.p.)	R (3)	4,000–5,000 (max. 7,000)	1–6	within river bed	minutes–hours
Karnaprayag**** (UK)	Alaknanda	V (1) & C (1)	5,760	14.7(C)/ 20(V)	$\leq 1^{M} – 25^{NM}$	$1^{M} – \geq 30^{NM}$ days
Rishikesh (UK)	Ganga	C (2)	7,200	13–16	15–25	n. d.
Gaya, Dandi Bagh (Bihar)	Falgu	V (12)	~10,000	25	5–10	n. d.
Nainital (UK)	Lake Nainital	V (9)	12,000–16,000	22–37	4–94	8–>30 days
Medinipur (WB)	Kangsabati	R (1)	15,900	laterals 6 &11 m beneath river bed		n. d.
Kharagpur (WB)	Kangsabati	R (1)	22,700	laterals 6 & 8 m beneath river bed		n. d.
Visakhapatnam, Boni (AP)	Gosthani (n.p.)	R (5)	27,300	10	within river bed	hours–days
Haridwar (UK)	Ganga & UGC	C (22)	59,000–67,000	7–10	4–110	2–>100 days
Delhi, Palla	Yamuna	V (~90)	~100,000 (in 2007)	45–54	few m to 600 m	few weeks
Ahmedabad (Gujarat)	Sabarmati	R (7)	110,000	laterals 10 & 11 m beneath river bed		n. d.

* Water used primarily for irrigation; ** constructed in 2008; *** 1 well built in 2010; **** 1 well built in 2010 and remaining wells built in 2016-2017; 2016/17: Well built in 2016/2017. M: monsoon; NM: non-monsoon; UP: Uttar Pradesh; UK: Uttarakhand; JH: Jharkhand; AP: Andhra Pradesh; WB: West Bengal; UGC: Upper Ganga Canal; C: large-diameter (5–10 m) caisson well; V: vertical filter well; R: radial collector well; R(s): Koop well or small-scale radial collector well; n. d.: not determined; n. p.: non-perennial – extreme low flow in pre-monsoon season.

Vertical wells have been constructed in relatively thick-layered homogeneous fine to medium alluvium. This is invariably related to the economical and fast construction of such wells compared to the other types. Nevertheless, the presence of large cobbles and boulders in foot-hill and mountainous regions (e.g. of Uttarakhand) can hinder the construction of vertical wells using conventional rotary bore-hole drilling techniques that allow more accurate grain-size distribution and classification of the subsurface material.

Large-diameter (~ 10 m) caisson wells are used for RBF systems designed to meet high water demands in areas with shallow groundwater tables (≤3 m below ground level) having medium to coarse alluvium containing cobbles and boulders (Fig. 3-2; Table- 2-1 & 3-1; Rishikesh and Haridwar). The caisson wells allow a significant storage capacity on account of their large-diameter.

The RBF sites in the cities of Ahmedabad, Baroda and Mathura are designed to abstract very large volumes of water using RCW sited within the river bed (Fig. 3-3; Table- 2-1 & 3-1). The practise in India of siting the RCW within the river bed is quite successful where groundwater is saline as there is little or no mixing of the filtered river water with the groundwater[4]. However, the travel time is relatively short (from few hours up to 3 days) and correspondingly only moderate purification in terms of organics and microorganisms occur.

In the Indian Peninsula region, including the Deccan Plateau, south Bihar, Jharkhand, coastal Andhra Pradesh and Odisha, the rivers have a seasonal discharge related to the monsoon and the rivers are generally incised in rock or alluvium and have stable channels[5].For RBF wells in these areas (Fig. 3-4; Table- 2-1 & 3-1), the river beds consist of medium to coarse sand and gravel 3 to 10 m thick and thereby exhibit a suitable hydraulic conductivity for RBF. Due to this most of these rivers have a substantial subsurface flow in their beds even during the summer pre-monsoon, when no or only negligible flow is visible on the surface. This feature allows the RBF systems to operate duringthe relatively dry non-monsoon period also, albeit usually with lower discharges and reduced operating hours.

On the other hand, in North America some RBF sites combine RCW with vertical wells to abstract large quantities of water (76,000–322,000 m^3/day) with relatively short bank filtrate travel times of <1 to 17 days (mainly for RCW) and flow distances to the RCW of <1 to <30 m. In comparison, RBF sites along the Elbe River in Germany abstract 6,000 to 150,000 m^3/day from as few as three vertical wells to a battery of up to 42 vertical wells further away from the riverbank (80–300 m) with longer travel times of 25–300 days.

Figure 3-1. Vertical well in Srinagar (Alaknanda R., UK)

Figure 3-2. Caisson well in Haridwar (Ganga River, UK)

Figure 3-3. Radial collector well (RCW) in Ahmedabad (Sabarmati River, Gujarat)

Figure 3-4. RCW connected to a single collector in Gumla (Nagpheri River, Jharkhand)

Koop wells for small-scale rural RBF schemes in hills

Koop wells are small radial collector wells and are typically used in hilly terrain regions of Uttarakhand for rural water supply. Their application is in remote areas where they can pre-treat the water from streams or small rivers. There are a large number of Koops in Uttarakhand because they are comparatively inexpensive to construct (compared to other water abstraction systems). The Koop consists of a 1.5 m long cylindrical steel tube, at the bottom of which 0.5–1 m long laterals are connected (Fig. 3-5). The inner and outer surface is painted with an epoxy paint for corrosion protection.The Koop can be opened from above for cleaning purposes. For this purpose, a steel cover is screwed onto the cylinder from above. To prevent water from entering the well from the top, the cover is provided with a rubber seal. The bottom of the cylinder is open and usually has 4 horizontal filter laterals at the lower end. The Koops are installed near or beneath the river bed of streams or creeks (Fig. 3-6). They are

Figure 3-5. Assembled Koop on display

normally placed around 2–4 m beneath the stream or river bed depending on the bed material. The Koop is connected to the water supply via an outlet which is usually located in the centre of the vertical cylinder. The position of the outlet must be under the water level, due to which the water infiltrates from the stream to the Koop. The passage through the river bed and aquifer subsurface, filters the water to some extent.

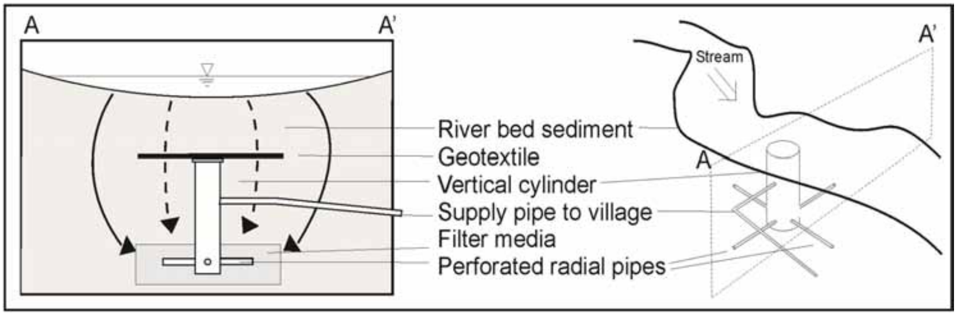

Figure 3-6. Principle of a Koop[6]

Exploratory and production well drilling considerations

Although not strictly a design aspect, the well type, geology, availability of well construction equipment and qualified personnel influence the interpretation of information about the subsurface (grain-sizes, stratification), especially when drilling boreholes for exploratory and vertical wells. In the absence of large cobbles and boulders, rotary borehole drilling techniques without borehole stabilization fluids (drilling muds, bentonite) permit large borehole diameters of up to 500 mm (Fig. 3-7). For smaller diameter wells the auger method can also be used (Fig. 3-8). Although these are time- and cost intensive techniques, they provide a more accurate interpretation of the borehole material and lithology compared to faster and cheaper methods such as the "overburden drilling with excentric bit (ODEX)" [7] technique as shown in Fig. 3-9.

Fig.3-7. Bit used for rotary drilling of production well in Srinagar

Fig. 3-8. Exploratory well construction in Karnaprayag by the auger method

Fig. 3-9. Eccentric bit used in ODEX drilling

However, it should be noted that ODEX is typically used where large cobbles, boulders or hard rock are found in the subsurface. A further aspect to be considered is that the availability of rotary drilling rigs capable of drilling larger diameter (>300 mm) boreholes is limited, especially at short notice. To circumvent these practical difficulties, ODEX is favoured in practise and frequently used in Uttarakhand. The drawback of ODEX is that it can reduce the actual size of the grains of the aquifer material through the elliptical grinding motion of the drilling bit thereby causing an underestimation of the grain-size and an inaccurate interpretation of the subsurface. The diameter of the boreholes that can be drilled using the ODEX technique is also limited to a maximum of 200 mm. A filter gravel pack cannot be installed in boreholes drilled by ODEX, which results in the development of a natural filter in the borehole annulus. Nevertheless fine aquifer material can enter ODEX wells or clog the well screen, eventually decreasing the specific yield of the well faster compared to wells drilled with other methods.

Thus the construction of the first well at a proposed / potential RBF site should be an exploratory well drilled either with the auger or rotary drilling technique because this is advantageous for accurately determining particle grain-sizes required for dimensioning the well filter-screens, accurately interpreting pumping test data and for determining the lithology. But in case only the ODEX method can be used, the interpretation of the geological subsurface profile and pumping test data has to be viewed with caution. The derived hydraulic conductivity should be cross-checked with other sources.

Geohydraulic aspects

Geohydraulic parameters such as thickness and hydraulic conductivity of the aquifer, and the flow velocity, gradient and discharge of rivers and clogging of the river bed are relevant for RBF. In general, the river should be perennial with a stable bank. The river bed and aquifer material should comprise sand and/or gravel with a hydraulic conductivity $>1\times10^{-4}$ m/s. The aquifer thickness should be more than 3 m with a preferred depth of the filter screen / well entrance area between 5 and 20 m below lowest groundwater level. To avoid clogging of the river bed and to ensure long term sustainability during operation of the RBF scheme, the average infiltration rate through the river bed should be <0.2 $m^3/(m^2$ day) [8]. An important parameter is the local gradient of the river water level as the shear stress, depth and average grain size of the bedload of the river is connected to it; consequently the average grain-size of bed load material can give an indication of the average grain-size of the river bed and a first assessment of the hydraulic conductivity of the adjacent aquifer [9]. As an example, the thickness of some existing RBF sites ranges from a minimum of 3–5 m at Böckingen by the Neckar River to a maximum of 40–55 m at Torgau by the Elbe

River in Germany (and in exceptional cases even up to 120 m at Kalinkovo by the Danube River in the Slovak Republic), with hydraulic conductivities ranging from 1×10^{-2}–7.5×10^{-5} m/s [10]. As an example, the average gradient and flow velocity of the Rhine River at Düsseldorf is 0.18–0.21 ‰ and 1.0–1.4 m/s, respectively [11]. For a minimum and mean discharge of 800 m^3/s and 2,300 m^3/s, respectively (approx. 100 km upstream of Düsseldorf), operational experience over decades confirms sufficient self-cleaning capability of the clogged areas of the river bed [11].

An estimate of the river sediment load is required to ensure that a RBF scheme does not have its performance impaired by excessive sediment deposition or scouring of the river bed. Consideration should be given to seasonal flow variations, which will affect the volume of sediment being transported, the method of transport (i.e. bed load or suspended), localised areas of accretion/erosion and human activities upstream of the proposed site.

Well design

Main parameters

The focus in this chapter is on geohydraulic investigations for a RBF site and designing vertical wells for RBF. Depending on the quantity of water to be abstracted and the site-specific geohydraulic conditions, other well types can also be considered (section *Typical well types*). To design a well, information on the grain-size diameter of the aquifer and river bed material, the hydraulic conductivity (K), aquifer capacity (Q_A), well yield (Q_F), groundwater level at rest above aquifer base (H), water level in the well at steady-state drawdown conditions (h), radius of influence or cone of depression (R) and borehole radius (r_0) are mainly required. Once the hydraulic conductivity is known the aquifer capacity and well yield can be calculated. A sustainable well abstraction rate is attained when $Q_A > Q_F$.

Aquifer parameters

Hydrogeological testing should be used to determine the governing properties of the aquifers, aquitards and aquicludes identified in the geological strata graph report and also include an estimation of saturated aquifer thickness (D), transmissivity (T), storativity (S) and hydraulic conductivity (K). Table- 3-2 presents the various methods available to determine aquifer parameters.

Table 3-2. Methods to determine aquifer parameters

Category	Test	Details
On site	Well pumping test	Large mass/volume estimation
On site	Borehole	Results limited to locality of bore
Visual Assessment	Classification	Can give approximate guide

The determination of the aquifer matrix permeability is of significant importance and is also crucial for the calculation of the RBF systems safe yield. The following points should be considered before conducting any hydrogeological testing:

- The ground is likely to be heterogeneous and anisotropic, which prevents a definitive permeability value from being obtained. A conservative approach should be adopted to account for the variability in the ground conditions.
- Hydraulic conductivity may be anisotropic i.e. horizontal (K_h) is greater than the vertical conductivity (K_v).
- Hydraulic conductivity is not only dependent on the soil's description and grading, but also on fissuring and layering, which can cover an extensive area. Laboratory testing of borehole material should only be used if in-situ well pumping tests, which provide a better estimate of localised transmissivity, cannot be conducted.

During borehole drilling an estimate of the hydraulic conductivity (K) can be obtained by sieving the borehole material. For this, equation 3-1 after Beyer and Schweiger[12] should bepreferred to Hazen[13] because it was developed for alluvial sediments. It accounts for the grain-size diameter corresponding to10% cumulative undersize particle distribution and thereby takes into account the portion of finer aquifer material which affects K given in m/s.

$$K = C_B \cdot d_{10}^2 \qquad (3\text{-}1)$$

Where C_B is the coefficient for the natural state of compaction of the sediment after Beyer and Schweiger[12][-] and d_{10} is the grain-size diameter corresponding to 10% cumulative undersize particle distribution [mm].

Calculation of K based on eq. 3-1 is valid for $2\cdot10^{-5}$ m/s <K< $4\cdot10^{-3}$ m/s, 1 < C_U< 20 and for 0.06 mm < d_{10} < 0.6 mm. Depending on the natural state of compaction (packing) of the sediments, C_B can be calculated using equations 3-3 to 3-5[12,14]. In this context, C_U is defined as granulometric non-uniformity coefficient which is the ratio of d_{60} to d_{10} (Eq. 3-2).

Non-uniformity coefficient: $C_U = d_{60}/d_{10}$ (3-2)

Loosely compacted sediment: $C_B = 14797\cdot C_U^{-0.147}$ (3-3)

Medium compacted sediment: $C_B = 11864\cdot C_U^{-0.200}$ (3-4)

Densely compacted sediment: $C_B = 10041\cdot C_U^{-0.232}$ (3-5)

Unless K has not been obtained from interpretation of pumping tests conducted on other wells nearby, the K derived from the grain-size distribution analyses can be used to obtain an initial estimate for Q_A and Q_F (section *Aquifer capacity and well yield*).

Else pumping test data analysis provides the most representative *K*. Depending on the boundary conditions prevailing at the site, an appropriate method can be used to determine *K* from pumping test data. As these methods are well known, published in standard literature and are available in the internet or as numerical tools such as AQTESOLV, these are not discussed further.

Aquifer capacity and well yield

Aquifer capacity and well yield depend on the aquifer conditions, thus unconfined and confined aquifers have to be distinguished (Fig. 3-10).

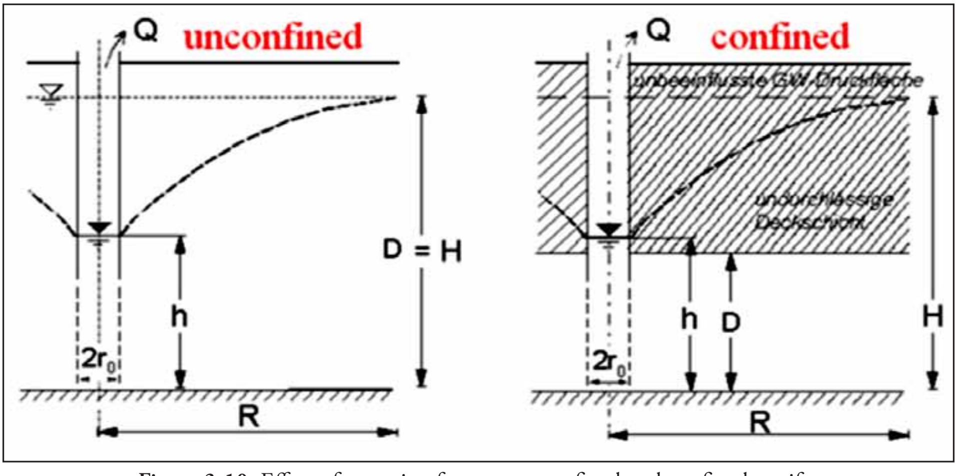

Figure 3-10. Effect of pumping from an unconfined and confined aquifer

The maximum extractable safe well yield (discharge) from an aquifer is calculated after the hydraulic conductivity has been determined. By plotting the steady state flow rate towards an abstraction well or the aquifer capacity (Q_A) [L^3/T] by equations 3-6 and 3-8 and the yield of the abstraction well (Q_F) [L^3/T] given by eq. 3-7 and 3-9, versus the water level in the well, the maximum extractable yield (discharge) for a well is determined at the intersection of Q_A and Q_F. Q_F should be greater than Q_A to account for well aging during the course of operation of the well.

Unconfined aquifer

$$Q_A = \frac{\pi \cdot K \cdot \left(H^2 - h^2\right)}{\ln R - \ln r_0} \tag{3-6}$$

$$Q_F = \frac{2}{15} \cdot \pi \cdot r_0 \cdot h \cdot \sqrt{K} \tag{3-7}$$

Confined aquifer

$$Q_A = \frac{\pi \cdot K \cdot \left(H^2 - h^2\right)}{\ln R - \ln r_0} \tag{3-8}$$

$$Q_F = \frac{2}{15} \cdot \pi \cdot r_0 \cdot h \cdot \sqrt{K} \tag{3-9}$$

Where K is the hydraulic conductivity of the aquifer [L/T],

H is the pre-test rest water level measured from the aquifer base (before pumping) [L],

h is the steady-state water level after a constant drawdown is obtained (during pumping) [L],

R is the radius of influence (cone of depression or drawdown) of the well at a constant drawdown [L], and r_0 is the radius of the well-bore [L].

This approach is documented in many textbooks, neglecting the practical aspect of placing the pump not within the filter screen. As the pump has to be placed at least 1 m below the lowest water level during pumping and >1 m above the filter screen, the determination of Q_A and Q_F has to be adjusted according to Fig. 3-11.

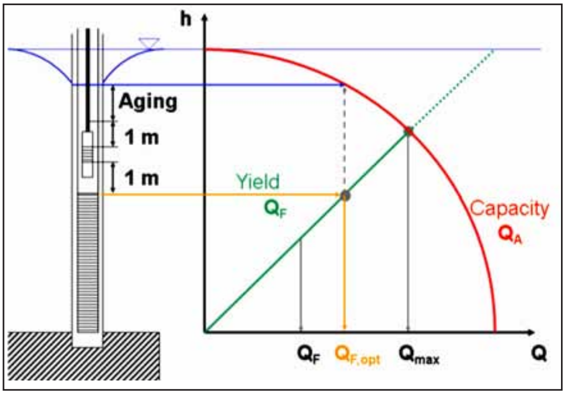

Figure 3-11. Aquifer capacity and well yield if the pump is placed in the upper part of the well[15]

However in some cases when there is an uncertainty in the hydraulic conductivity, it is beneficial to consider different scenarios ("worst" and "best" cases) ranging from lower to higher hydraulic conductivities. To illustrate this, an example is provided for the design of RBF wells in Srinagar, Uttarakhand (Fig. 3-12). The calculations took into account field data and are based on surface and groundwater levels measured during low flow conditions.

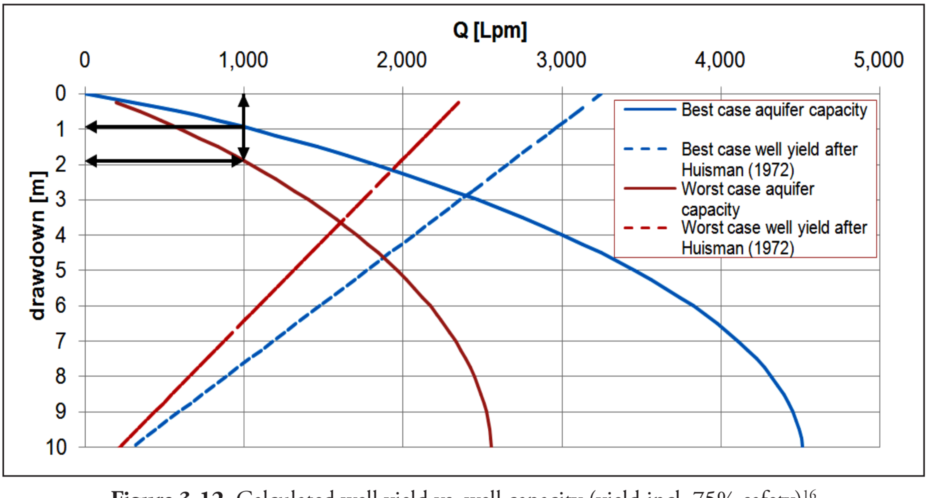

Figure 3-12. Calculated well yield vs. well capacity (yield incl. 75% safety)[16]

The "worst case" assumed $K = 4 \cdot 10^{-3}$ m/s, whereas the "best case" is based on $K = 7.3 \cdot 10^{-3}$ m/s. Both K lie within the range of literature values for medium gravel. Well capacity was calculated according to Huisman [17], wherein the maximum well borehole entry velocity of Sichardt[18]is reduced by 50% to account for well aging. The theoretical optimum well discharge (intersection of Q_A and Q_F) is in the range of 1,580 to 2,360 L/minute. However, to take into account for unusual well aging (as observed from an older well nearby) it is recommended to use state-of-the-art filter screens, ensure a proper gravel pack and not to exceed a maximum discharge of 1,000 L/minute.

Design of vertical well filter media and well filter screens

General considerations

This section is based primarily on standard guidelines and literature used in Germany[19-21]. However national guidelines and literature should also be considered where applicable. Vertical wells should use a central screen surrounded by a filter pack. The shaft is dug or drilled to a much greater diameter than that of the screen, say 550 mm for a 300 mm screen, and a temporary liner such as a large steel casing pipe is inserted to stop the surrounding borehole material from collapsing. The screen is put in place, the filter material is inserted in the gap and the liner is removed. This technique enables a good thickness of filter material but is more suited to shallower wells of up to 25 m depth. Following this, the well is usually surged to pull small sand through the screen; this process is called well development.

The filter sand or gravel pack must prevent sand and other soil or suspended particles from being washed into the well. The filter pack should also ensure a good water permeability in the entrance area and its vicinity because the highest hydraulic gradients occur here. Therefore afilter pack has to guarantee both the development of the well and a sand-free abstraction of water. For this the grainsize of the filter pack has to be carefully calculated.

The filter media should be natural sand or gravel having almost spherical grains with a smooth surface. Artificially made fragments (e.g. grit) are not recommended. The filter media should consist of pure quartz (approx. 96 % SiO_2 by weight[22]), with the content of clay, lime, mica, feldspar and other components not exceeding 4 % total and organic material not exceeding0.5 %. The over- and under-size composition should be < 10 %. Good filter material usually has a C_U of 1.5 or lower.

Density of grainsize packing

The density of packing of the grains of the filter gravel is important concerning the passing of small grains through the interspaces between larger grains. With the theoretically loosest packing, the diameter of the large grains d_1 is 2.41 times greater than the largest diameter d_2 for a round grain between them (Fig. 3-13, left). With the theoretically most compact packing density, d_1 is 6.46 times greater than the largest passage d_2 (Fig. 3-13, right). But in practice, the real density of packing ranges between the theoretically loosest and densest packing. Therefore, the ratio of the largest passage to the grainsize, called the screening factor, lies between these two limits and is around 4 to 5. For the example of the granulometric curve provided in Fig. 3-14, the screening factor of 4.5 is given. In practice the aquifer material does not have a uniform grainsize, the degree of non-uniformity C_U is of great importance (3-2; Fig. 3-14).

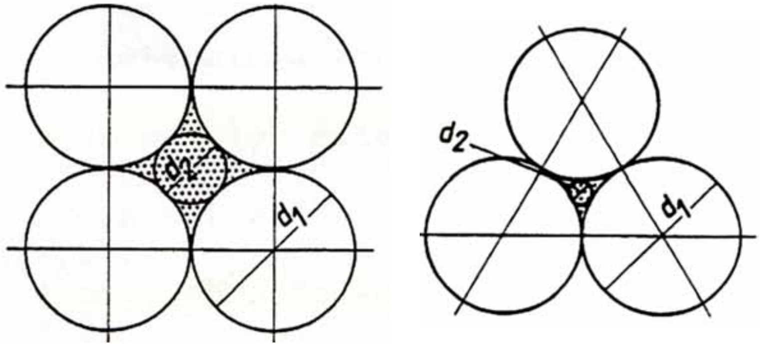

Figure 3-13. Loose packing density(left) and compact packing density(right)[23]

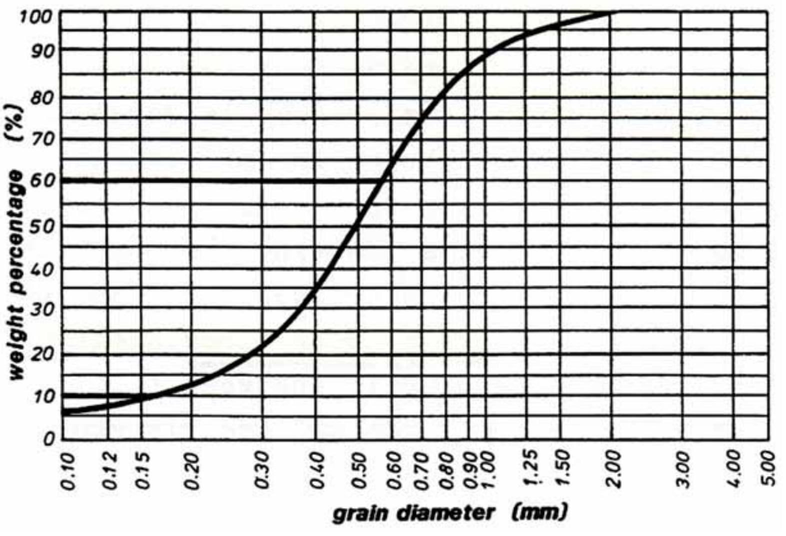

Figure 3-14. Granulometric (grainsize distribution) curve showing grainsize diameters corresponding to 10 % and 60 % passing[23]

Determination of grainsize of filter pack

For $C_U < 5$, the grainsize of the gravel pack is calculated as follows:

1. For $C_U < 3$, theoretically 75–85 % of the rock in place are supposed to go through the interspaces of the filter grain; for $3 < C_U < 5$, the theoretical removal is 85–95 %.
2. Calculate the "removal grainsize" or relevant grainsize from the granulometric curve (example of Fig. 3-14). Look up the 75–85 % and 85–95 % intercepts on the Y-axis of Fig. 3-14 and corresponding grainsize diameter (removal grainsize or relevant grainsize) on the X-axis.
3. Multiply the "removal grainsize" by the screening factor 4.5. The result is the grainsize of the gravel pack.
4. It should be checked if the planned abstraction rate of the well can cause buoyancy of the gravel pack. If so, the grainsize for a second gravel pack, which is placed above the first one, has to be calculated.

For $C_U > 5$, the portion with the coarsest grainsize of the borehole material (sample) has to be removed and thereafter another granulometric curve has to be evaluated by sieving. This procedure must be repeated until $C_U \leq 5$.

Another method, that of Nahrgang & Schweizer[24], can also be used to calculate the grainsize of the filter gravel pack (3-10). Therein, the grainsize that theoretically allows an out-wash of 50 % of the aquifer material (D_{50}) is determined for the filter sand or filter gravel.

$$D_{50} = d_g \times F_g \qquad (3\text{-}10)$$

Where, D_{50} is the grainsize of the filter sand or gravel in mm, d_g is the relevant grainsize of the sediment in mm and F_g is the screening factor.

To determine d_g, the normally s-shaped granulometric curve is graphically differentiated (Fig. 3-15). The result is a curve with a maximum at the point of inflection (Fig. 3-15, dashed / broken line). The grain diameter corresponding to the point of inflection, is the relevant grainsize of the sediment (d_g), which is often around D_{50} in magnitude. In case of mixed grain sediment no point of inflection may occur and in such

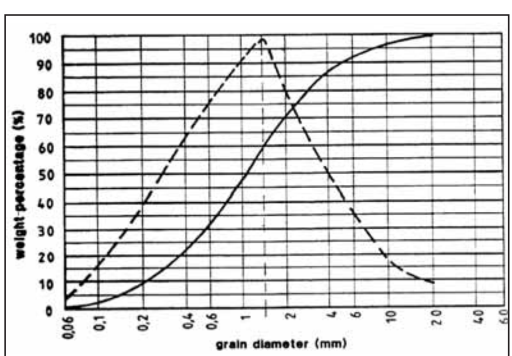

Figure 3-15. Example of a granulometric curve for the determination of d_g using the methodology of Balke[23] and Nahrgang & Schweizer[24]

cases $d_g = d_{30}$. If there are two points of inflection, it is recommended to select the corresponding grainsize of the smaller value.

The screening factor F_g can be calculated, as given by (3-11) and (3-12), for

$$1 < C_U < 5, F_g = 6 + C_U \quad (3\text{-}11)$$

$$C_U \geq 5, F_g = 11 \quad (3\text{-}12)$$

The basis for this is also the granulometric curve of the aquifer sediment. Several calculations to determine the grainsize of the filter pack using both methods, have shown to give comparable results[23]. In practice sand and/or gravel with a diameter between 0.71 mm and 16 mm is mainly used for the filter pack.

Well filter screen design

If the calculations for the *aquifer capacity and well yield* imply that the aquifer should be exploited as deep as possible, the well screen (filter section) should cover all water-bearing layers, with casing section covering layers of low permeability (silt, clay) or at the location (depth) of the pump (in case it is installed approx. at mid-depth). Furthermore, even at maximum drawdown during pumping (including during peak non-monsoon / dry season), the water level in the well should not reach the perforations of the screen. Hence the upper edge of the screen has to be installed at least about 1 or more meters below the deepest expected water level.

The length of the screen (l_s) of a well can be calculated by eq. 3-13.

$$l_s = d_b - (d_l + 1 \text{ m above pump} + l_p + 1 \text{ m blind pipe below pump entrance} + l_s) \quad (3\text{-}13)$$

Where,

d_b is the depth of the well bore [L],

d_l is the greatest depth of the water level [L],

l_p is the length of the pump [L] if not placed in the sump pipe,

l_s is the length of the sump pipe [L], if not placed in the confining layer.

The diameter of the screen is determined by the diameter of the pump and the additional equipment, as well as by the permissible entrance velocity of the groundwater flowing into the well. In case that the pump is placed within the sump pipe, then all the pipes above the sump pipe must be wide enough to allow the pump and additional devices to be lowered without endangering the casing and the screens.

The velocity of groundwater entering a well (entrance velocity) has an important influence on the life span of the well, especially the screens. Normally, groundwater flow in an aquifer is laminar. But when approaching a well, the flow conditions in the aquifer or in the filter pack around the screens change to turbulent, if the water exceeds a certain flow velocity. This change is disadvantageous because turbulence favours the influx of fine particles and iron hydroxide deposition, both of which result in well-clogging. Therefore the screens must have a sufficient entrance area to avoid a turbulent inflow of water. The entrance area varies with the diameter of the screen pipe and width of the openings.

The flow conditions in the pore spaces can be determined with the help of the Reynolds number (3-14)

$$Re = \frac{v_f \times d_{wk}}{v} \qquad (3\text{-}14)$$

Where, Re is the Reynolds number [-],
v_f is the filter velocity in m/s,
d_{wk} is the effective grainsize diameter in mm,
ν is the kinematic viscosity for water in m^2/s.

Turbulence occurs when a certain filter velocity is exceeded. For sand and gravel, the limiting Re value for laminar flow is 10, turbulent flow is 300 and a transition between R_e 10 and 300 [23]. However, it is controversial whether the transition from laminar to turbulent flow is at Re = 10, or below (approx. 6 to 2) due to influences of grain roughness[23].

The mean filter velocity (v_f) at the borehole well can be calculated by the empirical formula after *Sichardt*[18] based on the hydraulic conductivity of the aquifer (K) as in (3-15).

$$v\_f = \sqrt{}(K\_/15) \qquad (3\text{-}15)$$

The washing-out of fine sediment from the aquifer into the borehole is generally expected for $C_U > 6$ and at critical filter velocities ($v_{crit.}$) of 0.002–0.003 m/s[19,21]. Therefore the groundwater velocity should not exceed 0.002 – 0.003 m/s at the time of leaving the filter media and entering the well screen. The permissible effective filter velocity in the filter pack and the permissible flow rate through a screen (DN 600) is given in Table- 3-3.

Table 3-3. Grainsize, effective velocity and flow rate for a screen diameter of 600 mm, Reynolds number 10 and water temperature 9.5 °C[25]

Grainsize of filter pack [mm]	Permissible filter velocity [m/s]	Permissible flow rate per 1 m flow length [m³/h]
3	0.0044	29.78
4	0.0033	22.46
6	0.0022	14.89
8	0.0016	11.23
12	0.0011	7.44
16	0.00083	5.62
25	0.00053	3.59
35	0.00038	2.57

Higher filter velocities of 0.03 m/s are given by other authors[26-28], with the US Environmental Protection Agency recommending filter velocities in a similar range of magnitude of up to 0.01 to 0.03 m/s[29-30]. Although the differences in filter velocities appear high, these are based upon different boundary surfaces and borehole diameters.

Design of horizontal well filter media and radial collector filter screens

For rivers with high sediment concentration and/or poorly graded soils, a significant emphasis should be placed on the design of a suitable filter media for a horizontal well in an effort to reduce the risk of clogging and the need for frequent and costly maintenance. The filter size for horizontal well screens is selected according to the grain-size distribution of the natural gravel. The following general expressions provide a suitable thumb rule for the design of permeable filters.

To prevent the migration of natural soil's fine particles (*s*) through the filter material of the well (*f*):

$$d_{15\mathrm{f}} \leq 5 \times d_{85\mathrm{soil}} \tag{3-16}$$

To ensure that the filter is more permeable than the soil: $d_{15f} \geq 5 \times d_{15s}$ (3-17)

To ensure good performance: $4 \leq d_{60f} / d_{10f} \leq 20\ and d_{maxf} \leq 50\ mm$ (3-18)

To ensure adequate drainage of water: $d_{5f} \geq 0.075\ mm$ (3-19)

To prevent any segregation of the filter material: $d_{50f} \leq 25 \times d_{50s}$ (3-20)

Where the filter is to be placed against a screen mesh: d_{85f} should not be less than twice the mesh size

Where high permeability is the primary requirement, the following general expression provides a suitable thumb rule. $\mathrm{d}_{15f}/\mathrm{d}_{15s} > 4\ to\ 5$ (3-21)

In special cases, the filter media can be separated from the surrounding soil by a geotextile fabric to avoid the passage of fines sediments into the infiltration well.

It is a common practice that slotted pipes are used in well construction. For tube well pipes perforations should be more than 50% of the total pipe area to allow more water entering at low velocity. Eq. 3-22 can be used to approximate the screen entrance velocity:

$$v_e = \frac{Q}{\pi D L p b} \tag{3-22}$$

Where, v_e is entrance velocity (m/s); L is net length of screen; Q discharge (m^3/s); D is diameter of screen pipe (m); p is proportion of open area of screen; b is a blocking factor (usually 0.5).

For water distribution, pipes should be designed as such to facilitate the further increase of water demand.

Safeguarding RBF wells from floods

The direct entry of floodwater, resultant contamination and damage to groundwater and RBF wells frequently cause the disruption of drinking water production in flood prone areas worldwide, including India (e.g. Uttarakhand, Fig. 3-16). Direct flood risks include a deterioration of abstracted water quality (turbid water and microbiological contamination) and damage to well infrastructure, as observed for the RBF sites in Uttarakhand.

During a flood or intense rainfall event, the following deficits can result in seepage or direct entry of water into a RBF well (Fig. 3-17):

- absence of water-tight well chamber,
- non-watertight well head or cracks / fissures in caisson,
- absence of concrete base around well head (sanitary seal),
- absence of borehole annulus sealing with swelling clay pellets between groundwater table and ground surface.

Figure 3-16. RBF sites in Haridwar (left) and Karnaprayag (right) before and after the June 2013 flood

Consequently there is a need for the construction of flood-proof RBF wells and flood risk mitigation measures32. In this regard and taking into account the availability of local materials and site-specific conditions, the following general criteria have been formulated to flood-proof the wells:

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

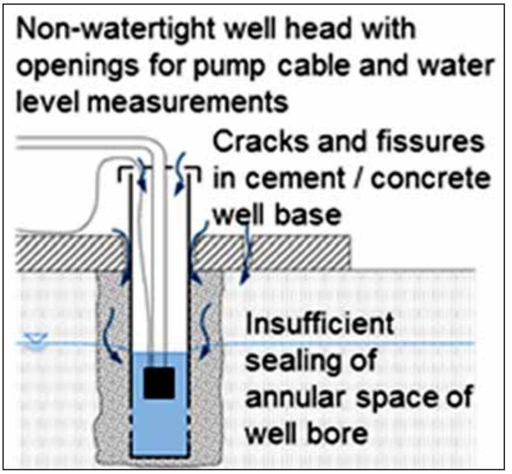

Figure 3-17. Vulnerable locations for the direct entry of water / rainfall into a vertical well[31]

Based on the above, the need to maintain caissons (large-diameter wells) and well heads (vertical wells) in good technical and sanitary condition (cracks / fissures should be immediately repaired) and to appropriately seal the well base is imperative. It must be noted that in the present practice of constructing wells in India, the annulus in the borehole around the casing in between the groundwater table and ground surface is not always sealed with swelling clay, although this is recommended[33,34]. For the improved sealing, the annulus should ideally be sealed using commercially available swelling clay pellets at critical points such as at the ground surface and at the depth of the groundwater table (Fig. 3-18).

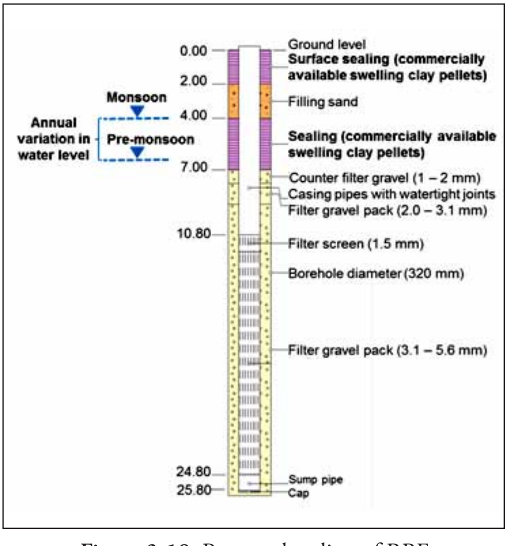

Figure 3-18. Proposed sealing of RBF well annulus (depth in m BGL)[32]

The available bentonite in India can be used for sealing. The sealing at the groundwater table should, as far as possible, remain moist year-round. It is necessary to take the lowest pre-monsoon (deepest) groundwater table into consideration so that the lower most clay sealing (pellets) is in continuous contact with the groundwater table and thus the continuous swelling is sustained. If this is not the case, then drying of the pellets will result in shrinkage leading to the formation of cracks in the clay of a gap between the clay seal and the casing pipe of the well and eventually also with the borehole wall.

As illustrated in Fig. 3-17, the well head should also be watertight and attached in a watertight manner to the baseplate of the well chamber. Such a well head can be

Figure 3-19 (clockwise from top left). Corrosion resistant stainless steel inner and outer well head elements, laying of bitumen sheets, attachment of well head to base of well platform, concreting, sealing annulus between outer and inner well head elements with well foam[31]

made of stainless steel as demonstrated for a RBF well in Uttarakhand (Fig. 3-19)[31]. After the annulus of the borehole has been sealed with bentonite and the concrete base laid for the well, bitumen sheets are laid to prevent floodwater from seeping through the concrete base into the ground near the well. Thereafter the outer well head element is attached to the base using a rubber seal. The rising pipe and pump are then attached to the bottom of the inner well head element.The disinfection equipment and associated electrical components should be placed either within the watertight well-head chambers (Fig. 3-20) or if the dimensions of the disinfection equipment is too large, then in a separate secure chamber located before the drinking water is supplied into the distribution pipes. Both options should remain unaffected by the flood. All the electrical components should also remain unaffected by the flood.The back-up electrical power supply is ensured via e.g. generators that are also protected by appropriate measures. Thus operation (pumping) of the RBF well and disinfection of the abstracted water are guaranteed at all times.

Figure 3-20. Installed well head with supply (distribution) pipe attached to the top (left) and completed flood-proof RBF well chamber (right) by the Alaknanda river in Srinagar, Uttarakhand (August 2017)

Operation and maintenance of a RBF scheme

Apart from the installation of any RBF system, some form of routine maintenance is needed to ensure the system does not incur any significant reduction in performance. Some wells require regular mechanical cleaning. Intensive pumping or compressed air bubbles may be used for vertical well systems, large diameter wells can be cleaned manually. Table 3-4 provides a summary of the routine and non-routine maintenance requirements which may or may not be applicable to any given situation.

Table 3-4. Maintenance requirements

Routine maintenance	Non-routine maintenance
Well yield test	Clean well by pumping/ air compressor/ manually
Service of pump sets	Replace pump sets
Inspect water quality	Clean the gravel pack using hydraulic and chemical well rehabilitation methods
Flushing pipeline system	Corrosion prevention

When considering maintenance, it is well known that it is frequently ignored until the failure occurs. Such crisis maintenance is likely to be expensive as well, as it may require re-excavation and cleaning of much of the intake portion of the well. However, those personnel who do regular maintenance will recognize that regular maintenance will prolong the life of the system. Recurring costs includes replacement costs, maintenance and repair costs.

RBF wells should be operated continuously to avoid changes in mixing portions of bank filtrate and groundwater and thus water quality. Especially if anoxic conditions occur and post-treatment is required to remove iron and/or manganese, continuous well operation is of advantage. Operation should be monitored by frequent readings of water levels in the well and total volume of water abstracted (water metering).

Costs of RBF systems

Costs of large-diameter caisson well RBF systems

Especially in hilly regions, the higher capital, operation and maintenance cost of water production schemes creates management and functional problems. Capital cost is a fixed and one-time expense, incurred on the purchase of land and installation of equipment. When considering costs, an economic or financial view may be taken. The perspective taken will depend on the required result. A financial review will only look at the systems associated with capital cost, operating cost and any expected revenues. In contrast, an economic review will investigate the higher costs associated with the system which may include the financial impact of system failure on the business or changes to the maintenance cost of the system, further down the pipeline. Regardless of the perspective taken, whole life cost must be developed.A summary of the unit capital expenditure (capex) for one large diameter (~10 m) and shallow (7–10 m) RBF well in Haridwar is presented in Table- 3-5[35].

Table 3-5. Average capital cost of a large diameter caisson well in Haridwar[35]

Capex component	Total cost for 22 RBF wells	Unit cost for one RBF well [1]	
	INR	INR	€[a]
Average cost of civil engineering works for excavation, and construction of well caisson (large diameter ~10 m and 7-10 m deep) and pump house	110,000,000	5,000,000	63,532
Average cost of electrical engineering works for pumps, automation and control panels	22,000,000	1,000,000	12,706
Average cost of diesel-electric generator, construction of foundation, earthing and electrical connection to pump [3]	16,280,000	740,000	9,403
Average cost of connection of pump and control panel to main electricity supply [b]	17,600,000	800,000	10,165
Installation and testing of valves, flow meters and disinfection equipment [b]	9,020,000	410,000	5,210
Total	174,900,000	7,950,000	101,016

[a]Currency exchange rate for December 2018: 1 € = INR 78.7; [b] common for GW abstraction well

Consequently the capital cost of constructing one large diameter and relatively shallow RBF well, excluding the cost for constructing the distribution pipeline, is around INR 6 million. The average operating cost (opex) for one BF well is presented in Table- 3-6, and is around INR 4,500,000 or 57,000 €.

Table 3-6. Average O&M cost of a large diameter and shallow caisson well in Haridwar[35]

Opex component	Total cost for 22 RBF wells in 2011-2012[36]	Unit cost for one RBF well[a]	
	INR/a	INR/year	€/year [b]
Personnel	29,814,000	1,355,182	17,220
Annual repair and maintenance including consumables (for disinfection / post-treatment)	15,824,000	719,273	9,139
Electricity	53,437,000	2,428,955	30,863
Total	99,075,000	4,503,409	57,222

[a] Reference financial year in India: 1st April 2011 – 31st March 2012; [b]Currency exchange rate for December 2018: 1 € = INR 78.7

The electricity and salary of staff account for the largest expenditures, with electricity being the single highest opex cost component accounting for nearly 54% of total opex. This proportion, as well as those for personnel and annual repair and maintenance including consumables such as chemicals (in this case sodium hypochlorite as a disinfectant) match the average proportions of 30–50% for electricity, up to 36% for personnel and 13–19 % for chemicals, repair and maintenance[37]. Based on the year-round average total abstraction of around 61,000 m^3/day from the 22 RBF wells in Haridwar, then the average operating cost of drinking water production is calculated at 4.45 INR/m^3 or 0.06 €/m^3 (Table- 3-7) by dividing the O&M costs (in Table- 3-6) by the average total daily drinking water production.

Table 3-7. Unit-cost of drinking water for RBF system in Haridwar

Opex component	Total O&M cost for 22 RBF wells in 2011-2012 [a, 36]	Cost [b] of drinking water for a 22 well RBF system with a total average production of ~61,000 m^3/day	
	Indian Rupees (INR/a)	(INR/m^3)	(€/m^3)
Personnel	29,814,000	1.34	0.02
Annual repair and maintenance including consumables (for disinfection / post-treatment)	15,824,000	0.71	0.01
Electricity	53,437,000	2.40	0.03
Total	99,075,000	4.45	0.06

[a] Reference financial year in India: 1st April 2011 – 31st March 2012; [b]Currency exchange rate for December 2018: 1 € = INR 78.7

If a debt service of 20% and depreciation of 2% on the total capital cost (Table- 3-5) for a RBF well in Haridwar is included in the operating cost, which wouldamount to 1.57 INR/m^3 and 0.16 INR/m^3 respectively, then the average total operating cost for drinking water production would be 6.18 INR/m^3 (0.08 €/m^3). In most of the cities in India, the water tariffs for the consumer are so low that they do not even cover the annual operation and maintenance cost. However it is important to include debt service and capital costs in water tariffs for the consumer to ensure an economically sustainable water supply service.

Costs of vertical well RBF systems

Unlike the shallow large diameter caisson wells in Haridwar, the RBF well in Srinagar (Uttarakhand) is of the vertical filter design and is around 18 m deep. A summary of the capex for this well is presented in Table- 3-8. Consequently the capital cost of constructing one 200 mm diameter vertical well, excluding the cost for constructing the distribution pipeline, is around INR 1.6 million or 20,000 €. The capex to only drill a larger diameter borehole of 550 mm to a depth of 18 m by the rotary drilling technique in Srinagar and subsequently construct a 300 mm diameter well assembly (excluding other items as listed in Table- 3-8) is around INR 1 million, or nearly four times that of a 200 mm diameter well. Depending on the pump selected, the other capex would vary accordingly but be slightly higher as the well would have a higher yield and thus more water (compared to 200 mm diameter well) could be abstracted with a higher capacity pump.

Table 3-8. Capital cost of a vertical 200 mm diameter production well in Srinagar[35]

Capex component	Unit cost for one RBF well[1]	
	INR	€[a]
Civil engineering works for drilling of 18 m deep borehole by ODEX method, and construction of well assembly	250,800	3,187
Pump, related items, installation and testing	234,400	2,978
SCADA motor-starter control panel	94,000	1,194
Diesel-electric generator, construction of foundation, earthing and electrical connection to pump[b]	851,300	10,817
Connection of pump to control panel[b]	50,000	635
Installation and testing of valves, flow meters and disinfection equipment[b]	120,000	1,525
Total	1,600,100	20,336

[a]Currency exchange rate for December 2018: 1 € = INR 78.7; [b] common for GW abstraction well

The average operating cost (opex) for one RBF well is presented in Table- 3-9, and is around INR 901,000 or 11,400 €. Based on an average daily abstraction of around 900 m^3 from the RBF well, then the average operating cost of drinking water production is calculated at 2.74 INR/m^3 or 0.035 €/m^3 by dividing the total O&M costs by the average daily drinking water production (Table- 3-9). Furthermore, if a debt service of 20% and depreciation of 2% on the total capital cost (Table- 3-8) for the RBF well in Srinagar is included in the operating cost, which would amount to 0.97 INR/m^3 and 0.10 INR/m^3 respectively, then the average total operating cost for water production from this particular RBF well would be 3.81 INR/m^3 (0.05 €/m^3).

Table 3-9. Average O&M cost of a 200 mm diameter vertical production well in Srinagar[35]

Opex component	Unit cost for one BF well[a]	
	INR/year	€/year
Personnel	237,000	3,011
Annual repair and maintenance including consumables (for disinfection / post-treatment)	158,000	2,008
Electricity	506,000	6,429
Total	901,000	11,448

[a] Reference financial year in India: 1st April 2011 – 31st March 2012; [b]Currency exchange rate for December 2018: 1 € = INR 78.7

Capital costs of Koop wells

The capital cost of a Koop well, compared to the conventional surface water treatment system in small streams of mountain areas is shown in Fig. 3-21. It shows that Koop wells are around 6 times cheaper than conventional surface water abstraction structures built for rural water supply schemes on small streams. The maintenance and operational cost of a Koop well is very low. A Koop well abstracting around 432 m^3/day in 24 hours (~300 L/minute) was constructed with a capital cost of INR 0.15 million.

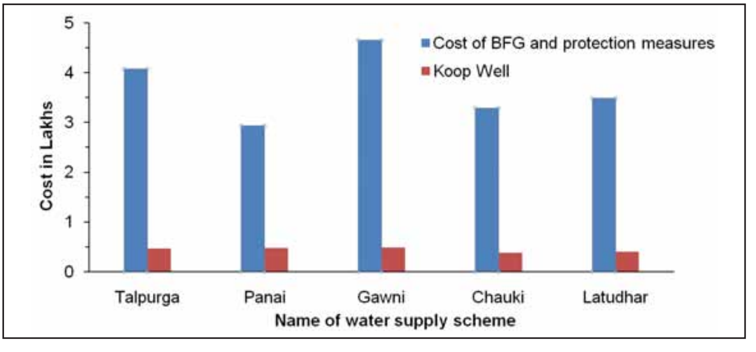

Figure 3-21. Capital cost of Koop wells compared to conventional surface water abstraction structures, called boulder filled galleries (BFG), in rural Uttarakhand.

CONCLUSIONS

Sustainable water abstraction by RBF wells is ensured if there is no over-pumping of wells with high filter entrance velocities and no severe riverbed clogging. The presence of perennial surface water bodies in hydraulic connection with a sufficiently thick alluvial aquifer provides potential for RBF. In this context, locations with surface water boundaries on two or more sides, which are influenced by the existing naturally occurring surface water – groundwater gradient, are optimal sites for new RBF wells. However, sufficient travel time of the bank filtrate, well head protection measures, source protection zones based on the flow path of bank filtrate and ambient groundwater and robust disinfection have to be taken into account when constructing RBF wells and for maintaining the high quality of the abstracted water.

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REFERENCES

1. Grischek, T., Schoenheinz, D., Ray, C., Siting and design issues for riverbank filtration schemes. In: Ray C., Melin G., Linsky R.B. (eds.) Riverbank Filtration – Improving source-water quality. *Water Science & Technology Library,* 2002, **43**, 291-302, Kluwer Academic Publishers, Dordrecht.
2. Hunt, H., Schubert, J., Ray, C., Conceptual design of riverbank filtration systems. In: Ray C., Melin G., Linsky R.B. (eds.) Riverbank Filtration – Improving source-water quality. *Water Science & Technology Library*, 2002, **43,** 19-27, Kluwer Academic Publishers, Dordrecht.
3. Sandhu, C., Grischek, T., Ronghang, M., Mehrotra, I., Kumar, P., Ghosh, N.C., Rao, Y.R.S., Chakraborty, B., Patwal, P.S., Kimothi, P.C., Overview of bank filtration in India and the need for flood-proof RBF systems. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context – Saph Pani. IWA Publishing, London*, UK, 2016, 17-38. ISBN13: 9781780407104.
4. Kumar, P., Mehrotra, I., Boernick, H., Schmalz, V., Worch, E., Schmidt, W., Grischek, T., Riverbank Filtration: An Alternative to Pre-chlorination.*J. Indian Water Works Association,* Special Issue, 2012, 50-58, ISSN 0970-275X.
5. Kale, V. S., Geomorphic effects of monsoon floods on Indian Rivers. *Natural Hazards,* 2003, **28**(1), 65-84.
6. Sandhu C., Grischek T., Riverbank filtration in India – using ecosystem services to safeguard human health. *Water ScienceTechnology,* 2012, **12(6),** 783-790.
7. Murphy, J., Application of ODEX / TUBEX drilling method in a variably fractured volcanic / igneous environment. *Ground Water Management,* 1991, **5,** 799-814.
8. Grischek, T., Schoenheinz, D., Eckert, P., Ray, C., Sustainability of river bank filtration: Examples fromGermany. In: Maloszewski P., Witczak S., Malina G. (eds.) *Groundwater Quality Sustainability*, 2012, 213-227, Taylor & Francis Group: London, UK.
9. Grischek, T., Ray, C., Bank filtration as managed surface - groundwater interaction. *J. Water*, 2009, **5**(2), 125-139.
10. Grischek, T., Schoenheinz, D., Ray, C., Siting and design issues for riverbank filtration schemes. In: Ray C, Melin G, Linsky RB (eds.) Riverbank Filtration – Improving source-water quality. *Water Science & Technology Library,* 2002, **43**, 291-302, Kluwer Academic Publishers, Dordrecht.

11. Schubert, J., Hydraulic aspects of riverbank filtration – field studies. *J. Hydrol*, 2002, **266**(3-4), 145-161.
12. Beyer, W., Schweiger, K. H., Zur Bestimmung des entwässerbaren Porenanteils der Grundwasserleiter (On the determination of the effective porosity of aquifers). Wasserwirtschaft-Wassertechnik (WWT), 1969**, 19**, 57-60.
13. Hazen, A., Some physical properties of sands and gravels. 24th annual report, *Massachusetts State Board of Health, Boston, MA, USA*, 1893.
14. Houben, G. J., Bluemel, M., Automatisierung des Verfahrens nach Beyer & Schweiger (1969) zur Bestimmung von Durchlässigkeit und Porosität aus Kornverteilungskurven (Automating the Beyer and Schweiger (1969) method for the determination of hydraulic conductivity and porosity from grain size data). *Grundwasser*, 2017, **22**, 309-312.
15. Grischek, T., *Lecture Groundwater Engineering*. Script MSc programme Civil Engineering, University of Applied Sciences Dresden, 2010.
16. Bartak, R., Well design proposal for Srinagar RBF site, India. Report, *Division of Water Sciences*, Faculty of Civil Engineering and Architecture, University of Applied Sciences Dresden, Germany, 2015.
17. Huisman, L., *Groundwater recovery*. Macmillan civil engineering hydraulics, Macmillan, 1972, pp. 336.
18. Sichardt, W., Das Fassungsvermögen von Rohrbrunnen und seine Bedeutung für die Grundwasserabsenkung, insbesondere für größere Absenkungstiefen (The yield of vertical wells and its implication for drawdown, especially for greater drawdowns). Springer, Berlin, Heidelberg, 90 pp. DOI: 10.1007/978-3-642-92262-6, 1928.
19. Balke, K.D., Beims, U., Heers, F.W., Hölting, B., Homrighausen, R., Matthess, G., Grundwassererschließung (Groundwater Development), volume 4, *Lehrbuch der Hydrogeologie (Textbook for Hydrogeology)*. Gebr. Borntraeger, Berlin, 2000.
20. DVGW W 113, Bestimmung des Schüttkorndurchmessers und hydrogeologischer Parameter aus der Korngrößenverteilung für den Bau von Brunnen (Determination of the filter grainsize diameter and hydrogeological parameters for the construction of wells). Deutscher Verein des Gas- und Wasserfaches (German Technical and Scientific Association for Gas and Water), Bonn, 2001.
21. DVGW W 118, Bemessung von Vertikalfilterbrunnen (Design of vertical wells). Deutscher Verein des Gas- und Wasserfaches (German Technical and Scientific Association for Gas and Water), Bonn 2005.
22. DIN 4924, Sande und Kiese für den Brunnenbau - Anforderungen und Prüfverfahren (Sands and gravels for well construction – Requirements and testing procedures). Beuth Verlag, Berlin, July, 2014
23. Balke, K.D., *Well construction*. Lecture notes, Institute for Geology and Palaeontology, University of Tübingen, Tübingen, Germany, 1999.

24. Nahrgang, G., Schweizer, W., Untersuchung über die Stabilität und das Dichtverfahren von Filtern aus Sanden und Kiesen bei Bohrbrunnen: Stufe I and II (Investigation of the stability and compaction procedure of filters from sands and gravels for drilled wells: Stage I and II). DVGW-Schriftenreihe Wasser Nr. 11, ZfGW-Verlag, Eschborn, 1982.

25. Bieske, E., Wandt, K., *Nold – Brunnenfilterbuch* (Nold Well filter pack book). Nold Company, Stockstadt, 1977,314.

26. Smith, R. C., Relation of screen design to the design of mechanically efficient wells. *J American Water Works Association*, 1963, **55,** 609-614.

27. Driscoll, F. G., *Groundwater and wells*. 2. ed., Johnson Screens, St. Paul, 1986.

28. Tholen, M., *Arbeitshilfen für den Brunnenbauer* (Tools for the well driller). R. Müller, Köln, 1997.

29. EPA,*Manual of water well construction practices*. EPA-570/9-75-001, Office of water supply, Washington DC, 1975.

30. Langguth, H. R., Voigt, R., *Hydrogeologische Methoden (Hydrogeological methods).*2nd ed., Springer, Berlin, 2004.

31. Musche, F., Sandhu, C., Grischek, T., Patwal, P.S., Kimothi, P.C., Heisler, A. (2018) A field study on the construction of a flood-proof riverbank filtration well in India – challenges and opportunities. *International Journal of Disaster Risk Reduction*, 2018, DOI: 10.1016/j.ijdrr.2018.06.003.

32. Sandhu, C., Grischek, T., Musche, F., Macheleidt, W., Heisler, A., Handschak, J., Patwal, P.S., Kimothi, P.C., Measures to mitigate direct flood-risks at riverbank filtration sites with a focus on India. *Sustainable Water Resources Management*, 2018, **4**(2), 237-249, DOI: 10.1007/s40899-017-0146-z.

33. Bieske, E., Rubbert, W., Treskatis, C., *Bohrbrunnen* (Drilled water wells). 8. ed., Oldenburg, Vienna, 1998.

34. RDSO,*Guidelines on construction & maintenance of bore wells and tubewells*. Report No. WKS-01-2014 2014, Government of India, Ministry of Railways, Research Designs and Standards Organisation (RDSO), Works Directorate, Lucknow, 2014.

35. Saph Pani, *D.1.4 Report on bank filtration economics and cost-estimates*. Saph Pani Project Deliverable D1.4, 2014. Available: *http://www.saphpani.eu/downloads.*

36. Essl, L., Starkl, M., Kimothi, P.C., Sandhu, C., Grischek, T., Riverbank filtration and managed aquifer recharge as alternative water supply technologies for India: strengths – weaknesses – opportunities – threats analysis. *Water Science & Technology: Water Supply*, 2014, **14**(4), 690–697.

37. CPHEEO & WHO,*Manual on Operation and Maintenance of Water Supply Systems*. Central Public Health and Environmental Engineering Organisation, Ministry of Urban Development, Government of India and World Health Organisation, 2005.

4

Chapter

WATER QUALITY PARAMETERS AND THEIR FATE DURING RIVERBANK FILTRATION

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In a water supply scheme, water quality has to be assessed at several stages of drinking water production, e.g. collection, transmission, treatment and distribution, to ensure safe and potable water at consumer's tap. There is a long list of parameters - physical, chemical and biological - to be evaluated, as per the Indian standard. Riverbank filtration (RBF) significantly reduces contaminants, pathogens and organic compounds present in the river/ lake water. If the river water is not highly polluted, then bank filtration leads to complete removal of pathogens and thereby reduces health risk directly due to pathogens and indirectly due to disinfection by-products (DBPs). RBF provides partial treatment to water from polluted rivers and reduces the overall cost of the treatment.

KEYWORDS: Monitoring, organic micropollutants, biodegradation, sorption, column experiments

INTRODUCTION

Impurities are added as water falls through the atmosphere and as it flows on or below the surface of the earth. Treated water has to agree with the Indian Standards for Drinking Water[1]. Sample collection, preservation of samples (if required), transportation and analysis is done as per Standard Methods for the Examination of Water and Wastewater[2]. Physical, chemical and biological characteristics and fate during bank filtration are discussed in following sections.

Physical, chemical and biological characteristics and fate during bank filtration

Physical water-quality parameters

Physical parameters define those characteristics of water that respond to the senses of sight, touch, taste, or smell. Suspended solids, turbidity, color, taste, odor, and temperature fall into this category.

Suspended solids

Suspended solids (SS) in water may consist of inorganic or organic particles or immiscible liquids. SS enter into surface waters either due to natural processes such as the erosive action of water flowing over surfaces or as a result of human use of water. Clay, silt and other soil constituents are common examples of natural inorganic solids present in surface waters. Organic material such as biological solids, e.g. algal cells, bacteria etc. and plant fibres are also common natural constituents of surface waters. The release of domestic and industrial wastewaters in surface waters often results in the presence of large quantities of organic and inorganic SS. As water enters in the ground, these materials are filtered out easily and are rarely present in groundwater or bank filtrate.

Turbidity

In place of direct measurement of SS of natural surface waters or drinking waters, a test for turbidity is used. Turbidity is a measure of the extent to which light is either absorbed or scattered by material present in water. Because absorption and scattering are influenced by both size and surface characteristics of the SS, turbidity is not a direct quantitative measurement of SS. In almost all studies on RBF, the turbidity of filtrate has been found to be very low (< 0.3 NTU). It is one of those characteristics of surface waters, which is altered very easily as river water flows towards an RBF well. Turbidity is retained on the interface and in the adjacent layers of the aquifer material. Inert material builds up while organic one undergoes changes. During high flow, it is washed off, and a fresh filtering layer is laid.

Color

Pure water is colourless, but surface waters are often coloured due to the presence of foreign substances. Water may have true or apparent colour. Color contributed by the dissolved material is defined as true while that partly due to SS is classified as apparent. In RBF, apparent colour is removed while true colour is not eliminated in many cases requiring post-treatment of filtrate.

Taste and odor

Substances that produce an odour in water will almost invariably impart a taste as well. The reverse is not true, as there are many mineral substances that produce taste but no odour. A comprehensive study regarding the attenuation of taste and odour during RBF is not reported.

Temperature

Temperature is not used to evaluate the potable waters directly. Surface waters experience large fluctuations in temperatures. In the case of the filtrate, wide variations have not been reported.

Chemical water-quality parameters

Water is a universal solvent. Total dissolved solids, alkalinity, hardness, metals, organics, and nutrients are some of the chemical parameters of concern.

Total dissolved solids

Dissolved solids (DSs) enter in natural waters due to solvent action of water on solids, liquids, and gases. Like SSs, DSs are also inorganic and organic in nature. Examples of inorganic DSs are minerals, metals, and gases while common organic DSs are materials from the decay products of vegetation, from organic chemicals, and from the organic gases. Water comes in contact with these materials in the atmosphere, on surfaces, and within the soil. During RBF, DSs increase mainly due to the dissolution of aquifer material and mixing with groundwater. In general, at particular place groundwater has more DSs compared to surface waters. Accordingly, bank filtrate has been found to contain more DSs than the corresponding surface source.

Alkalinity

Alkalinity causing compounds result from the dissolution of mineral substances present in the soil and atmosphere. Wastewater discharges, fertilisers and microbial decomposition of organic material also contribute. By far the most common constituents of alkalinity are bicarbonate, carbonate, and hydroxide. In addition to their mineral origin, these substances also originate from carbon dioxide, a constituent of atmosphere and a product of microbial decomposition of organic material in the aquifer adjacent to the interface. As water travels from the surface source to the well its alkalinity increases. Bank filtrates have been found to have greater alkalinity than corresponding natural surface waters.

Hardness

Hardness is defined as the concentration of multivalent metallic cations in solution. Calcium and magnesium are the most abundant ones, and for all practical purposes, hardness is represented by the sum of the calcium and magnesium ions. During RBF, hardness has been found to increase. The increase depends on the proportion of groundwater in the pumped water, time surface water takes to reach the well and distance it travels, and geology/aquifer characteristics. As long as hardness remains within prescribed desirable/permissible limits, no post-treatment of filtrate is required. In most of the studies, increase in hardness has been reported to be within limits as specified in the Indian Standard for Drinking Water[1].

Metals

All metals are soluble to some extent in water. An excessive amount of any metal may present health hazards. However, only those metals that are harmful in relatively small amounts are commonly labelled toxic; others fall into the nontoxic group. Sources include dissolution from natural deposits and discharges of domestic, industrial, or agricultural wastewaters. In the case of RBF, it is essential to know the geology of the well surroundings.

Organics

Many organic materials are soluble in water. In natural waters, organics come from either natural sources or result from human activities. Most of the natural organics are the result of the decay of organic solids. Synthetic organics are due to discharges of wastewaters or runoff from agricultural lands. Organics are classified as biodegradable/ non-biodegradable (refractory). In studies related to RBF, the important parameter is total/ dissolved organic carbon (TOC/ DOC), which includes both biodegradable and non-biodegradable fractions. Presence of organics is also related to disinfection by-products. A filtrate having DOC < 2 mg/L is considered to be safe for further chlorination. In some of the studies on RBF, it has been found that if the source water is polluted, bank filtrate had unacceptable DOC and post-treatment for the removal of organics was unavoidable.

Nutrients

A wide variety of minerals and trace elements can be classified as nutrients. Those required in most abundance by aquatic species are carbon, nitrogen, and phosphorus. In most cases, nitrogen and phosphorus are the nutrients that are limiting factors. Nutrients are of more relevance in the case of lakes/ reservoirs rather than rivers. As lake bank filtration sites are limited, the fate of nutrients during RBF is not studied much.

Biological water-quality parameters

Water serves as a medium in which literally thousands of biological species spend part of their life cycles. Aquatic organisms range in size and complexity from the smallest single-cell microorganism to the largest fish.

Pathogens/ pathogen indicators

Pathogens are the most important biological organisms in water from the perspective of human use and consumption as they are capable of infecting, or of transmitting diseases to humans. These organisms are not native to aquatic systems and usually require an animal host for growth and reproduction. They are only temporary members of the system and can survive and maintain their infectious capabilities for significant periods of time. These waterborne pathogens include species of bacteria, viruses, protozoa, and helminths. The range of values of total and fecal coliform for source water and bank filtrate for different RBF sites is shown in Table 4-1.

Table 4-1. Range of values of total and fecal coliform for source waters and bank filtrate at bank filtration sites in India

River/ lake bank filtration site	Period of study	Fecal coliform (MPN/100 mL)		Total coliform (MPN/100 mL)	
		River/ lake	Production well*	River/ lake	Production well*
Haridwar	2005–2011	1.6×10^2–2.4×10^4	< 2–9×10^1	1.6×10^2–9.3×10^5	<2–1.7×10^2
Nainital	1997–2013	5×10^1–5×10^4	<2	5×10^1–5×10^5	<2
Kaleshwar	2011–2013	8×10^1–1.3×10^4	<2	1.3×10^2–6×10^4	<2–9×10^2
Satpuli	2011–2013	5×10^1–9×10^4	<2	5×10^2–3.5×10^5	<2–7×10^1
Agastyamuni	2011–2013	9×10^2–5×10^4	<2	1.6×10^3–3×10^5	<2–5×10^1
Srinagar	2011–2013	8×10^2–3×10^5	<2	3×10^3–9×10^5	<2–3×10^3
Mathura	2006–2008	1.5×10^2–2.3×10^5	4.3×10^1–9.3×10^3	2.3×10^3–1.5×10^6	4.3×10^1–7.5×10^4
Delhi	2013–2014	7×10^4–2×10^6	<2–6.9×10^2	3×10^5–7×10^6	<2–1.2×10^3

Organic micropollutants – occurrence and fate during bank filtration

Occurrence of organic micropollutants

Over the past recent years, the analysis of anthropogenic organic trace pollutants and investigation of their fate in environment and during water treatment has shifted to an essential part in water quality assessment due to their potential or already proven negative impacts on human health and/or ecosystems[3]. Generally, the term "organic micropollutants" (OMPs) includes all single substances or groups of compounds, which possess the attributes 1) relatively stable concerning chemical/ biological degradation, 2) verified occurrence in the environment (often in very low concentrations), 3) relatively high production/consumption amounts and 4) negative effects for humans and/or on ecosystems. OMPs can be divided into "classic" organic pollutants and "emerging pollutants". The classic organic pollutants (also known as persistent hydrophobic organic pollutants) are typical chemicals from industry, waste disposal sites, and agriculture, e.g. polycyclic aromatic hydrocarbons (PAH), halogenated aromatics or chlorinated pesticides. They are often non-polar and therefore hydrophobic, which results in a high geo- or bioaccumulation potential. A wide global distribution is possible because of their binding to suspended matter, colloids, and dissolved natural organic matter (NOM) as well as onto fine dust particles in the air. Nevertheless, sorption onto the surfaces of solid materials (soil, sediment, suspended matter) is the main attenuation process in the groundwater or RBF in the case of persistent compounds. Their occurrence, effects, and environmental fate have been studied extensively.

Emerging pollutants are mostly considerably polar / hydrophilic. Until a few years ago, the determination of such highly water soluble compounds at trace concentrations was very difficult and often connected with high effort and analytical inaccuracies. Due to the enormous progress of analytical techniques during the last few years, particularly the combination of liquid chromatography (LC) and mass spectrometry (MS), the occurrence of a high number of anthropogenic organic compounds in different parts of the water use cycle could be demonstrated. Some typical representatives of such polar pollutants are pharmaceuticals, antibiotics from human or veterinary use, iodinated X-ray contrast media, polar herbicides, complexing agents, plasticizers, endocrines, ingredients of personal care products, and the more polar metabolites of all these groups. In recent years, the focus of environmental research has shifted to emerging pollutants due to their low biodegradability, their continuous discharge from wastewater treatment plants (WWTPs) into the environment, and their ubiquitous occurrence.

During the last two decades, numerous measurement campaigns, primarily in Europe and North America, have been carried out that have demonstrated the ubiquitous occurrence of pharmaceutical residues in domestic wastewater and identified the effluents of wastewater treatment plants (WWTPs) as a major input pathway of micro pollutants into the aquatic environment In particular, pharmaceuticals are partially released untransformed from the human body. The existing conventional municipal sewage plants are not suited to completely remove these emerging pollutants or their stable transformation products. Thus, the upgrade of existing WWTPs with an additional tertiary treatment step and other technical measures are under discussion in Europe. To advance this cause, the European Water Framework Directive (WFD) set up environmental objectives to achieve a "good water status" for all European water bodies by 2015 and established a conceptual framework to achieve these objectives. Here, the main goals were to develop new research initiatives on most pressing issues and to support the policy making community in the implementation of the WFD with the need to identify "river basin specific pollutants". Furthermore, despite systematic scientific investigations, there is still a lack of knowledge about the long-time occurrence and the behavior of polar micropollutants in the environment and in water treatment processes as well as their effects (particularly combined effects of mixtures of anthropogenic trace compounds) on human and/or ecosystems.

Although mainly surface water is used for drinking water production in India, especially from rivers, there is only scarce information about the occurrence of

OMPs. Recent publications show relatively high concentrations of pharmaceuticals and pesticides in Indian waste waters as well in surface and groundwater.

Fate of organic micropollutants during bank filtration

A comprehensive understanding of the attenuation processes of OMPs is important for the modelling and forecasting of contaminant transport as well as for the assessment of the effectiveness of its attenuation during RBF. From a practical standpoint, field investigations are the most appropriate approach to considering real-world conditions, but the required effort, the complexity and heterogeneities of field conditions, and environmental risks are often too high. In contrast, column experiments at laboratory scale are useful tools in carrying out systematic studies with defined boundary conditions to address practical issues with comparatively low effort and to gain a better understanding of the relevant processes and interactions. From the breakthrough curves determined by column experiments the transport behavior of a compound can be estimated. Furthermore, such results allow a verification of applied transport models and a comparison of different compounds.

From laboratory column experiments the following information can be obtained:

- retardation behavior of selected compounds or groups of compounds and sum parameters like DOC,
- sorption kinetics,
- simulation of shock or long-term loads,
- desorption behavior (wash out effects),
- influence of boundary conditions or competition effects,
- microbial degradation rates and adaptation effects and
- providing model data for the comparison of known and unknown pollutant behavior.

Limitations of laboratory column experiments are for example:

- restriction to one-dimensional mass transport,
- problems avoiding degradation processes without a significant change of conditions,
- no short-term predictions,
- potential wash-out effects in sediments with a high organic carbon content,
- potential for redox gradient formation within the column bed and
- high effort compared to simple batch experiments.

For the systematic investigation of sorption and biodegradation behavior of OMPs,lab-scale column systemsas described below can be used[4].*Flow through column experiments* for estimating breakthrough behavior of compounds at a given water/ sediment system can be realized with using following technique and procedure[4]. Stainless steel columns with a length of 0.25 to 2 m and an inner diameter of 30to 80 mm respectively are filled with sediment material from natural aquifers taken in the vicinity of rivers at plannedRBF sites and sieved to a grain size fraction less than 2 mm. The organic carbon content of the sediment material should be analyzed due to the compound transport calculation as described above. The effective porosity andthe average solid bulk density of dried sediment should be determinedfor the calculation of partition coefficients. For the experiments, the regarded raw water spiked with certain concentrations of selected OMPsis pumped through the column at a rate of 0.5 to 2.5 mL/min. After passing the column, the water is regularly sampled, filtered, in case of lower concentrations enriched by a factor of 10 to 100, and analyzed, for example with HPLC-MS or GC-MS. The velocity of the water and the effective porosity of the column filling material are estimated by recording the breakthrough curve of chloride as non-absorbable tracer. For every experiment, a new column should be filled to ensure constant starting conditions.

Small-scale biologically active filters, so called "test filters", can be additionally used to study the specific degradation of OMPs at the first centimeters of RBF. These experiments arecarried out by circulating raw (river) water through glass or stainless steel columns (suggested dimensions: 30–50 mmdiameter, 80–120 mm height) filled with pumice (no sorption affinity to most of the OMPs). The columns are operated in the dark, at constant temperatureand at a pumping rate in the range of 1–5 mL/min. Stable aerobic conditions can be proven by measuring dissolved oxygen concentrations in the column discharge. After filling of columns with pumice, unfiltered water from the regarded raw wateris circulated for a minimum of one month and replaced byfresh river water every week. During the following experiments the water is replaced with filtered river water every 6 to 8 days. For the experiments selected OMPs are added to the river water to achieve concentrations relevant for the investigation tasks.

Because of the high number of known and continually newly discovered OMPs, the experimental characterization of the fate of such compounds cannot keep pace. Therefore, various correlations and forecasting models exist and continue to be refined. For example, the retardation of organic compounds in aquifers can be predicted by using common log K_{OW}-K_{OC} correlations (Eq. 4-1):

$$\log K_{OC} = A \cdot \log K_{OW} + B \quad (4\text{-}1)$$

Where K_{OC} is the organic carbon normalized sorption coefficient and K_{OW} is the n-octanol water distribution coefficient. Such correlations exist for different types of compounds, e.g. for the group of non-hydrophobic substances[5]:

$$\log K_{OC} = 0.52 \cdot \log K_{OW} + 1.2 \tag{4-2}$$

Based on this approach, the retardation factor R_d can be further calculated from K_{OW} data based on known sediment characteristics (organic content f_{OC}, bulk density ρ, effective porosity n_e) and assuming a linear sorption isotherm (Eq. 4-3 and 4-4).

$$K_{OC} = \frac{K_d}{f_{OC}} \tag{4-3}$$

$$R_d = 1 + \frac{\rho}{n_e} \cdot K_d \tag{4-4}$$

For acidic and basic compounds a modified pH-dependent n-octanol water distribution coefficient log D (Eq. 4-5 and 4-6) was introduced by Scherrer & Howard (1977)[6]:

$$\log D_{acid} = \log K_{OW} + \log\left(\frac{1}{1+10^{pH-pK_S}}\right) \tag{4-5}$$

$$\log D_{base} = \log K_{OW} + \log\left(\frac{1}{1+10^{pK_S-pH}}\right) \tag{4-6}$$

According to Equation 4, the anionic proportion of acidic compounds increases at higher pH. In this case, log D decreases because the higher deprotonation results in lower log K_{OC}. On the other side, bases become cationic due to the increasing protonation at low pH values (Eq. 4-6). However, the transport behavior of ionic, particularly cationic micropollutants in aquifers is often not predictable by using these correlations. Several positively charged compounds, for example different antibiotics or beta blockers, show a strong retardation despite their highly polar character, because of additional interactions, e.g. ion exchange[7].

Biodegradation of organic micropollutants can occur during aquifer passage depending on local boundary conditions (e.g. redox milieu, water matrix, temperature, compound concentration). From the breakthrough curve of column experiments, such degradation effects can be observed as a constant difference between column inlet and outlet concentration of model compounds after their breakthrough. Although such biodegradation processes in nature are normally very complex, the overall kinetics often follow a pseudo-first order rate law. Such a simplified approach can be considered in transport modelling and the rate constants can be calculated by non-linear regression analysis. In the case of an accelerating decrease of concentration after breakthrough, the most likely cause is an adaptation of microorganisms.

In different cases the lengthening of breakthrough curves cannot be explained only by dispersion and diffusion. Such strong spreading or tailing effects are caused by slow and therefore rate-limited mass transfer processes from the bulk solution to the surface (film diffusion) or in the pores or at the surface of a sorbent (intra particle diffusion. An exact description of these effects can be obtained by using non-equilibrium methods, which provide a numerical and therefore more complex solution. Rahman et al. (2003)[8]introduced a modified ("effective") dispersivity α_{eff} an equilibrium model can be used, that allows the application of an analytical solution (Eq. 4-7):

$$\alpha_{eff} = \alpha_{tracer} + \frac{v_W}{k_{sor} \cdot R_d} \tag{4-7}$$

Where α_{tracer} is the dispersivity of a conservative tracer, v_W is the mean pore water velocity, and k_{sor} is the overall mass-transfer coefficient (summarized film and intraparticle diffusion). Mostly the film diffusion is rapid and can be neglected, so that eq. 4-7 can be written as:

$$\alpha_{eff} = \alpha_{tracer} + \frac{v_W}{k_S a_V \cdot R_d} \tag{4-8}$$

Wherek_S represents the intraparticle mass transfer coefficient and a_V is the mass transfer area per volume. From this equation, the extent of the influence of the sorption kinetics in a given sorbate-sorbent system can be characterized. The impact of sorption kinetics decreases with lower water velocities.

Combined use of laboratory experiments, transport modelling, and comparative field studies is very helpful in gaining a better understanding of emerging pollutants behavior in the aquatic environment. For the prediction of the retardation of polar trace compounds new approaches have to be developed and verified.

Analysis of OMPs

Generally, the existing methods for sampling, pre-treatment and analysis of OMPs are so far now not harmonized[9]. That means, the national guidelines onwater quality in different countries usedifferentparameters or "watch lists" for waterqualityassessment or even donot include OMPsin many cases. The established methods for the determination of OMPsare high-performance liquid chromatography (HPLC) with diode array, UV- or fluorescence detection and gas chromatography (GC) coupled with electron capture, flame ionization or mass spectrometric detection. A variety of OMPs exhibits high polarity and high water solubility, which made their analysis challenging in the past. The recent advancement of sensitive LC-MS/MS techniques now allow for their determination at a trace level in the ng/L and lower µg/L range[10]. Due to the low concentration of trace pollutants, an appropriate enrichment is often required. For an efficient and automatable sample pre-treatment, solid phase extraction (SPE) on modified silica or on polymeric materials is usually used. Using the recent generation of high sensitive mass spectrometry detectors, particularly triple quadrupole systems, and the direct determination of OMPs in different water matrices pollutants can be realized.However, till now, such expensive instruments arehardlyusedforroutine monitoring. In complex matrices (polluted surface water, influent and effluent from WWTP) a sample purification (clean up) using SPE is often necessary to protect the sensitive detection system and to avoid cross-sensitivities.

The availability of alternative methods of analyzing OMPs which can be used on-line or at least on site are highly needed but presently still at the research stage. For example, cell-based immune-essays, biosensors or highly sensitive optical or impedimetric systems can be used in the future for a permanent and save control of raw and drinking water.

Strategy of OMP monitoring and fate investigations for RBF

General regulations or approaches for OMPs monitoring in case of RBF are not available. A recommended action schedule is given in Figure4-1, what is also in accordance with the methodology given in Figure 2-3. For its realization, the available analytical capabilities should be considered. A commercial contract laboratory can be commissioned to carry out the determination of selected relevant OMPs. However, the water suppliers should be intensively involved within the processes of compound selection, determination of monitoring strategies and additional decisions, e.g. about construction of monitoring cross sections, of appropriate post-treatment steps and its analytical control.

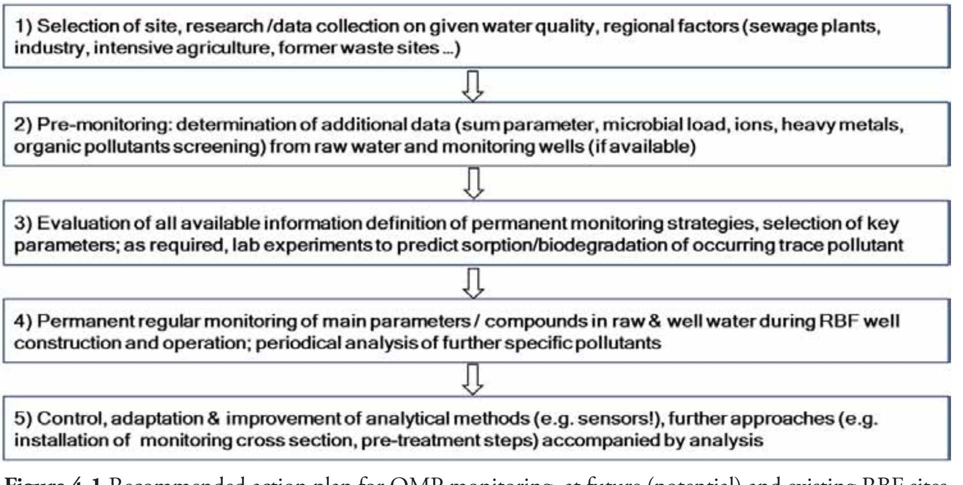

Figure 4-1. Recommended action plan for OMP monitoring, at future (potential) and existing RBF sites

Before the installation of a RBF scheme at a selected site is started, a comprehensive research on the following aspects in view of OMPs should be carried out (phase 1): a) available data on water quality, particularly occurrence of OMPs (type, concentration) from literature, reports, unpublished regional material from research or administrations and others; b) consideration of regional conditions, e.g. former, existing or projected sewage plants, industry locations, intensive agriculture or livestock farming. From this research, a first pre-monitoring of missing information on water quality should be derived (phase 2). For this, selected on-spot samplings of raw water or extended sampling and analysis of water from constructed monitoring wells are suitable. Additionally, passive samplers can be used for raw water sampling to get further time-integrated qualitative information on occurring OMPs. Due to the possible occurrence of strongly varying compounds, a widest possible range and number of OMPs should be considered within theanalytical screening approach of phase 2. A non-target screening methods using high-resolution LC-MS systems ("time of flight" or "orbitrap" mass spectrometry) is here the most appropriate tool. However, due to the fact that in the most of routine laboratories such systems are not available, a target screening using LC-MS/MS or other detectors (UVD, FD) can be performed. In case of target screening, a pre-selection of regarded (targeted) compounds is necessary. Known occurrence at similar sites, risks for human health or results from the regional research (phase 1) are important criteria for OMPs pre-selection.

In phase 3, a strategy for a comprehensive and long-term monitoring during construction and operation of the RBF system is derived from the in-depth evaluation of all data and information estimated in phases 1 and 2. From the first screening results, the main occurring OMPs can be estimated. For the further monitoring, the most relevant compounds ("key compounds") in view of frequency and maximal observed concentrations should be selected. In case of uncertainties relating to determined specific OMPsand their elimination efficiency during RBF, additional laboratory experiments (see chapter 4.2) can be carried out to estimate the biodegradation and sorption behavior at given boundary conditions.

As a result from such column experiments, essential compound-specific parameter describing the attenuation behavior at given conditions for the regarded site can be derived, e.g. retardation (sorption affinity), degradation rate, or kinetic of mass transfer. It can be assumed that compounds with higher retardation factors ($R_d > 5$) often not reach the well, due to the increased residence time in the aquifer and related improved chances of biodegradation. For a more accurate discussion of the potential of a certain compound, the distance from river to the well and the flow velocities of infiltrate should be considered. Further effects, like adaptation of biocenosis or co-metabolism, can be observed and characterized.

The exploration, selection, installation and operation of RBF facilities should be systematically accompanied by the defined monitoring procedure of appropriate parameter (phase 4). In view of OMPs, a periodical repetition of OMPs screening seems useful, e.g. in the framework of an annual special measurement program (phase 5). This is particularly important in case of considerable regional changes (e.g. strong urban development, land use, industrial settlement, climate factors). Furthermore, modifications of RBF operation or additional post-treatment technologies by the water supplier should be intensively accompanied by analytical monitoring.

In addition to an effortful analysis of organic trace pollutant with LC- or GC-MS techniques, other and simpler parameters can be used as indicators for an assessment of organic pollutants. These include, inter alia, sum and group parameters such DOC, TOC, UVA_{254} or AOX. However, for amore precise characterization of risks, the determination of main relevant organic compounds cannot be replaced by an analysis of such parameter.

Claimer

The section "Occurrence of organic micropollutants" is based on authors book contribution[11] and articles[12,13].

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REFERENCES

1. IS 10500 Drinking Water - Specification. Indian Standard (second revision), *Bureau of Indian Standards,* New Delhi, India, 2012.
2. Standard Methods for the Examination of Water and Wastewater. 22nd edition, prepared and published jointly by American Public Health Association, American Water Works Association and Water Environment Federation. Washington, DC, 2012.
3. Schwarzenbach, R.P., Escher, B.I., Fenner, K., Hofstetter, T.B., Johnson, C.A., Von Gunten, U., Wehrli, B., The challenge of micropollutants in aquatic systems. *Science,* 2006,**313**, 1072–77.
4. Boernick, H., Schaffer, M.,Worch, E., Grischek, T., Characterization of the attenuation behavior of organic micro pollutants in water/sediment systems using column experiments. Proceedings of the International Conference on Geology, Geotechnology

& Mineral Resources of Indochina *(GEOINDO 2011),* Khon Kaen, Thailand, 2011, 1-3 Dec. 2011.

5. Sabljic A., Güsten H., Verhaar H., Hermens J., Qsar modelling of soil sorption. Improvements and systematics of log KOC vs. log KOW correlations. *Chemosphere*, 1995, **31**, 4489–4514.
6. Scherrer R.A., Howard S.M., Use of distribution coefficients in quantitative structure-activity relationships.*J Med Chem*. 1977,**20**(1), 53-58.
7. Kutzner, S., Schaffer, M., Börnick, H., Licha, T., Worch, E., Sorption of the organic cation metoprolol on silica gel from its aqueous solution considering the competition of inorganic cations. *Water Research*, 2014, **54**, 273–283.
8. Rahman M., Amiri F., Worch E., Application of the mass transfer model for describing nonequilibrium transport of HOCs through natural geosorbents. *Water Research*, 2003,**37**, 4673–4684.
9. Geissen V., Mol H., Klumpp E., Umlauf G., Nadal M., van der Ploeg M., Sjoerd E.A., van de Zee T.M., Ritsema C.J., Emerging pollutantsinthe environment: A challenge for water resource management. *Intern. Soil and Water Conservation Res.*, 2015, **3**, 57–65.
10. Reemtsma T., Jekel M., Organic pollutants in the water cycle. 2006, Wiley-VCH, ISBN 9783527312979.
11. Abbt-Braun G., Boernick H. et al., Water quality of tropical reservoirs in a changing world – the case of Lake Paranoá, Brasília, Brazil. In: LorzC., Makeschin F., Weiss H. (eds.) *Integrated water resource management in Brazil*. 2014, IWA Publishing.
12. Boernick H., Schaffer M., Worch E., Grischek T., Characterization of the attenuation behavior of organic micro pollutants in water/sediment systems using column experiments. *Proceedings International Conference on Geology, Geotechnology and Mineral Resources of Indochina*, 01.-03.12.2011, KhonKaen, Thailand.
13. Börnick H., Grischek T., Worch E., Determination of aromatic amines in surface waters and comparison of their behavior in HPLC and on sediment columns. *Fresenius J. Anal. Chem.*, 2001,**371**, 607-613.

5
Chapter

RISK ASSESSMENT AND POST-TREATMENT OF RBF SCHEMES IN INDIA

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A sustainable water quality delivered by a RBF scheme can be managed to a large extent, if a thorough assessment of human health and environmental risks is conducted. Risks may eventually arise from inducing river water into an aquifer or due to inherent groundwater quality issues. In this context, the post-treatment of water abstracted from an RBF scheme depends on its intended use that in most cases is for drinking. Safe disinfection of drinking water requires detailed knowledge concerning the reactions of chlorine as well as chlorine like agents in water. These are key questions in order to guarantee a low chlorine demand, low by-products as well as no odor formation. This chapter illustrates and discusses the risk assessment and management of RBF schemes and the most important factors which influence the efficiency of drinking water disinfection. Options for improved application of chlorine disinfection including the new process of inline-chlorination are presented.

KEYWORDS: Risk assessment, water safety plan, disinfection, inline-chlorination, by-products formation, odor

INTRODUCTION

Risk assessment of RBF systems

When considering managed aquifer recharge (MAR), generally in many cases the recharge water (water induced into an aquifer) is of comparable quality to water already in the aquifer and enhancing recharge may improve the quality of groundwater, for example by freshening brackish groundwater1. Though policy and technical frameworks in India consider RBF as a method to induce recharge into an aquifer by virtue of augmenting well yield2, induced recharge (including RBF) may also introduce microbiological or chemical pollutants to aquifers, or mobilize minerals from the aquifer matrix, which may be harmful to human health or adversely affect the aquatic environment. If the same aquifer being recharged is also used as a drinking water source, it should be an obligation of those enhancing recharge to protect the health of those whose drinking water is affected by their operations1. In this context, a risk assessment means the application of a common holistic framework, which provides a staged approach to assess the highest priority hazards commonly encountered in RBF operations and provides a scientifically-founded basis for further risk management plans.

As RBF is considered crucial to the removal of microbial pathogens from drinking water derived from surface water in India3,the evaluation of microbiological risks for RBF sites is particularly relevant there and in other parts of South and Southeast Asia4,5.The burden of diarrhoeal diseases in India was projected to be 0.0218 disability-adjusted life years (DALYs) for 20166.Diarrhoeal diseases are the leading cause of mortality amongst children under 5 years age resulting in 300,000 deaths per year, such that amongst pathogens causing diarrheal disease, only rotavirus is currently vaccine-preventable7. Accordingly, rotavirus causes about 40% of all diarrhoea hospitalizations in India, 2 million outpatient visits and 113,000 to 153,000 child deaths per year. Although India has introduced a vaccine against rotavirus, non-rotavirus diarrhoea will continue to be an important cause of morbidity and mortality[7].

Where the intention is to use RBF for drinking water production and in addition to assessing the risk from chemical parameters, it is necessary to focus on a thorough assessment of the potential pathogen risks to human health using quantitative microbial risk assessment8. Microbial risks are more acute compared to chemical hazards, because the latter may cause subtle, chronic health effects on account of their potential toxicity, carcinogenicity or being suspected endocrine disruptors[9].

Considering the above, a risk assessment and management plan for a RBF system taking the example of Haridwar is summarized in subsequent sections. As disinfection is the necessary post-treatment to safeguard against microbial risks, relevant aspects of chlorination of RBF water are presented in detail. The specific aspect of risks from floods and mitigation measures at RBF schemes in India is summarized in chapter 3 and is available in detail through accessible literature[10-13].

Post-treatment of RBF systems

If the naturally (pre-) treated water from a RBF system does not meet the required local water quality guidelines or standards for intended use (in case intended use is drinking water, then Indian Standard IS 10500 2012 is applicable), then the abstracted water from the RBF well(s) will require post-treatment. The requirements for post-treatment of a RBF system depend upon the quality of the source and abstracted water and the type, design and operation of the system.

Chlorination is the main post-treatment applied to most RBF systems in Uttarakhand (Table- 5-1). Due to relatively high concentrations of natural organic matter in bank filtrates found usually in RBF wells of radial collector design constructed within the riverbeds of very polluted rivers with fast travel times (e.g. Yamuna River in Mathura), formation of THMs or other DBPs is a major water quality concern14. In summary, depending upon the raw water quality (of river or lake), local hydrogeological conditions and contaminant removal efficiency at a particular site, the post-treatment of filtrates of RBF schemes in India would need to address pathogens, hardness, -iron, manganese, ammonium, nitrate, arsenic and fluoride and / orbulk organics and organic micropollutants[15].

Table 5-1. Post-treatment applied in selected RBF schemes in India[15]

RBF site	Source of water for RBF	Main water quality concern after RBF	Post-treatment applied
Haridwar (Uttarakhand)	Ganga River	Occasional presence of pathogen indicators	Chlorination only
Nainital (Uttarakhand)	Nainital Lake	As above / some hardness	Water softening and chlorination
Srinagar (Uttarakhand)	Alaknanda River	Nitrate > 45 mg/L in abstracted water due to geogenic origin	Chlorination of RBF water & then mixing with conventionally treated surface water
Satpuli (Uttarakhand)	East Nayar	Occasional presence of pathogen indicators in very low concentrations	Chlorination only
Mathura (Uttar Pradesh)	Yamuna River	Organic matter (DOC), Hardness; Pathogens; Arsenic; Organic micro pollutants	Aeration- filtration- chlorination
Ahmedabad (Gujarat)	Sabarmati River	Pathogens; Organic matter	– Abstraction from RBF wells is discontinued when breakthrough of turbidity is high – Non-monsoon: Chlorination (of bank filtrate) only
Medinipur (West Bengal)	Kangsabati River	Occasional presence of pathogen indicators	Chlorination only
Delhi - Palla (National Capital Territory)	Yamuna River	Iron, manganese fluoride (present in deeper aquifer) Pathogens during monsoon	Chlorination only

Risk assessment and management and water safety plans for RBF systems in India

For the RBF scheme in Haridwar, whose water quality has been monitored continuously and regularly since 2005, a QMRA was conducted in 2013/2014[4]. Accordingly, microbiological analyses of the water abstracted from the RBF wells indicated that the residual risks posed by the reference bacteria E. coli O157:H7 were very low (0.00165 DALYs) and below the national diarrhoeal incidence of 0.027 DALYs and meet the health target in this study of 0.005 DALYs per person per year. This target corresponds to the WHO regional diarrhoeal incidence in South-East Asia. However, in the general absence of quantitative data on pathogens, an approach summarized in Table- 5-2 serves as a guide to assess risks of RBF schemes in India. This approach adapts elements of an entry-level assessment[16], incorporates the WHO sanitary survey approach[17] and was applied to the RBF schemes of Haridwar and Palla well field (North Delhi), that abstract water from an alluvial aquifer (Table- 5-3, overleaf). Stages 1, 2, 3 and 5 correspond to Figs 2-1 and 2-2.

The timely response to risks affecting a RBF scheme is important to guarantee the supply of potable water even during emergency situations. Responses can be framed into a WHO-based water safety plan (WSP) that is specific for each RBF site and which should be implemented prior to more engineered post-treatment options. Such WSPs address preventive measures to control general pathogen-related risks in the catchment and in the treatment process (Table- 5-2).

Table 5-2. Measures to control general pathogen-related risks in well-catchment and treatment process, example of Haridwar RBF scheme[4]

Measure	Hazard arising from	Identified specific improvement plan	Time frame
Well sanitation	Leakage from pipe joints and valves, insufficient sanitation, well head housing and use as public washing place	Clean well heads (house) [18] Waterproof the floors and base around the vertical line shaft pumps in the well house to prevent ingress of foreign matter into the well-caisson Prohibit defecation, housing, public washing and cattle	Immediately
Well protection I	Unrestricted accessibility	Restrict access to wells (house) Liaise with landholder about security of premises Fence off buffer zone around well head	Immediately –short
Well protection II	Wet season and flooding Ingress	Install water-tight covers on entrance hatches on top of well-caisson and their regular maintenance Improve well head seal[12,13,18]	Short–medium
Groundwater protection	Unsanitary defecation in well catchment zone Use of unsealed pit latrines	Liaise with municipalities to improve design of existing pit latrines or design and implement alternative solutions	Medium

Source water protection	Partially treated sewage discharge Untreated stormwater run-off	Liaise with municipalities Reduce discharge of partially treated wastewater and treat storm water run-off	Long
Improve disinfection	Requirements for residual free chlorine > 0.2 mg/L not met within the distribution system Insufficient disinfection	Improve disinfection (residual chlorine > 0.2 mg/l) Increase chlorine contact time Add additional chlorine injection points within the network	Medium
Well management	Not existing	Investigate well performance Rehabilitate wells Implement well operation philosophy	Medium Medium
Improve distribution network	Unrestricted tapping, insufficient pressure head Wastewater ingress	Liaise with municipalities Increase pressure, reduce UFW Increase awareness to minimize wastage (open/ dripping taps)	Long

Table 5-3. Risk-assessment stages (modified only for RBF from[5]

1.	**Simple assessment (answer with "yes (Y)" or "no (N)")**
a.	Is the aquifer, from which RBF wells are / will be abstracting water, is or will be used for drinking water supply? **Y**
b.	Is the scale of RBF larger thandomestic rainwater harvesting? **Y**
c.	Does the source water (river) contain sewage effluent, industrial wastewater or urban stormwater? **Y**
d.	Is the area around the recharge area ever waterlogged? **Y**,occasionally during monsoon *Simple assessment is satisfied if all answers are "No". Then no need to continue assessment because there is a low inherent risk. However if any answer is "Yes" proceed to Viability assessment.*
2.	**Viability assessment (Y/N)**
a.	Is there a sufficient demand for water? **Y**
b.	Is there an adequate source of water available for RBF? **Y**
c.	Is there a suitable aquifer for RBF? **Y**
d.	Is there sufficient space available for RBF and eventual post-treatment measures? **Y** *If the answer to any question is "No", then the project is not viable or else it has has a major constraint. If answers are "Yes", then proceed to Guidelines applicability assessment.*
3.	**Guideline applicability assessment (Y/N)**
a.	Isthe source of water for RBF only from a natural catchment including rural / overland runoff with less human activity and / or snow melt (i.e. not much affected by sewage effluent, industrial wastewater or urban stormwater)? **Y**
b.	Isthe aquifer unconfined and not polluted? **Y** *If answers are "Yes", then monitor / compare quality of water from RBF wells to Indian water quality standard [19] and if any parameters exceed permissible limits, then consider post-treatment measures*
4.	**Sanitary survey (Y/N)**
a.	Is there a latrine (unsealed, open-pit), open sewer or leaky sewer or human (open defecation) or animal faeces within the catchment area of the RBF wells? **Y**
b.	Is there a latrine, open sewer, leaky sewer or animal faeces in close proximity to the RBF wells? **Y**
c.	Are there industrial, transport or agricultural activities generating stockpiles, wastes, spills or emissions reaching the surface of the catchment area of the RBF wells? **Y** (only road / petroleum transport)

d. Are there industrial, transport or agricultural activities generating stockpiles, wastes, spills, or emissions in close proximity to the RBF wells? **Y** (only road / petroleum transport)

e. Is there post-treatment of water to be recovered? If so describe its design and resilience to power and mechanical failure, and any alarm systems. **Y** (only chlorination. Sodium hypochlorite dosage via pumps).

f. Does the existence and condition of any barriers around of the RBF wells prevent short circuit of contaminated water? **Y** (concrete base around wells; short circuit may occur if crack / fissures in base)

*Any question answered by **Yes** needs to be taken into specific account in the Water Safety Plan. Even if not observed, the possibility of these hazards occurring or barriers being breached also needs to be taken into account.Proceed to Aquifer assessment.*

5. Aquifer assessment (Y/N)

a. Does source (river) water have low quality; is water turbid, coloured, contains algae, has a surface slick or does it smell? **Y** (mainly high turbidity during monsoon and presence of pathogens year-round in Ganga)

b. Does the unconfined aquifer have a shallow water table (< 8m in urban area and say < 4m in rural area)? **Y**

c. Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100m of the recharge site? **Y** (a few private wells near some RBF wells)

d. Is the aquifer known to contain reactive minerals (e.g. pyrite) or is groundwater in this area known to contain arsenic? Is the aquifer contains soluble minerals such as calcite and dolomite? **N**

e. Is the aquifer composed of fractured rock or karstic (fissured or cavernous) limestone or dolomite? **N**

f. Is the proposed project of such a scale that it requires approval? Is it in a built up area; built on public, flood-prone or steep land; or on land used for religious or cultural festivals / rites / rituals or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts? *(In this case the RBF scheme already exists and is operational)***Y**

*Any question answered by **Yes** needs to be taken into specific account in the Water Safety Plan (Table-5-3). Even if not observed, the possibility of these hazards occurring or barriers being breached also needs to be taken into account.*

Disinfection by chlorination of RBF systems

General conditions

Water for human consumption has to guarantee the microbiological pureness in any case from the waterworks up to the customers tap. Due to the different quality of raw waters used for drinking water production and according to their pollution level, a conventionally or enhanced treatment regime supplemented by a final disinfection is necessary in most countries. This process is always connected with the undesirable formation of organic as well as inorganic disinfection by-products (DBPs), some of which are toxic. Hence the disinfection process has to consider both a complete inactivation of all microbiological pollutants and DBP formation. The latter should be as low as possible after the treatment process.

The method of choice for drinking water disinfection worldwide is the application of chlorine in form of chlorine gas as well as hypochlorite solution. Nevertheless, there are some other options which are quite efficient and applied in a number of countries. These are the disinfection regimes using chlorine dioxide and UV-radiation. In all cases, detailed knowledge concerning the complex disinfection process is necessary for the staff in waterworks.

The subsequent sections summarize fundamental knowledge of drinking water disinfection in the field of (i) framework conditions, (ii) the characterization of the disinfection agent applied and (iii) the avoidance of undesirable reactions in water that cause the formation of DBPs including taste and odour. This basic knowledge is a pre-condition for safe drinking water disinfection and the application of an optimized process which is focused to the actual water quality.

Frameworks, guidelines and regulations

Framework conditions of drinking water quality including the disinfection process are published by World Health Organization[17]. On the other hand, each country has to establish its own standards, which consider local conditions appropriately[19]. In Table- 5-4 the DBP limits set by the WHO and European Union are summarized.

The dosage of chlorine causes the formation of several DBPs. In general, these are halogenated inorganic and especially organic compounds, which can be of human toxicity and/or form disagreeable taste and odor of the water (described as musty and foul by consumers). The most important organic DBPs belong to the so called trihalogenmethane (THM) group[20-23]. This group consists of four compounds: chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$) and bromoform ($CHBr_3$). The WHO guideline value of 200 µg/L is not ambitious, nevertheless it considers the rule: disinfection first and is thereby most important. In order to guarantee the least possible formation of DBPs in water, special knowledge concerning the characteristics of chlorine and its reactions in water are necessary.

Table 5-4. Relevant standards of disinfection by-products

By-product	Formula	EU guideline in µg/L	WHO standard in µg/L
THM	CX_3H	100	200[a,b)]
Chlorite[c)]	ClO_2^-	-	700
Bromate	BrO_3^-	10	25
Chlorate	ClO_3^-	-	700
Perchlorate[d)]	ClO_4^-	-	-
Chloral hydrate	Cl_3CCHO	-	10
Dichloroacedic acid	HCl_2CCOOH	-	50
Trichloroacedic acid	Cl_3CCOOH	-	100
Formaldehyde	HCHO	-	900

[a)] 200 µg/L: to Chloroform regarded; [b] $[CHBr_3]/100 + [CHBr_2Cl]/100 + [CHCl_2Br]/100 + [CHCl_3]/200 \leq 1$; [c)] in case of chlorine dioxide application; [d)] in discussion

Some of the inorganic DBPs are also relevant for human consumption. These are chlorite in case of chlorine dioxide application, chlorate which is formed in hypochlorite stock solutions by higher temperatures and effects of light, both of which are relevant to Indian conditions. Bromate is also a relevant DBP because it is known that this ion shows carcinogenic impact[24-27].

Those compounds which give the water a musty and septic impression are so called chlorinated amines which are formed by chlorination of amino acids, a group of compounds found ubiquitous in natural waters. Nevertheless, problems concerning taste and odor arise if the concentration of these acids is at a "normal" level (< 10µg/L). On the other hand, in case of algal growth in raw water used for drinking water production and/or impact of wastewater, e.g. if river water is used as a source, the level of amino acids can be quite high. This is always problematic for drinking water quality[28].

Another aspect which has to be considered is the bromide concentration in the water. Bromide is always a part of wastewater impacted source water and cannot be removed during drinking water treatment. Bromide is the decisive pre-cursor for bromate and bromo-organic DBPs formation[29]. Today it is known that brominated by-products are of higher toxicity than the chlorinated by-products.

Characteristics of disinfection agents

The most common disinfection agents are chlorine gas and hypochlorite solution, which are strong oxidation agents. This attribute is the basis of disinfection, because in consequence the cell walls of the microorganisms present in water will be oxidized and thereby destroyed. The scientific base of this process is described by the NERNST equation (5-1)

$$E = E_0 - \frac{R \cdot T}{z \cdot F} \ln \frac{a(Ox)}{a(\mathrm{Re}\,d)} \tag{5-1}$$

Where, E: electromotive force in Volt, E_0: normal potential in Volt, R: gas constant, T: absolute temperature, F: Faraday constant, z: current equivalent and a: redox activity.

In this equation the term E_0 describes the so called normal potential, a constant which is characteristic for different redox pairs of chlorine in water. These values are pH-value dependent and describe the rate of oxidation - or disinfection power[30].

For the normal pH-range of drinking water, the states of hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) are relevant. The oxidation power of the acid is much stronger than that of the hypochlorite ion. Therefore, the disinfection efficiency of chlorine in water is pH-value dependant. The higher the pH-value, the lower is the disinfection power. In the case of drinking water this can be problematic, because the optimal pH-value for drinking water lies between 7 and 8. The reaction of chlorine with water is described by Eq. 5-2 and 5-3.

$$Cl_2 + H_2O \Leftrightarrow HCl + HOCl \quad (5\text{-}2)$$

$$HOCl \Leftrightarrow H^+ + OCl^- \quad (5\text{-}3)$$

A decisive factor for disinfection is the contact time of chlorine. It is known that chlorine needs up to 30 minutes for the process of cell destruction of the microorganisms to be completed. The undesired, but not avoidable reaction is that of chlorine with the bromide ion, which can occur in natural waters in concentrations of several µg/L (Eq. 5-4 and 5-5).

$$2Br^- + Cl_2 \Leftrightarrow Br_2 + 2Cl^- \quad (5\text{-}4)$$

$$Br_2 + H_2O \Leftrightarrow HBr + HOBr \quad (5\text{-}5)$$

This active bromine has also a disinfection impact, nevertheless, it is much lower than that of active chlorine and it forms brominated DBPs, such as bromoform. Today it is well known, that the kinetics of the formation of brominated DBPs is favoured against the chlorinated structures. Active bromine reacts more easily with organic compounds. This is always a problem, because brominated DBPs are more toxic for humans. In order to classify and estimate the disinfection efficiency, very often the so called ct-concept is used. This concept describes the disinfection by the mathematical product of c (concentration of the disinfection agent) and t (contact time of the disinfection agent). In Table- 5-5 the ct-values achieved under laboratory conditions for complete disinfection of several microorganisms are summarized as an example. It should be noted that in practice these values can be different because of the occurrence of particles in water which can reduce the disinfection efficiency of all agents significantly.

Table 5-5. ct-values in mg/min/L for 99% elimination of several microorganisms

Microorganism	Chlorine	Chlorine dioxide	Ozone
E. Coli	0.062	0.118	0.02
Enterococcus faecium	0.070	0.339	
MS 2	0.477	0.101	
PRD 1	0.082	0.047	
Polio 1			0.1–0.2
Rotavirus			0.006–0.06
Gardia lamblia			0.5–0.6
Gardia muris			1.8–2.0
Cryptosporidium			3.5–10

Besides the halogenated DBPs formation, there are some other negative effects of disinfection, which are caused by the oxidative impact of the disinfectants especially on organic molecules. This process is called "cracking" of high molecular organic structures. As a consequence, the so called biologically degradable organic carbon dissolved in water (BDOC) is formed, which is generally of lower molecular weight[31].

Disinfection by-products formation

The most important factors for DBPs formation are:

- dose of disinfection,
- contact time,
- concentration of the reaction partners with chlorine, the so called precursors, and
- pH–value of the water.

The reaction of chlorine with natural organic matter is the reason of THM and chlorinated acid formation which are the precursors of the THM (Eq. 5-6). In any case the rule, which should be noted is: the higher the chlorine dose and the higher the contact time of free chlorine the higher the THM formation in disinfected waters.

$$\text{NOM (e.g.: } RCOCH_3) \quad Cl_2/HOCl/OCl^- \quad CHX_3 + R\text{–}COOH \qquad (5\text{-}6)$$

CHX_3: chloroform, dichlorobromomethane, dibromochloromethane, bromoform
NOM: natural organic matter

Due to the reaction kinetics (5-6) it can be noted that one of the most important factors of DBPs formation is the content and the character of NOM. The content is analysed in form of DOC. The knowledge concerning DOC (as exact as possible) is important for all waterworks. Nevertheless, the analysis is difficult and requires special instruments, e.g. TOC/DOC-analysers and/or fluorescence spectrometers. In cases where this technique is not available simple mathematical correlations with the UV-254 coefficient can be used. Several portable field techniques are available for measurement of UV signals. This configuration is much cheaper. However in this case an exact individual calibration for each source of water is necessary.

Formation of odour

One of the most aggravating side effects of water disinfection with chlorine is the formation of musty and mouldy / septic odour. This is especially the case when the residual chlorine during distribution of the water decreases. The odour threshold concentration of those organoleptic by-products is much lower than that of chlorine which is always connected with a fresh impact. On the other hand, if chlorine reacts with nitrogen-containing organic compounds an intensive organoleptic odour is possible.

The sources of N-containing organic matter are manifold. Two of the most important and possible impacts are the contamination of the water with waste and the algae growth. Different species of algae grow in most surface waters if nutrients are available as well as the temperature and the light conditions are suitable, e.g. during summer. The cells of the algae consist of peptides and biopolymers such as proteins. The components of these materials are amino acids (AA). According to the life cycle, the algae grow and die-off. The occurrence of AA follows the same cycle, i.e. they are bound in the frame of biopolymers and will be released. So they occur in a free state in the water. In this form they are intensive odour precursors if chlorine is added to the water. On the other hand, if AA are bound in peptides and polymers they do not form intensive taste and odour compounds.

The results of this systematically monitoring show that the average range of the total AA concentration (21 compounds) in natural waters has been determined in the range from 10 to 35 µg/L. A removal of such compounds is only possible if RBF is applied as a pre-treatment. On the other hand, the application of activated carbon can even increase the AA level as a result of the biodegradation of several organics. This is a real situation in many waterworks.

In Table- 5–6 a ranking concerning the impact of free AA to the odour of the disinfected water is given. It was found that the most relevant amino acids forming taste and odour in drinking water after chlorination are *histidine*, *ornithine*, *iso–leucine* and *methionine*.

Table 5–6. Relevance of free amino acids as precursor of odour formation[26]

Amino acid	Characteristics	Intensity [a]	OTC in µg/L[b]	Ranking
Histidine	sweety	3.0	5	high
Iso–Leucine	chemical	3.5	5	high
Leucine	aromatical	4.0	10	medium
Lysine	musty	2.5	10	low
Methionine	spicy	3.5	5	high
Ornithine	musty	3.0	5	high
Phenylalanine	flowery	4.0	30	low
Proline	musty	3.0	10	medium
Serine	sweety	2.0	5	low

[a] Intensity from 1 to 5 (highest); [b] OTC: Odour Threshold Concentration at 0.3 mg/L chlorine residual

Optimization of disinfection

The removal of organic matter dissolved in water is one of the most promising actions for improvement of the disinfection efficiency and the reduction of DBP formation. Organic matter in water means humid compounds (in most of the cases). These organic macromolecules are non-toxic for humans. Nevertheless, they form DBPs if chlorine is used. The removal of humid compounds is expensive. Today, activated carbon application is common and more and more membrane filtration is used in modern facilities.

The impact of NOM reduction on DBP formation, especially the THM formation is exemplarily shown in the Figs. 5-1a and 5-1b. In order to understand the background, two methods were applied under laboratory conditions: 1. Activated carbon and 2. Dilution water (Milli-Q-quality). The activated carbon reduces the organic matter dissolved in water, but inorganic components will not change in their concentration. Dilution water reduces both, the organic matter and inorganic ions, like bromide. The effect of reduction is shown for the chlorinated part of by-products (THM) in Fig. 5-1a. The reduction is working and the level of chlorinated by-products is reduced clearly.

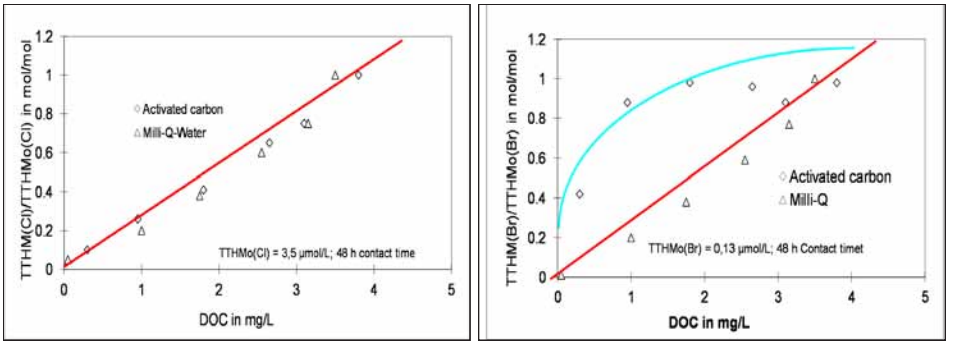

Figure 5-1a (left) and 5-1b (right). Impact of NOM removal on the formation of chlorinated and brominated THM

The effect concerning the brominated part of the THM is shown in Fig. 5-1b. The results look different. The dilution water reduces the brominated part of THM in the same way like the chlorinated ones. In contrast to that, if activated carbon is applied, there was no effect. The reason is the bromide content of the water, which is not reduced by activated carbon filtration. Chlorine reacts with bromide and forms active bromine which is the reason of brominated THM formation (compare Eq. 5-4 and 5-5).

Hence if bromide concentration in water are < 200 µg/L, the application of activated carbon filtration in combination with chlorination for disinfection is suitable for water treatment. If there are no other options the disinfection regime has to be changed, e.g. from chlorine to chlorine dioxide. This example describes one aspect of optimization. Other rules are also very important. These are e.g. the combination of chlorine with chlorine dioxide, the application of chlorine electrolysis or the UV-disinfection. In any case the selected process should consider the water quality and the technology of water treatment which is used.

Disinfection of RBF by Inline–Chlorination

The inline-chlorination process, according to anodic oxidation, is one of the most innovative developments of the last decades, because the natural chloride content of the water is used for chlorine production. This decisive fact makes the process self-sustaining and independent from chlorine transport. On the other hand, a chlorine generator needs an adequate standard of maintenance, technical knowhow and monitoring.

Through long-term studies, it could be shown that the inline-chlorination process guarantees a stable and safe water disinfection under Indian conditions, which are defined by hydrological extremes (monsoon and aridity).Exemplarily, the concentration of chlorine generated by an inline-chlorination pilot-plant that receives water abstracted from a RBF well in Haridwar is illustratedin Fig. 5-2. It is observed that the chlorine formation changes with weather conditions. So, at any given time, the optimal chlorine dose was achieved. On the other hand, the graph also shows that such units absolutely need to be serviced by professionals. The gaps in chlorine production are caused by discontinuouselectricity supply, which destroyed several vessels of the chlorine generator. Nevertheless, this problem could be solved by an autarkic electricity supply, e.g. using solar modules.

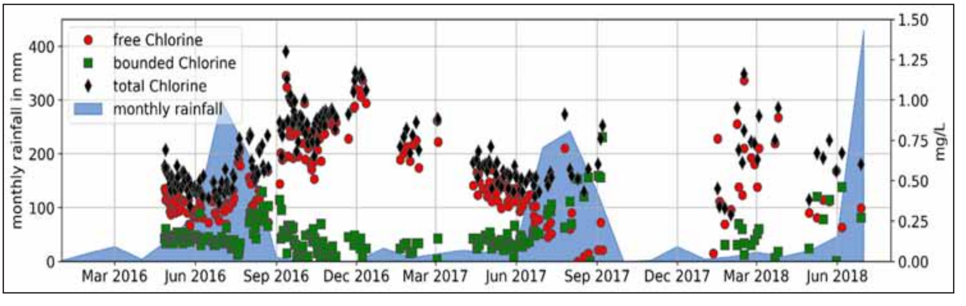

Figure 5-2. Inline-chlorination of water abstracted from RBF well 18 in Haridwar – long-term pilot plant studies

The monitoring, which is needed for quality control and regulation, should be organized by online-measurements using suitable sensors. The list of regulation-parameters covers the actual chlorine level (1), the electrical conductivity (2), and the spectral adsorption coefficient at 254 nm.For chlorine monitoring, a novel technique, adopted for Indian conditions, was developed and applied. This procedure is based on the online determination of the hypochlorite UV-spectrum by an online spectrometer unit. The regular control and documentation of the chronological value trend guarantees a complete and safe disinfection of the bank filtrate.

The measurement of free chlorine is the most important parameter for disinfection control. It is complemented by modeling of chlorine formation using the operational parameter and the electrical conductivity of the water (provided by the generator unit, see Eq. 5-7). This helps to operate the plant in cases where no monitoring of chlorine is possible.

$Cl_{free} = -\,0.6075U + 0.0379I + 0.0023EC$ (5-7)

Cl_{free}: free chlorine in mg/L

U: voltage in V

I: current in A

EC: electrical conductivity in µS/cm

Nevertheless, the coefficients in Eq. 5-7 are only valid for the site (RBF water quality in Haridwar) where the plant was operated. When using the plant at another site, the coefficients may vary due to different water quality (chlorine demanding compounds). In Fig. 5-3 the correlation of calculated and measured free chlorine is illustrated. The calculated coefficient of correlation (R^2) was determined to be 0.937 and with an average error of 0.14 mg/L for validation.

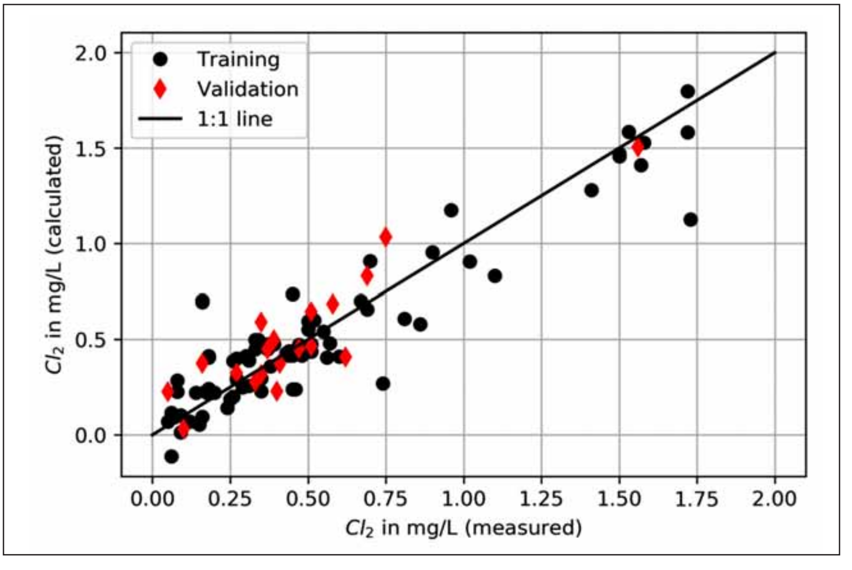

Figure 5-3. Correlation of measured and calculated chlorine formation during inline–chlorination

Summary and conclusions

The risk assessment and management strategy, including water safety plan (WSP) measures, presented in this chapter is consistent with the WSP of the WHO. The stage-wise risk assessment of the RBF scheme in Haridwar showed that risks from inorganic chemicals, salinity, nutrients and turbidity were acceptable low.

The QMRA indicated that the risks to human health from bacterial pathogens are also very low. Nevertheless, this QMRA was limited by inadequate characterization of viral and protozoan pathogen numbers in source water. However, pathogen removal capabilities for RBF reported in literature indicate high removal capabilities even for viral and protozoan pathogens. The QMRA approach applied to the RBF scheme in Haridwar was not found to be useful for data-scarce RBF sites in India. However, general recommendations taken from this case study (Table- 5-2) such as the need for well head protection, characterization of both source and groundwater quality and management of monsoon effects as part of a WSP, can be applied to all Indian RBF sites including sites with scarce data. Hence for planning and designing a new RBF scheme, information gaps according to Table- 5-3 should be taken into consideration from the beginning. The information should be filled in order to assess the risks and the prospective measures required.

Safe disinfection of drinking water means the complete inactivation of pathogens. In order to achieve this, the application of chlorine gas as well as hypochlorite solution can be very efficient. In any case,the correct application and design of the disinfection regime at the end of the treatment process in waterworks and also during the distribution of the water up to the costumer's tap is necessary. This requires detailed knowledge. One of the most important aspects is to guarantee residual concentration of free chlorine at all times and at all places where a microbiological risk can occur. In such a case an exact chlorine dosage and its correct control by continuous measurements is necessary. Sufficient free residual chlorine is one of the safest measures for protection against infection.

A promising option for India and comparable regions worldwide is the use of the so called inline-chlorination. This procedure is safe and guarantees long-term stability. On the other hand, the process needs maintenance and defined control strategies in form of online-monitoring, which have to be upgraded continuously.

In order to reach this quality all measures of disinfection have to be adjusted. As a positive add-on effect, waterworks who follow this strategy, can achieve the following advantages by safe disinfection:

- reduction and minimization of the chlorine demand,
- minimization of disinfection by-products formation and
- reduction of non-hygienic organoleptic effects like musty taste and/or odour.

The measures to achieve these aims are summarized in Table- 5-7 to 5-9. Nevertheless, the facilities should consider that some measures can take longer and others will have a rapid effect.

Table 5-7. Strategies for reduction of chlorine demand

Strategy	Measures
Control of water quality	Online control of organic precursors
Reduction of precursors (NOM)	Activated carbon, advanced oxidation (AO), membrane/ filtration
Combining reactions	Use of additional disinfectants like chlorine dioxide

Table 5-8. Strategies for reduction of DBP-formation

Strategy	Measures
Improvement of raw water quality	Re-naturation, sewage plants
Removal of precursor compounds	Optimization of treatment chains
Reduction of disinfection dose	Optimization of treatment chains, restoration of networks
Use of alternative disinfectants and combinations	Chlorine dioxide, UV radiation

Table 5-9. Strategies against odour formation

Strategy	Urgent	Problems
Reduction of chlorine dose	Reduce demand of disinfection agent	Inefficient disinfection
Use of post disinfection	Control of dosage	Sometimes very little effect
Use of alternative agents like chlorine dioxide or UV radiation	Reduce demand of disinfection agent	High demand High turbidity

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REFERENCES

1. Dillon P., Page D., Vanderzalm J., Sidhu J., Sandhu C., Boisson A., Lakshmanan E., Natural water treatment systems for safe and sustainable water supply in the Indian context – Saph Pani *Application of a Water Quality Guide to Managed Aquifer Recharge in India*. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.), 2016, ISBN13, 265–282. 9781780407104. Available:https://zenodo.org/record/61088/files/9781780408392_16.pdf
2. IS 15792 Artificial Recharge to Ground Water – *Guidelines. Bureau of Indian Standards*, New Delhi, India, 2008.
3. Sandhu C., Grischek T., Kumar P., Ray C., Potential for riverbank filtration in India. *Clean Technologies and Environmental Policy*, 2011, **13**(2), 295–316
4. Bartak R., Page D., Sandhu C., Grischek T., Saini B., Mehrotra I., Jain C.K., Ghosh N.C., Application of risk–based assessment and management to riverbank filtration sites in India, *Journal of Water and Health,* 2015b,**13**(1), 174–189.

5. Dillon P., Vanderzalm J., Sidhu J., Page D., Chadha D., A Water Quality Guide to Managed Aquifer Recharge in India. *CSIRO Land and Water and UNESCO Report of AusAID PSLP Project ROU 14476, 2014.*

Available:https://publications.csiro.au/rpr/pub?pid=csiro:EP149116 (accessed 15 May 2017).

6. NCMH Background Papers: Burden of Disease in India. National *Ministry on Macroeconomics and Health, Ministry of Health & Family Welfare, Government of India, New Delhi*, 2005.

7. Nandi A., Megiddo I., Ashok A., Verma A., Laxminarayan R., Reduced burden of childhood diarrheal diseases through increased access to water and sanitation in India: A modeling analysis. *Social Science & Medicine,* 2017, **180**, 181–192.

8. Page D., Dillon P., Vanderzalm J., Toze S., Sidhu S., Barry K., Levett K., Kremer S., Regel R., Risk assessment of aquifer storage transfer and recovery with urban stormwater for producing water of a potable quality. *J. Environ. Quality,* 2010, **39**(6), 2029–2039.

9. Schwarzenbach R.P., Egli T., Hofstetter T.B., von Gunten U., Wehrli B., Global water pollution and human health. *Annual Review of Environment and Resources,* 2010,**35**, 109–136.

10. Sandhu C., Grischek T., Kimothi P.C., Patwal P.S. et al., Guidelines for flood–risk management of bank filtration schemes during monsoon in India. Saph Pani project deliverable number D1.2.

Available:http://www.saphpani.eu/fileadmin/uploads/Administrator/Deliverables/Saph_Pani_D1_2_Guidelines_for_flood–risk_managementof_bank_filtration_schemes_during_monsoon_in_India.pdf. Accessed on 25 November 2016.

11. Sandhu C., Grischek T., Ronghang M., Mehrotra I., Kumar P., Ghosh N.C., Rao Y.R.S., Chakraborty B., Patwal P.S., Kimothi P.C., Overview of bank filtration in India and the need for flood–proof RBF systems. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context* – Saph Pani, IWA Publishing, London, UK, 2016, 17–38. Available:https://zenodo.org/record/61088/files/9781780408392_2.pdf. Accessed on 15 May 2017.

12. Sandhu C., Grischek T., Musche F., Macheleidt W., Heisler A., Handschak J., Patwal P.S., Kimothi P.C., Measures to mitigate direct flood–risks at riverbank filtration sites with a focus on India. *Sustainable Water Resources Management*, 2018, **4**(2), 237–249, DOI: 10.1007/s40899–017–0146–z.

13. Musche F., Sandhu C., Grischek T., Patwal P.S., Kimothi P.C., Heisler A., A field study on the construction of a flood–proof riverbank filtration well in India – challenges and opportunities. *International Journal of Disaster Risk Reduction*, 2018, DOI: 10.1016/j.ijdrr.2018.06.003.

14. Kumar P., Mehrotra I., Boernick H., Schmalz V., Worch E., Schmidt W., Grischek T., Riverbank Filtration: An Alternative to Pre–chlorination. *Journal of Indian Water Works Association,* Special Issue, December 2012, 50–58, ISSN 0970–275X.

15. Sharma S.K., Sandhu C., Grischek T., Gupta A., Kumar P., Mehrotra I., Grützmacher G., Sajilkumar P.J., Lakshmanan E., Ghosh N.C., Pre– and Post–treatment of BF and MAR in India: Present and Future. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context* – Saph Pani. IWA Publishing, London, UK, 2016, 191–206. ISBN13: 9781780407104. Available: https://zenodo.org/record/61088/files/9781780408392_12.pdf

16. NRMMC–EPHC–NHMRC. Australian Guidelines for Water Recycling: Managed Aquifer Recharge (Phase 2). Report of the *Natural Resource Management Ministerial Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra,* 2009.

17. WHO *Guidelines for drinking–water quality* – 4th ed. incorporating 1st addendum. World Health Organization, Geneva, Switzerland, 2011, **4**, ISBN 978–9241548151.

18. WHO/WEDC Technical Notes on Drinking Water, Sanitation and Hygiene in Emergencies: Technical Note 1 – *Cleaning and Disinfecting Wells.* World Health Organization, Water Engineering Development Centre, 2011.

19. IS 10500 Drinking Water – Specification. Indian Standard (second revision), *Bureau of Indian Standards*, New Delhi, India, 2012.

20. Müller U., Wricke B., Baldauf G., Sontheimer H. THM–Bildung bei der Trinkwasseraufbereitung (*THM–formation during drinking water treatment*). Vom Wasser, 1993,**80,** 193–209.

21. ISPRA An assessment of the presence of trihalomethanes (THMs) in water intended for human consumption and the practical means to reduce their concentrations without compromising disinfection efficiency. *Report to Directorate General for Environment, Nuclear Safety and Civil Protection (DGXI) of the European Commission, Study contract* 11492–95–12 A1 CO ISP B, Administrative arrangement: B4–3040/95/000436/MAR/D1, 1996.

22. European Union directive 98/EG on the quality of water for human consumption. Brüssel, 1998.

23. Bundesgesundheitsblatt Liste der Aufbereitungsstoffe und Desinfektionsverfahren (*List of treatment agents and disinfection methods*). Bundesgesundheitsblatt (German federal health gazette/bulletin) 2002, **45**, 827–845.

24. Gordon G., Adam L.C., Bubnis B.P., Wliczak A., Controlling the formation of chlorate ion in liquide hypochlorite feedstocks. *J. Amer. Water Works Assoc.*, 1993, **85**, 89–97.

25. Gordon G., Adam L., Bubnis B., Minimizing chlorate ion formation. J. Amer. Water Works Assoc., 1995, **87**, 97–106.

26. Schmidt W., Böhme U., Brauch H.J., Nebenprodukte der Desinfektion: Chlorit, Chlorat, Bromat und Jodat – Entstehung und Bewertung bei der Trinkwasseraufbereitung in den neuen Bundesländern (Byproducts of disinfection: chlorite, chlorate, bromate and iodate – Formation and assessment during drinking water production in the new German federal states). DVGW–Schriftenreihe Wasser, 1994, **86,** 285–301.

27. von Gunten U., Hoigne J., Factors controlling the formation of bromate during ozonation of bromide containing waters. *J. Water SRT–Aqua,* 1992, **41**, 299–304.

28. Schmidt W., Grübel A., Vermeidung organoleptischer Beeinträchtigungen des Trinkwassers durch aminosäurebürtigen DOC (*Prevention of interference from organoleptic compounds in drinking water by aminoacidic DOC*) F+E–Projekt 7/02/08, TZW, Aussenstelle Dresden, 2009–2011.

29. Schmidt W., Böhme U., Brauch H.J., Die Bildung von Organobromverbindungen bei der Aufbereitung bromidhaltiger Wässer. Vom Wasser, 1993, **80,** 29–39.

30. Christen H.R., Grundlagen der allgemeinen und anorganischen Chemie (*Basics of general and inorganic chemistry*). Sauerländer, Aarau, 1973.

31. Werner P., Untersuchungen zur Substrateigenschaft organischer Wasserinhaltsstoffe bei der Trinkwasseraufbereitung (Investigations of the substrate characteristics of organic water constituents during drinking water treatment).*Zentralblatt für Bakteriologie, Mikrobiologie und Hygiene*, I, Abt. Orig. B, 1984, 180, 46–61.

6
Chapter

NUMERICAL FLOW MODELING OF A BANK FILTRATION SYSTEM

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This chapter highlights relevant theoretical aspects of river–aquifer interaction and numerical modeling and also presents a step–by–step procedure for modeling of a bank filtration system with an illustrated example. The data used in the illustrated example has relevance to field conditions.

KEYWORDS: Numerical modeling, finite difference model, grid, boundary conditions, MODFLOW

What is numerical modeling ?

Numerical modeling is the process of solving physical problems by appropriate simplification of reality. It is a computer model that is designed to simulate and reproduce the mechanisms of a particular system. The definition of modeling may vary depending on the application, but the basic concept remains the same.

Why are numerical simulations needed ?

Numerical simulations are calculations that are performed on a computer following a program that implements a mathematical model of a physical system.It is required to study the behaviour of the system whose mathematical models are too complex to provide analytical solutions. Numerical simulations are also needed because experiments are sometimes impossible or very cumbersome or very expensive and time consuming. Numerical modeling is used for solving both forward problems and inverse problems.

River–aquifer interaction

River (or stream)–aquifer interaction is a common occurrence in nature. Flow in river having hydraulic connection to an adjoining aquifer is governed by the exchange of water between the river and aquifer. The magnitude of exchange of water depends on hydraulic properties of river, aquifer and the riverbed materials together with the potential head difference between the two domains (Fig. 6-1A to 6-1D).

A river can be influent (loosing river) (Fig.6-1A), or effluent (gaining river) (Fig. 6-1B) or disconnected with the underneath aquifer (Fig. 6-1C) or can absorb andstore water in the voids of bed andbank material of a river as bank storage (Fig. 6-1D), that depends on the river bank materials, aquifer materials beneath the river, and the position of water level in both the domains. An effluent river receives water from aquifer; an influent river releases water to aquifer; a disconnected river always recharges to underneath aquifer; and a river with properties to absorb andstore water may return in whole or in part as the level of surface water body falls.

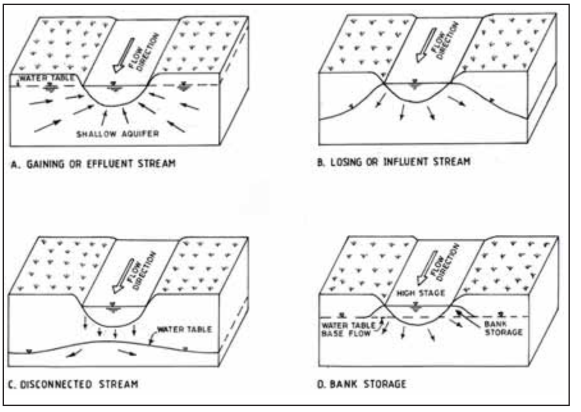


Figure 6-1. Different possibilities of river–aquifer interactions

The basic principles of river–aquifer interaction can be derived from the flow mechanisms between canal and aquifer that states, the process of seepage starts as soon as water is filled in the canal1. As time elapses, the soil layers around the canal get saturated and the saturated front moves slowly downwards. After a certain period of time, it reaches the water table below the canal bed. During the downward propagation, part of the infiltrated water is stored within the extending saturated zone, whereas the remaining part recharges the groundwater.

Based on the position of the water level, water losses from canal can be categorized as: (a) when a canal is perched above the groundwater table (Fig.6-1C), the loss from the canal approaches a constant value. This loss is approximately proportional to the width of the canal, the vertical hydraulic conductivity and thickness of any lining or material deposits below the canal bed; (b) for canal with intersected regional groundwater table to its sides (Fig. 6-1B), losses from canal to aquifer depends primarily on the difference of water levels between the canal and regional groundwater. The losses, in such case, are not directly proportional to the width of the canal, or vertical hydraulic conductivity and thickness of lining or deposits below the canal bed, but depend on properties of the aquifer and dimensions of canal and its bed materials. In other words, the seepage loss depends on the difference of water levels between the canal and groundwater, width of the canal at the water surface, side slope, distance of the governing drainage, and coefficient of permeability of the porous medium. The similar analogy also holds good for river–aquifer interaction processes except the difference in hydrogeological setup. Thus, the rate of movement of water between a river and its underlying groundwater is proportional to the hydraulic gradient of water, as described by Darcy's equation, and the proportionality coefficient depends on the riverbed and aquifer materials. Mathematically, the processes of river–aquifer interaction can be derived by Darcy's equation using Fig. 6-2 and its parametric description, as follows.

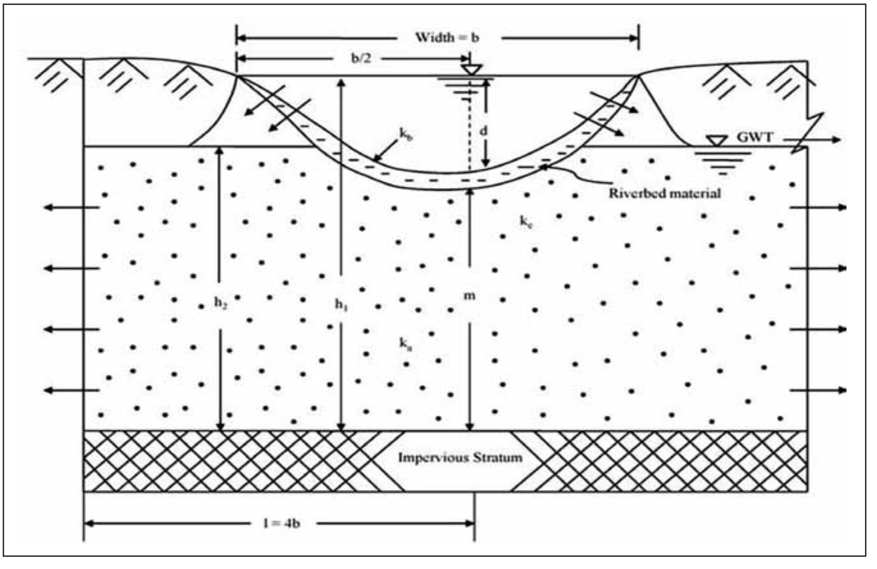


Figure 6-2. River–aquifer interaction and parametric description.

The flow rate per unit length of the river to aquifer, Q_{rg} is given by Eq. 6-1:

$$Q_{rg} = \bar{A} K_e \frac{(h_1 - h_2)}{\bar{l}} \tag{6-1}$$

in which, $\bar{A}$ is the wetted area per unit length of the river through which water moves to aquifer = $\left[{W_p}/{2} + (m + d) \right]$; K_e is the equivalent permeability (hydraulic conductivity) of riverbed and aquifer materials =; ${(K_b T_b + K_a m)}/{(T_b + m)}$; $\bar{l}$ is the average length of flow path = $\left(l + {m}/{2} - {b}/{4} \right)$; W_p is the wetted perimeter; K_b is the permeability of riverbed materials; T_b is the thickness of the riverbed; K_a is the hydraulic conductivity of the aquifer; m is the thickness of the aquifer below the riverbed materials; b is the width of the river; d is the depth of water in the river; h_1 and h_2 are the height of water levels in the river and aquifer above an impervious stratum measured upward.

Groundwater flow processes

Eq. 6-1 holds good for estimation of recharge rate, Q_{rg} from river to aquifer and vice versa. Groundwater around a river is basically 3-dimensional. River water after it induces to aquifer move around in all three directions. Alternately, for a gaining river, groundwater from three directions contributes to river. The case where aquifer thickness is three times smaller than the river width, the flow may be regarded as horizontal[2], and Dupuit-Forchheimer assumption, in such case, holds good. The governing 3-dimensional groundwater flow equation together with recharge and pumping[3,4]is given by Eq. 6-2:

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) \pm \sum W \qquad (6\text{-}2)$$

where, S_s is the specific storage, (L^{-1}); K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities along three principal directions, x, y, and z, (LT^{-1}); $\sum W$ is the recharge (+ve) to, and extraction (–ve) from, the aquifer in volumetric form per unit volume, ($L^3L^{-3}T^{-1}$); h is the state variable that depends on properties of aquifer in all Cartesian coordinates ,(L); and t is the time, (T).

Eq. 6-2 helps compute the response of aquifer, in terms of $h(x,y,z,t)$, due to input forcing functions, recharge and extraction and it is a 3-dimensional partial differential equation (PDE); its analytical solution is a tedious job and will involve a lot of simplifications and approximations. Real field problems, however, may have a number of complexities, which an analytical solution cannot accommodate. Therefore, one has to rely on numerical solution of Eq. 6-2.

Contaminant transport processes

The flow from river to aquifer or vice–versa is influenced by contaminants present in either domain. The contaminants in river induce along with the recharge water and mix with the groundwater as flow moves in the groundwater domain. Alternately, contaminants in groundwater, for a gaining river, mix with river water from all three directions. The fate of contaminants depends on travel time, dispersive characteristics, decay and sorption kinetic of contaminants. The governing equation for contaminant transport processes in porous media derived from mass balance together with Fick's law of diffusion can be described by 3-dimensional advection-dispersion equation(ADE) with decay (if, non–conservative pollutants) and sorption kinetics[5], as given in Eq. 6-3.

$$\frac{\partial C}{\partial t} + \frac{1}{R}\left\{ \frac{\partial (v_x C)}{\partial x} + \frac{\partial (v_y C)}{\partial y} + \frac{\partial (v_z C)}{\partial z} - \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) - \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right\} + \lambda C + \sum_{i=1}^{N} W_i = 0 \qquad (6\text{-}3)$$

in which, C is the concentration of immiscible contaminant, (ML^{-3}); v_x, v_y and v_z are the seepage velocities of water along 3principal directions (x,y,z) through which a contaminant moves, (LT^{-1}) = Darcy's velocity/Porosity; D_x, D_y and

D_z are the dispersion coefficients along 3principal directions (x,y,z), (LT^{-2}); R is a dimensionless constant called the "retardation factor"; λ is the decay rate coefficient, (T^{-1}); and is $\sum_{i=1}^{N} W_i$ the source of the contaminant, ($ML^{-3}T^{-1}$).

The transport equation 6-3 is linked to the flow equation 6-2 through the relationship

$$v_{ii} = -\frac{K_{ii}}{\eta}\frac{\partial h}{\partial X_i} \qquad (6\text{-}4)$$

where, v_{ii} is the seepage velocity along three principal directions, [LT^{-1}]; K_{ii} is the hydraulic conductivity tensor in three principal directions, [LT^{-1}]; ∂X_i represents derivative of length in 3principal directions, x, y and z; and η is the porosity.

Eq. 6-3 helps compute the spatiotemporal variability of concentration of contaminant, *C(x,y,z, t)* as it moves through the aquifer due to induced flow from the river by the extraction of water by pumping. For contaminant transport modeling, one has to first solve the flow field using Eq. 6-2 to calculate v_{ii}.

Parameter estimation

Flow parameters

To compute Q_{rg} using Eq. 6-1, K_b and K_a are to be known to estimate K_e. K_b (permeability of riverbed materials) can be estimated from the grain size distribution analyses of riverbed materials if clogging is low; and K_a (hydraulic conductivity of aquifer) can be estimated from the pumping test data.

For groundwater flow modeling using Eq. 6-2, one requires hydraulic conductivities; K_{xx}, K_{yy} and K_{zz}, and specific storage coefficient, S_s. K_{xx} (= T_{xx}/H) and S_s (= S/H); T_{xx} is the transmissivity (L^2T^{-1}) along x–x direction, S is the storage coefficient or storativity (dimensionless); and *H* is the aquifer thickness; can be determined from long duration pumping test data. From the pumping test data, T_{xx} and *S* are determined. The value of $K_{xx} = T_{xx}/H$ and $S_s = S/H$. Generally, $K_{yy} = K_{xx}$, and $K_{zz} = 0.1*K_{xx}$. Table 1 gives representative values of hydraulic conductivity for different aquifer material[6].

Table 6-1. Representative values of hydraulic conductivity (after[6])

Material	Hydraulic conductivity (m/day)	Material	Hydraulic conductivity (m/day)
Gravel, coarse	150	Dolomite	0.001
Gravel, medium	270	Dune sand	20
Gravel, fine	450	Loess	0.08
Sand, coarse	45	Peat	5.7
Sand, medium	12	Schist	0.2
Sand, fine	2.5	Slate	0.00008
Silt	0.08	Till, predominantly sand	0.49
Clay	0.0002	Till,predominantly gravel	30
Sandstone, finegrain	0.2	Tuff	0.2
Sandstone, medium grain	3.1	Basalt	0.01
Limestone	0.94	Granite, weathered	1.4

Transport parameters

In Eq. 6-3, v_x, v_y, v_z, D_x, D_y, D_z, R, and $\lambda$are the transport parameters. v_x, v_y and v_z are obtained from the simulation of flow modeling using Eq. 6-4. The dispersion coefficients, D_x, $D_y$and D_z are function of mean pore velocity. The following form for estimation of dispersion coefficients was suggested by[7](Eq.6-5a & 6-5b):

$$D_x = \alpha_x v_s^n \tag{6-5a}$$

$$D_y = \alpha_y v_s^n \tag{6-5b}$$

In Eq. 6-5a & 6-5b, α_x and α_y are the dispersivities towards x and y directions, respectively (L); $v_x$and v_y are the mean pore velocity towards x and y direction, respectively (LT^{-1}); and m is power of velocity that ranges, $1.07 \leq m \leq 1.1$. The same value of '*m*' for α_x and$\alpha_y$was suggested by[7], but the value of α_y is 6 to 20 times smaller than α_x.

The retardation factor $R = \left(1 + {}^{\rho_b K_d}/_{n}\right)$, in which, $K_d = Sm/C$;S is the ratio of mass of sorbed material to the mass of solid material, and is given by: $\left({}^{\eta\, C_s}/_{\rho_b}\right)$, in which, η is the porosity; C_s is the concentration of material sorbed, (ML^{-3}); and $\rho_b$is the bulk density of sorbed materials, (ML^{-3}). λ, the decay rate coefficient, can be determined from laboratory analysis.

Numerical solution of groundwater flow equation

A number of numerical methods, finite difference[8], finite element[9], and analytical element[10] have been developed for solving 3-dimensional PDE. A number of public domain and commercial software based on Eq. 6-2 using the above numerical methods have been developed and are widely used. Few widespread used models are: (i) MODFLOW–2005: a modular 3-dimensional finite difference groundwater flow model by USGS[11]; (ii) FEFLOW–2006: 3-dimensional finite element groundwater model by DHI[12]; and (iii) GFLOW–2016: an analytic element groundwater model by Haitjema Software[10].

The main features of these numerical models are:

- Solution is sought for the state variable, h(x,y,z,t) at specified points in space and time domains.
- PDE is replaced by a set of algebraic equations written in terms of discrete values of h(x,y,z t)at discrete points in space and time.
- Solution is obtained for specified set of numerical values of model coefficients.
- Because of large number of equations, which are to be solved simultaneously, a computer program has been developed.

Modeling of a bank filtration system by MODFLOW

Bank filtration (BF) processes rely on river–aquifer interactions together with the processes of adjoining groundwater system. Modeling of BF processes thus considers Eq. 6-2 for flow and Eq. 6-3 for contaminant transport. The rate at which river flow induces into the groundwater corresponding to a setup of pumping, how induced river flows mix with ambient groundwater, how much of total extraction possesses the induced flow, the fate of contaminants in the mixed up flow, what impact pumping would cause on river and groundwater regime, etc. are some of the concerns to be answered by modeling.

Why MODFLOW?

MODFLOW (Modular 3-dimensional finite difference groundwater flow model developed by USGS) is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface water interactions and it's modular structure provides a robust framework to simulate steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. MT3D (Modular 3-dimensional finite difference groundwater solute transport simulator coupled with MODFLOW developed by USGS) accommodates flow terms calculated by MODFLOW packages and provides flexibility in simulation of solute transport and reactive solute transport. Both MODFLOW and MT3D are widely used models and have open access.

Modeling of riverbank filtration by MODFLOW

MODFLOW considers a grid mesh representing 'X' and 'Y' direction; and in 'Z' direction, it accounts for depth representing geological formations. Grid size, recognized as cell, can vary according to the interest of computations and outputs, and the depth of the grid can also be varied to account for the hydrogeological variations. A schematic of the conceptualized arrangement of grids and their vertical discretization as conceived in MODFLOW is shown in Fig. 6-3a &6-3b.

In MODFLOW package, Eq. 6-2 in finite difference scheme has been written in following algebraic form:

$$\begin{aligned} &CR_{i,j-\frac{1}{2},k}\left(h^m_{i,j-1,k}-h^m_{i,j,k}\right)+CR_{i,j+\frac{1}{2},k}\left(h^m_{i,j+1,k}-h^m_{i,j,k}\right)+\\ &CC_{i-\frac{1}{2},j,k}\left(h^m_{i-1,j,k}-h^m_{i,j,k}\right)+CC_{i+\frac{1}{2},j,k}\left(h^m_{i+1,j,k}-h^m_{i,j,k}\right)+\\ &CV_{i,j,k-\frac{1}{2}}\left(h^m_{i,j,k-1}-h^m_{i,j,k}\right)+CV_{i,j,k+\frac{1}{2}}\left(h^m_{i,j,k+1}-h^m_{i,j,k}\right)+\\ &P_{i,j,k}\,h^m_{i,j,k}+Q_{i,j,k}=SS_{i,j,k}\left(\Delta r_j\Delta c_i\Delta v_k\right)\frac{h^m_{i,j,k}-h^{m-1}_{i,j,k}}{t^m-t^{m-1}} \end{aligned} \qquad (6\text{-}6)$$

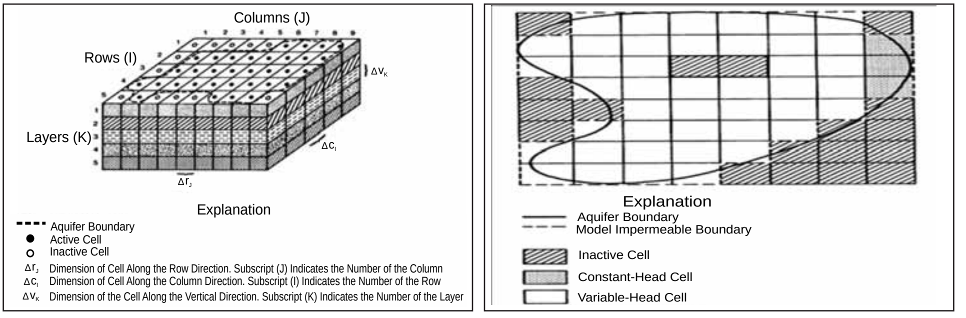


Figure 6-3. Discretized schemes of 'Cuboids' considered in MODFLOW; (a) arrangement of rows (x–direction, *Δri*)), columns (y–direction, *Δcj*)), and layers (hydrogeological strata, *Δvk*) and active and inactive cell; and (b) modeling domain showing arrangement of inactive cell, constant and vertical head boundaries.

In Eq. 6-6, $h^m_{i,j,k}$ is the hydraulic head at cell *i,j,k* at time step *m*; $P_{i,j,k}$ is the sum of coefficients of head from source and sink terms; $CV_{i,j,k}$, $CR_{i,j,k}$ and $CC_{i,j,k}$ are the hydraulic or branch conductances between node *i,j,k* and a neighbouring node; $Q_{i,j,k}$ is the sum of constants from source and sink terms; for flow out of the groundwater system (such as pumping) and flow in (such as injection); $SS_{i,j,k}$ is the specific storage; Δr_j, Δc_i, and Δv_k are the dimensions of cell *i,j,k* which, when multiplied, represent the volume of the cell; and t^m is the time at time step *m*.

Rearranging Eq. 6-6 in terms of state variable, $h^m_{*,*,*}$ is given by:

$$\begin{aligned} &CV_{i,j,k-\frac{1}{2}} h^m_{i,j,k-1} + CC_{i-\frac{1}{2},j,k} h^m_{i-1,j,k} + CR_{i,j-\frac{1}{2},k} h^m_{i,j-1,k} \\ &+ \left(-CV_{i,j,k-\frac{1}{2}} - CC_{i-\frac{1}{2},j,k} - CR_{i,j-\frac{1}{2},k} - CR_{i,j+\frac{1}{2},k} - CC_{i+\frac{1}{2},j,k} - CV_{i,j,k+\frac{1}{2}} + HCOF_{i,j,k}\right) h^m_{i,j,k} \\ &+ CR_{i,j+\frac{1}{2},k} h^m_{i,j+1,k} + CC_{i+\frac{1}{2},j,k} h^m_{i+1,j,k} + CV_{i,j,k+\frac{1}{2}} h^m_{i,j,k+1} = RHS_{i,j,k} \end{aligned} \quad (6\text{-}7)$$

Where $HCOF_{i,j,k} = P_{i,j,k} - \left(SS_{i,j,k}\Delta r_j \Delta c_i \Delta v_k\right) / (t^m - t^{m-1})$

and $RHS_{i,j,k} = -Q_{i,j,k} - \left(SS_{i,j,k}\Delta r_j \Delta c_i \Delta v_k\right) h^{m-1}_{i,j,k} / (t^m - t^{m-1})$

In Eq. 6-7, all other terms except, $h^m_{*,*,*}$ are known. Hence, Eq. 6-7 in matrix form for all grids is written as (Eq. 6-8):

$$[A_{i,j}][h^m_{i,j,k}] = [q_i] \quad (6\text{-}8)$$

where, $A_{i,j}$ is the m x n matrix of coefficients of head for all active nodes; $h^m_{*,*,*}$ is the 'n' number column vector of head values at the end of time step *m* for all nodes; and q_i is the 'n' number column vector of constant terms, *RHS*, for all nodes of the grid.

In Eq. 6-8, elements of matrix, $[A_{i,j}]$ represent the LHS of Eq. 6-7 and are known, elements of column vector $[q_i]$ represent the RHS of Eq. 6-7and are known, only unknown is the elements of the column vector $h^m_{i,j,k}$. By solving Eq. 6-8, $h^m_{i,j,k}$ for all grids at progressive time step, m = 1, 2, …, can be computed. These are the basis of computation in MODFLOW.

River–aquifer interaction in MODFLOW

In MODFLOW, river–aquifer interaction has been included by the "River Package" with functionality "RIV" that simulates head–dependant flux boundaries (Fig. 6-4). The mathematical relationship considered for the river–aquifer interaction, based on Fig. 6-4, is as follows (Eq. 6-9):

Flow rate from river to aquifer or vice–versa is given by Eq. 6-9,

$$Q = C\,(h_R - h_{i,j,k}) \tag{6-9}$$

in which, C= Riverbed Conductance = $(KWL)/M$; K is the hydraulic conductivity of riverbed material; W is the width of the river, L is the reach length of the river; M is the thickness of the riverbed material; h_R is the height of water in the river ; and $h_{i,j,k}$ is the height of groundwater level in cell, i,j, k, both measured upward from same reference datum.

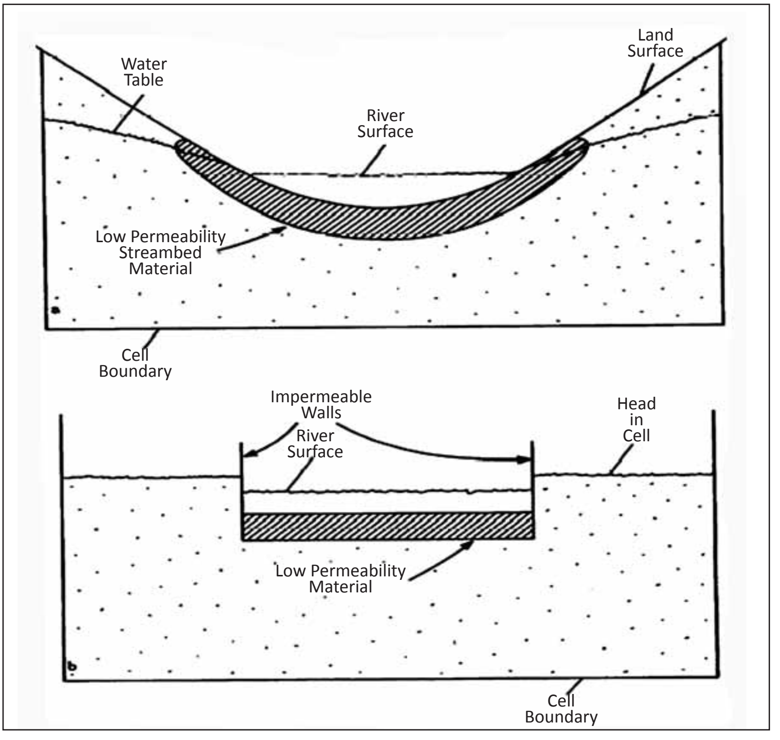


Figure 6-4a & 6-4b. Conceptualized scheme of river–aquifer interaction in MODFLOW. (a) field setting; (b) representation in MODFLOW

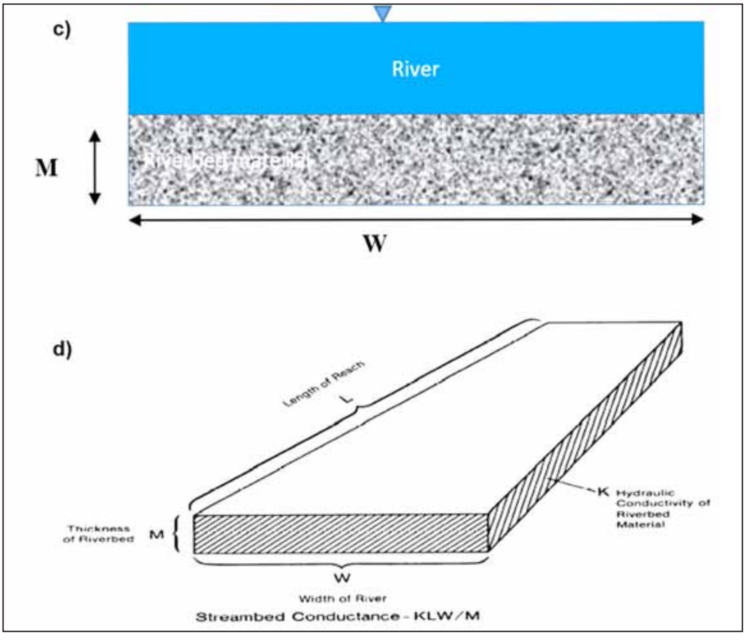


Figure 6-4c & 6-4d. Conceptualized scheme of river–aquifer interaction in MODFLOW. (c) sectional view of river and riverbed, and (d) longitudinal setting of riverbed material in MODFLOW

An illustrated example

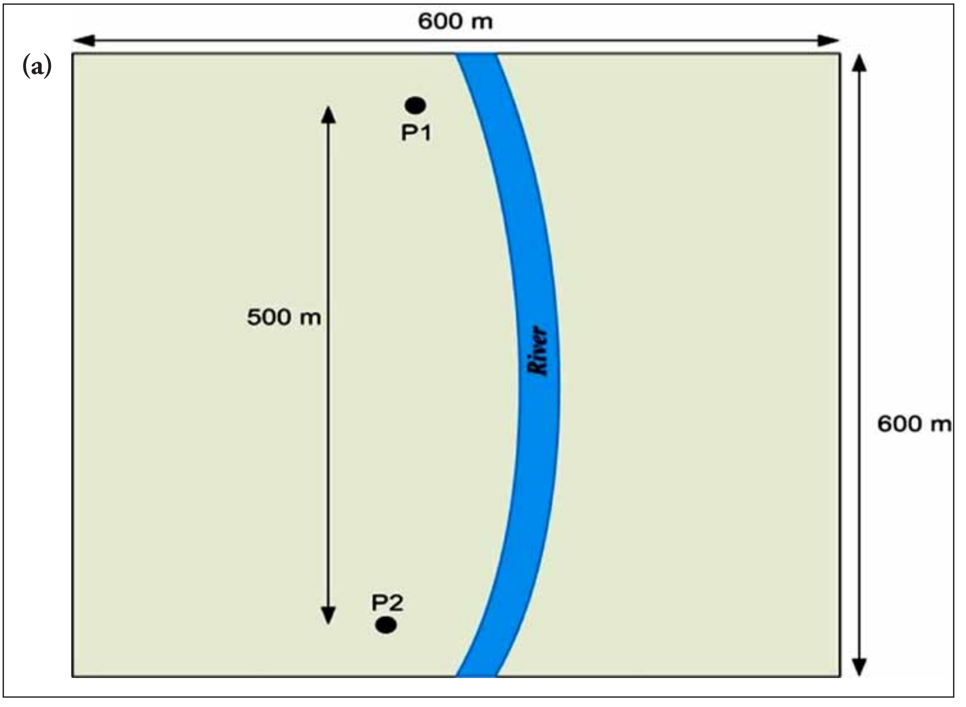
Based on the numerical schemes considered in MODFLOW, an illustrated example of RBF modeling is demonstrated with the input databases given in Box 6-1.

Box 6-1.*Input data*:*Let us consider a meandering river reach of uniform river width, W = 30 m; depth of water in the river, D = 1.5 m; the riverbed material thickness= 0.5 m; and the hydraulic conductivity of the riverbed material, K = 2 m/day, as shown in Fig. 6-5a & 6-5b.*

Two RBF wells located on the concave side of the river at 500 m apart, the one at 50 m and the other one at 75 m from the river, as in Fig. 6-5a, have been constructed to extract bank filtrate. The well at 50 m is operated for 10 hours a day with pumping rate 75 m^3/hr*, and the well at 75 m is also operated for 10 hours a day with pumping rate 100* m^3/hr*. The wells are fully penetrating, and the depth of the aquifer is 25 m below the normal ground surface; the aquifer hydraulic properties,* K_a *= 20 m/day, S = 0.1, andporosity, =0.35; and the initial groundwater level is at the riverbed level and in equilibrium condition before start of pumping.*

The responses of pumping on the river and aquifer is required to be modeled, in terms of:
- *Groundwater flow field,*
- *Pathlines of river water extraction*

Quantification of bank filtrate.



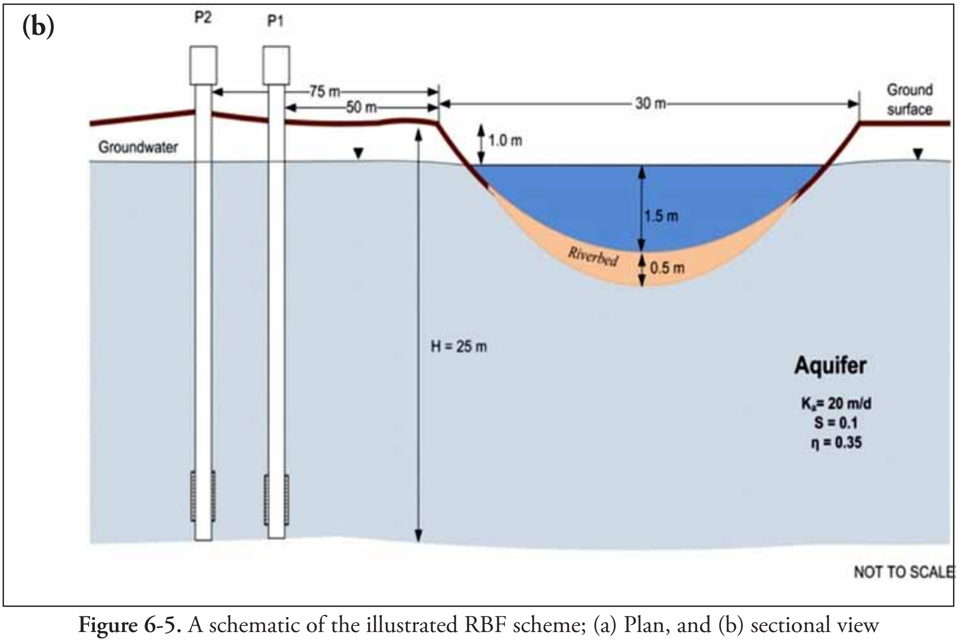


Figure 6-5. A schematic of the illustrated RBF scheme; (a) Plan, and (b) sectional view

The step-by-step procedure for setting the modeling scheme is described below.

Step 1: Create and define a flow model

To create a new model using Visual MODFLOW, 'Double Click' on this icon,  on your windows desktop.

Thereafter, Click '**File'** from the top menu bar, and then Click **New.** Create new modelwindow will appear. Save your project with a name.After saving the project window as shown in Fig. 6-6 will appear, in which the following information are to be assigned:

- The Project Information,
- **Units** associated with various flow and transport parameters, and
- The **Engines** for the flow (recommended, MODFLOW–2005) and transport simulation

In the present case, the name RBF is given as project information; units as illustrated in the example and shown in Fig. 6-6 are assigned; and numeric engine MODFLOW–2005 (generally, recommended) is selected.

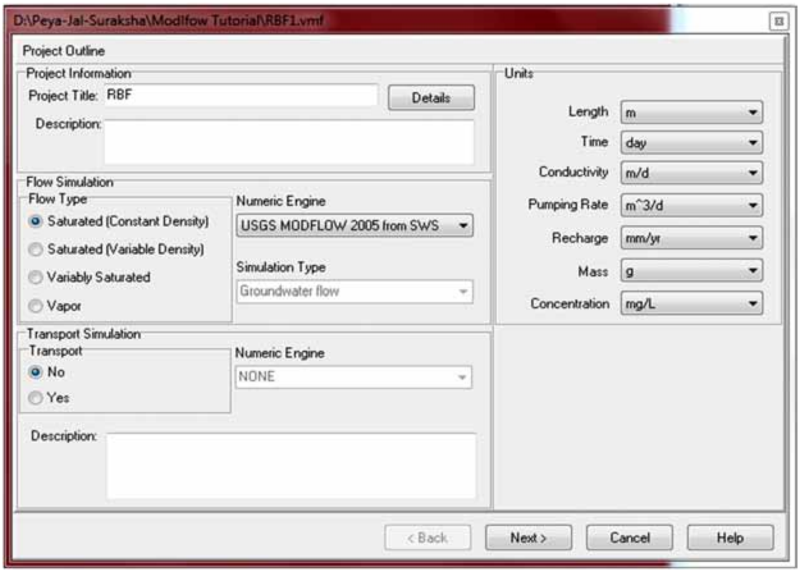


Figure 6-6. Screen for assigning project information, units, and for selecting 'Numeric Engine'

Step2: Assigning model flow data on project outline

*Click **"Next"** of screen as shown in Fig.6-6, to have screen as in Fig.6-7.*

On the "Time Option", type starts date and start time as shown in *Fig.6-7*. Select "Steady–State Flow" option on the "Run Type" with "Steady–State Simulation time" period. On the "Default Parameters" screen, assign the value of parameters on "Value" column as per the units shown in the "Units" column.

In the present case, the start date is considered "01–01–2017" and start time as 00:00:00 with simulation time as 365 (Fig.6-7). The value of the parameters is assigned as illustrated in the example with units as shown in the screen (Fig.6-7).

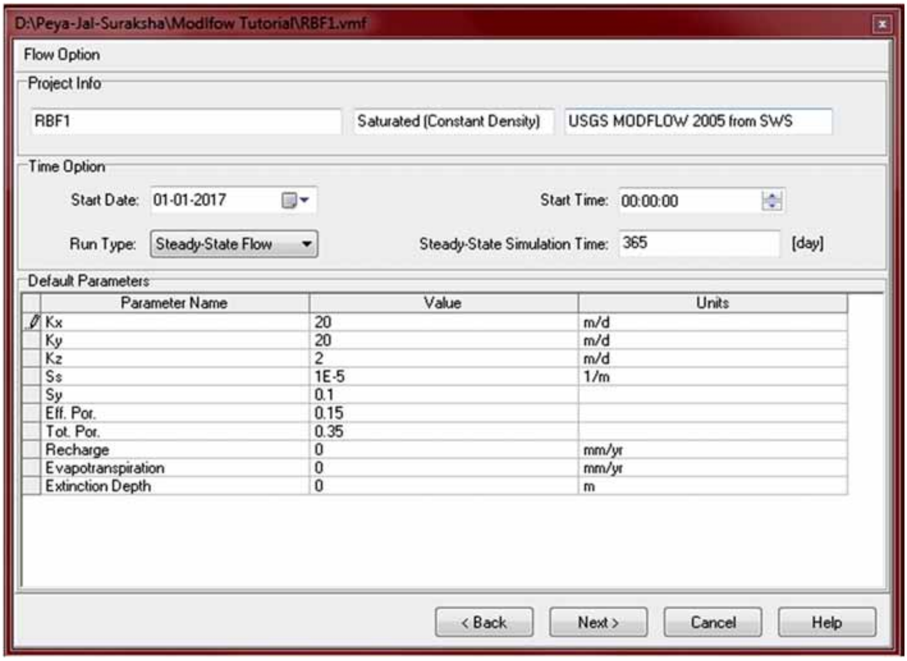


Figure 6-7. Screen for assigning flow parameters

Step3: Create the model grids and domain

*Click **"Next"** on screen as shown in Fig. 6-7 to have the screen as in Fig. 6-8.*

In this step one can import a site map by **clicking the option "Import a site map" and then browse the file where the 'sitemap.bmp' file is located.** Thereafter,specify the dimensions of the Model Domain **on option "Grid"** by assigningnumber of rows, columns, and layers.

*In the present case, number of column, (j)= 20, and number of row, (i) = 20 with x_{max} = 600 m and y_{max} = 600 m are considered, that means grid size of x= 30 m and y =30 m. Number of layer (k) of aquifer = 2 with z_{max} = 24 m is considered. By 'Clicking' the option "import a site map", the 'bmp' file of the present site map is imported. The gridded model domain is shown in Fig. 6-9.Click **[OK]** to accept the model dimensions.*

Step4: Assigning pumping wells

For assigning pumping wells, **Click [Wells]** from the top menu bar and then **Click [Pumping Wells]** from the drop–down menu, you will be asked to save your data, Click **[Yes]** to continue. After it is saved, the input screen for "**Pump Wells**" will appear. The left–hand toolbar buttons now contain well–specific options for importing, adding, deleting, editing, moving, and copying pumping wells. To add the pumping well, Click onto **[Well]** location one by one as shown in site map Fig. 6-9. There can be more number of wells than as in Fig. 6-9. After clicking on "Pumping Well", a screen as in Fig. 6-10 will appear.

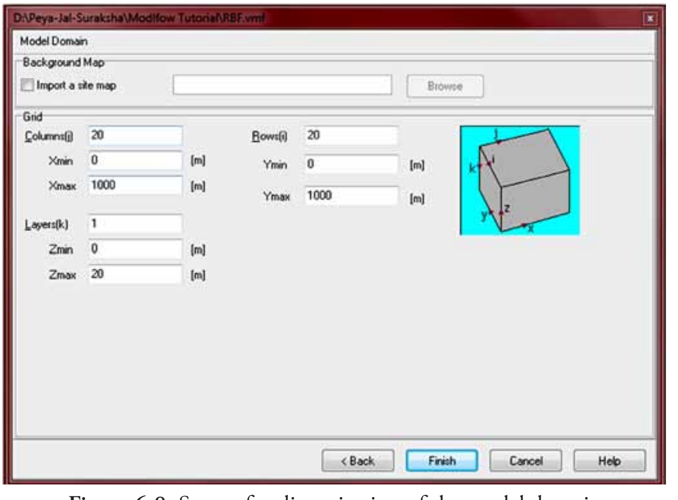


Figure 6-8. Screen for discretization of the model domain

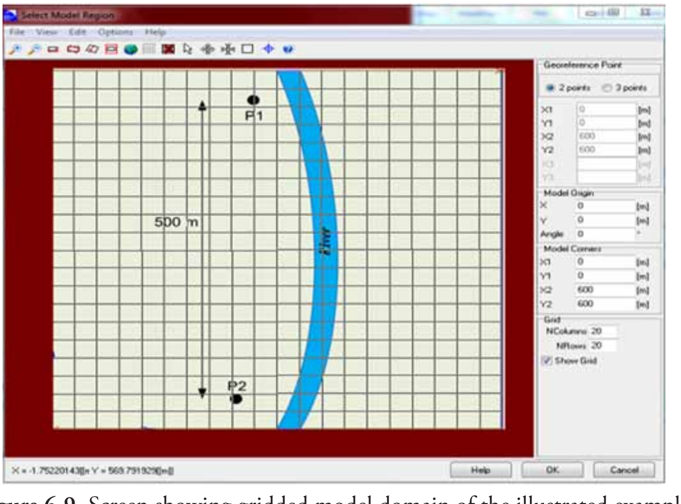


Figure 6-9. Screen showing gridded model domain of the illustrated example

In the present case, we have two pumping wells, P_1 and P_2. The locations of P_1 and P_2 are already referenced with respect to the modeling domain. Therefore, if by clicking onto P_1, its coordinates, x and y will automatically appear. Thereafter, define the well screen using 'screen interval' option. Define top and bottom elevation of the well screen as shown in Fig. 6-10 for P_1. There can be multi screens in a well, which can be defined by setting different entries of top and bottom elevation.

Assign pumping schedules of the well giving start and end day including pumping rate as in Fig. 6-10. Click [OK] for saving data of pumping well P_1.Follow the same procedure for P_2 and other wells (if any) as well.

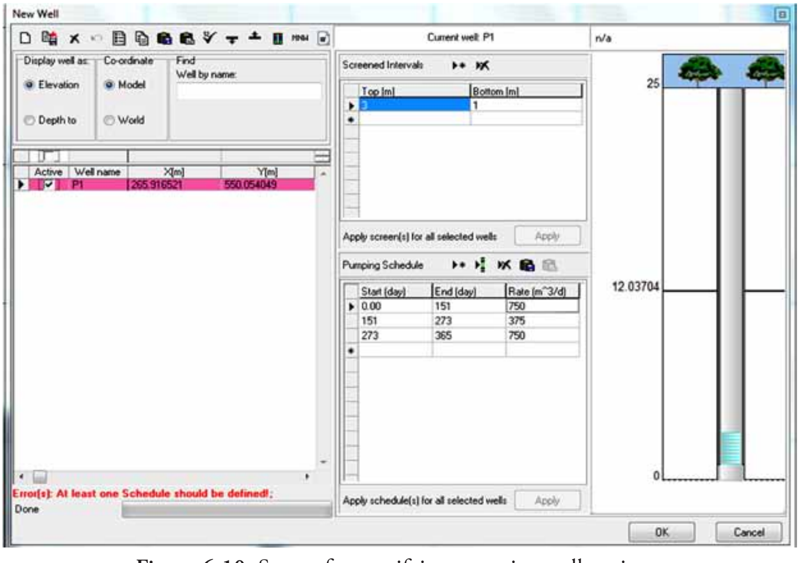


Figure 6-10. Screen for specifying pumping well options

Step5: Refining grid size

One may require smaller grid size within the modeling domain for better resolution of the results in and around a zone or specific interventions. A grid can be refined by options available in 'Grid' input screen of the model. The Grid screen can be recalled anytime in the model by selecting 'Grid' option available in the dropdown menu on the left hand toolbar of the model window. The options provide a complete assortment of graphical tools for refining model grid, delineating inactive grid zones, importing layer surface elevations, assigning elevations, optimizing (smoothing) the grid spacing, and contouring the layer surface elevations.

Grid can be refined in the X–direction by clicking **[Edit Grid >] Edit Columns** and in the Y–direction by [**Edit Grid >] Edit Rows.** A window similar to as in Fig. 6-11 will appear containing options for editing column. One of the option is 'refine by'.

In the present case, we wanted to refine grids around pumping wells, P_1 and P_2, from 30 m to 10 m by refining columns in X and rows in Y direction as shown in Fig. 6-11. Choose refine by option, while editing columns and rows and enter 3 (Fig. 6-11) to refine the grids from default size of 30 m to 10 m. The final view of the site map showing refined grids around pumping wells P_1 and P_2 is shown in Fig. 6-12.

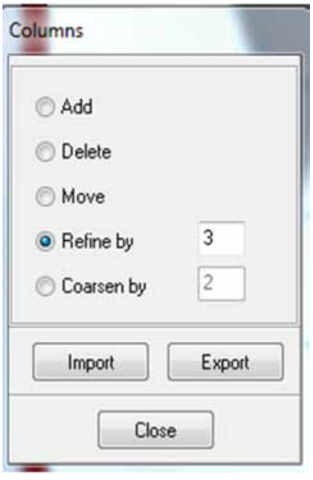


Figure 6-11. Screen for specifying pumping well options to refine grid

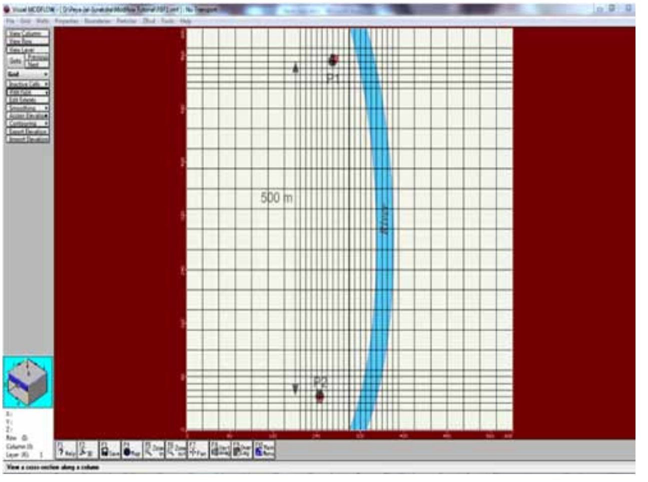


Figure 6-12. Model screen showing refined grids around pumping well P_1 and P_2

Step 6: Assign boundary conditions

Boundary conditions are necessary to define how the site specific model interacts with entire flow system. In a numerical model, the boundary conditions can be; general head; constant head; river recharge; etc. All these boundaries can be assigned to a model by going to **'Bound=aries'** in the Top menu bar and then select respective boundary.

a) **A river boundary** can be assigned in the model by selecting **'River'** boundary and 'Click' **[Assign >] polygon** from the left toolbar. Using the sitemap as a guide, a line of grid cells can be digitized along the river by clicking along its path using the left mouse button. At the end of the river, **Right–Click** the mouse button at the end point of the line to finish selecting grids.

*In the present case, river as shown in blue color in the site map is selected as the boundary. The grids falling on the river are selected by **assigning > polygon option** in the left toolbar for digitization. After that, the model prompted to enter the details of the river data as in Fig. 6-13. Click OK to finish assigning river boundary to the model.*

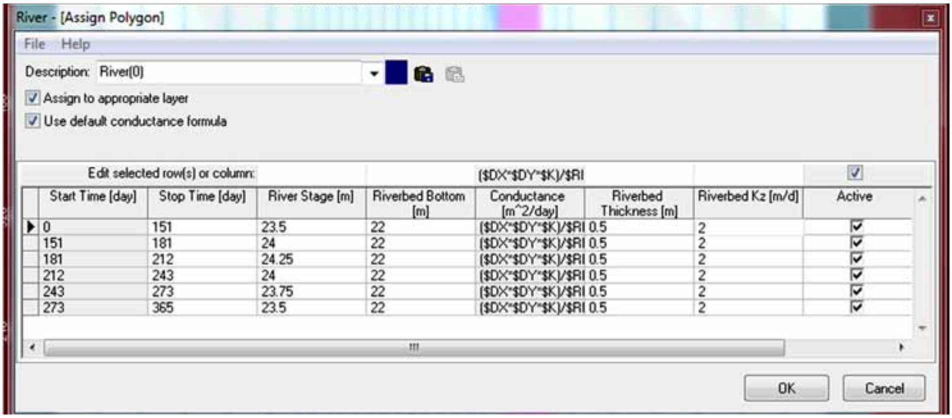


Figure 6-13. River boundary condition details

b) **General head boundary** (GHB) condition accounts for the flow into or out of a cell from an external source in proportion to the head differences between the two sources. General Head boundary condition is usually assigned along the outside edges of the model domain. Click **Boundaries** and select **General Head (GHB).** From the side menu bar, Select **Assign by line.**

*In the present case, east and west side of the domain are considered as no–flow boundaries where flow is neither coming in from outside of the domain nor going outside. Top and bottom boundaries (North and South) of the model domain are the boundaries where flow can come in and go out. Therefore, the grid cells of the top and bottom boundaries are assigned as general head boundary (GHB) conditions. Starting from the top left grid a line till the end of top right grid is selected and then right clicked to finish it. A window for specifying options for the boundary condition, as in Fig. 6-14, appears and thereafter, assigned the required data as shown in Fig. 6-14. Click [**OK**] to accept all the changes. Similar way, assigned the GHB condition to the bottom grid cells. If the values were correctly assigned, a green colour in the full extent views of the grid domain like as in Fig. 6-15.*

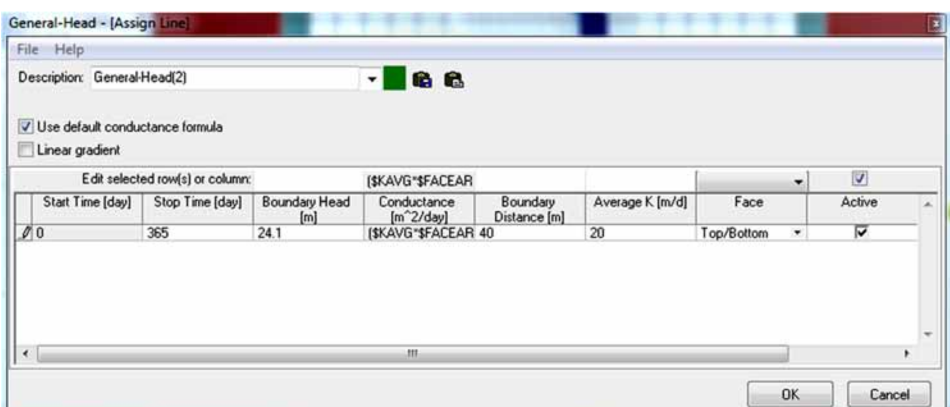


Figure 6-14. General head boundary condition details

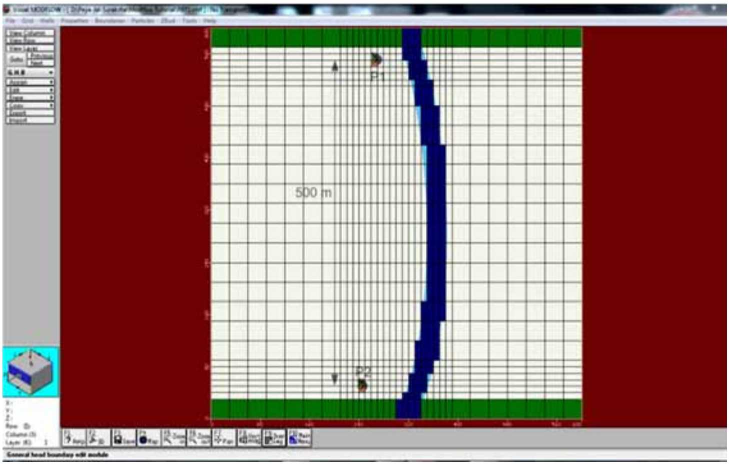


Figure 6-15. General head boundary defined

c) **No flow boundary.**This boundary condition is assigned to the grids which are not considered in the model simulation. For assigning this condition, Click [**Grid]** from the Top menu bar. Select **Inactive cells – Mark poly inactive** grid from the side menu.

In the present case, the left and right (west and east) sides of the domain are considered to be no–flow boundaries. The cells on the extreme left and right boundaries are assigned as no–flow cells or made them inactive. Starting from the top left grid cells, a polygon extending from top to bottom grids is made and then right clicked to finish the polygon. A changed grids colour from white to cyan colour has appeared for correct assignment of the grids. These grid cells have now become inactive. We need to assign no–flow boundary condition to the next layer(s) by copying the inactive cells from layer–1 to other layer(s).In similar way, no–flow boundary condition is assigned to the right hand cells. The final view of the model domain will look like as in Fig. 6-16.

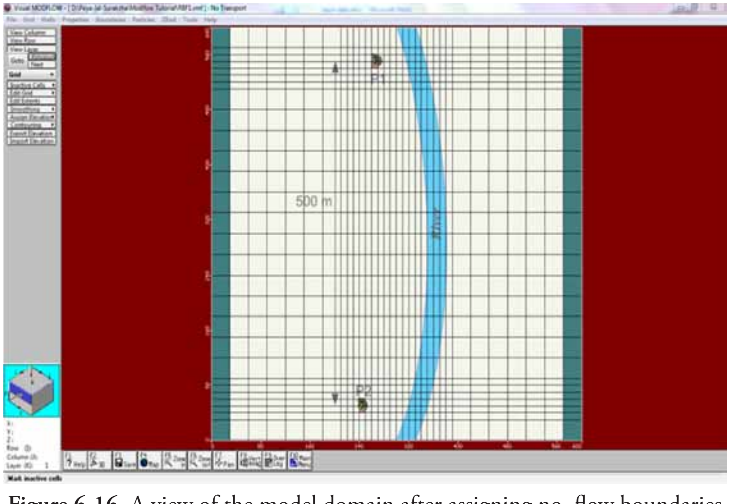


Figure 6-16. A view of the model domain after assigning no–flow boundaries

Step 7: Initial condition of the groundwater level

Initial condition of groundwater level is essentially required to be specified in each cell. To assign initial heads, click '**Properties**' from top menu bar and then select **'Initial Heads'.** This will enable the option to assign initial heads and would be visible on the screen at the left hand side. **Click 'Assign'** and select **'window'** option. Drag an area starting from topmost left grid cell to bottom most right grid cell covering the entire study domain. This will open up a window for specifying initial water head (m) as shown in Fig. 6-17. Initial condition may be different in different cells or zones. By selecting the respective cells or zones, initial groundwater level in those cells/zones can be assigned.

In the present case, we have uniform groundwater elevation of 24 m. Therefore, for the entire modeling domain, the same initial condition of groundwater level is considered.

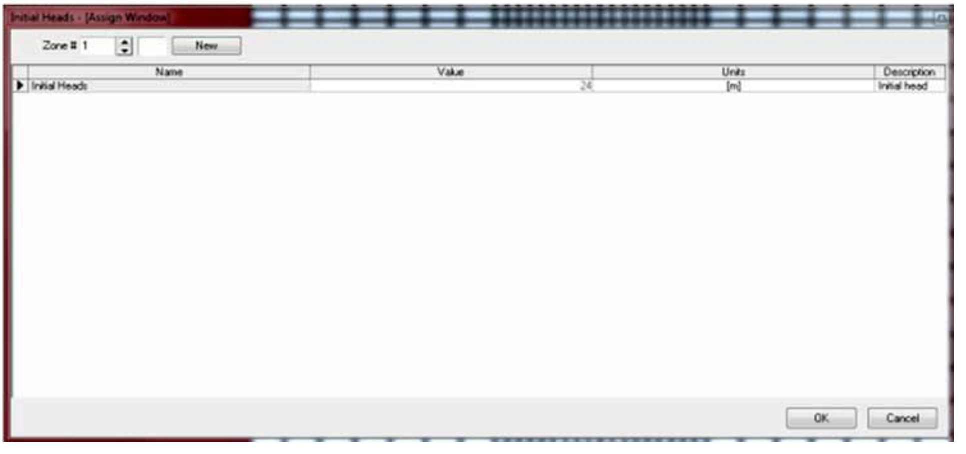


Figure 6-17. Screen for assigning **i**nitial head options window

Step 8: Particle tracking

Particle tracking is used to determine the flow pathways of groundwater by inserting 'particles' from a known location. Forward tracking of particles to determine the pathways and travel time is used. To assign the particle tracking, **Click 'Particles'** from the top menu bar. The **Particle** input screen will appear, with the various options will display along the left–hand toolbar for assigning particles. Particles can be assigned on individual grid or along a line.

*In the present case, a line of particles in the vicinity of the river near pumping wells P_1 and P_2 is assigned to demonstrate transportation of bank filtrate from the river to the pumping wells. Two zones are considered, the first one near to P1 and the second one near to P_2. For assigning particles; **Click [F5 – Zoom In]** from the bottom toolbar. Click the left mouse button near vicinity of P_1 and drag an area, as shown in Fig. 6-18, covering* *river. **Click[Add>] Add Line** to add a line of particles, and stretch the line upto the right side of P_1 to cover the river bank. A **Line Particle** window will appear (Fig. 6-18). The default number of particles is **10** (This can be changed). We choose, no.of particles as10, and thenClick **[OK].** The line of green particles indicates forward tracking particles. Thereafter, return to the full–screen display of the model domain. Click **[F6 – Zoom Out]** (from the bottom toolbar). Similarly, repeat the steps for P_2 as also shown in Fig. 6-18.*

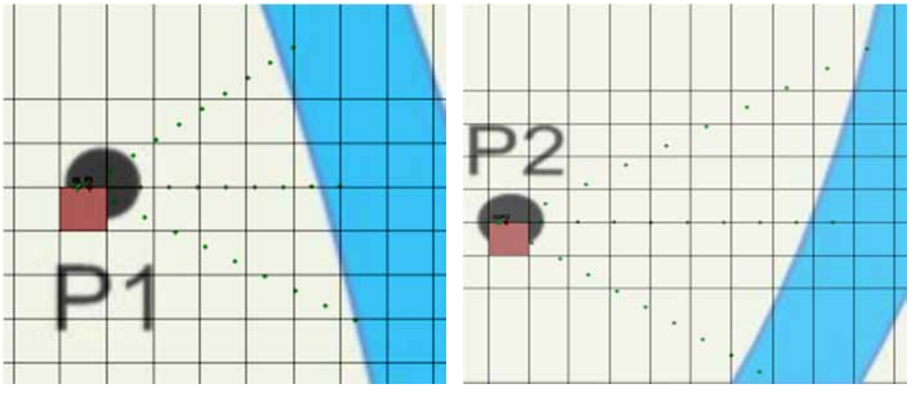


Figure 6-18. Zoom–In view around pumping wells P_1 and P_2 showing particles for particle tracking function

The model setup is now ready for the simulation run.

Step9: Running the model

a) **Click** [F10–Main Menu], **Click** [Yes] (to save the particle information), **Click** **Run** (from the top menu bar). Run Options screen for Visual MODFLOW as shown in Fig. 6-19 will appear. This screen allows the user to customize some of the run–specific settings for running the MODFLOW.

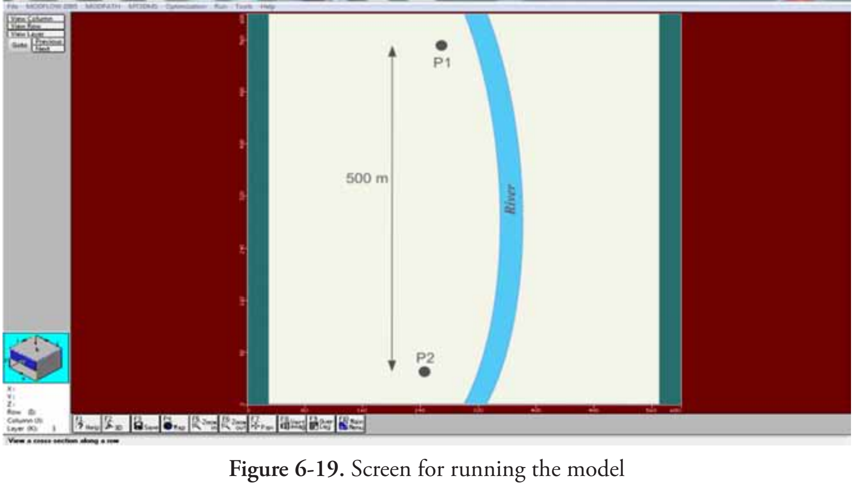


Figure 6-19. Screen for running the model

b) Select **'MODFLOW–2005'** from the top menu bar and then 'Click' **Time steps.** This help specifies the different stress period of the model. It allows dividing the stress period into desired number of steps. The options shown in Fig. 6-20 will prompt to enter time step details.Enter the details and click 'OK'.

In the present case, six stress periods for one year run are considered. The details of the stress periods with start and end day together with number of time steps are shown in Fig.6-20. As the time step size for all time steps are same, hence, multiplier is 1 in all cases.

c) After assigning stress periods, again 'Click', '**MODFLOW–2005**' from the top menu and select '**Output controls'.**A window showing different time steps in a year will appear (Fig. 6-21).

In the present exercise, the outputs at the end of each month are preferred. Therefore, the time steps in multiples of thirties starting from 30, 60, 90, and so on are assigned. Then Click OK for saving all the data.

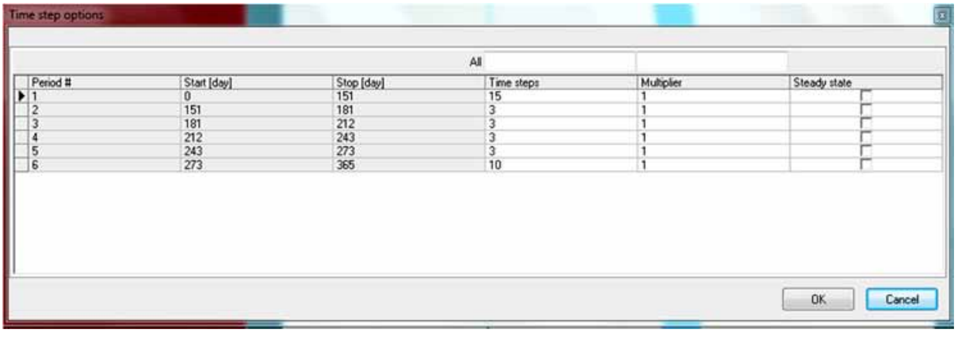


Figure 6-20. Time step options

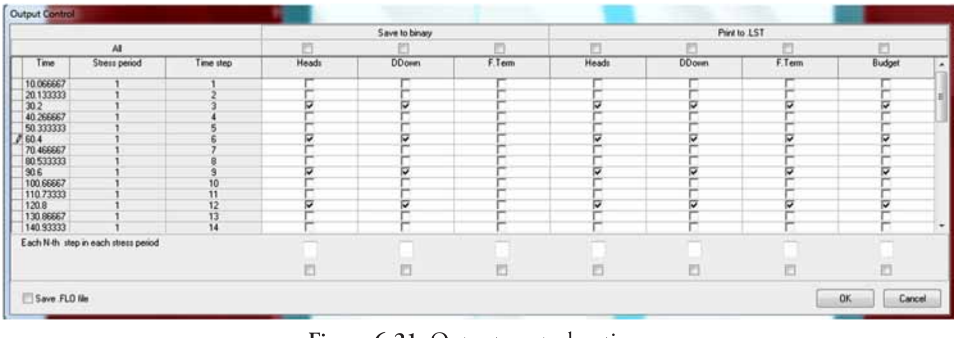


Figure 6-21. Output control options

For other, the default run settings can be accepted for running the model. Click '**RUN'.** A window will appear, select both **Modflow 2005 and Modpath**, and then Click **Translate and run**.

A Visual Modflow Engine window will appear after successful execution of the model, as shown in Fig. 6-22. It will show a graph indicating residual and maximum head change versus iteration number in one of the tab, Modflow–2005. The other tab will have information on results and progress of the MODPATH calculations (Fig. 6-23). It also provides a travel time summary for all the particles and explanation on where each particle become inactive or stopped in the simulation.

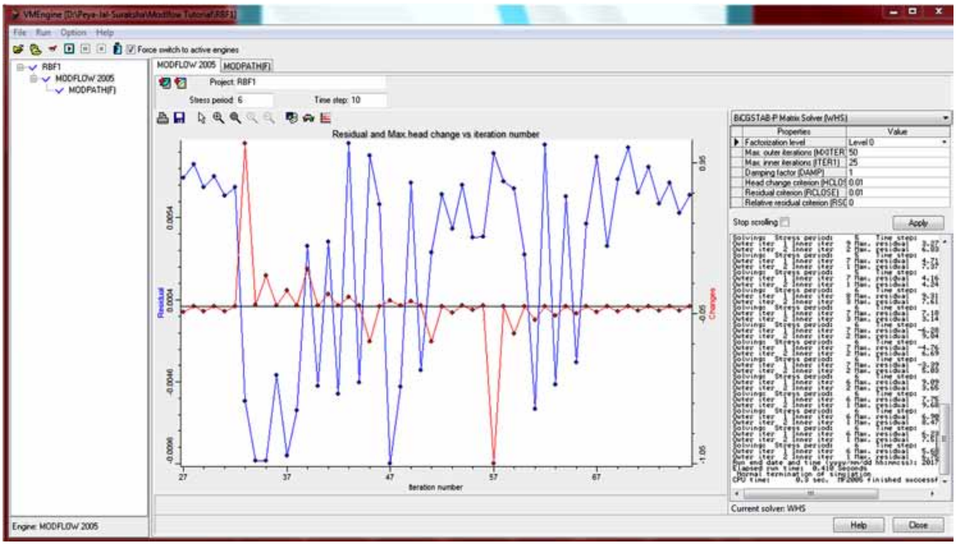


Figure 6-22. Window showing status of Modflow–2005 engine

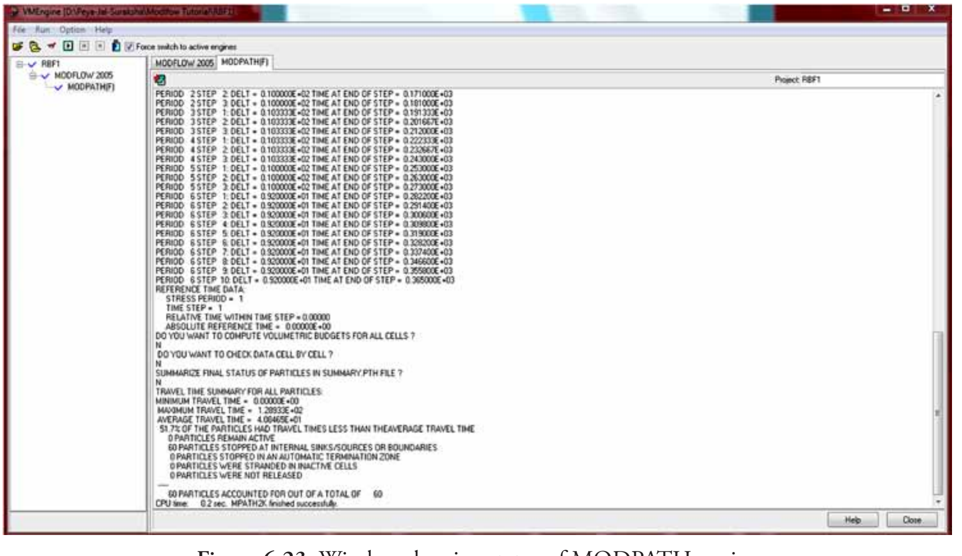


Figure 6-23. Window showing status of MODPATH engine

Step10: Visualizing the model results

To visualize the model results, go back to the **main menu**, and select '**Output'**. The **output** menu screen will appear that will allow selecting and customizing the display of results. If we wanted to visualize the results of 'heads'; by default, the side menu options are highlighted for 'heads' (If not, then select 'heads' from the drop down menu). This will help visualize the 'head' contours for first time step (Fig. 6-24). Using the side menu options, results can be visualized for all the time steps by selecting time options (Fig. 6-25).

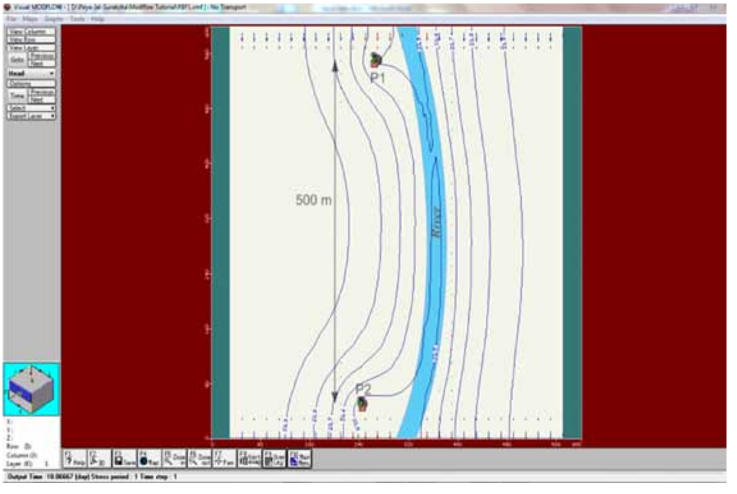


Figure 6-24. Results of groundwater head at time step 1–30 days

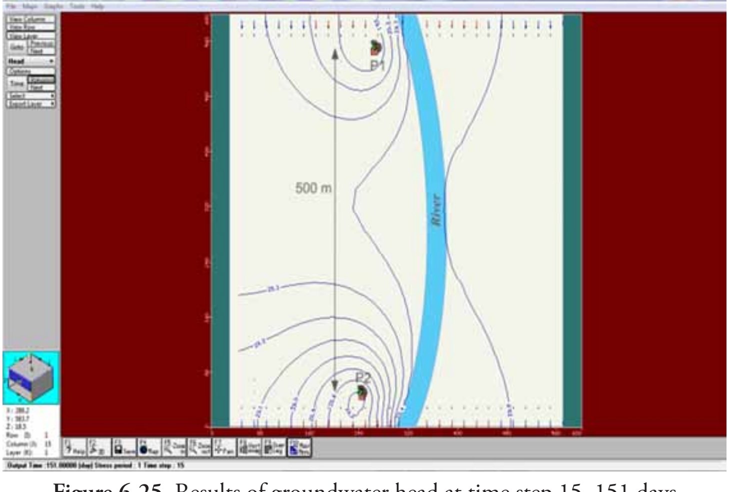


Figure 6-25. Results of groundwater head at time step 15–151 days

To visualize path lines output screen, choose path lines from the side menu options. Zoom into the pumping wells P_1 and P_2 to examine these path lines more closely (Fig. 6-26, left).**Click [F5] Zoom in.** Drag onto the area around pumping well P_1.

Pathlines are indicated with arrows (Fig. 6-26, left). These arrows show the direction in which the particles have moved. The width of these pathlines can be changed and direction arrows properties can also be customized using path line options. Click **Options** from the left menu bar. A path line option dialogue box options will appear (Fig. 6-26, right). The path lines allow to select either steady state or time related path lines.

In the present case, time related pathlines that display flow path lines from time zero to end of the simulation, is selected. The time interval for the path line time markers is displayed in the bottom right–hand section of the dialogue box.

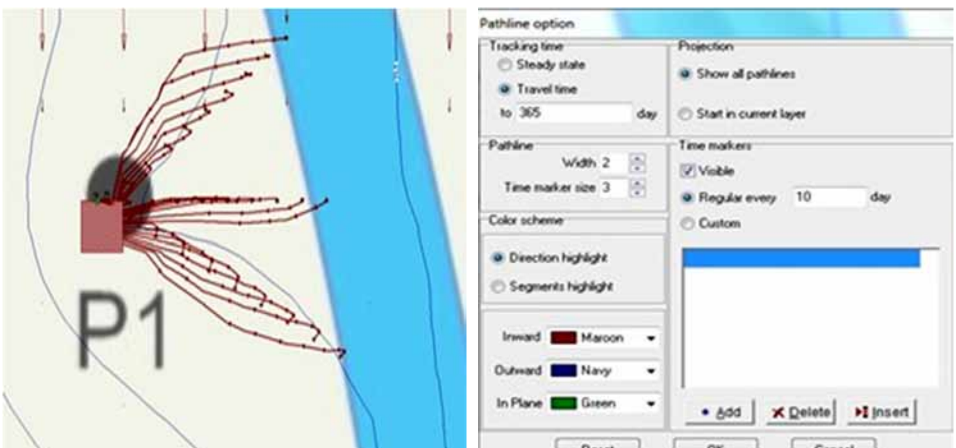


Figure 6-26. Figure 6-25. Pathlines to well showing flow-path and travel time of bank filtrate and path line option dialogue box

Concluding remarks

Theoretical aspects illustrating the processes of river/stream-aquifer interactions have been explained in brief. The governing equations for modeling of flow and contaminant transport in a 3-dimensional groundwater system as considered in visual MODFLOW have also been described together with description of the algebraic schemes. A detailed step-by-step procedure for numerical modeling of river bank filtration system using visual MODFLOW with an illustrated example has been demonstrated.

REFERENCES

1. Rushton, K.R., Groundwater hydrology: conceptual and computational models. *Wiley Publication*, 2003, 430p. ISBN: 9780470-850046.
2. Harada, M., Hantush, M.M., Marino, M.A., Hydraulic analysis on stream-aquifer interaction by storage function model. In: Sato, K., Iwasa, Y., (eds.) *Groundwater Updates*, Springer, New York, 2000, 229–234.
3. Freeze, R.A., Cherry, J.A., Groundwater. *Prentice–Hall*, Englewoods Cliffs, New Jersey, USA, 1979, 604p.
4. Bear, J., Hydraulics of Groundwater, *McGraw Hill*, New York, 1979, 569p.
5. Bear, J., Bachmat, Y., Theory and applications of transport in porous media. *Kluwer Academic Publishers*, Dordrecht, The Netherlands, 1990, 553p.
6. Morris, D.A., Johnson, A.I., Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948–1960. *U.S.G.S. Water-Supply Paper 1839-D*, 1967, 42p.
7. Klotz, D., Seiler, K.P., Moser, H., Neumaier, F., Dispersivity and velocity relationship from laboratory and field experiments.*J. Hydrol.*, 1980,**45**(3–4), 169–184
8. Smith, G.D., Numerical Solution of Partial Differential Equations: Finite Difference Methods.*Oxford University Press*, 3rd ed., 1985, 337p.
9. Reddy, J.N., An introduction to the finite element method. *McGraw-Hill*, 2006, 766p. ISBN9780071267618.
10. Haitjema, H.M., Analytic element modeling of groundwater flow. *Academic Press,* San Diego, 1995, ISBN9780123165503.
11. Harbaugh, A.W., MODFLOW-2005. The U.S. Geological Survey modular ground-water model – the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods, 2005, 6-A16.
12. Diersch, H.-J.G.,FEFLOW – Finite element modeling of flow, mass and heat transport in porous and fractured media.*Springer*, Berlin Heidelberg, 2014, 996p.ISBN 9783642387395(eBook), doi:10.1007/978-3-642-38739-5.

7

Chapter

AWARENESS STRATEGIES ON BANK FILTRATION IN INDIA

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This chapter discusses and analyses the importance of awareness for up scaling bank filtration technology in India. It also suggests the strategy to be followed for widespread acceptability and promotion of the technology in different states of India. The existing functional arrangements and the activities carried out in India on RBF since the technology was first introduced are also presented in brief.

KEYWORDS: riverbank filtration network, training course, workshop, conference, demonstration, up-scaling, hyporheic zone.

INTRODUCTION

Having recognized worldwide acceptability, scientific prospect, feasibility, design aspects, associate drisk, etc. of the bank filtration (BF) technique; the next questions arise; (i) what is its prospect of upscaling BF in India?; (ii) how can the technology be upscaled and promoted for supplementing drinking water supply in feasible locations?; (iii) what strategy can be adopted for upscaling the BF technology in India ?; and (iv) who should be taken into board for furthering the technology? All these questions need a systematic appraisal before one recommends for creation of awareness.

India has composite diversity of socio-economic, socio-culture and water usages. It has varied hydrology and hydrogeological setups, large network of perennial rivers across its length and breadth having fluvial and alluvium deposits with or without hydraulic connectivity between the river and the adjoining aquifer, hard rock formations around the surface water bodies, etc. Seasonality in river flows, steep gradient of river slopes in hilly terrains, crisscrossing of river-aquifer flows, etc. are other issues, which pose major constraints in suo-motu implementation of BF technology in many areas. India also has a large numbers of surface water bodies, viz. lakes, reservoirs, tanks, ponds, etc., of varying sizes distributed over the country. Those surface water bodies, in many parts of the country, act as the source for drinking water supply. Inflow of organic pollutants from the catchments of such water bodies is another issue that obstruct direct use of water from surface water bodies. BF, as a pre-treatment technique, can provide a solution to safe drinking water supply in areas where they belong to.

In India, 85 % of rural drinking water requirement is met from groundwater extraction. Depleting groundwater levels in many areas, and deteriorating groundwater quality from anthropogenic and geogenic sources of contaminants e.g., arsenic, fluoride, nitrate, salinity, and iron, pose threat in direct uses of groundwater for domestic purposes in those problematic areas. Surface water bodies are mainly free from arsenic, fluoride, salinity and iron, and the shallow aquifers (< 20 m), which are normally found hydraulically connected to the adjoining rivers/surface water bodies, have less risk to contaminants of geogenic origin. The BF as a pre-treatment technique can provide a sustainable solution to maintain continuum of domestic water supply in those areas. Many India's rural clusters and sub-urban areas located along riverside do have neither organized water supply schemes nor do have access to safe drinking water supply. The BF technology either as standalone scheme or as supplementary to the existing scheme can provide a sustainable solution as a pre-treatment technique. In hilly terrains, particularly in the Himalayas valleys and plateau areas where river stretches have very less organic contaminants but have turbid water during monsoon period and act as losing river, BF can be an effective technology[1]. A series of workshop was organized on RBF/BF to discuss various issues for effective implementation and it was decided that hyporheic zone (is a self purification zone act as a refuge as well as hatchery and nursery for stream organism, responsible for mineralization of organic matter which accumulates within interstitial spaces. These zones are waterflow regulators, permanent sinks for organic and mineral matter and contaminants from watersheds, filter and buffer system that protect groundwater quality and improve surface water quality. Interstitial organisms are also instrumental for improving the water quality of the river through the process of filtration, sedimentation, deposition and decomposition) to be included as one of the criteria for RBF site selection as it helps in improving the water quality[6,7].

In European countries, particularly in Germany, Hungary, Slovak Republic and The Netherlands, BF has been a common practice for more than a century and today large quantity of the drinking water supply of those countries are met by BF[1]. Due to increased understanding of various advantages of BF technique, it is now becoming increasingly popular in many countries viz., South and South East Asia, North Africa and in India. The conventional technique, which mainly relies on surface water abstraction and subsequent treatment, requires high level of technology, high investment, recurring operation and maintenance (O & M) cost and skilled personnel for O & M. These aspects of conventional technique have put many areas in India deprived to have organized water supply schemes.

Uttarakhand, out of its geographical area of 53,483 km^2, has 86% mountainous. The state witnesses a large variation in surface water quantity and quality. During monsoon period, the rivers & streams carry high turbid water, while in non-monsoon months, the flows in rivers and streams reduce considerably. Many habitations in hilly areas do not have access to organized water supply scheme. Typically, drinking water is supplied by directly abstracted surface water from springs, rivers and streams with a highly variable seasonal discharge. These surface water abstraction systems face two major recurring problems with respect to quantity and quality for drinking water production:

- In the pre-monsoon, especially the hot-dry summer season (March–May), the discharge of spring-fed streams and small rivers decreases considerably, thereby significantly reduces the quantity of drinking water produced and making such schemes drought-prone resulting in a drinking water production-deficit.
- During monsoon (June–September), the rapid sand filters or other treatment devices used in the conventional water treatment plants are unable to remove the turbidity from the raw water and the subsequent conventionally-applied disinfection by chlorination does not guarantee the elimination of pathogens.

In collaboration with the University of Applied Sciences Dresden (HTWD) on use of BF technology and its performance evaluation in Uttarakhand since the year 2005, presently the state has BF schemes operational in Haridwar, Srinagar, Nainital, Karnaprayag, Agastmuni and Satpuli and has planned to upscale it in many other potential areas. Various studies on BF technology have demonstrated that as integrated part of water resource management, BF has an enormous potential to secure quality and quantity of water supply[2].

Keeping the above in view, the awareness strategy on the promotion of BF technology in India is analysed and suggested in this chapter.

Initiative for promotion of bank filtration in India

Drinking water supply using BF technology has been initiated in many states in India namely; Uttarakhand, Haryana, Bihar, Uttara Pradesh, Jharkhand, Gujrat and Andhra Pradesh (Chapter 1; Fig.1-2). Amongst these states, Uttarakhand has successfully established BF schemes in Satpuli, Agastmuni, Srinagar, Karnaprayag, and Gaucher. These initiatives were possible by the combined efforts and technical network of Uttarakhand Jal Sansthan (UJS) (Drinking Water Supply Department, Uttarakhand), Uttarakhand State Council for Science & Technology (UCOST), Dehradun (State co-coordinator), and University of Applied Sciences Dresden (HTWD), Germany, Indian Institute of Technology Roorkee (IITR) and National Institute of Hydrology (NIH), Roorkee (Research & Development, Institute). The feasibility established to develop BF in Srinagar along the bank of Alaknanda River as well as sustainability of BF sites in Haridwar and Nainital motivated the UJS to develop RBF at five additional locations in Uttarakhand. These are currently successfully running in the state.

In India, RBF promotion was initiated a way back in year 2005 by establishing a Cooperation Centre for Riverbank Filtration (CCRBF) at Haridwar by UJS and HTWD, Germany with its members as; UCOST, NIH and IIT Roorkee. Since then, the CCRBF had initiated a number of R & D projects in Uttarakhand, started demonstrating RBF technology in different states, and expanded its membership to a number of other states and organizations[2] (Fig. 7-1).

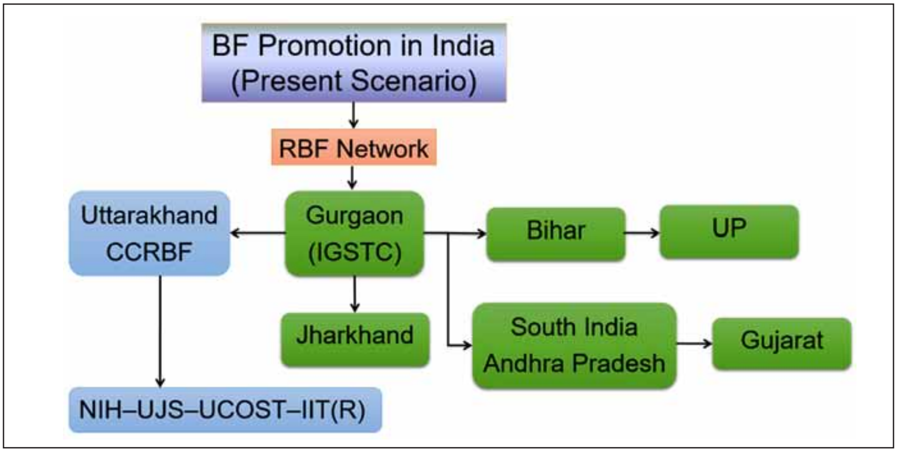

Figure 7-1. Network for promotional activities on BF technology in India

In year 2011, recognizing the need of upscale and more research for improve understanding of the technology in Indian context, NIH-Roorkee and HTWD, Germany with the approval of the respective federal Government Ministries, i.e., Water Resources Ministry of Government of India and German Federal Ministry for Education and Research (BMBF) approved establishment of an Indo-German Competence Centre for Riverbank Filtration (IGCCRBF) at NIH, Roorkee initially for five years and later on extended for five more years up to year 2021. The objectives for establishing this centre are to: (i) work jointly in research programs exchanging technical know-how and initiating new projects at potential sites for sustainable water resources management; (ii) encourage cooperation in related areas, and in carrying out joint research programs in water resources management, exchanging technical know-how, organizing training programmers, workshops and other such activities, in particular RBF for its large scale viable use in India; (iii) encourage cooperation within the framework of joint activities to develop RBF systems to ensure sustainability in India's hydrologic and hydro-geologic setups, and provide technological support to national projects related to RBF through dissemination of information and know-how. The IGCCRBF has provision to associate co-partners both from India and Germany on a case-by-case basis on mutually agreed terms and conditions. Based on the approved functional arrangements, the IGCCRBF has associated a number of co-partners for promotional and R & D activities on the area from both Germany and India. The structure of the IGCCRBF and its cooperation are as in Fig. 7-2.

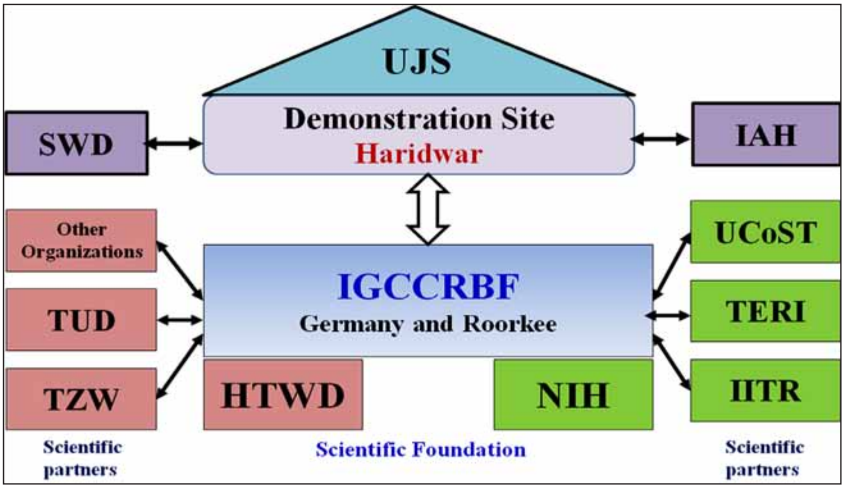

Figure 7-2.The structure of the Indo-German Competence Centre for Riverbank Filtration (IGCCRBF) at the National Institute of Hydrology (NIH), Roorkee, Uttarakhand

The functional arrangement (Fig. 7-2) helped initiate a number of promotional and R & D activities related to RBFin India; these included: (i) undertaking the R & D project **"Saph Pani"**(2011-2014) sponsored by the European Union, (ii) conducting the Indo-German Workshop on ***"Science-based Master Planning for Bank Filtration Water Supply in India"***, 7-11 April 2014 in Dresden (Fig. 7-3) sponsored by Indo-German Science and Technology Cooperation (IGSTC), India; and (iii) conducting four training courses for country-wide capacity building program on ***"Bank filtration for sustainable drinking water supply in India",*** (2016-2018;

Fig. 7-4), sponsored by the Department of Science and Technology (DST), India. All these scientific projects and programs have developed a wide range of scientific and technical consensus, awareness and network on the BF technology with the water supply utility groups, R & D organizations and academics both in India and Germany. The subsequent tasks for upscale and promotion of the BF technology in India, would be; (i) developing a science based master plan for the country and its systematic implementation through feasibility study, and (ii) developing awareness amongst community and sensitization of utility and user groups.

Figure 7-3. Participants of Indo-German Workshop on "Science based Master Planning for Bank Filtration Water Supply in India", sponsored by IGSTC and organized at HTW Dresden, Germany, 08–10 April 2014

Figure 7-4. Participants of one of the training courses on"Country-wide Capacity Building Programme on Bank Filtration for Sustainable Drinking Water Supply in India", sponsored by DST and organized at Goa, 06–10 Feb. 2017

Promotion of bank filtration in Uttarakhand

Both the establishments of the competence centre on RBF, viz., CCRBF and IGCCRBF are located in Uttarakhand. These establishments can be recognized as the knowledge repositories on the respective areas as mandated in their framework of activities. For example, CCRBF has more focused to guiding on design, implementation and technical aspects of the technology; while the IGCCRBF has focused to carry out R & D activities, technology upgrading, capacity building and feasibility studies. Both the CCRBF and IGCCRBF have large association of common partners, with lead organizations as UJS, and NIH, Roorkee from India and HTWD from Germany. Working more than last one decade since 2005 by this consortium in Uttarakhand on different projects, and dissemination of R & D findings through capacity building programs, workshops, seminars, symposia etc., as per the work flow diagram (Fig. 7-5), it was generously noted the need of a user guide book on RBF with documentation of all scientific and technical aspects together with the need of simultaneous capacity building and awareness programme. This approach of dissemination would help in sustainable promotion, adoption and acceptance of BF technology in India. Inclusion of this technology in the course curriculum and text book particularly; in higher level

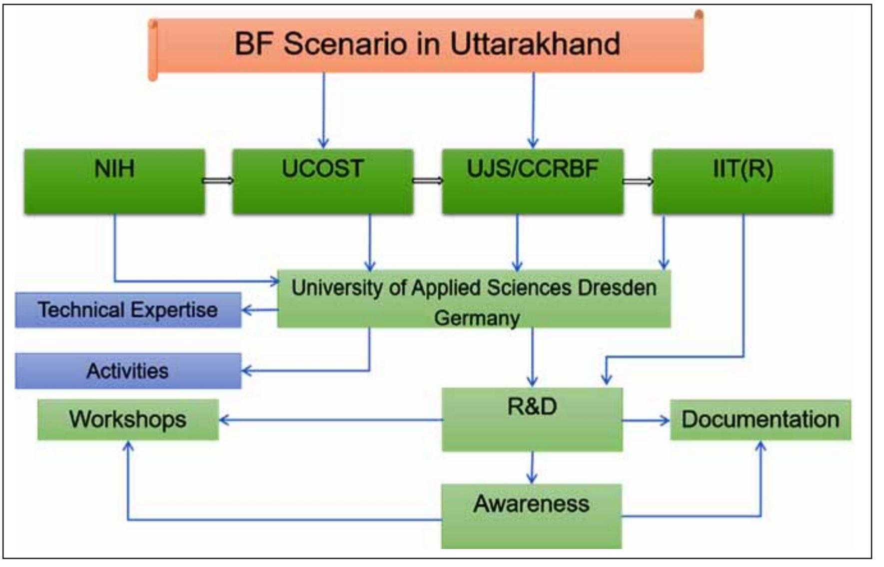

Figure 7-5. RBF promotional flow chain in Uttarakhand

of education can also be an excellent proposition for wide scale acceptability of this technology amongst the professional engineers and utility groups[3].

Initiatives required for promoting bank filtration

The beneficiaries of bank filtrate water are the communities whom these waters would be supplied. Therefore, public awareness is one of the important way forward to increase the level of understanding on importance and implications of BF technology amongst communities. Public awareness is not just saying what to do and what not to do; it should mainly be focused on explaining issues and disseminating knowledge to make them capable for taking own decisions and developing confidence on how their participatory decisions would help safeguard drinking water sources from health risks. The success of a public awareness programme depends on: how do one formulate a program; who are the targeted public and what are their background, rural or urban; what are their level of social and economic acceptability of the technology, etc. There could be two main areas of focuses for public awareness; the one could be focusing to general public awareness involving widespread understanding and acknowledgement of the issues on a societal level, and the other one could be about creating self-awareness on understanding emphasizing how safe drinking water can safeguard from health risks and hazards. These awareness measures can be done through specific planned events, poster campaigns, websites portal, documentaries, and newspaper articles and by establishing pilot demonstrating unit on the technology. Public awareness is indeed an integral part of achieving success in sustainable management of BF schemes, however, it would come into force when BF schemes are up scaled and implemented in a big way.

For doing so, the government agencies and water supply departments are to be sensitized first through regular workshops, training courses, distribution leaflets and fact sheets, developing dedicated website portals, and visits to different levels of officials. In last couple of years, more than 300 engineers, decision and policy makers, water resources experts from governmental organizations and NGOs from Uttarakhand, Uttar Pradesh, Himachal Pradesh, Haryana, Delhi, Gujarat, Madhya Pradesh, Rajasthan and West Bengal had been sensitized through different scientific activities and dissemination programs. The resulting outcome is that the Government of Uttarakhand has given a blanket policy approval for large upscale of BF schemes in feasible areas of the state, particularly in hilly regions. The experiences and lessons learnt from Uttarakhand have to be systematically disseminated to other potential states in India[4,5].

In Uttarakhand, the policy adaptation on upscaling BF technology by the government was achieved through aggressive campaigns about the technology and its performance in the state by convening a number of workshops, symposia and brainstorming discussions (Fig. 7-6). The lessons learnt from Uttarakhand were; unless and until government and top government's officials who are responsible to take decisions, are convinced, adopt and promote a technology, getting success in upscale of a technology including its awareness and sensitization programme is difficult. The effectiveness of BF technology including its performances for different hydrogeological settings in India has largely been tested successfully and the technology has enormous potential to upscale in different parts of the country, mainly in rural and sub-urban clusters either as a standalone technique or by integrating with the existing schemes. A list of major projects and awareness creation activities carried out by the group in Uttarakhand in collaboration with HTWD, Germany since initiation of BF technology in India is given in Table- 7-1.

Figure 7-6. Indo-German workshop on "Source, treatment and distribution of drinking water", in Dehradun, 14–15 September 2009

Table7-1. Major activities carried out on BF in collaboration with HTWD, Germany since year 2004

Year / Location	Description of activity	Coordinator / partners	Funding agency
2004 / Roorkee	Two-day International Workshop on RBF	IITR, University of Hawai'i at Manoa, USA	Fulbright Programme, SWD, INCOH, IITR, UoH
2005–2006 / Dresden, Germany & Roorkee, India	Establishment of EU-India Riverbank Filtration Network (RBFN)	HTWD, IITR	EU-ECCP
2005 / Dresden	Training Course on RBF	EU-India RBFN	EU-ECCP
2006 / Roorkee	EU-India International RBF Conference	EU-India RBFN	EU-ECCP
2007 / Dehradun & Dresden	Cooperation Centre for RBF (CCRBF)	UJS, HTWD, SWD, IITR	SWD (seed funding)
2007 / Roorkee	Workshop on Pathogen Removal during RBF	CCRBF	SWD / CCRBF
2008–2011 / Dresden	Indo-German RBFN	HTWD, TUD, TZWD, UJS, IITR, UCOST	BMBF
2008 / Ahmedabad	Workshop on Design and Operation of Riverbank Filtration Schemes	HTWD, Nirma University of S&T, Gujarat Water Supply & Sewerage Board	GTZ-ASEM (MoEF & CC, Govt. of India) and SWD / CCRBF
2009 / Dehradun	Workshop on Source, Treatment and Distribution of Drinking Water	UCOST, UJS, HTWD	UCOST & BMBF
2010 / Dresden	Indo-German RBFN Workshop	HTWD	BMBF, CCRBF
2010–2013 / Dehradun	Development of RBF in Hills of Uttarakhand	UCOST, UJS, HTWD, CCRBF, IITR	DST-WTI, with technical support from RBFN & Saph Pani
2011 / Roorkee	Indo-German Competence Centre for RBF/ IGCCRBF	NIH, HTWD	Own / third party
2011 / Dehradun	Indo-German Workshop on RBF for Sustainable Drinking Water Supply	UCOST, HTWD, UJS, NIH	UCOST & BMBF
2011–2014	Project Saph Pani	FHNW, HTWD, NIH, UJS, IITR and others	EU Framework Programme 7 (FP7)
2012 / New Delhi	Training Course on RBF for Sustainable Drinking Water Supply in India	NIH & HTWD	EU-FP7
2014 / Dresden	Indo-German Workshop on Science-based Master Planning for Bank Filtration Water Supply in India	HTWD & NIH	Indo-German Science & Technology Centre (IGSTC)
2014 / New Delhi	Int. Conference on Natural Treatment Systems for Safe and Sustainable Water Supply in India	NIH, FHNW	EU (FP7)

2015–2018 / Dresden	Project NIRWINDU	HTWD, TZWD, TUD, UJS, NIH, UCOST, CCRBF	BMBF, with co-funding to Indian partners from other third parties
2015 / Roorkee	Indo-German Workshop on Consolidation and Future of RBF Projects in India	NIH & HTWD	NIH, with technical support from NIRWINDU
2016–2018 / Roorkee (2), Goa, Shillong	4 Training Courses on BF for Sustainable Drinking Water Supply	NIH, HTWD, UJS, UCOST, CCRBF, TERI Western Regional Centre	DST, with support from NIRWINDU
2018 / Dehradun	Indo-German Workshop on RBF for Sustainable Water Supply in India – Vision 2030	HTW, NIH & UJS	CCRBF, IGCCRBF, with technical support from NIRWINDU

BMBF: Federal Ministry of Education and Research, Germany; EU-ECCP: EU Economic Cross Cultural Programme; FHNW: Fachhochschule Nordwestschweiz (University of Applied Sciences & Arts Northwestern Switzerland); Fulbright Programme: US Educational Foundation in India; INCOH: Indian National Committee on Hydrology; SWD: Stadtwerke Düsseldorf AG, Germany (utility services of the city of Düsseldorf); UoH: University of Hawai'i at Manoa (USA)

For helping practicing professionals on BF technique, the Department of Science and Technology (DST), India, has entrusted the task to UCOST for bringing out a Guidelines on RBF technology covering all its aspects such as, site selection, design, water quality and risk assessment, flood protection of wells and post-treatment requirements. This Guidelines is the outcome of assignment given by the DST.

Future strategy for RBF promotion

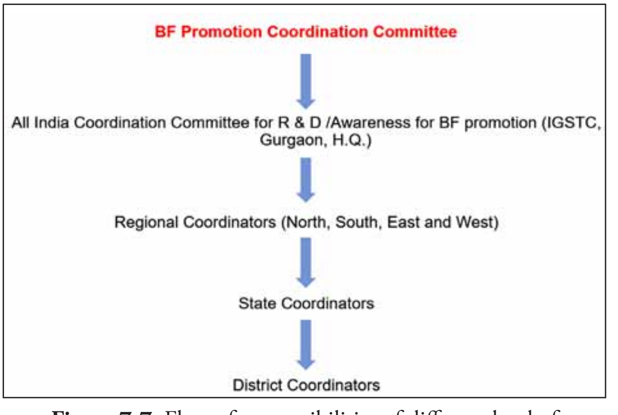

Figure 7-7. Flow of responsibilities of different level of coordination committee for RBF promotion

As way forward towards future tasks on RBF, a national coordination committee has to be constituted that will have the primary tasks to identify research gaps, formulate strategies and modalities for expanding awareness among the community, and coordinate the matters with the regional coordinators. There can be four regional coordinators (North, South, East, West), who will maintain a liason with the national committee. The regional coordinators can have state and district level coordinators for pursuing the awareness and sensitization programme (Fig. 7-7). The strategies for implementation and sensitization of community could be achieved as detailed in Fig. 7-8.

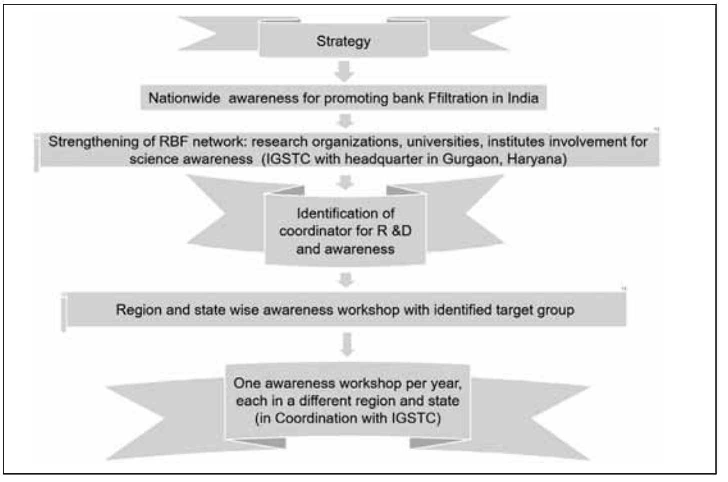

Figure 7-8. Strategy for promotion of RBF in India

CONCLUSIONS

For upscaling of BF technology and maintaining its sustainability in India, comprehensive awareness and sensitization programs through different mode of communications would be necessary. For achieving success in the promotion of BF technology, water utility groups and top government officials, who take decisions on matter related to adopting and implementation of a technology, need to be appraised and sensitized simultaneously along with the community who are the beneficiaries as water users. For increasing awareness, there is a need of strengthening of RBF Network in India. The existing functional arrangement of the Competence Centre for RBF located at Haridwar and NIH, Roorkee, which can act as the knowledge repositories, can be strengthened to take bigger responsibilities like coordination of activities related to bank filtration in India.

As way forward, regional level sensitization workshops (North, South, East and West) can be organized on regular basis. More orientation workshops of shorter duration with top officials from government as the target audiences can be organized in every state to develop more acceptability of the technology. Awareness campaign can be done through specific planned events, poster campaigns, websites portal, documentaries, and newspaper articles. Conducting regular short duration courses to impart training to professional implementing agencies will help in dissemination of technical know-how.

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REFERENCES

1. Lorenzen, G., Sprenger, C., Greskowiak, J. Results of background work and data integration of MAR systems for an Integrated Water Resources Management. *TECHNEAU deliverable* D 5.2.12010.
2. Ray, C., Drinking water supply in India and future potential for riverbank filtration. In: Ray, C. and Ojha, C.S.P. (eds.) Riverbank Filtration –Theory, Practice and Potential for India. *Proc. Int. Workshop Riverbank Filtration*, Indian Institute of Technology Roorkee, India. Wat. Res. Res. Center, Univ. of Hawaii, Manoa, Cooperative Report CR-2005-01, 3-8.
3. Sandhu, C., Grischek, T., Schoenheinz, D., Ojha, C.S.P., Irmscher, R., Uniyal, H.P., Thakur, A.K., Ray, C. Drinking Water Production in India –Bank Filtration as an Alternative. *Water Digest* 2006,**1**(3), 62-65.
4. Uniyal, D. P., Bari, S. Khadija, Aswal, J. S**.**, Dobhal Rajendra, Pokhriyal, A., and Kaushik, P.K. River Bank Filtration: An Innovative Solution for Safe Drinking Water, *Every mans Science* 2018, Vol.LIII, No. 2, June-July,18, 70-76.
5. Sharma B., Uniyal D.P., Dobhal R., Kimothi P.C., Grischek T., A sustainable solution for safe drinking water through bank filtration technology in Uttarakhand India. *Curr.Sci.*, 2014,**107**(7), 1118–1114.
6. Uniyal Manisha. Conservation and mangement of hyporheic biodiversity of the River Bhagirathi downstream the Tehri dam, Uttarakhand, India, *Science and Technology in Uttarakhand* 2014, Vth & VITh Uttarakhand State Science and Technology Congress,183-191.
7. Uniyal Manisha and Sharma, R.C. Conservation and Mangement of Hyporheic Diversity of river Alaknanda (Upper Ganges), Uttarakhand, India, *J.Env.Bio-Sci.* 2016**, 30** (1),1-4.

8

Chapter

SUSTAINABILITY OF RIVERBANK FILTRATION –EXAMPLE FROM GERMANY

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Riverbank filtration (RBF) has been well established as a technique for water treatment in Germany. Because RBF systems utilize natural filtration processes, this strategy can provide advantages in terms of sustainability compared to conventional water treatment. Advantages include lower energy and resource requirements, little generation of waste streams, reduced environmental impacts during construction and system operation, and greater adaptability to changing water supply conditions due to climate change. Selected sustainability aspects are discussed based on two examples from RBF sites in Germany.

KEYWORDS: Riverbank filtration, sustainability, Germany

INTRODUCTION

In Germany, RBF systems have been in place at a large scale since 1870[1]. RBF in Germany provides about 8 % of total drinking water supplies. This percentage is low compared to some other European countries, as RBF provides 50% of the public water supply of Slovakia, 45% in Hungary[2,3]and 25% in Switzerland[4]. The city of Budapest is fully supplied with bank filtrate from the River Danube[5] from 766 wells with a total maximum capacity of 1 million m^3/day[6]. Today in Europe, RBF is mainly used for pre–treatment, the focus lying on strong removal of organic compounds.

Fig. 8-1shows locations of high capacity RBF waterworks in Germany along the major rivers Rhine, Elbe, Danube, Ruhr and lakes in the city of Berlin. The city of Dusseldorf, situated on the River Rhine, is entirely supplied with drinking water from RBF. In the Rhine basin, more than 20 million inhabitants receive drinking water which is directly or indirectly derived from river water, mostly via bank filtration.

In the city of Dresden public water supply on average relies on up to approximately 32 % bank filtrate and 66 % surface water from reservoirs. Typical characteristics for bank filtration sites in Germany are given in Table 8-1.

Figure 8-1. Large bank filtration waterworks in Germany abstracting >50% bank filtrate[7]

Table 8–1. Characteristics of bank filtration sites in Germany[8]

Condition	Typical range
Aquifer thickness	4 to 70 m
Hydraulic conductivity	0.0001 to 0.05 m/s
Distance bank – well	20 to 860 m
Well fields length along river	1 to 2 km
Travel times	3 days to 0.5 years

Intensive investigations in Germany and The Netherlands started after the pollution of the Rhine River by the Sandoz accident in 1986[9]and with further development of analytical techniques for identifying trace organic compounds. Meanwhile, numerous studies have shown RBF to be effective in the removal and/or degradation of microorganisms, turbidity, pesticides, dissolved and total organic carbon and organic micropollutants[2,8,10-16].

In countries with long-term RBF scheme operation, recent issues are river hydrology and clogging[17-19], economic and/or technical optimization, modeling redox processes responsible for iron and manganese release and attenuation of micropollutants and pathogens[20-26], adaptation to changing conditions such as water demand and climate change[27-29] and combination with sophisticated post-treatment techniques[30-31].

Riverbank filtration schemes in Duesseldorf and Dresden

In the summer of 1866, there were 57 cases of cholera in the urban area of Duesseldorf. About half of those who contracted the disease died. This forced the town council to adopt a resolution to construct and operate a waterworks. The English engineer William Lindley was called in to provide expert advice on the choice of location and planning of the technical equipment. The first well field at Flehe of Duesseldorf, on the banks of the River Rhine, was put in operation for the first time on May 1, 1870 and has been continuously used since then till the present day. Up to that point in time, the population had obtained water from rainwater storage tanks, as well as from open and pumped wells. In the following years, the increasing water demand had to be met. Driven by the increasing population and the industrial water demand, the expansion of the water supply was the main task. In the period between 1948 and 1956, the water requirement almost doubled. While the increasing demand could be met by the continuous development of well fields, the simultaneous decrease of the river water quality posed an additional challenge[12].

At present 600,000 inhabitants are supplied with treated bank filtrate by three waterworks. A water demand of about 55 million m^3/year and up to 210,000 m^3/day has to be met. The vertical wells and the horizontal collector wells are situated between 50 m and 300 m from the river bank. Fig. 8-2 shows a line of vertical wells at Flehe waterworks that have been in operation since 1900.

Figure 8-2. Gallery of vertical wells along the River Rhine at Duesseldorf-Flehe

The raw water is collected here using a siphon system. Depending on the hydraulic situation, the residence time of the bank filtrate in the aquifer varies between one week and several months, which was determined using a monitoring cross-section as shown in Fig. 8-3[32].

In Dresden, there exist three RBF waterworks. The first waterworks, the Dresden-Saloppe Waterworks was built between 1871 and 1875 on the bank of the River Elbe (Fig. 8-4). Drain pipes were installed near the river bank to abstract raw water. Due to geological boundary conditions, more than 90 % of the abstracted water is bank

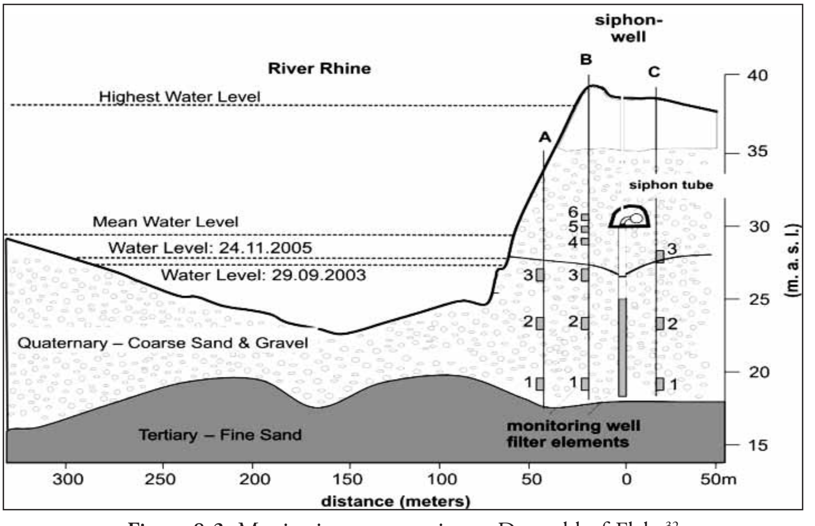

Figure 8-3. Monitoring cross-section at Duesseldorf-Flehe[32]

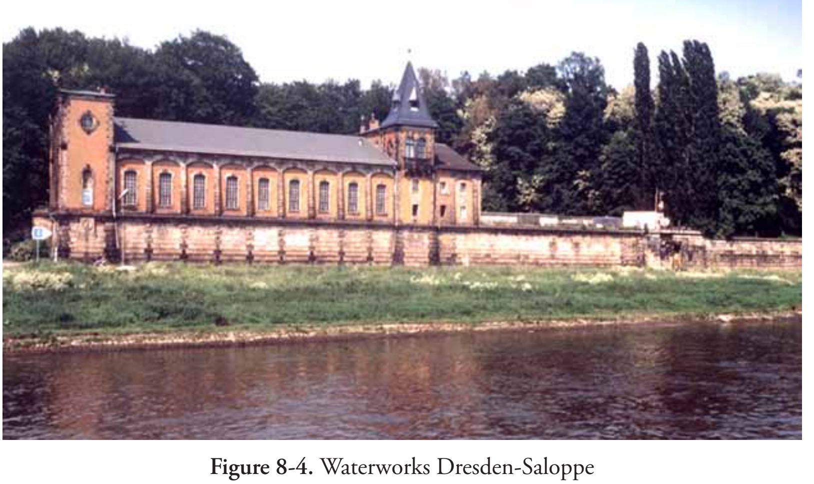

Figure 8-4. Waterworks Dresden-Saloppe

filtrate. Today, the waterworks is still in operation and produces up to 12,000 m^3/day for industrial water supply for microelectronics.

Rising water demand at the end of the 1880s exceeded the capacity of the Dresden-Saloppe Waterworks. In 1891, the city council assigned the building officer, Bernhard Salbach, to write an expert report on the future water supply of the city. Salbach proposed building a test well on the left bank of the river, which abstracted 4,000 m^3/day in 1891. Four more wells were completed in 1893 resulting in a total water abstraction from the left bank of 20,000 m^3/day. Wells were connected using a siphon pipe and a collector well. Between 1896 and 1898, the second waterworks, the Dresden-Tolkewitz Waterworks, was constructed. A further rise in water demand resulted in the construction of four more wells and a second siphon pipe in 1901 to raise the capacity to 40,000 m^3/day. In the 20^{th} century, the number of wells was again increased and the water treatment facilities improved. Between 1919 and 1928 a third siphon pipe with 39 wells was built. Fig. 8-5 shows the scheme with wells and siphon pipes. A significant decrease inthe water demand after the reunification of Germany in 1989 allowed for the closure of the well fields in April 1992 in order to plan a general reconstruction to modernize the waterworks. After intensive construction, the Dresden-Tolkewitz Waterworks and the well fields were put into operation again in February 2000. The maximum capacity is now 35,000 m^3/day.

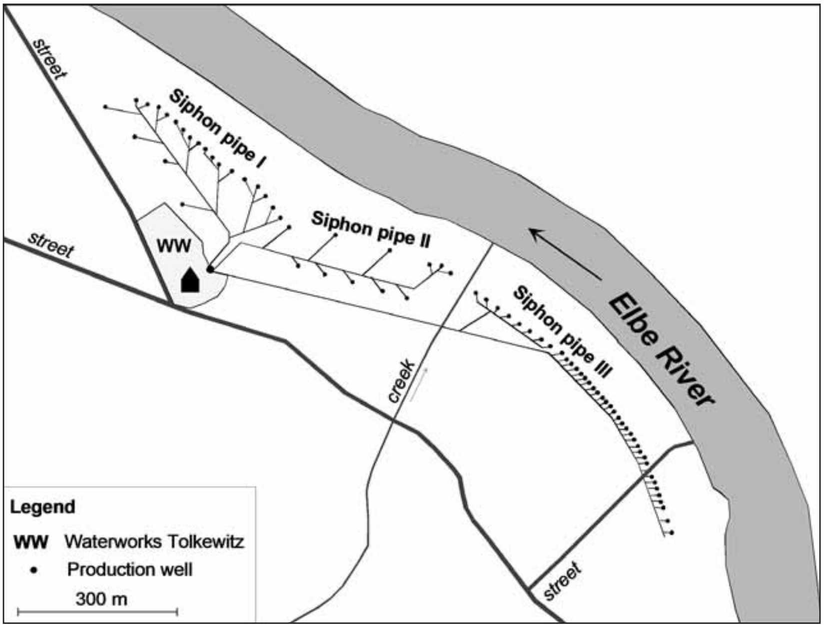

Figure 8-5. Location map of the RBF scheme of Dresden-Tolkewitz

River water quality in Duesseldorf and Dresden

During the first 80 years (1870-1950), the quality of the River Rhine water in Germany permitted the production of drinking water without further treatment; the pumped bank filtrate had only to be disinfected. After 1950, the quality of the river water began to deteriorate gradually. Increasing quantities and insufficient treatment of effluents from industry and communities caused a noticeable drop in the oxygen concentration of the river water. In the Rhine valley, the water pollution was caused by rapidly growing industrial activities and increasing density of urban settlements after World War II[33] In the 1950s and 1960s, sewage systems in the destroyed cities had been built prior to wastewater purification plants leading to increasing pollution of the rivers. The oxygen concentration in the River Rhine decreased continuously until the beginning of the 1970s. The consequence of this and the increasing organic load in the river water changed the redox situation in the adjacent aquifer from previously aerobic to anoxic conditions. A low point was marked by an enormous death rate of fishes in 1969, caused by an accidental release of the insecticide Endosulfan, which resulted in an oxygen concentration of less than 4 mg/L[33].

Despite the poor river water quality in the middle of the last century, drinking water supply based on RBF remained possible. The attenuation processes during RBF made a significant contribution to ensuring safe drinking water production. Nevertheless, the colour, taste and odour of the bank filtrate became so bad that the waterworks were forced to develop and install sophisticated new treatment steps. One main goal was to remove iron, manganese and ammonium. At many sites, subsequent technologies such as ozone treatment, biological filtration or granular activated carbon (GAC) adsorption were established.

In addition to the application of technical treatment methods, the waterworks reinforced their efforts to achieve better river water quality by forming a common organisation. The International Association of Waterworks in the Rhine Catchment Area (IAWR) was founded in 1970 in Duesseldorf, Germany. Its goal was to demand measures for water protection. In 1973, the IAWR published their first "Memorandum" on raw water quality that served as a "yardstick" for local government bodies and for the public debate on Rhine water quality. Together with other stakeholders, such as environmental groups, the IAWR promoted a public discussion of water protection. At the end of this process the federal government issued its first program for environmental protection which included measures to ensure that river water quality would reach a high standard within twenty years.

Furthermore, spectacular industrial spills underlined the need for sanitation measures and pollution control. On November 1, 1986, a fire broke out in an agrochemical storage facility of a chemical plant in Basel, Switzerland. Insecticides, herbicides and fungicides were carried into the adjoining River Rhine with the fire-fighting water. The effects on the river were serious. On the stretch of the Rhine up to the Middle Rhine region, the entire stock of eel was destroyed. Other species of fish were also affected and damaging effects were detected on fish food organisms. The question then arose, whether such a wave of poison could simultaneously contaminate the water source in the adjacent aquifer. This accident has given fresh impetus to the improvement of pollution control on the Rhine and was the reason for projects aimed at understanding the effects of accidental shock loads on RBF plants[7].

The numerous measures taken to reduce nutrients and pollutants were consistent with the best available technology in wastewater treatment and production along the Rhine. Consequently, river water quality has improved significantly since the mid 1970's with the return of salmon to the river in 2000. The historical development of water pollution of the Rhine is illustrated in Figs. 8-6 and 8-7 by the concentration-time plots of oxygen and dissolved organic carbon (DOC). The oxygen concentration in the River Rhine decreased continuously until the beginning of the 1970's. One of the many negative consequences of this decrease was the occurrence of manganese in the anaerobic well water, which increased the cost of treatment. Between 1975 and 1980 the river water DOC showed values higher than 7.5 mg/L, while the raw water concentration never exceeded 3 mg/L. Then, as a consequence of the restoration efforts, the DOC concentration decreased to a level between 2 and 4 mg/L and the oxygen concentrations returned to saturation level at the beginning of the 1990's. The higher oxidation capacity, combined with the lower oxygen demand of the infiltrating river water, led to more efficient natural attenuation processes within the aquifer. This, in turn, enabled the waterworks to reduce their treatment expenses[12]. However, the occurrence of chemical pollutants in the river water, like pesticides and pharmaceuticals, remained an issue.

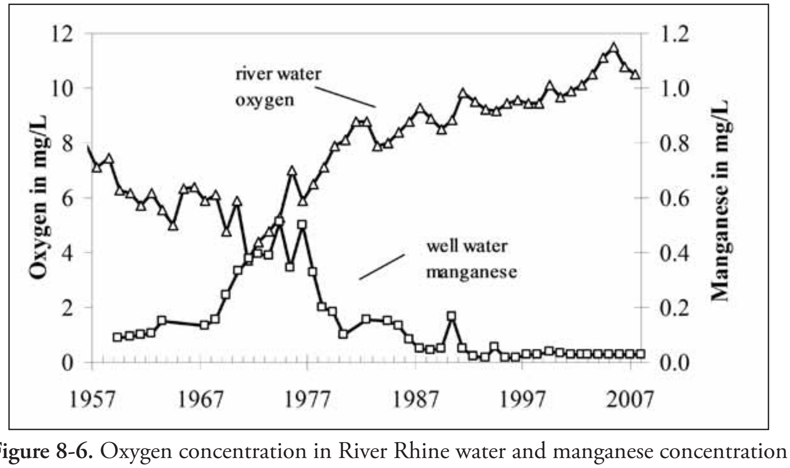

Figure 8-6. Oxygen concentration in River Rhine water and manganese concentration in bank filtrate at Duesseldorf-Flehe.

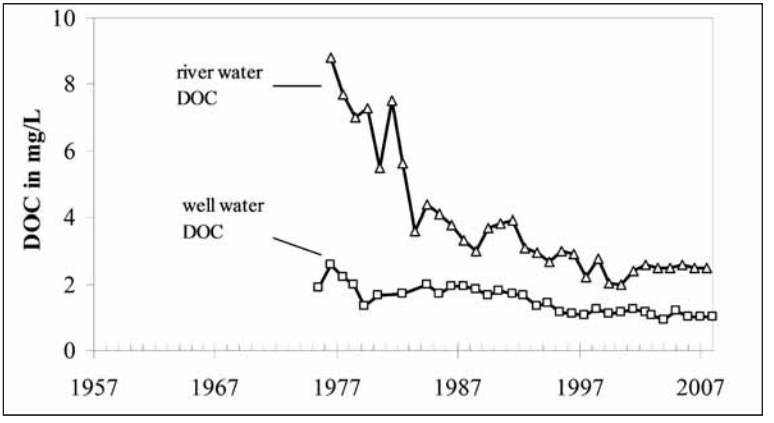

Figure 8-7. DOC concentrations in the River Rhine and in the raw water of the production wells

A similar situation has been reported for the River Elbe. The industries along the Upper Elbe River valley previously discharged a wide range of organic contaminants into the river. Hence, together with urban sewage, the DOC comprises a complex mixture of easily degradable and refractory substances. In addition to the industrial effluents, paper mills, cellulose processing plants and the pharmaceutical industry played an important role in the 1980`s. From 1988 to 1990 the average DOC concentration on the left bank of the River Elbe at Dresden-Tolkewitz was 24 mg/L and the UV-absorbance at a wavelength of 254 nm was 55 m^{-1}. Along a flow path length of approximately 100 m at a cross-section at Dresden-Tolkewitz, the DOC concentration was reduced to about 20 % of the input concentration[34]. Problems with bank filtrate quality occurred due to the high load of organic pollutants, foul taste and odour, and the formation of disinfection by-products. Fig. 8-8 gives an impression of the organic load in the River Elbe in 1987–1992.

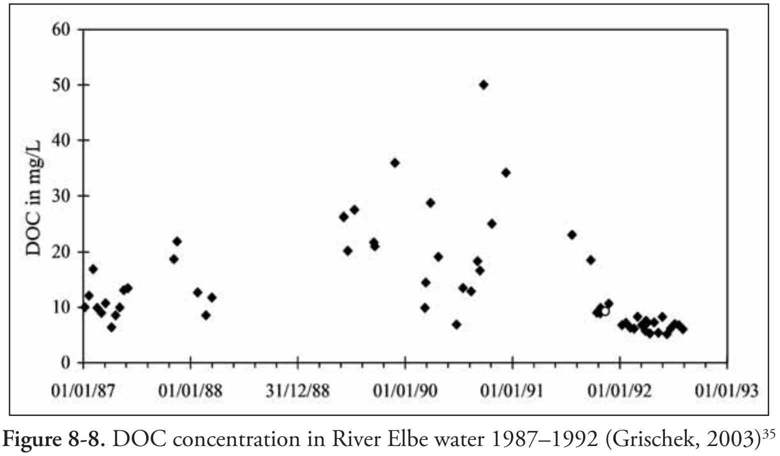

Figure 8-8. DOC concentration in River Elbe water 1987–1992 (Grischek, 2003)[35]

Results from 17 measurements in 1991/92 at a cross-section at Dresden-Tolkewitz showed a mean DOC concentration of 6.9 mg/L in River Elbe water and 3.4 mg/L at an observation well near a production well. From that, a reduction of DOC concentration of about 50 % can be seen as an effect of RBF processes. Investigations in 2003 at the same cross-section included 7 samples. In 2003 the mean DOC concentration in River Elbe water was 5.6 mg/L and 3.2 mg/L in bank filtrate at the same observation well sampled in 1991/92. The mean DOC concentration in raw water from all wells was found to be 2.6 mg/L as a result of mixing with groundwater[36]. These results show that the period of strong pollution of Elbe river water did not limit the further use of the Dresden-Tolkewitz site. Measurements of total organic carbon (TOC) concentration in aquifer sediments at different distances from the river and different depths showed that there is only an accumulation of organic compounds in the riverbed. TOC concentrations in the <2 mm grain size fraction from Tolkewitz aquifer sediments were found to be 50–120 mg/kg which is in the range of TOC in aquifer material in the river valley not affected by RBF. This agrees with the findings by[35] that there is no indication of accumulation of organic compounds and overloading of the aquifer/ attenuation capacity between the river and abstraction wells at RBF sites along the River Elbe with infiltration rates lower than 0.2 $m^3/(m^2 \times day)$ proposed for long-term operation.

Clogging of riverbeds

A very important aspect of the sustainability of riverbank filtration is the effect of particulate organic matter which can intensify clogging of the riverbed and significantly reduce the well yield. The proportion, and thus volume, of pumped bank filtrate strongly depends on riverbed clogging. Clogging is the formation of a layer on top of or within the riverbed which has a lower hydraulic conductivity and reduces the flow rate of the filtrate through the riverbed. It is the result of the infiltration and accumulation of both organic and inorganic suspended solids, precipitation of carbonates, iron- and manganese-hydroxides and biological processes. Erosive conditions in the river and floods limit the formation of a clogging layer by disturbing the riverbed via increased flow velocity and shear stress. The permeability of clogged areas varies with the flow dynamics of the river. There are not only variations in the pressure head between the river and the aquifer but also remarkable variations in the concentration of suspended solids in the river water. The concentration of suspended solids in the River Rhine varies from 10 to more than 400 mg/L with an average concentration of less than 40 mg/L. Highest values appear in periods of rising water levels following storm events. Due to difficulties in determining the thickness of the clogging layer, the term leakage coefficient is introduced, which is defined as hydraulic conductivity of the clogging layer in meters per second divided by the thickness of the clogging layer in meters. Under specific conditions, the leakage coefficient can be calculated for RBF sites using water levels in the river and two observation wells positioned between the river and the production borehole using an analytical solution. Otherwise it has to be determined by calibration procedures in groundwater flow modelling. Based on water levels and known pumping rates, the leakage coefficients of the River Rhine at Duesseldorf and the River Elbe at Dresden have previously been determined for different river stages and measuring campaigns and compared with former data.

An early field study of the riverbed adjacent to the Flehe Waterworks was done in 1953 and 1954 with a diving cabin. In 1987, a second study of the riverbed at the Flehe Waterworks was carried out. This investigation revealed a zone of almost 80 m which had a fixed surface and was entirely clogged by suspended sediments . The expansion of the clogged areais limited especially by bed load transport in the river. In regions with sufficient shear force, the deposits are whirled up and removed. The zones at the Flehe site are characterised by different permeability's. The infiltration occurs mainly in the middle of the river.

At Dresden-Tolkewitz, a significant decrease in groundwater levels was observed between 1914 and 1930 and attributed to riverbed clogging by suspended materials caused by increased infiltration rates since 1901. In the 1980s severe river water pollution caused by organics from pulp and paper mills in conjunction with high water abstraction led to unsaturated conditions beneath the riverbed, especially at the Dresden-Tolkewitz Waterworks. However, investigations of riverbeds using a dive-chamber showed that the material responsible for the pore clogging in the gravel bed consisted of up to 90 % inorganic materials[37]. Heeger[37] calculated a leakage coefficient of about 1×10^{-4} s^{-1} for the riverbed without bank filtration and a mean value of 5×10^{-7} s^{-1} at RBF sites in and around Dresden. After improvement of river water quality from 1989 to 1993, the hydraulic conductivity of the riverbed increased. In 2003, groundwater flow modeling was used to test former assumptions about groundwater flow towards the production wells and clogging of the riverbed. From model calibration, a leakage coefficient of 1×10^{-5} s^{-1} was determined. Using an analytical approach, it was determinedby[18] that the mean leakage factor had further improvedto $1–1.5\times10^{-6}$ s^{-1} for 2008–2015.

Looking at the long–term operation of the waterworks, it is clear that the observed clogging of the riverbed did not result in the closure of wells under the existing erosive conditions in the river. After a period of additional organic pollution and observed slime on the riverbed surface (assumed to act as an organic outer clogging layer) there was a marked recovery of hydraulic conductivity in the riverbed.

Sustainability of RBF

From a sustainability point of view, RBF systems make better sense than full-scale treatment plants using surface water, since the energy and resource use in RBF will be lower and little to no chemical residues will be produced. Three major advantages the RBF systems possess compared to traditional water treatment plants are: (a) minimization of energy and other resource use and waste generation, (b) lower environmental impact, and (c) operational flexibility. Klein[38]reported that 20 % of a community's total energy use is associated with the treatment, conveyance, and delivery of water. Greenhouse gas emission (GHG) can be reduced when an elaborate treatment unit is eliminated in favour of RBF. Energy intensive coagulation, flocculation, sedimentation, and membrane filtration processes are typically avoided with RBF. Elimination of the coagulation and flocculation process reduces the need for sludge disposal. The footprint of RBF systems is typically smaller than that of full–scale treatment plants. In ecologically sensitive river systems, RBF wells draw a portion of groundwater, and this reduces the reduction of stream flow lower than that for a surface water treatment plant of equal size.

The future utilization of RBF requires an integrated assessment of the sustainability of bank filtration under changing boundary conditions, e. g. caused by potential climate change. Boundary conditions of bank filtration influenced by climate change are mainly the frequency, duration and peak behaviour of floods and droughts affecting the available water quantity, and the river water temperature resulting in changing biomass production and biological activity and thus influencing the water quality. Expected effects with respect to water quantity are increasing drawdown or lower portion of bank filtrate abstracted due to the formation of clogging layers during low flow periods, and contamination of production wells and damage of power supply during flooding[28,29]. Anticipated effects with respect to water quality of bank filtrate are

- higher global radiation and higher temperatures resulting in an increase in algae growth, lower dissolved oxygen concentration and additional depletion due to degradation of biomass in the surface water,
- increased algae growth resulting in higher concentrations of TOC and DOC in the surface water,
- greater release of adsorbed, poorly degradable DOC components from the sediment due to higher water temperature,
- decrease in dilution potential during low flow periods,
- longer retention times during low flow periods resulting in longer contact times for degradation of organic compounds,
- decreased attenuation potential of soil passage with respect to microbial and organic loads due to reduced travel times during flood periods.

To our present knowledge, the potential climate changes do not jeopardise the bank filtration effectiveness, although adaptation strategies have to be developed to account for an increase in extreme events[39]. In Hungary, mainly horizontal collector wells have been installed ensuring sufficient water abstraction during low flow periods.

Low flow conditions are critical for RBF operation if the extraction rates per unit area of the riverbed and river bank are high. From long-term experiences in Germany, an average infiltration rate of less than 0.2 $m^3/(m^2 \times day)$ over the riverbed ensures limited clogging and stable infiltration conditions[40]. Furthermore, the amount or percentage of induced river water infiltration during low flow conditions is an important requirement for obtaining operational permits for bank filtration sites. As an example, the maximum pumping rate of the wells for waterworks employing RBF along the River Elbe in the city of Dresden, Germany, is 97,000 m^3/day. At low flow conditions in summer, the river discharge is about 8,600,000 m^3/day, thus the induced infiltration reduces the river discharge by 1.1 % in the worst case. A few kilometres downstream from the RBF site, treated effluent is discharged back to the River Elbe.

The potential impact of droughts in the River Rhine on the operation of the siphon system at Duesseldorf-Flehe was studied by Eckert et al.[41]. Due to the foresighted construction of the siphon system and the depth of the siphon pipe at 9 m below ground level, the wells can be operated even at very low water level in the river. Nevertheless, effects of long-term erosion of riverbeds and increased drawdown caused by well clogging have to be carefully checked for RBF sites to cope with future droughts.

Sprenger et al.[28] state that bank filtration is vulnerable to climate change, but less vulnerable than surface water or groundwater abstraction alone, as RBF uses two source waters. Furthermore, they conclude that only bank filtration systems comprising an oxic to anoxic redox sequence ensure maximum removal efficiency due to the redox-dependent degradation rate of many contaminants. Schoenheinz & Grischek[29]discussed the effect of climate change on the removal of DOC during bank filtration and give an overview of possible changes in boundary conditions for bank filtration sites as a consequence of the anticipated climate change and their effects on bank filtrate water quality and optional adaptive measures.

CONCLUSIONS

Two examples from Germany – from the Lower Rhine region and the Upper Elbe River – have been presented where riverbank filtration has been employed for more than 145 years. During this time the RBF systems were able to overcome extreme conditions with respect to poor river water quality, and to withstand spills in the rivers. Drain pipes at the Dresden-Saloppe Waterworks have been in operation for more than 145 years whilst four production wells at the Dresden-Tolkewitz Waterworks only had to be replaced after 60 years. In Dresden, severe clogging of the riverbed occurred in the 1980s mainly due to high loads of organics from pulp and paper mills upstream. Following improvement of river water quality in the 1990s, no problems with riverbed clogging or foul taste and odour have been encountered.

Field studies are part of ongoing efforts to assess the risks of RBF and to obtain knowledge of the best practice for sustainable operation of bank filtration plants. Raw water quality and treatment are optimized by managing specific mixing ratios of bank filtrate and landside groundwater. Pumping rates can be reduced to get longer retention times in the aquifer and higher attenuation rates of organic compounds. No indication of a decrease in attenuation capacity of the aquifer over time was observed. Long-term experiences and results of the evaluation of historic and recent data and of investigations using modern modelling tools strongly indicate that RBF is a sustainable water resource for water supply in Germany.

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REFERENCES

1. Jülich W., Schubert J. (eds) *Proc. Int. Riverbank Filtration Conf.*, 2-4 Nov 2000, Düsseldorf, Germany, IAWR-Rheinthemen, 2001, 4.
2. Hiscock K., Grischek T., Attenuation of groundwater pollution by bank filtration. *J. Hydrol.*, 2002, **266**(3–4), 139–144.
3. Sprenger C., Hartog N., Hernández M., Vilanova E., Grützmacher G., Scheibler F., Hannappel S., Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives. *Hydrogeol. J.*, 2017, **25**, 1909–1922.
4. Von Rohr M.R., Hering J.G., Kohler H.-P.E., von Gunten, U., Column studies to assess the effects of climate variables on redox processes during riverbank filtration. *Water Research, 2014*, **61**, 263–275.
5. Laszlo F., The Hungarian experience with riverbank filtration. *Proc.2nd Int. Riverbank Filtration Conf.*, 16–19 Sept. 2003, Cincinnati, 2003, 193–196.
6. Till G., Safe riverbank filtration in Budapest. *Proc. 4th Saxon Drinking Water Conf.,* 7 Sept. 2017, Dresden (in German), 2017, 61–70.

7. Lenk S., Remmler F., Skark C., Schulte–Ebbert U., Technical concepts and adjusted operational modes for an optimal adaptation of riverbank filtration to local boundary conditions. *BMBF report,* 2006, ISBN 3000154787 (in German).
8. Kuehn W., Mueller U., River bank filtration – an overview. *J. AWWA,*2000, **92**(12), 60–69.
9. Sontheimer H., Trinkwasser aus dem Rhein? (*Drinking water from the River Rhine?*), Academia Verlag, Sankt Augustin (in German), p. 295.
10. Stuyfzand P.J., Fate of pollutants during artificial recharge and bank filtration in the Netherlands. In: Peters J. (ed.) Artificial Recharge of Groundwater, *Proc. 3rd Int. Symp.Artificial Recharge of Groundwater,* Amsterdam, AA Balkema, Rotterdam, The Netherlands, 1998, 119–125.
11. Jekel M., Grünheid S., Bank filtration and groundwater recharge for treatment of polluted surface waters. *WST Water Supply*, 2005, **5**(5), 57–66.
12. Eckert P., Irmscher R. (2006) Over 130 years of experience with riverbank filtration in Dusseldorf, Germany. *J. Water SRT – Aqua***55**(4), 283–291.
13. Ray C., Melin G., Linsky R., *Riverbank Filtration: Improving Source–Water Quality*. Kluwer Academic Publ., Dordrecht, 2003.
14. Maeng S.K., Sharma S.K., Amy G.L., Magic–Knezev A., Fate of effluent organic matter (EfOM) and natural organic matter (NOM) through riverbank filtration. *Wat. Sci. Technol.,* 2008, **57**(12), 1999–2007.
15. Hoppe-Jones C., Oldham G., Drewes J.E., Attenuation of Total Organic Carbon and unregulated trace organic chemicals in U.S. riverbank filtration systems. *Wat. Res*., 2010, **44**, 4643–4659.
16. Schijven J.F., Hassanizadeh S.M., Removal of viruses by soil passage: overview of modeling, processes, and parameters. *Critical Reviews in Environ. Sci. Technol*., 2000, **30**(1), 49–127.
17. Martin R., (ed.) Clogging issues associated with managed aquifer recharge methods. IAH Commission on Managing Aquifer Recharge. 1st clogging monograph, *https://recharge.iah.org/working–groups/clogging–and–its–management*, 2013.
18. Grischek T., Bartak R., Riverbed clogging and sustainability of riverbank filtration. *J. Water*, 2016, **8**(12), 604; doi: 10.3390/w8120604.
19. Hubbs S.A., (ed.) Riverbank filtration hydrology. *Proc. NATO Advanced Research Workshop on Riverbank Filtration Hydrology*, Sept 2004, Bratislava, Slovakia, and Springer Netherlands, 2006.
20. Henzler A., Greskowiak J., Massmann G., Seasonality of temperatures and redox zonations during bank filtration – A modeling approach, *J. Hydrol*., 2016, **535**, 282–292.
21. Grischek T., Paufler S., Prediction of iron release during riverbank filtration. *J. Water*, 2017, **317**, 1–13, doi 10.3390/w9050317.

22. Sharma L., Greskowiak J., Ray C., Eckert P., Prommer H., Elucidating temperature effects on seasonal variations of biochemical turnover rates during riverbank filtration. *J. Hydrol.*, 2012a,**428–429**, 104–115.

23. Sharma S.K., Chaweza D., Bosuben N., Holzbecher E., Amy G., Framework for feasibility study and performance analysis of bank filtration system for water treatment. *Wat. Supply: Research and Technology – Aqua*, 2012b, **61**(2), 73–81.

24. Postma D., Mai N.T., Lan V.N., Trang P.T., Sø H.U., Nhan P.Q., Larsen F., Viet P.H., Jakobsen R., Fate of arsenic during Red River water infiltration into aquifers beneath Hanoi, Vietnam. *Environ Sci. Technol.,* 2017, DOI: 10.1021/acs.est.6b05065.

25. Romero L.G., Mondardo R.I., Sens M.L., Grischek T.,Removal of cyanobacteria and cyanotoxins during lake bank filtration at Lagoa do Peri, Brazil. *Clean Techn. Environ. Policy*, 2014, **16**(6), 1133–1143.

26. Sandhu C., Grischek T., Riverbank filtration in India – using ecosystem services to safeguard human health. *Water Science Technology*, 2012, **12**(6), 783–790.

27. Gross-Wilke A., Gunkel G., Hoffmann,A., Temperature effects on bank filtration: redox conditions and physical–chemical parameters of pore water at Lake Tegel, Berlin, Germany. *Water and Climate Change*, 01.1, doi:10.2166/wcc.2010.005, 2010.

28. Sprenger C., Lorenzen G., Hülshoff I., Grützmacher G., Ronghang M., Pekdeger A., Vulnerability of bank filtration systems to climate change. *Sci. Total Environ.*, 2011, **409**(4), 655–663.

29. Schoenheinz D., Grischek T., Behavior of dissolved organic carbon during bank filtration under extreme climate conditions. In: Ray C., Shamrukh M. (eds.) *Riverbank filtration for water security in desert countries.*Springer Science+Business Media B.V., 51–67, doi: 10.1007/978–94–007–0026–04, 2014.

30. AquaNES, Demonstrating synergies in combined natural and engineered processes for water treatment systems. http://www.aquanes.eu.

31. Wintgens T., Nättorp A., Elango L., Asolekar S.R., (eds.) *Natural water treatment systems for safe and sustainable water supply in the Indian context*. IWA Publishing, London, UK, DOI 10.2166/9781780408392,openaccess, https://zenodo.org/record/61088#.WHEd37lK569, 2016.

32. Schubert J., Hydraulic aspects of river bank filtration–field studies. *J. Hydrol.*, 2002, **266**(3–4), 145–161.

33. Friege H., Incentives for the improvement of the quality of river water. *Proc. Int. RBF Conf., Duesseldorf, Germany*, 2–4 Nov. 2000, IAWR–Rheinthemen, 2001, **4**, 13–29.

34. Nestler W., Socher M., Grischek T., Schwan M., River bank infiltration in the Upper Elbe River Valley – hydrochemical aspects. *IAHS Publ.*, 1991, **202**, 247–356.

35. Grischek T., Zur Bewirtschaftung von Uferfiltratfassungen an der Elbe [*Management of bank filtration sites along the River Elbe*]. PhD thesis, Department of Forestry, Geo– and Hydrosciences, Dresden Univ. of Technology, 2003.

36. Fischer T., Day K., Grischek T., Sustainability of riverbank filtration in Dresden, Germany. In: UNESCO IHP-VI Series on Groundwater No. 13, Recharge systems for protecting and enhancing groundwater resources. *Proc. Int. Symp. Management of Artificial Recharge*, 11–16 June 2005, Berlin, 23–28.

37. Heeger D., Untersuchungen zur Kolmationsentwicklung in Fließgewässern [*Investigations on clogging of riverbeds*]. PhD thesis, Bergakademie Freiberg, 1987.

38. Klein G., Krebs M., Hall V., O'Brien T., Blevins, B.B., California's water–energy relationship - Final staff report. California Energy Commission, 2005. http://www.energy.ca. gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF.

39. Grischek T., Schoenheinz D., Herlitzius J., Kulakov V., River bank filtration in towns and communities of the XXI century: Design and operation. *Proc. IWA Specialist Conference on Water and Wastewater Treatment Plants in Towns and Communities of the XXI Century: Technologies, Design and Operation*, 2-4 June 2010, Moscow.

40. Grischek T., Schubert J., Jasperse J.L., Stowe S.M., Collins M.R., What is the appropriate site for RBF? In: Fox P. (ed.) Management of aquifer recharge for sustainability. *Proc. ISMAR 6*, 2007, Acacia, Phoenix, 466–474.

41. Eckert P., Lamberts R., Irmscher R., Einfluss extremer Niedrigwasserereignisse im Rhein auf den Betrieb einer Heberbrunnenanlage [Impact of extreme droughts in the River Rhine on the operation of a siphon system]. *DVGW energie–wasser praxis*, 2005, **12**, 20–23.

9

Chapter

CASE STUDIES ON RIVERBANK FILTRATION IN UTTARAKHAND, INDIA

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This chapter highlights the development of RBF in Uttarakhand, by discussing the benefits of the application of RBF in Haridwar and Srinagar. The RBF demonstration site in Haridwar is presented as an effective means of communicating scientific / research results to the public. The development of RBF in Srinagar is an example of a renaissance of RBF in India.

KEYWORDS: Haridwar, Srinagar (Uttarakhand), monitoring, demonstration, development

INTRODUCTION

The concept of RBF is not new in India. The withdrawal of "clear or clean water" from dug wells located near riverbanks has been practiced for centuries[1]. RBF occurs as a natural consequence of other uses such as abstraction of irrigation-water from wells located near canals and rivers (e.g. in the Indus, Ganga and Brahmaputra river basins). This may not necessarily have negative implications. On the other hand, the unsustainable abstraction (over-abstraction) of groundwater and eventuallyresultant but unintentionallyinduced surface water infiltration due to irrational and unscientific siting of wells must be considered, because it can cause base flow depletion and localized deterioration of groundwater quality (e.g. Gomti River in Lucknow[2]).

In an Indian context, RBF can occur during conjunctive use of surface water and groundwater or for groundwater banking[3]. RBF has been highlighted as a technique for long-term sustainability of drinking water resources in Uttarakhand by taking into account the challenging topography, changing climatic conditions, deforestation and traditional water resources[4,5]. An evaluation of water quality aspects of intentional RBF schemes for drinking water production in Uttarakhand, Delhi and Mathura shows that RBF is an effective and sustainable water treatment technique for different environmental conditions typical for North India[6].

The state of Uttarakhand has used RBF intentionally for drinking water production for more than 50 years. In Haridwar the first caisson well was constructed in 1965, with 15 more constructed between 1980 and 1998. Thereafter six new caisson wells were constructed to meet the anticipated increase in water demand for the Kumbh Mela in 2010 (total 22 RBF wells). The oldest vertical production wells still in operation in Nainital were constructed in 1999/2000. Investigations to develop a new RBF site in Srinagar commenced in 2006, with pilot wells constructed there and at four other sites in 2010. In response to the damage caused by the extreme flood of June 2013 to the water supply infrastructure in Uttarakhand, new RBF wells have been constructed in the state in 2016/2017. Thus within seven years (since 2010), the number of urban RBF sites developed in Uttarakhand has increased by eight, resulting in a total of 12 urban

Figure 9-1. Riverbank filtration sites in Uttarakhand

RBF sites as of (Fig. 9-1). This chapter discusses the two representative RBF schemes of Haridwar and Srinagar and highlights main aspects associated with these schemes.

RBF scheme in Haridwar, Uttarakhand, for urban water supply

General description and motivation to use RBF

Haridwar is considered as one of the seven holiest places of Hinduism. The city receives an average of 50,000 pilgrims on normal days and 150,000–300,000 persons on semi-festive days, with 1–8.2 million on specific religious / festive days such as Ardh-Kumbh, Kumbh, Kanwar Melas and on certain new moon days throughout the year[7]. In addition to this variable temporary population, a permanent population of 310,582 persons[8]residing in the entire urban agglomeration of Haridwar and its outgrowths / suburban areas, has to be supplied with drinking water.

Ensuring drinking water supply in Haridwar is a challenge due to:

- the city's year-round dynamic water demand,
- large-scale public bathing in the Upper Ganga Canal (UGC) and Ganga River,
- high turbidity in river water in monsoon,
- discharge of overland surface runoff and partially-to-untreated wastewater
- and the absence of source-protection zones around wells.

The above factors imply that the removal of pathogens during treatment of raw water to produce drinking water is a crucial aspect. Considering these factors and other land-use constraints, the water supply of Haridwar is predominantly based on RBF and groundwater abstraction.

RBF scheme

More than 68 % of the total drinking water production of Haridwar is produced mainly from 22 large-diameter (~10 m) and relatively shallow (5–11 m) caisson wells (Fig. 9-2, Fig. 9-3). Production from the RBF wells ranges from 59,000 to 67,000 m^3/day (Table- 3-1). The remainder is groundwater supplied by at least 52 deeper vertical production wells located further away from the Ganga River and UGC. After abstraction, the only post-treatment is by on-site disinfection at the wells using sodium hypochlorite and electro-chlorination at the RBF demonstration well 18 (section *RBF demonstration site*). Thereafter the drinking water is distributed to the consumer directly or pumped into storage reservoirs, which are also disinfected.

At locations such as Haridwar (and Rishikesh, Kapkot, Bageshwar, Gauchar and Karnaprayag) in fluvial sub-montane or foothill regions of the Himalayas, large-diameter caisson wells are used for RBF systems designed to meet high water demands

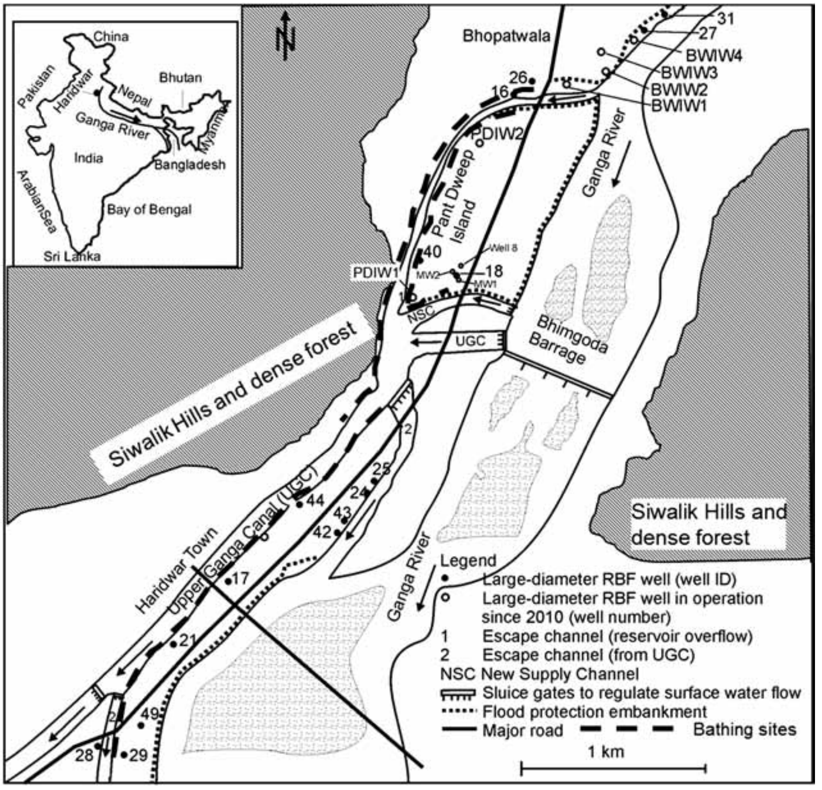

Figure 9-2. Location of RBF wells and public bathing sites in Haridwar[9]

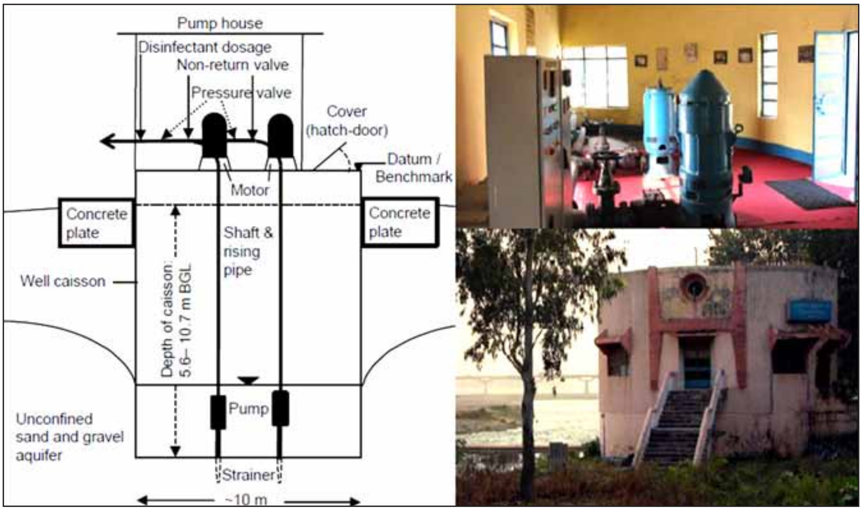

Figure 9-3. Typical cross-section and pump-house of a RBF caisson well[9]

in areas with shallow groundwater tables (≤ 6 m below ground level) having medium to coarse alluvium containing cobbles and boulders. The caisson wells allow a significant storage capacity on account of their large-diameter.

A numerical groundwater flow model was set-up in Visual MODFLOW (version 2011.1) to determine the catchment area of the RBF wells and the travel time of the bank filtrate to the wells (Fig. 9-4). The simulated flow paths of the water to the wells indicate that the RBF wells located in the northern part of Haridwar receive a considerable portion of groundwater in addition to some bank filtrate (Fig. 9-5). This is also confirmed by other studies[10], wherein the mineralization in terms of electrical conductivity of the RBF well water to the north of Pant Dweep is the highest of all wells and decreases towards the south. The mean portion of bank filtrate abstracted by the RBF wells has been calculated from long-term mean electric conductivity values[9] and Oxygen-18 isotope values[11] with the results from the two separate methods in good agreement with one another.

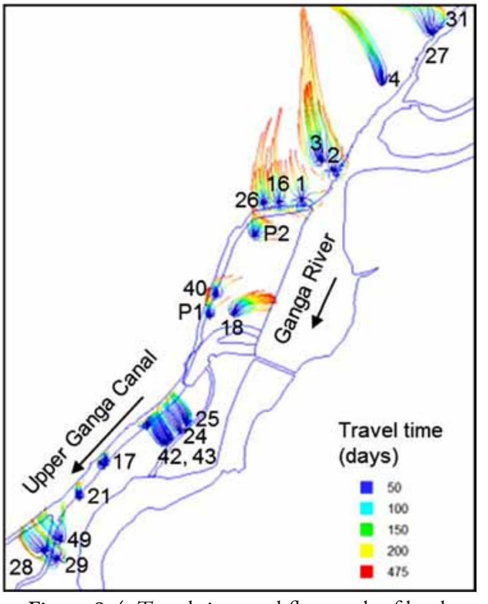

Figure 9-4. Travel time and flow path of bank filtrate for RBF system in Haridwar[9]

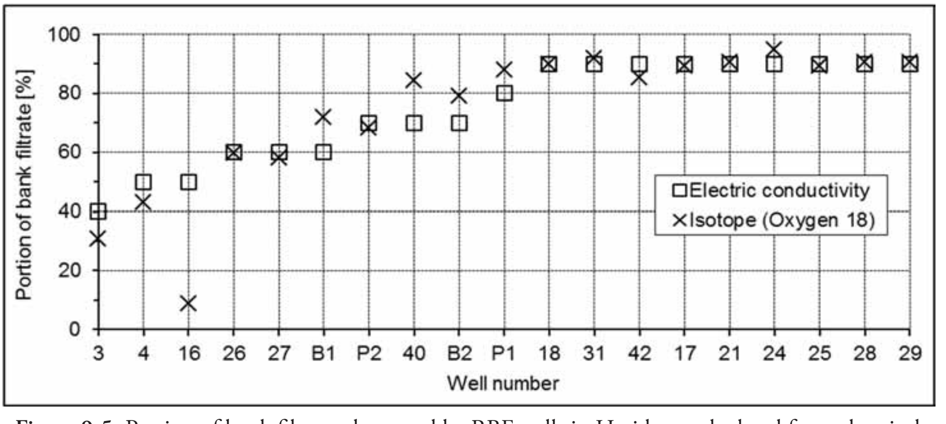

Figure 9-5. Portion of bank filtrate abstracted by RBF wells in Haridwar calculated from electrical conductivity data and $\delta^{18}O$ values(data from[9,11])

For the wells 3, 4, 26 and 1, the portion of ambient landside groundwater is 30–70%. Most of the wells on Pant Dweep Island and in the southern part of the study area abstract 70–90% bank filtrate.

Water quality

Long-term and regular water quality monitoring data from 2005 to 2013 documented in numerous peer-reviewed published literature confirms that the RBF scheme abstracts high quality water year-round, such that a very effective pre-treatment is achieved. A compilation of this data by[12] (that includes data from[9,10,13]) confirms that the main advantage of RBF in Haridwar lies in the removal of 3.5 to 4.4 $\log_{10}$ units (non-monsoon to monsoon) of thermotolerant coliforms (TTC) and removal of turbidity by 1 to >2 $\log_{10}$ in the non-monsoon and monsoon seasons respectively. On the other hand, the risk to human health mainly from turbidity and bacteriological indicators (TTC; E. coli) in surface water was found to be high if to be used directly as a source of raw water for drinking. But despite the observed high TTC removal efficiency, TTC counts up to 93 MPN/100 mL were still observed in some RBF wells, which is attributed to landside contamination of ambient groundwater and anthropogenic activities around wells. This contamination to wells does not reflect an insufficient treatment efficiency of RBF, because it is due to a lack of source-protection zones. Source protection zones for RBF wells are difficult to implement in Haridwar and in general in India, due to pressure on land-use.

All the other inorganic parameters (chemicals, salinity, nutrients and turbidity) were within the limits of the Indian drinking water standard[14]. The mean dissolved organic carbon (DOC) concentration in surface water was low at 1.4 mg/L in monsoon and 1.2 mg/L in non-monsoon, thereby showing no significant change. The mean DOC concentration in ambient groundwater was 1.9 mg/L, although this value is based on only one sample. However, mean total organic carbon (TOC) concentrations for ambient groundwater from other wells was 1.5 mg/L. Out of 54 environmentally relevant organic micropollutants (OMPs) screened in the pre-monsoon (beginning June 2014)[15], only paracetamol, theophylline, sulfamethoxazole and triclosan were found in very low concentrations in surface water and were not detected in one spring water source (artesian groundwater) collected from the north west of the study area.

RBF demonstration site

In 2005 the RBF well number 18 (well 18; Fig. 9-6) on Pant Dweep island was equipped with two monitoring wells (Fig. 9-7). Wide-ranging civil engineering works, including intensive well-cleaning and construction of a sanitary seal and a boundary wall to create a well-head protection zone, were conducted. Detailed hydrogeological and water quality investigations commenced same year on well 18. The results of the investigations are on display at the well. A steady transfer of technology on different aspects of RBF-based water production to the Uttarakhand State Water Supply Organisation (UJS) has also been achieved. During regular training courses, workshops and conferences conducted on RBF in nearby Roorkee and Dehradun, excursions have been organized to well 18 nearly every year since 2006. These

Figure 9-6. RBF well 18 at demonstration site

Figure 9-7. Monitoring wells at well 18

excursions have enabled scientists, water resources engineers and managers, students and policy and decision makers to acquaint themselves with RBF.

A major milestone as a result of these activities was the formal recognition as a RBF demonstration site by the UNESCO IAH Managed Aquifer Recharge Network in 2009. Feedback received from water supply / resource engineers and managers, who participated in these excursions to well 18, highlights the usefulness of RBF demonstration sites for greater visibility of RBF and for improving technology transfer. Thus at least one RBF demonstration site should be developed in the state where RBF can be applied.

One of the crucial issues in India for year-round safe drinking water from RBF schemes is to achieve a robust and sustainable disinfection[16,17]. A potential solution being tested 2016-2018 at the RBF well is the coupling of inline-electrolysis pilot-plants (to RBF wells) for stand-alone decentralized disinfection of water for rural water supply with a capacity to disinfect ~20 m³/day manufactured by AUTARCON GmbH[18,29] (Fig. 9-8 left & center) and a medium-capacity plant to disinfect around

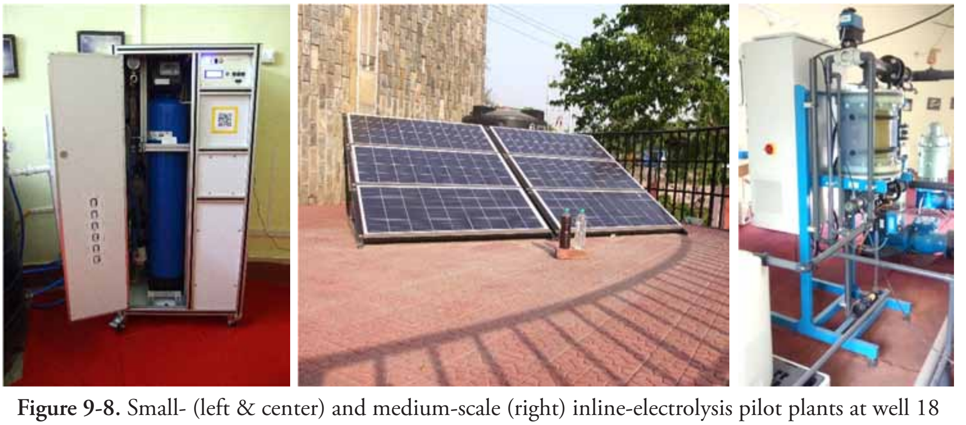

Figure 9-8. Small- (left & center) and medium-scale (right) inline-electrolysis pilot plants at well 18 (Photos left & center: P. Otter, AUTARCON, 2016; right: Hydrosys / TZWD, 2016)

1,600 m^3/day manufactured by Hydrosystemtechnik GmbH in research cooperation with the DVGW Water Technology Centre in Dresden, HTW Dresden and UJS[19]. Water quality monitoring results from both plants over 12months operation show that no total coliforms and E. coli were present in the produced (disinfected) drinking water. Therefor both systems are potential solutions to achieve continuous and robust disinfection.

RBF scheme in Srinagar, Uttarakhand, for urban water supply

General description and motivation to use RBF

The town of Srinagar in the Himalayas is located on the south bank of the meandering Alaknanda River along the main road to the Hindu shrine of Badrinath in a relatively wide valley. It is a major commercial, administrative and educational centre in the region. In 2011 the town had a population of around 20,115 persons[8]. FromApril to September every year, a substantial number of tourists stop-over enroute to pilgrimage sites upstream (Kedarnath, Badrinath, Hemkund Sahib).

In Srinagar, no wells existed until 2005, and the raw water was abstracted directly from the Alaknanda River and conventionally treated before being distributed to Srinagar and Pauri (located ~30 km above Srinagar). In 2006, UJS constructed two exploratory wells to explore the potential for RBF in Srinagar in order to:

- increase drinking water production to meet the current deficit and fulfil future demand,
- provide an alternative to conventionally treated water supply during monsoon that faced interruptions due to high turbidity in surface water and also during dry pre-monsoon months when spring-fed streams (sources of raw water) had extremely low to no surface flows
- and to provide an alternative to direct surface water withdrawal due to expected future reduction in flows because of flow-diversion to the Srinagar hydro-electric power plant.

The results of the investigations from the two exploratory wells indicated suitable hydrogeological conditions for RBF (Chap. 2; Table- 2-5). This fact and the sustainability of the existing bank filtration schemes in Haridwar and Nainital[20] in terms of quality and quantity, motivated UJS to develop one RBF pilot well in Srinagar and at four other towns in Uttarakhand[21].

Drinking water production and development of RBF (2010 to 2017)

Until 2015, approx. 80% of the total raw water for the drinking water supply of Srinagar and Pauri was abstracted upstream of the town directly from the Alaknanda River. The abstracted surface water is passed through rapid sand filters and chlorinated before being supplied to the distribution network. This was supplemented by approx.

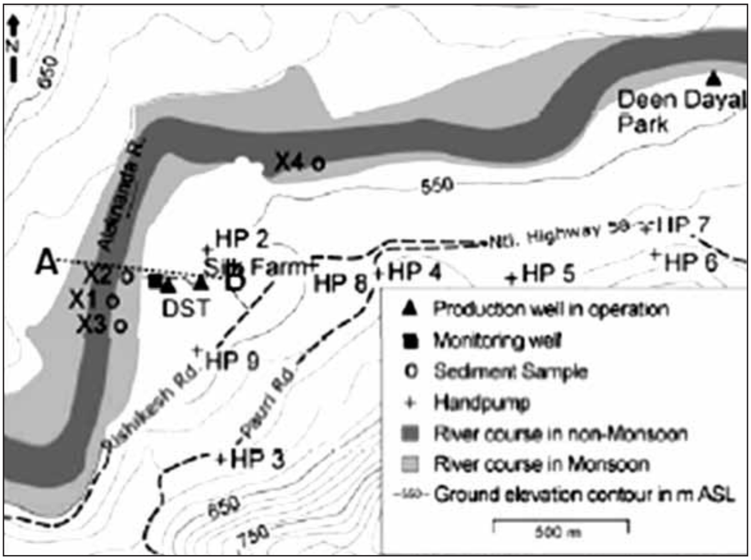

Figure 9-9. Production wells at Srinagar RBF site until 2015

10% water abstracted from the pilot RBF production well PW-DST constructed in 2010 and ~10% abstracted by the production wells in Silk Farm and Deen Dayal Park (Fig. 9-9; formerly the two exploratory wells constructed in 2006 and presently still in operation).

However, an extreme and unprecedented (highest-ever recorded) flood occurred from 15–17 June 2013 that was characterized by an increase in the Alaknanda River level of >15 m. The production well PW-DST was located around 7 m above the annual mean flood level and thereby considered sufficiently safe from inundation. But it was still inundated by the Alaknanda River and subsequently buried beneath 1.5–3 m thick sand deposits. Substantial damage was caused to the RBF site in terms of disruption of water supply and failure of abstraction equipment (pumps, disinfection apparatus, electricity supply and installations). The well PW-DST only became operational in 2014 again. Due to inundation of the wells and direct entry of river water into them, bacteriological contamination in the well-water was detected for at least five months after the flood[22].

After the flood of 2013, the Government of Uttarakhand launched the "Uttarakhand Disaster Recovery Initiative" that was funded by the Asian Development Bank's "Uttarakhand Emergency Assistance Project". The rehabilitation and reconstruction of damaged water supply schemes in nine towns affected by the flood was undertaken within the water supply component of the project. Accordingly, the RBF site in Srinagar was reconstructed with six new vertical wells in 2016/2017 having a discharge of 24 to 60 m³/hour (Fig. 9-10). The total discharge from the well field if all wells operate simultaneously is around 390 m³/h. Under the operational scenario

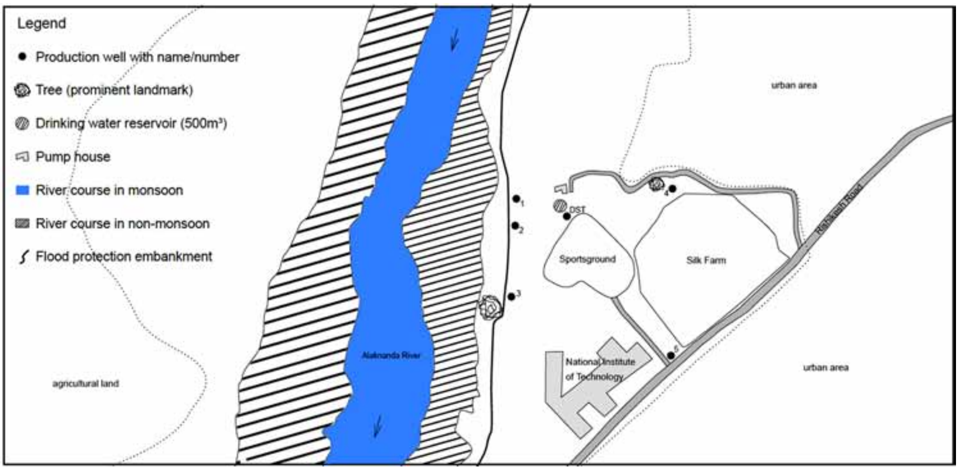

Figure 9-10. Reconstructed RBF site in Srinagar in 2016/2017

existing early 2018 at the RBF site, only some wells operate at any given time for a few hours per day until the storage reservoir is full.In addition to the new wells, a central pump house and a 500 m³ storage reservoir are located at the RBF site. The water from the RBF wells is pumped into the storage reservoir and then into the distribution network via the pump house.

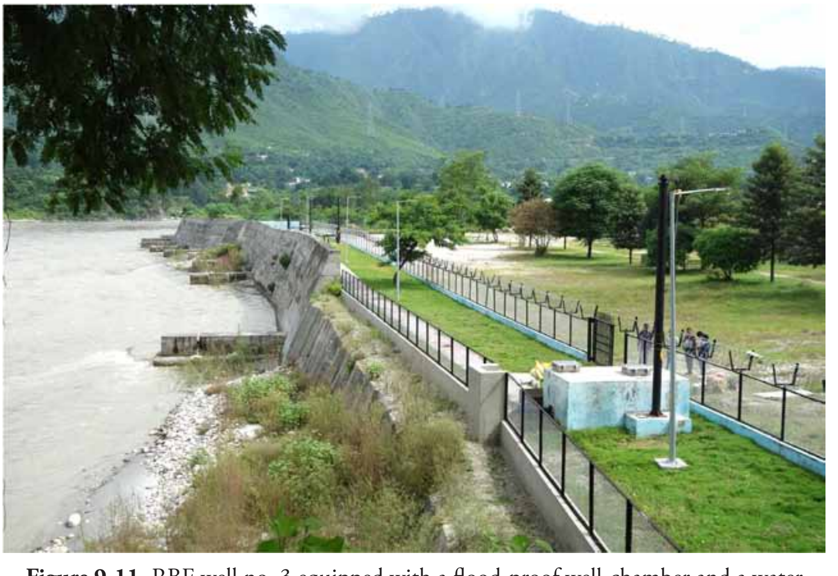

Figure 9-11. RBF well no. 3 equipped with a flood-proof well-chamber and a water tight well-head (Photo: Musche, 2017)

In context to the risk from floods to RBF sites and motivated by the June 2013 flood in Uttarakhand, a concept for flood-proof RBF wells was implemented on well 3 in 2016/ 2017 (Fig. 9-10). Accordingly, a watertight well head and flood proof well chamber were designed for Indian conditions by the HTW Dresden (HTWD). Thereafter the prototype well head was fabricated in Haridwar and built into the flood proof chamber of well 3[23](Fig. 9-11; chapter 3).

Water quality

The surface and well water quality for the site was compiled and interpreted from various collaborative investigations for the Alaknanda River and production well PW-DST from 2010 to 2014[24,25]. The main advantage of the abstracted water by the RBF well PW-DST, compared to direct surface water abstraction, is the significant removal of turbidity and bacteriological indicators by 5 log_{10} units, especially in monsoon when turbidity of up to 5,368 NTU is observed in the Alaknanda. The presence of total coliforms up to 300 MPN/100 mL in the raw water abstracted by the PW-DST was observed only on one occasion in monsoon 2012 and corroborates to data presented by[24]. As a breakthrough was only observed on one occasion, a sampling error cannot be ruled out. On the other hand, the presence of coliforms in wells is not uncommon, especially downstream of human habitation. But as E. coli numbers were consistently below the detectable limit of 2 MPN/ 100 mL, it can be inferred that the risk from bacteriological contamination to the well is low.

One water quality aspect of concern in the abstracted water by the production well PW-DST was the relatively high nitrate concentration in the range of 53–138 mg/L. While high nitrate concentrations in groundwater are a common occurrence in areas where agricultural activities lead to widespread fertilizer and/or manure application or sewage from leaky urban drains and sewers (such as in Srinagar) comes in contact with groundwater, subsequent investigations by[24]suggest that one of the possible sources of this nitrate seems to be certain parts of phyllite bedrock that were found to be leaching nitrate in water. Accordingly, seasonal variations in nitrate concentrations in the PW-DST well water and the isotopic data rule out the possibility of observed levels of nitrate contamination originating solely from anthropogenic sources such as sewage, agricultural run-off and industries because of the small population of the town and lack of large intensive agriculture farms and industries in the region. Furthermore aquifer material from the site did not leach any significant amount of nitrate and shows that the aquifer material at the site is not the dominant source of nitrate to the bank filtrate and groundwater leading to the hypothesis that the nitrate is of geogenic origin[24]. High nitrate at an RBF site is an extremely rare occurrence and therefore should not be exaggerated as a parameter of concern for other RBF sites.

The other parameters in the PW-DST were within the stipulated Indian Standard for drinking water[14].

Potential RBF site management strategy to lower nitrate concentration in well water

The case study site of Srinagar has favourable physical hydrogeological conditions for RBF (perennial river with sufficient year-round flow and minimal clogging of riverbed, high hydraulic conductivity of aquifer). The main advantage of using RBF in comparison to direct surface water abstraction is the high removal of pathogens and turbidity (5 $\log_{10}$ units). The issue of nitrate at a RBF site is very rare and is a special case because such high nitrate concentrations have been observed only at a few RBF sites worldwide, where the nitrate containing water originates from land-side groundwater due to fertilizer and manure application, such as in Dresden and Meissen by the Elbe R. in Germany[26,27]. For the cited example of Dresden, a specific abstraction rate was defined to limit the portion of land-side groundwater (and thus the amount of nitrate) in the pumped water. This solution prevented the need for any special post-treatment to remove nitrate or sulphate in the waterworks. Thus, in Srinagar, the nitrate concentration can be potentially lowered by increasing the portion of young bank filtrate (originating directly from the river to the west). Under the operational scenario existing early 2018 at the RBF site, only some wells operate at a time for a few hours per day until the storage reservoir is full. To develop a management strategy to achieve a higher portion of bank filtrate in the abstracted well water, intensive monitoring of nitrate concentrations from each well and a numerical groundwater flow modelling study that reflects the operational scenario from 2018 onwards, has to be conducted.

Table 9-1. Summary of RBF caisson wells constructed at some towns in Uttarakhand, 2016/2017

Parameter	Gauchar	Karnaprayag	Kapkot	Bageshwar
Distance: well–river [m]	61	25	32	14
Well depth [m]	14.70	14.75	12.50	14.40
Well diameter [m]	7	7	7	7
Height of water column in well [m]	6.75	7.00	5.15	7.34
Production capacity [m^3/day]	4,320	5,760	2,020	2,020
Number of persons additionally supplied (@ 135 LPCD)	32,000	42,666	14,962	14,962

Conclusions and further development of RBF in Uttarakhand and India

The development of RBF in Srinagar in a phased manner involving a decade of research and its implementation is an example of a renaissance of RBF in India for urban water production. At some other locations, the construction of new RBF wells in 2016/2017 are expected to provide at least 100,000 additional persons with high-quality drinking water (Table- 9-1). Nevertheless field experience of UJS indicates that there is potential to construct RBF wells at other locations in Uttarakhand.

As a result of the above activities, the states of Andhra Pradesh, Odisha, Jharkhand, Bihar and Uttarakhand are interested in developing new RBF sites with financial assistance from potential sources (e.g. their state governments, the Department of Science and Technology, Ministry for Water Resources, River Development and Ganga Rejuvenation (MOWR, RD & GR) and externally funded programmes (e.g. ADB, World Bank). Consequently, the vision of achieving 5% of drinking water supply from RBF has been set for 2030[28].

While this chapter has highlighted urban RBF water supply schemes, there are numerous small-scale RBF schemes for rural water supply in Uttarakhand that use Koop wells (chapter 3). Due to their construction within the riverbed at a shallow depth, the removal of pathogens is generally lesser compared to vertical wells. Hence there is an even greater need to guarantee the robust and safe disinfection of the water from the Koop wells. The application of photovoltaic-powered inline-electrolysis is a promising approach (section *RBF demonstration site*), especially in areas that are difficult to access.

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REFERENCES

1. Uniyal H.P.,Riverbank filtration in India: Existing Efforts and Future Prospects. In: Dobhal R., Grischek T., Uniyal H.P., Uniyal D.P., Sandhu C. (eds.) Drinking Water: Source, Treatment and Distribution. *Proc. Indo-German Workshop on Source, Treatment and Distribution of Drinking Water*, Dehradun, 14.-16.09.2009. Uttarakhand State Council for Science & Technology, Dehradun, India, Bishen Singh and Mahindra Pal Singh Publication,2011, 9–24, ISBN-9788121108133.
2. Foster S., Steenbergen F.van, Zuleta J., Garduno H., Conjunctive use of groundwater and surface water: from spontaneous coping strategy to adaptive resource management. GW MATE strategic overview series no. 2, Washington DC, World Bank. Available: *http://documents. Worldbank.org/curated/en/2010/01/13817037/*
3. Chaturvedi M.C., Srivastava V.K., Induced groundwater recharge in the Ganges basin. *Water Res. Res.*, 1979,**15**(5), 1156–1166.

4. Sharma B., Uniyal D.P., Dobhal R., Kimothi P.C., Grischek T., A sustainable solution for safe drinking water through bank filtration technology in Uttarakhand India. *Curr.Sci.*, 2014,**107**(7), 1118–1114.

5. Sharma B., Sustainable drinking water resources in difficult topography of hilly state Uttarakhand, India. *American Journalof Water Resources,*2016,**4**(1), 16–21. DOI: 10.12691/ajwr-4-1-2.

6. Kumar P., Mehrotra I., Gupta A., Kumari S., Riverbank Filtration: A Sustainable Process to Attenuate Contaminants during Drinking Water Production. *J. Sustain. Dev. Energy Water Environ. Syst.*, 2018,**6**(1), 150–161.

   Available: *https://doi.org/10.13044/j.sdewes.d5.0176*

7. Gangwar K.K., Joshi B.D., A preliminary study on solid waste generation at Har Ki Pauri, Haridwar, around the Ardh-Kumbh period of sacred bathing in the river Ganga in 2004. *Environmentalist*, 2008,**28**(3), 297–300.

8. COI Cities having population 1 lakh and above. Provisional Population Totals, Census of India. Office of the Registrar General and Census Commissioner, India, Ministry of Home Affairs, Government of India. Available:*http://www.censusindia.gov.in/2011–prov-results/paper2/data_files/India2/ Table_2_PR_Cities_ 1Lakh_and_Above.pdf;*Accessed: 16.04.2018

9. Sandhu C., A Concept for the Investigation of Riverbank Filtration Sites for Potable Water Supply in India. Ph. D. Dissertation. Dresden University of Applied Sciences, Faculty of Civil Engineering and Architecture, Division of Water Sciences and TU Dresden, Faculty of Environmental Sciences, Institute of Waste Management and Circular Economy, 2015, Available: *http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-208460*

10. Saini B., Mehrotra I., Kumar P., Verma R., Insight of riverbank filtration system at Haridwar for enhancement of drinking water quality. *Int. J. Current Engineeringand Technol.*, 2013,**3**(4), 1264–1270.

11. Kumar S., Isotope analyses for riverbank filtration site Haridwar. In: Saph Pani D1.2, Guidelines for flood-risk management of bank filtration schemes during monsoon in India. Saph Pani Deliverable D1.2, 2013.

    Available:*http://www.saphpani.eu/downloads*

12. Bartak R., Page D., Sandhu C., Grischek T., Saini B., Mehrotra I., Jain C.K., Ghosh N.C., Application of risk-based assessment and management to riverbank filtration sites in India. *J Water and Health*, 2015, **13**(1), 174–189.

13. Dash R.R., Bhanu Prakash E.V.P, Kumar P., Mehrotra I., Sandhu C., Grischek T., River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. *Hydrogeol. J.*, 2010, **18**(4)**,** 973–983.

14. IS 10500, Drinking Water – Specification. Indian Standard (second revision), Bureau of Indian Standards, New Delhi, 2012.

15. Saph Pani D1.4, Report on bank filtration economics and cost-estimates. Saph Pani Project Deliverable D1.4, 2014. Available: http://www.saphpani.eu/downloads

16. SharmaS.K., Sandhu C., Grischek T., Gupta A., Kumar P., Mehrotra I., Grützmacher G., Sajilkumar P.J., Lakshmanan E., Ghosh N.C., Pre- and Post-treatment of BF and MAR in India: Present and Future. In: Wintgens T., Nättorp A., Lakshmanan E., Asolekar S.R. (eds.) Natural water treatment systems for safe and sustainable water supply in the Indian context – Saph Pani. *IWA Publishing*, London, UK,2016, 191–206. ISBN13-9781780407104.

Available: *https://zenodo.org/record/61088/files/9781780408392_12.pdf*

17. Sandhu C., Grischek T., Voltz T.J., Schmidt W., Kumar P., Börnick H., Kimothi P.C.,Riverbank Filtration for Year-round Urban Water Supply in India. *Proc.Indo-German Conference on Sustainability, Chennai*, 2016, 124–128.

18. AquaNES – Demonstrating synergies in combined natural and engineered processes for water treatment systems. 2016. Available:http*://www.aquanes-h20.eu.*

19. NIRWINDU – Safe and sustainable drinking water production in India by coupling natural and innovative techniques.Available:2015 https*://www.htw-dresden.de/nirwindu*

20. Dash R.R., Mehrotra I., Kumar P., Grischek T., Lake bank filtration at Nainital, India: *water-quality* evaluation. *Hydrogeol. J.*,2008,**16**(6), 1089–1099.

21. Kimothi P.C., Dimri D.D., Adlakha L.K., Kumar S., Rawat O.P., Patwal P.S., Grischek T., Sandhu C., EbermannJ., Ruppert M., Dobhal R., Ronghang M., Kumar P., Mehrotra I., Uniyal H.P.,Development of Riverbank Filtration in Uttarakhand. *J. Indian Water Works Assoc., Special Issue on RBF*, July–September, 2012,13–18, ISSN 0970-275X.

22. Sandhu C., Grischek T., Musche F., Macheleidt W., Heisler A., Handschak J., Patwal P.S., Kimothi P.C.,Measures to mitigate direct flood-risks at riverbank filtration sites with a focus on India. *Sustain. Water Resour. Manag.,*2018, **4**(2), 237–249. DOI: 10.1007/s40899-017-0146-z.

23. Musche F., Sandhu C., Grischek T., Patwal P.S., Kimothi P.C., Heisler A. A field study on the construction of a flood-proof riverbank filtration well in India – challenges and opportunities. *Int. J. Disaster Risk Reduction*, 2018, DOI: 10.1016/j.ijdrr.2018.06.003.

24. Gupta A., Ronghang M., Kumar P., Mehrotra I., Kumar S., Grischek T., Sandhu C., Knoeller K., Nitrate contamination of riverbank filtrate at Srinagar, Uttarakhand, India: A case of geogenic mineralization. *J. Hydrol.*, 2015,**531**, 626–637.

25. Ronghang M., Gupta A., Mehrotra I., Kumar P., Patwal P., Kumar S., Grischek T., Sandhu C., Riverbank filtration: a case study of four sites in the hilly regions of Uttarakhand, India. *Sustain. Water Resour. Manag.*2018, doi.org/10.1007/s40899-018-0255-3

26. GrischekT., Nestler W., Piechniczek D., Fischer T., Urban groundwater in Dresden, Germany. *Hydrogeol. J.*, 1996,**4**(1), 48–63.

27. Grischek T., Schoenheinz D., Nestler W., Unexpected groundwater flow beneath the River Elbe at the bank filtration site Meissen, Germany. In: Schmitz G.H., (ed.) *Water resources and environment research*, ICWRER, 2002, **1**: 116–120.

28. Grischek T., Sandhu C., Ghosh N.C., Kimothi P.C., Uniyal D.P., Dobhal R., Riverbank filtration as an element for future water security in India – Vision 2030. *Proc. 7th Int. Ground Water Conference*, 2017, New Delhi, 3–4.

29. Otter P., Malakar P., Sandhu C., Grischek T., Sharma S.K., Kimothi P.C., Nüske G., Wagner M., Goldmaier A., Benz F., Combination of river bank filtration and solar driven electro-chlorination for safe drinking water supply in river bound communities – Experiences from a pilot study conducted in India. *Water* (*under revision*).

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