Saph Pani

Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India

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1 Context

This deliverable is to document the training activities that have been performed in Saph Pani during the first reporting period or which will be delivered in the second half of the project.

A central ambition of Saph Pani is to disseminate project results and experiences from field studies to end-users and stakeholders. Among the various activities in Work Package 7 on “Training and Dissemination” specific training courses on natural systems for water treatment in India are developed to transfer knowledge to practitioners.

The project findings are also meant to strengthen the science policy interface and point out ways for utilizing and considering project results in policy making and regulation.

Saph Pani has been designed in such a way that impacts of the project can be realized even beyond the lifetime of the project. Based on field investigations and case study oriented work beneficial for the local stakeholders, training and dissemination activities will help to spread the project results beyond the project partners and particularly address water authorities, water utilities, technology partners and providers, researchers, students as well as local communities.

2 Training Courses

Training will be a key element of dissemination and it should be seen as a tool that can maximize the impact of Saph Pani dissemination efforts. It will guarantee that the developed concepts and technologies are not only widely disseminated but they are also taken up by the target group and thus the scientific achievements can be put into practice.

To this end, two-day training workshops are organized at or near the location of the pilot-site cities with the objective to train local municipal and governmental decision makers and managers about concrete actions that will be required to address natural treatment processes using the Saph Pani knowledge pool. The developed training curriculum and the methodologies will jointly form a training program that is considered by the Consortium as a viable product for continuing training and education after the EC-funded period.

The trainings planned under the project focus on the physical process description together with case study results. They have been designed to help practitioners understand the physical processes involved in the three distinct treatment systems (i.e. BF, MAR and Constructed Wetlands). Also quality control and the pre- and post-treatment necessary in relation to these systems is covered. It was envisaged that training should be on the level of the practitioners not giving much description on theory; and the specific training courses should be organized in places near to the respective project site to enable participants to understand the concept and to realize practical utilities of such scheme. The trainings conducted, however, had mix participation of practitioners, researchers and students, with coverage of both theoretical and practical aspects.

These trainings are also considered to be important vehicles of creating awareness among researchers and students, who would take the knowledge forward both in terms of value addition through research inputs and later adoption in real practice when they enter into professional life. Organization of these training courses is expected to provide the expected impact among the user communities and stakeholders through dissemination and exploitation of project results.

Table 1 Training course schedule of Saph Pani

Training course	Target group	Date & Place
Bank Filtration for Sustainable Drinking Water Supply in India	Practitioners, researchers and students	April 13, 2012 New Delhi
Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment systems	Practitioners, researchers and students	December 11-12, 2012 Anna University, Chennai
Constructed Wetlands for Wastewater Treatment and Reuse	Practitioners, researchers and students	November 2013 IIT-Bombay, Mumbai

2.1 Design and Operation of River Bank Filtration Systems

2.1.1 Background

Riverbank filtration (RBF) or simply bank filtration (BF, a unified term for river and lake bank / bed filtration) can occur under natural conditions or be induced by lowering the groundwater table below the surface water level by abstraction from adjacent boreholes. Generally bank filtration is a natural, sustainable and low cost technology. Pathogens and organics can be effectively removed and there is the potential to compensate shock loads. In many cases disinfection is sufficient to ensure a safe drinking water supply.

Bank filtration (BF) has been used for many decades in Europe to provide drinking water to communities located by surface water bodies, typically rivers. In India, the further development of BF has the potential to provide drinking water to many towns and cities located on the Indo-Gangetic Plain currently using surface water for their public water supply. A number of Indian cities, with source waters of significantly varying quality, are already using BF. Bank filtrate from a few sites monitored in recent years has shown a significantly higher quality when compared to water abstracted directly from surface water sources.

The principle of bank filtration is illustrated in Figure 3.

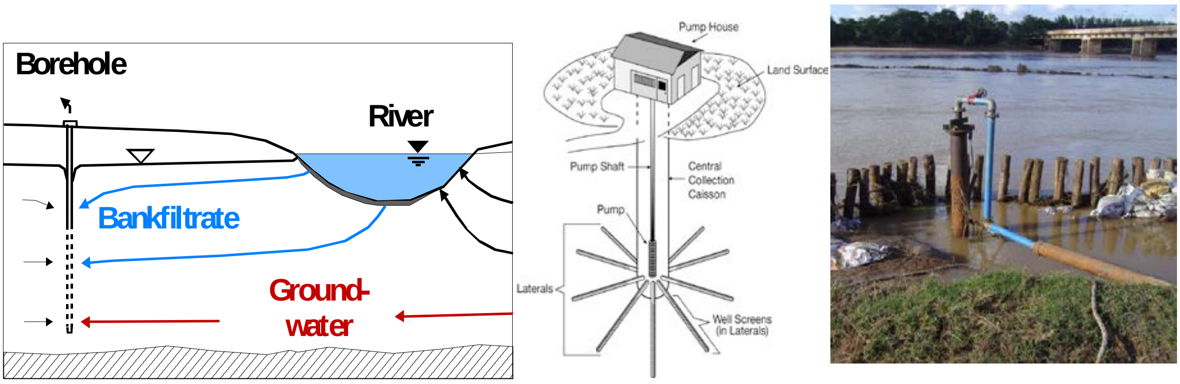

Figure 3 Bank filtration – schematic illustration and view of Kangsabati river site near Kharagpur

While BF has historically been used at multiple locations in India, concerted efforts are required to realize the full potential of BF and understand and scientifically document the processes involved. Hydrogeological conditions at several riverside Indian cities seem to indicate that these cities would be suitable for the successful implementation of BF systems. Although BF systems are seen as having a great potential for improving both the quantity and quality of water supplies throughout much of the nation, there are a number of feasibility issues that must be considered regarding the sustainability of such systems in India.

2.1.2 Training Course

In order to provide fundamental knowledge about BF for natural treatment of drinking water and for adopting it on a larger scale in India, a training course was jointly organized by NIH, Roorkee and HTWD, Germany at New Delhi in April 2012, with the objectives to:

- acquaint the participants with BF, and its national and international application,
- provide the participants with knowledge of design, construction and operation of BF systems, and water quality aspects with special attention to parameters relevant to BF under both general and Indian conditions
- highlight the relevance of groundwater modelling and the application of isotope methods
- present case studies on BF in India
- inform the participants about the Saph Pani project in the context of using natural water systems and treatment technologies in India

The modules covered under the training course on “Bank Filtration for Sustainable Drinking Water Supply” are shown in

Table 2.

Table 2 Modules for training course on “Bank Filtration for Sustainable Drinking Water Supply”

3 Module	4 Topic / Content
1	Introduction of bank filtration techniques
2	Bank filtration well design, construction & operation
3	Removal of pathogens by bank filtration
4	Water quality aspects during bank filtration
5	Fate of trace pollutants during bank filtration
6	Modelling and analysis of travel-time and flow-path during bank filtration
7	Investigation of bank filtration sites in India
8	Application of isotope hydrology in identifying a potential bank filtration site
9	Case studies on bank filtration from Uttarakhand
10	Case study on bank filtration from Haridwar
11	Case study on bank filtration from Delhi

The course content is available as Annex 1.

4.1 MAR Systems in India

4.1.1 Background

Excessive exploitation of groundwater for various purposes has resulted in depletion of resources and rapid decline in groundwater table in several parts of the world.

Managed Aquifer Recharge (MAR) is the planned, human activity of augmenting the amount of groundwater available through works designed to increase the natural replenishment or percolation of surface waters into the groundwater aquifers, resulting in a corresponding increase in the amount of groundwater available for abstraction (Oaksford 1985).

In urban areas, MAR can provide effective storage for desalinated seawater, recycled water or storm water. Methods of MAR currently include aquifer storage and recovery (ASR), aquifer storage, infiltration ponds, infiltration galleries, soil aquifer treatment, percolation tanks and check dams. Parimala Renganayaki and Elango (2013) reviewed the work related to managed aquifer recharge by check dams.

India has a long tradition in implementing MAR schemes. Artificial recharge of groundwater is one of the oldest activities undertaken all over the country to conserve rainwater above ground and underground. Since the 1970s numerous watershed development programs (WDP) have been implemented, which included the construction of check dams, percolation ponds or other structures to recharge water to the aquifers (Figure 4).

Figure 4 Examples of MAR schemes in India

4.1.2 Training Course

As a part of the Saph Pani project, a two-day training course on “Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment Systems” was jointly organized by NIH, Roorkee and Anna University, at Chennai, in December 2012.

The short course aimed to:

- Introduce the participants to MAR at national and international level
- Provide knowledge on the basics of artificial recharge by MAR, methods, hydrogeological characterisation
- Give an insight into case studies in India and abroad

The modules covered under the training course on “Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment Systems” are shown in Table 3. The course content is available as Annex 2.

Table 3 Modules for training course on “Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment Systems”

Module	Topic / Content
1	Introduction to MAR: Overview of schemes and settings worldwide
2	An overview of evolution of groundwater recharge in India
3	MAR practices in India
4	Site selection, characterization of variety of structures and their utility for MAR
5	Hydraulics of infiltration ponds and determination of relevant parameters
6	Potential of water harvesting structures for groundwater recharge in India
7	MAR for mitigation of seawater intrusion in Chennai
8	Role of temple tanks in MAR
9	Sustainability of groundwater abstraction structures in hard rock region through MAR
10	MAR with reclaimed water
11	Towards Indian Water Quality Guidelines for MAR
12	Pre-treatment and post-treatment for MAR systems
13	MAR risk assessment and water quality considerations
14	Assessment of impact of MAR structures by hydrogeological methods
15	Integrated modelling for assessment of impact of MAR structures

4.2 Constructed Wetland (CW) Systems in India

4.2.1 Background

Constructed Wetlands (CW) are typical natural engineered treatment systems, designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating the wastewater. They have been gaining increased international interest and now being assumed highly applicable in developing countries, due to their characteristic like utilization of natural processes, simple construction, simple operation and maintenance (O/M), process stability, and above all its cost effectiveness (Arceivala and Asolekar, 2006; Arceivala and Asolekar, 2012).

Wetlands, being defined as representative transitional areas between land and water, encircle a broad range of wet environments; including marshes, bogs, swamps, meadows, tidal wetlands, floodplain, and ribbon (riparian) wetlands along stream channels, behave like a kidney of the earth ecosystem. The larger aquatic plants growing in wetlands are usually called macrophytes. These include aquatic vascular plants, aquatic mosses and some larger algae (Brix, 1997).

The wetlands are often located at the Ecotones between dry terrestrial systems and permanently flooded deepwater aquatic systems such as rivers, lakes, estuaries, or oceans. As such they have an intermediate hydrology, a biogeochemical role as source, sink or transformer of the chemicals and generally high productivity if they are open to hydrologic and chemical fluxes.

The CWs appears to perform all of the biochemical transformations of wastewater constituents that take place in conventional energy intensive, environmental engineering based systems including activated sludge process, septic tanks, drain fields and other form of land treatments. Transformation of these naturalized treatment systems have been shown to have a significant capacity for both wastewater treatment and resource recovery (Hofmann, 1996).

There are numerous sites of CWs systems installed in India in last one decade- some of them are fictional and remaining become dysfunctional due of poor O & M. Recently a survey of CWs and other natural treatment systems (NTSs) across India was conducted by IIT Bombay team for their techno-economic evaluation. For this study, only engineered NTSs were selected so that the treatment process and governing equations may simulated in any place if the treatment systems gives the overall better pollutant removal efficiency in relevance with recycle and reuse of treated wastewater. The NTSs operated across India (approximately 108 in number) were visited by IITB team during assessment. Some examples are depicted in Figure 5.

The CW system can be effectively combined with advanced tertiary treatment alternatives and the resulting high quality treated effluent can be gainfully recycled into production and sanitation applications. The CWs are most prone to engineering adaptation and modular applications and that is the reason why these natural treatment technologies have been chosen as the theme technology for in the current research project in our group. Specifically, the construction of a pilot scale sewage treatment plant (Research Station) based on CWs are in progress at IIT Bombay campus. The treated effluent generated from various modules of CWs will then be subjected to the membrane processing units in the laboratory set-up and investigation of possibilities of combining CWs with advanced tertiary treatment unit will be undertaken - which is the main focus in our present research.

In order to finalize the plan for construction of constructed wetland pilot plant for sewage treatment in IITB premises, several discussions were conducted with experts during the past twelve months. The various topics of discussion included: the appropriate location on IITB premises, representative dimensions, best suitable plant species, and process flow diagram. After the broad discussions, appropriate location for CW has been now finalized to the plot adjoining IITB's sewage sump and pumping station behind Hostel 8. A large enough plot situated at the sewage sump of IITB community has been allotted for establishing the *Research Station*. The allotted location for setting CW technology is excellent for reclamation of sewage as well as remediation of Lake.

80 m3/day, CW, Ujjain, MP, India **50 m3/day, CW, Bhopal, MP, India**

70 m3/day, CW, Bhopal, MP, India **500 m3/day, CW, Ropar, Punjab, India**

50 m3/day, CW, Agra, UP, India

Figure 5 Operational CWs at various locations in India

4.2.2 Two-day training course on constructed wetlands for wastewater treatment and reuse

The successful operation and maintenance of CWs necessitate a level of technical acquaintance and hence the need for capacity building of CW practitioners. In order to enhance the eccentric approach of wastewater treatment through CWs in India as well as around the world– a two-day training course on constructed wetlands for wastewater treatment and reuse has been proposed to be conducted by IITB team at IIT Bombay campus in November 2013. The overall aim of this training course is to build capacity of stakeholders and CWs practitioners for their appropriate management. Moreover, the following specific objectives will be covered during the training program:

- to understand fundamentals of NTS and specifically CW related science and engineering principles,
- to generate capacity related to planning, designing, constructing, operating, maintaining and monitoring of CWs,
- to identify common understandings of multiple cost-effective benefits of CWs, and other NTSs; and
- to identify gaps, needs, barriers and opportunities in CWs for wastewater treatment and reuse.

The various activities that will be conducted during training program include presentation from experts, group discussion among participants, group assignments, quiz, field visits, recommendations etc. (Table 4). After completion of the training program, the participant will be taken for field visit. The field visit will be arranged considering suggestions by participants.

Table 4 Modules for training course on "Constructed Wetlands for Wastewater Treatment and Reuse"

Module	Topic / Content
1	History and development of constructed wetlands for wastewater treatment • Introduction to Natural Treatment Systems (NTSs) • Application of NTSs around the world and current status of technology acceptance in India • Types of constructed wetland (CW) systems
2	Classification and designated use of constructed wetlands • Classification of CWs • Place and significance of CWs in ecosystem • CWs for treating different kinds of wastewater
3	Structural components and their roll in constructed wetland systems • Mechanisms of pollutant removal and systems' limitations • Hydrology, water regimes and water and wastewater budgets
4	Planning, designing, and constructing of engineered wetlands for wastewater treatment: case studies • Planning, designing and construction of engineered wetlands for wastewater treatment
5:	Operation and maintenance of constructed wetlands

	• Issues associated with operation and maintenance, essential maintenance of the system. • Benefits of proper operation and maintenance to system performance, operator training, improved methods of CWs operation, harvesting of vegetation. • Factors affecting the clogging and its remedial measures, performance monitoring and assessment.
6	Policy issues associated with constructed wetlands • Water and wastewater related policies and regulations, case studies (from India and other countries)

5 References

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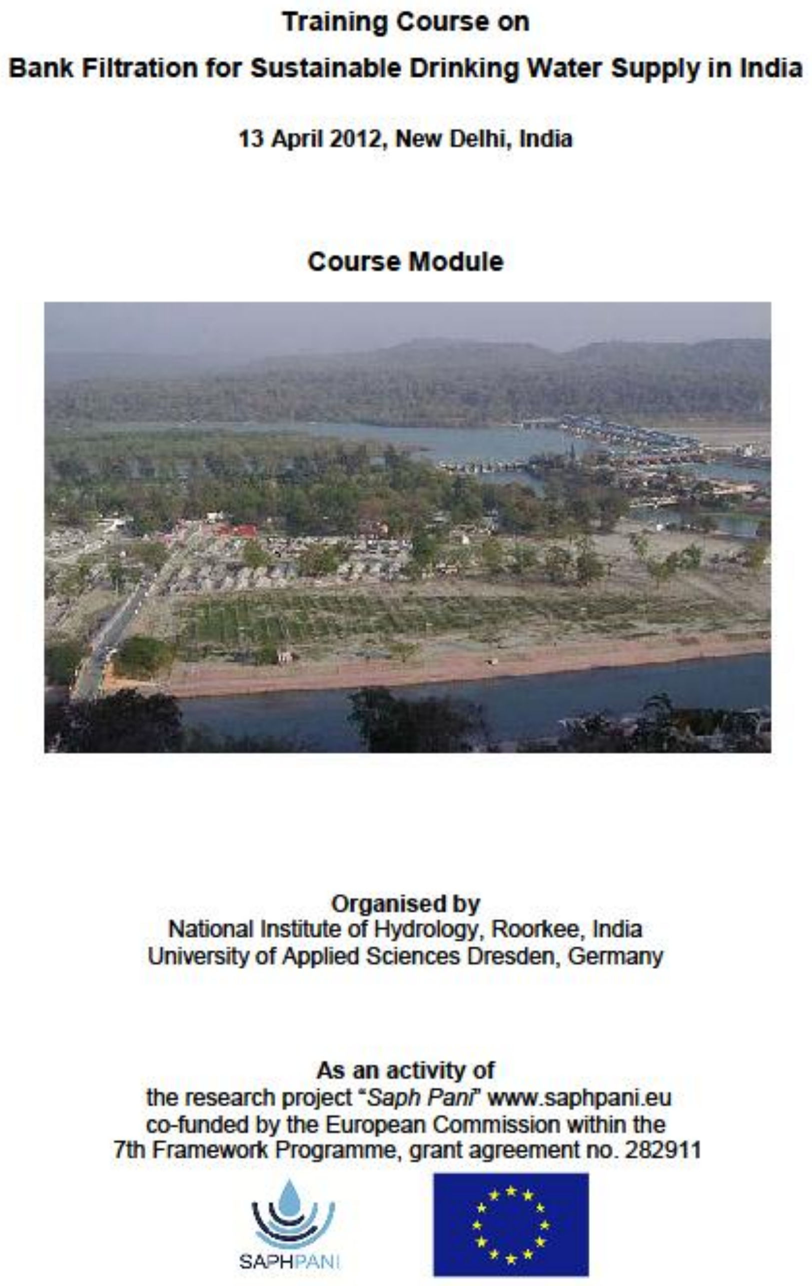
6 Annex-1: Modules for training course on “Bank Filtration for Sustainable Drinking Water Supply”



Training Course on

Bank Filtration for Sustainable Drinking Water Supply in India

13 April 2012, New Delhi, India

Course Module

Organised by
National Institute of Hydrology, Roorkee, India
University of Applied Sciences Dresden, Germany

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1 Introduction

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

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

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

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

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

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

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

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

2 Bank filtration – Overview

2.1 Process

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

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

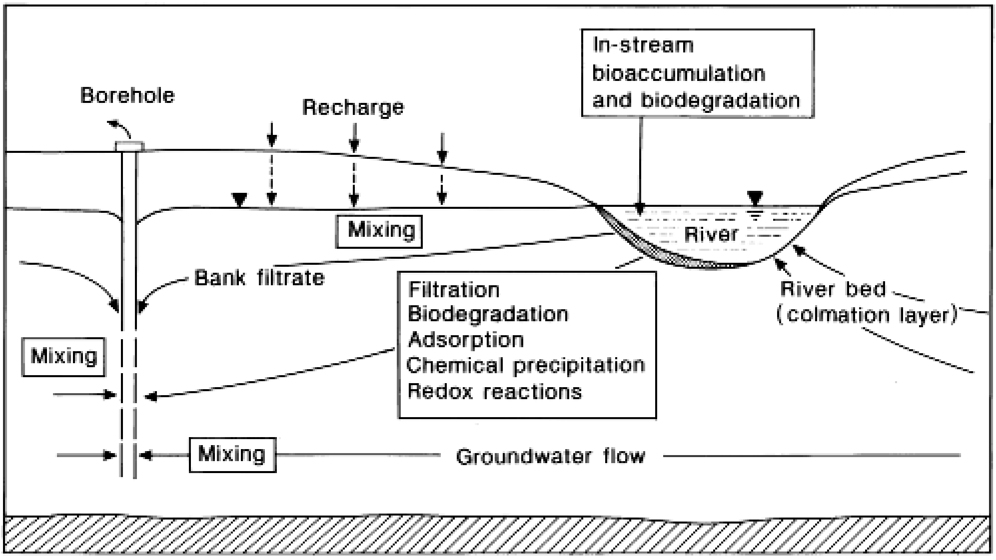


Figure 2-1 Schematic diagram of processes affecting water quality during bank filtration (Hiscock & Grischek, 2002)

2.2 Applications

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

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

2.3 Advantages and Disadvantages

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

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

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

Undesirable effects of bank filtration on water quality can include

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

2.4 Riverbank filtration examples from Dresden, Germany

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

Dresden, the capital of the federal state of Saxony, Germany, has half a million inhabitants. The city is situated in a rift valley along the Elbe River, which is mainly filled with glacial deposits consisting of gravels and coarse sands with a thickness of about 15 m and a hydraulic conductivity ranging from $0.6 - 2\times10^{-3}$ m/s. The Quaternary aquifer is in direct hydraulic contact with the Elbe River. In Dresden, the flow of the Elbe River ranges from 100 - 4,500 m^3/s with a mean of about 300 m^3/s. In general groundwater exfiltrates from both sides of the valley into the river.

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

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

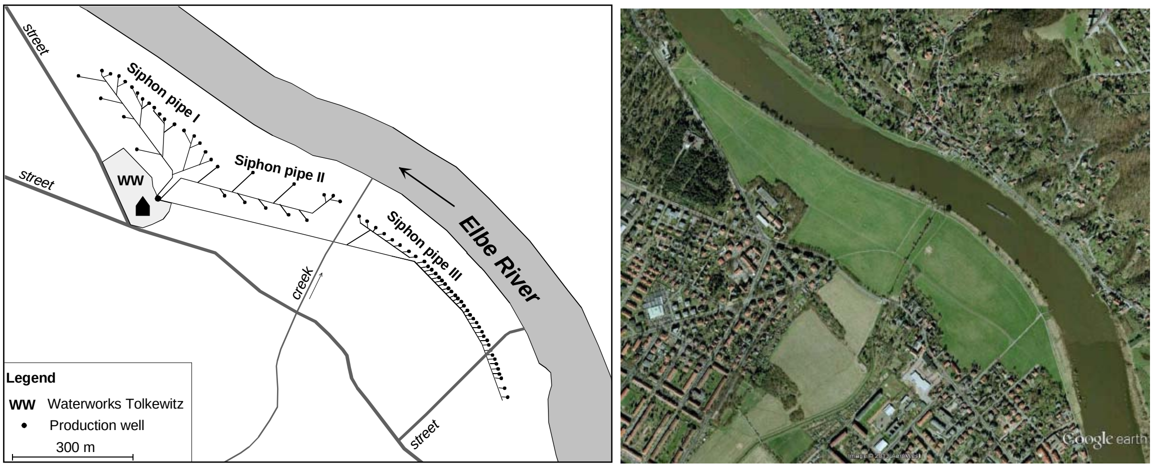


Figure 2-2 Location map of the bank filtration scheme of waterworks Dresden-Tolkewitz (Grischek et al., 2011) and satellite view on location (Source: Google earth)

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

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

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

3 Bank filtration - site investigation, assessment & well operation

3.1 Site investigation

3.1.1 Geological analyses

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

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

3.1.2 Surface water quality data review

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

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

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

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

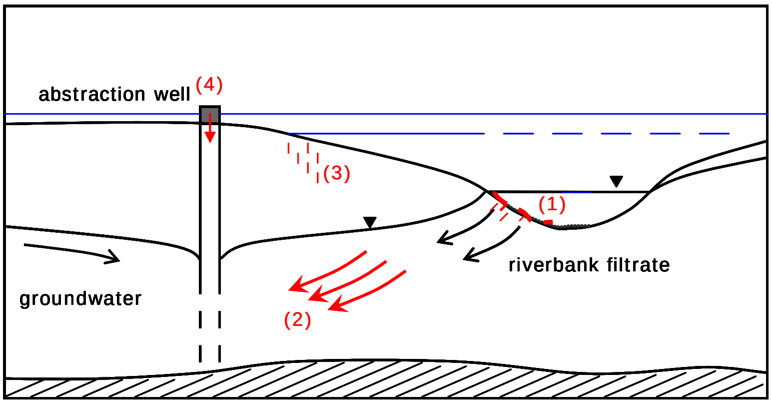
3.1.3 Hydrologic assessment

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

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

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

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



(1) Clogging layer

(2) Pressure gradient

(3) Unsaturated regions

(4) Flooding of the well

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

3.1.4 Groundwater flow and transport modelling

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

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

More details are given in Section 4.

3.1.5 Key characteristics of BF sites

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

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

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

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

3.2 Assessment

3.2.1 Pumping test

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

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

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

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

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

3.2.2 Monitoring

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

3.2.3 Example - pumping test at Srinagar, India

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

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

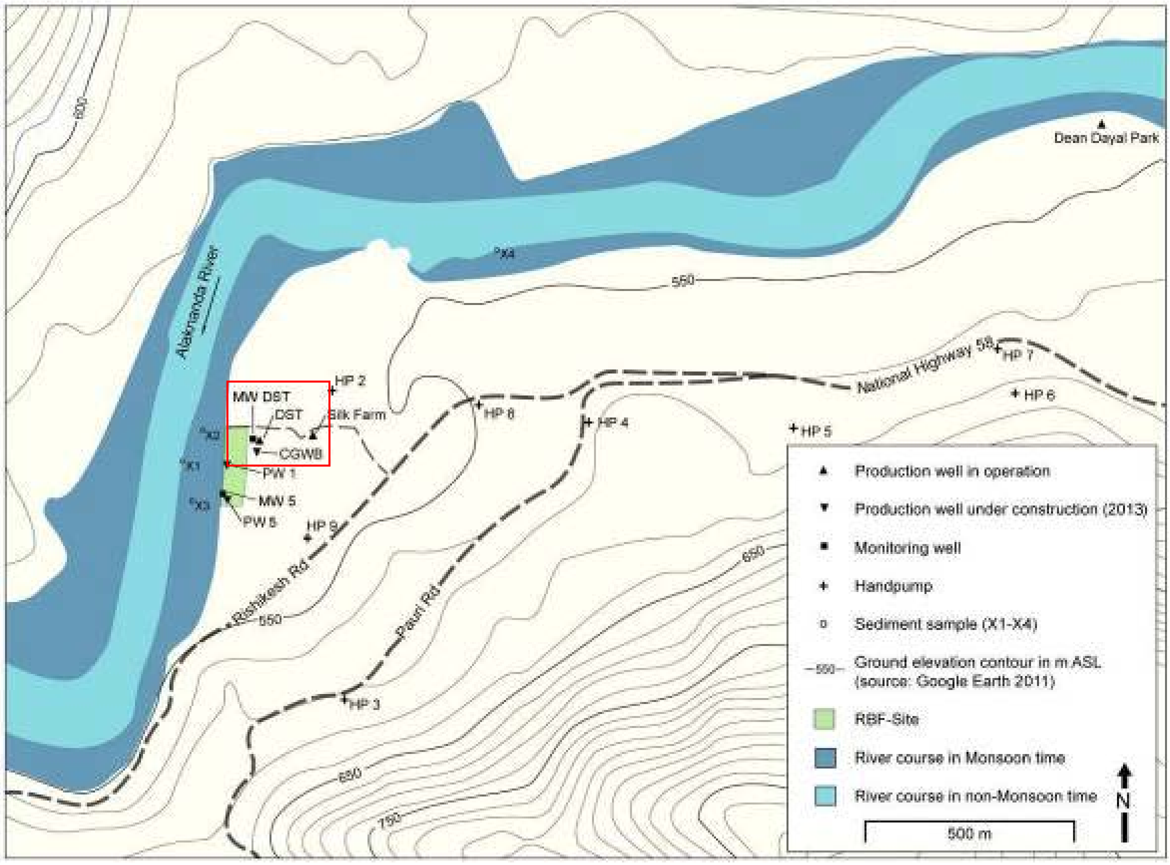


Figure 3-2 Location of pumping test wells at Srinagar (Saph Pani, 2013)

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

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

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

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

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

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

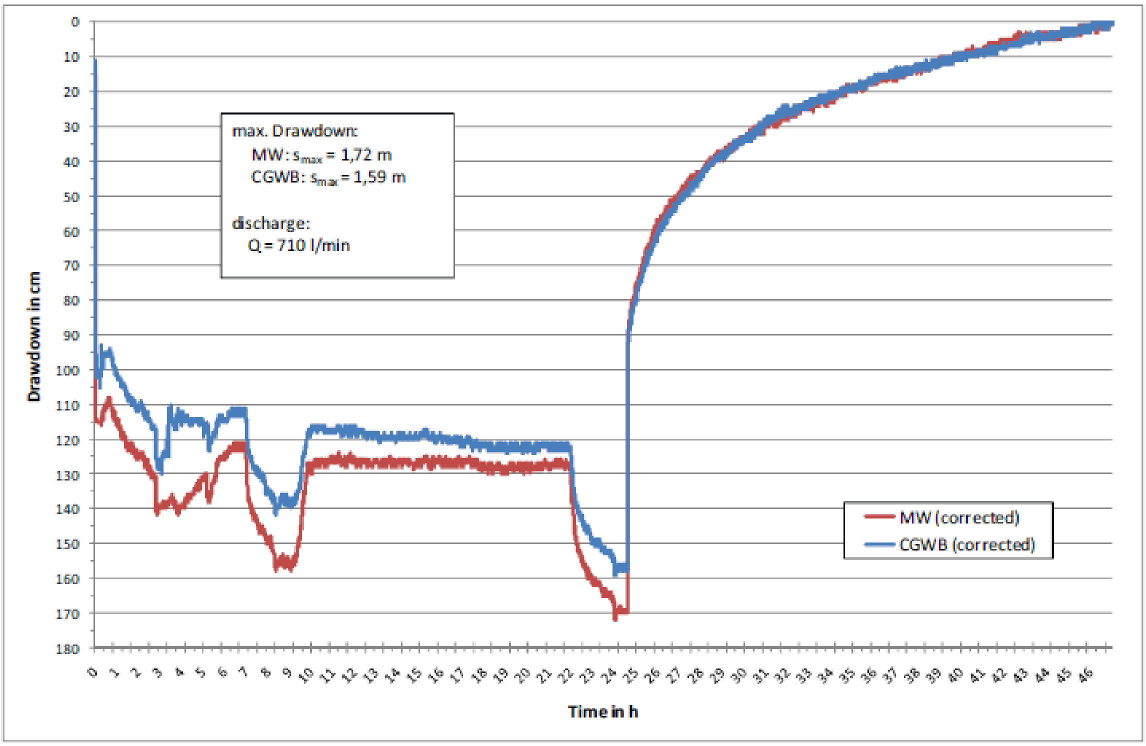


Figure 3-3 Location of pumping test wells at Srinagar (HTWD and UJS, 2012a)

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

The processed results are shown in Figure 3-4. The transmissivity was calculated using the Neumann method that takes into account boundary conditions such as rivers and no-flow boundaries e.g. presence of impermeable barriers such as rock-massifs of mountains. The calculated transmissivity of 0.045 m^2/s was then divided by the saturated thickness of the aquifer resulting in a hydraulic conductivity k of 4×10^{-3} m/s.

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

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

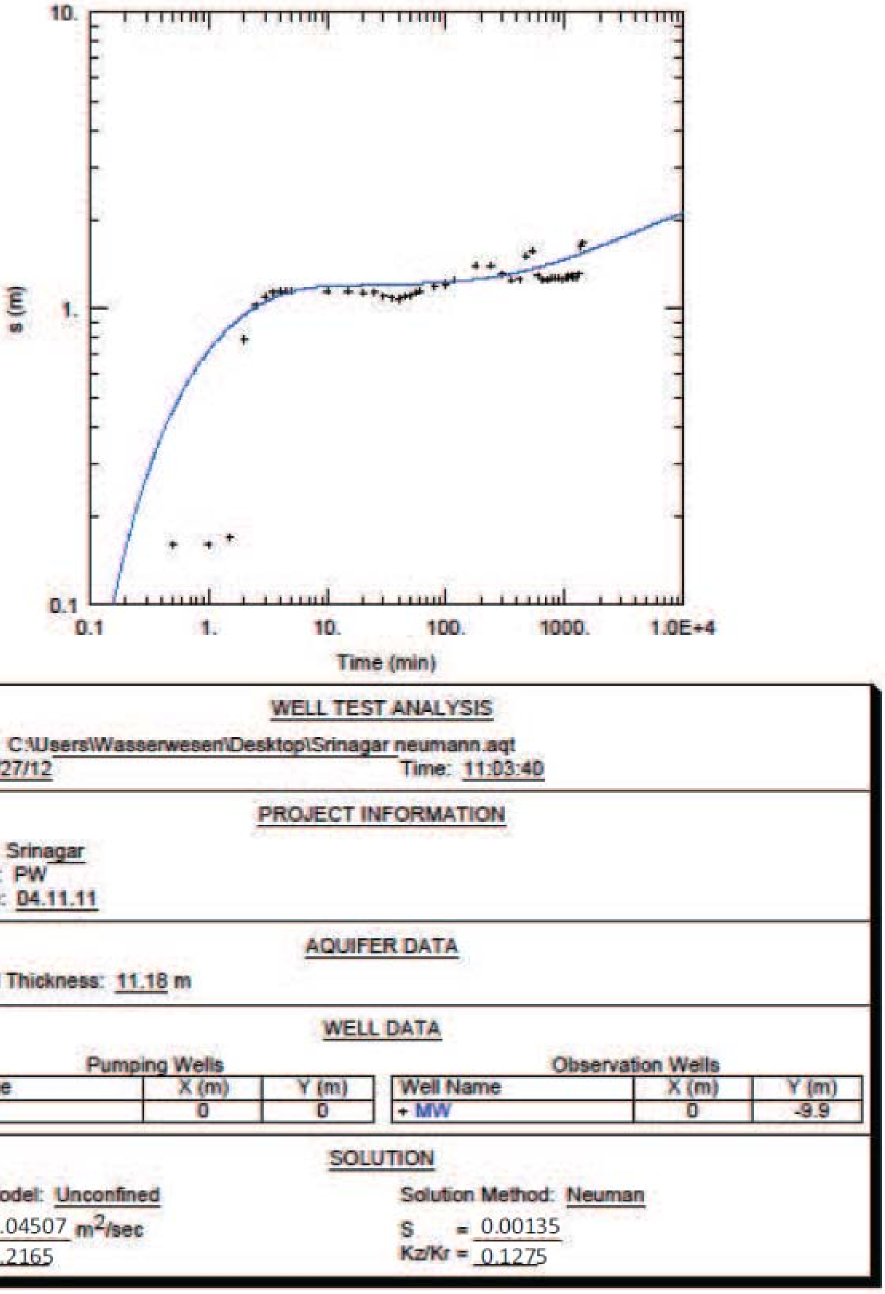
$$q = \frac{Q}{A} = k \cdot \frac{h}{l}$$

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

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

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

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



WELL TEST ANALYSIS

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

PROJECT INFORMATION

Location: Srinagar
Test Well: PW
Test Date: 04.11.11

AQUIFER DATA

Saturated Thickness: 11.18 m

WELL DATA

Pumping Wells

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

Observation Wells

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

SOLUTION

Aquifer Model: Unconfined
Solution Method: Neuman

T = 0.04507 m²/sec
Sy = 0.2165
S = 0.00135
Kz/Kr = 0.1275

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

3.3 Flood Risk

3.3.1 Introduction

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

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

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

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

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

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

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

3.3.2 Mitigation Measures

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

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

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

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

Sanitary sealing

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

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

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

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

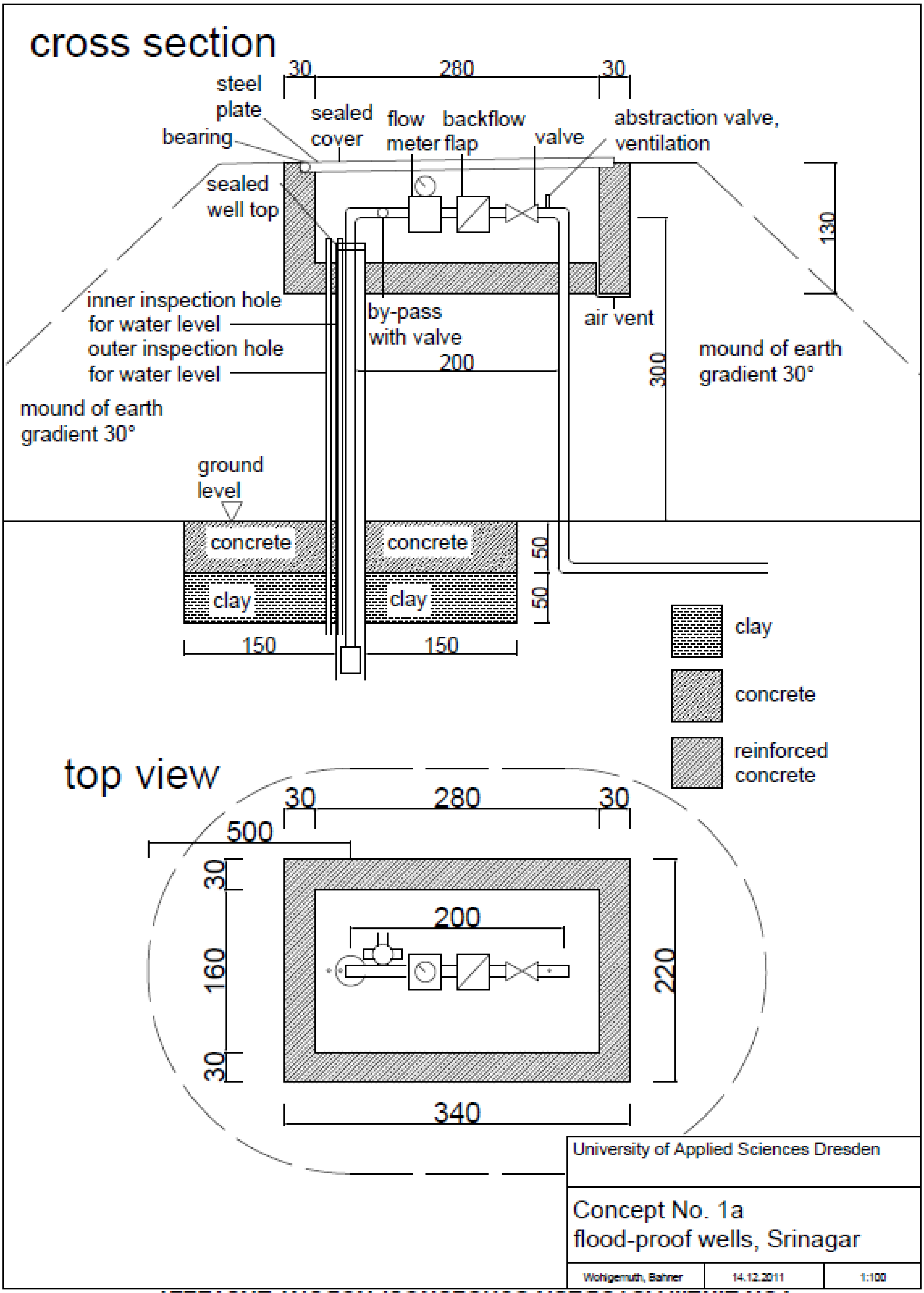


Figure 3-6 Design 1 - Cement-concrete well-head chamber built on elevated mound (Saph Pani, 2013)

Design 2 - Elevated platform

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

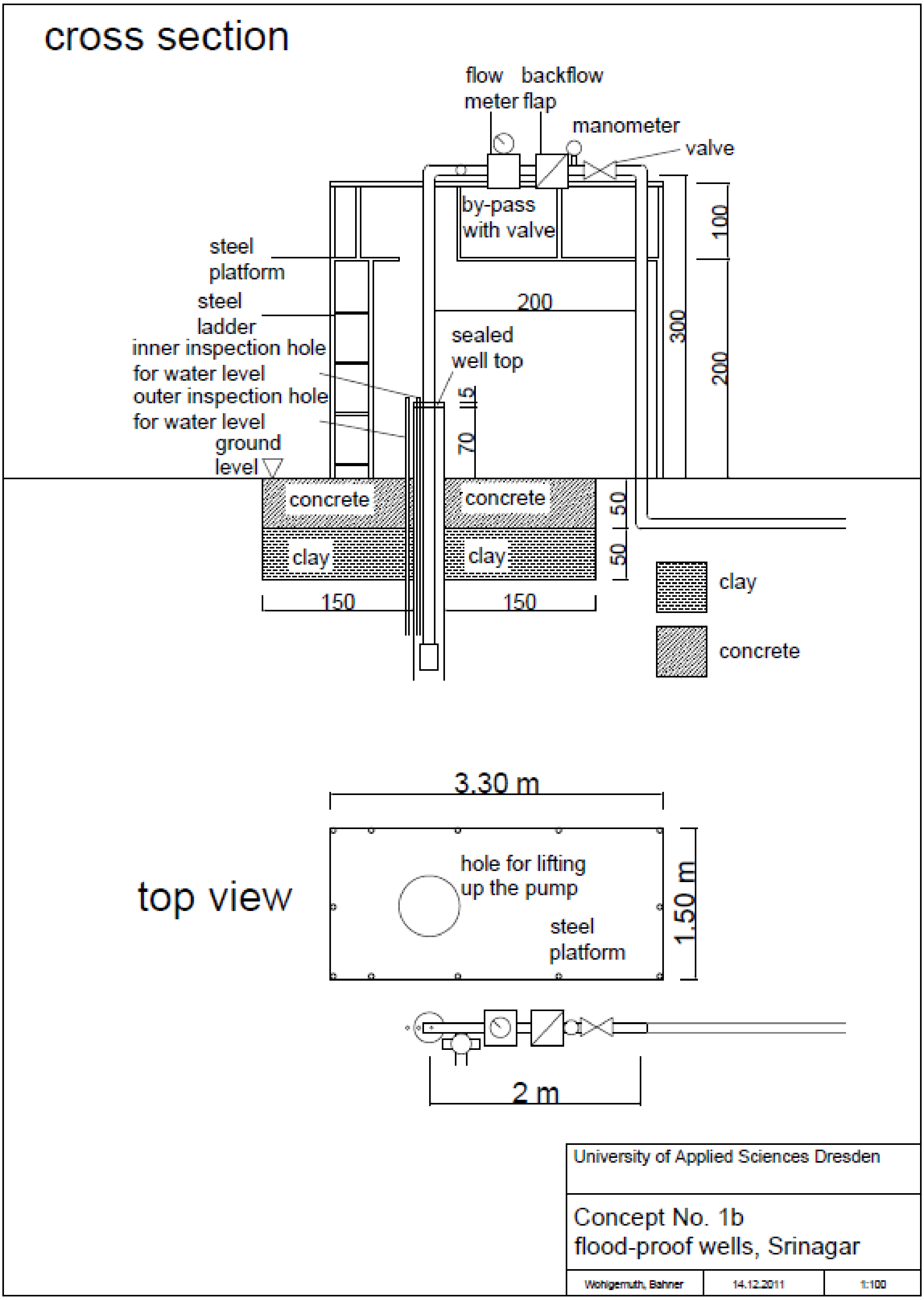


Figure 3-7 Design 2 – Elevated platform (Saph Pani, 2013)

Design 3 – Subsurface reinforced concrete well chamber

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

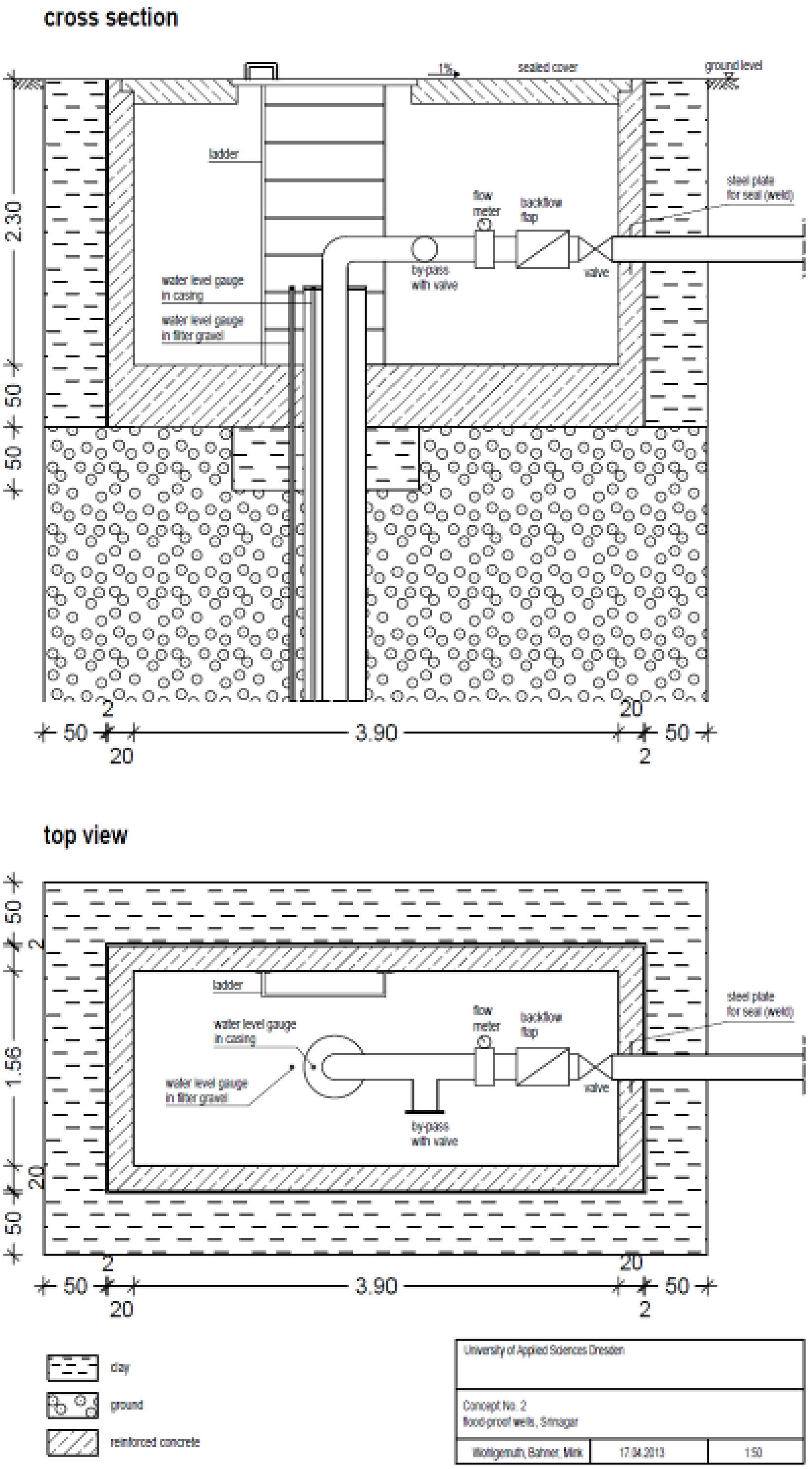


Figure 3-8 Design 3 – Subsurface reinforced concrete well chamber (Saph Pani, 2013)

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

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

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

Overview of identifiable risks

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

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

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

Existing flood protection measures

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

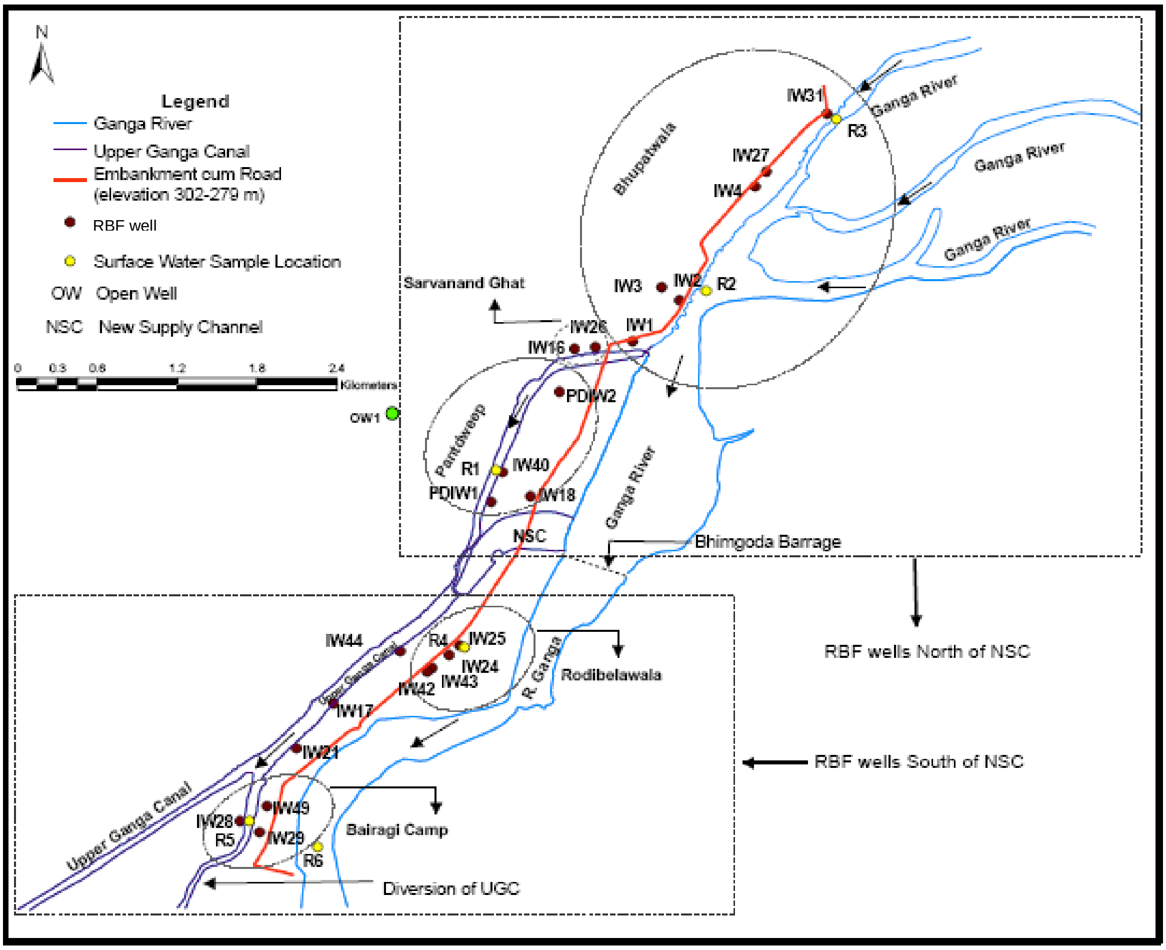


Figure 3-9 Flood protection embankment cum road (red line) (Saph Pani, 2013)

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

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

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

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

Design of wells and direct contamination

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

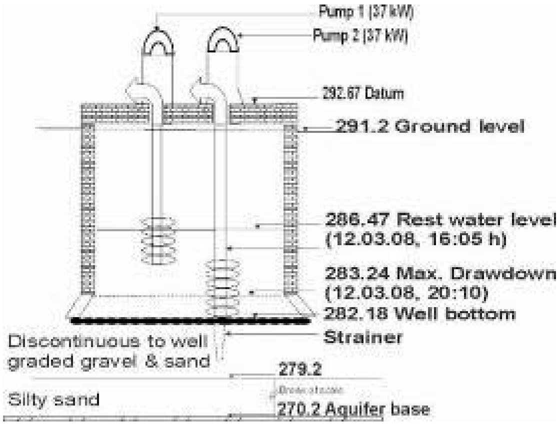


Figure 3-13 Cross-section of a typical large-diameter caisson RBF well (IW18) in Haridwar (Sandhu, 2013)

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

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

3.4 Isotope analyses

3.4.1 Isotopic characteristics of water

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

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

3.4.2 Methodology

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

$$m_r = m_1 + m_2 \tag{3.1}$$

$$m_r C_r = m_1 C_1 + m_2 C_2 \tag{3.2}$$

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

$$m_1 = 1 - m_2 \tag{3.3}$$

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

$$m_2 = \frac{C_1 - C_r}{C_1 - C_2} \tag{3.4}$$

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

3.4.3 Sampling locations and frequency

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

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

3.4.4 Results of isotope analyses

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

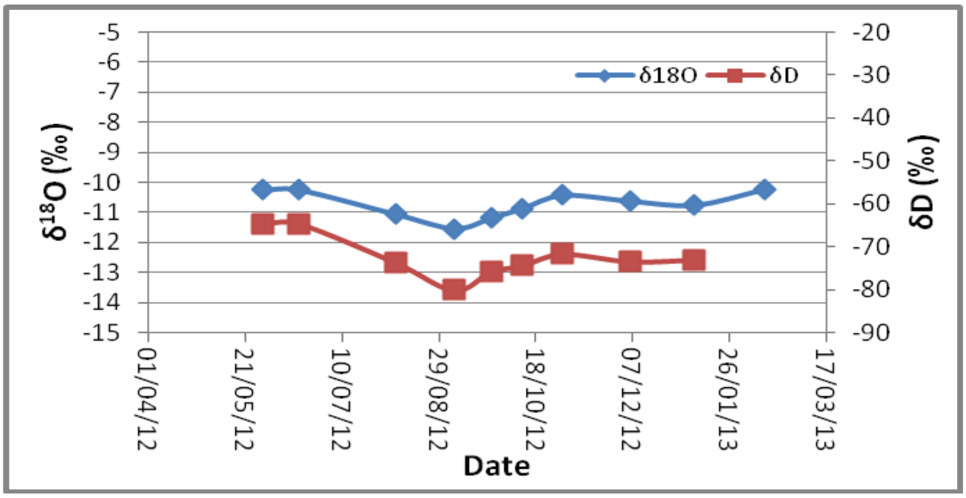


Figure 3-15 Isotopic characteristics of Ganga River water at Haridwar (Saph Pani, 2013)

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

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

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

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

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

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

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

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

		2012								2013	
Location	Well No.	30.05.	18.06.	07.08.	06.09.	25.09.	11.10.	01.11.	06.12.	08.01.	13.02.
Bhupatwala											
Jhanda Chowk Jawalapur	OW2		25	24		40	33		51	54	56
Firahediyan Jawalapur	OW3		42	39	26	36	31		33	38	30
Colour code	Dark green	>75%	Light green	50-75%	Light blue	25-50%	Pink	<25%			

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

4.1 Introduction

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

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

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

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

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

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

4.2 Modelling using MODFLOW and its application PROCESSING MODFLOW

4.2.1 Overview

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

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

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

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

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

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

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

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

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

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

4.2.2 Example - modelling of RBF site at Srinagar, India

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

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

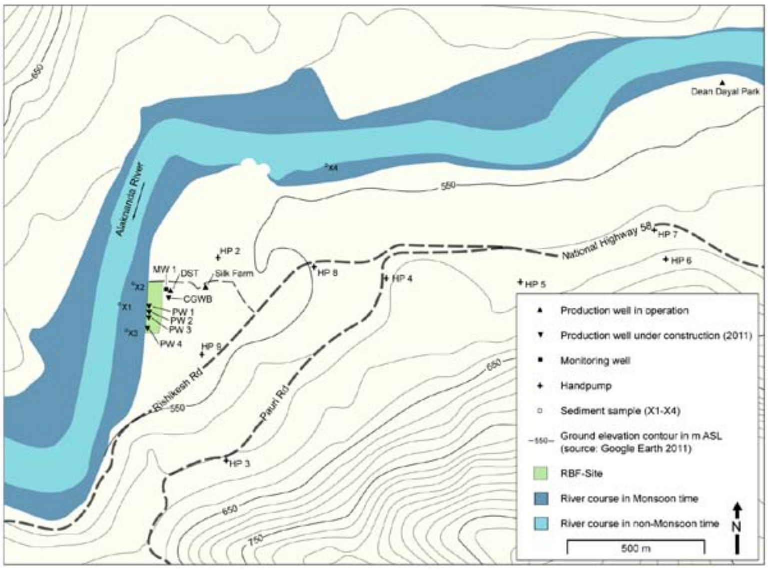


Figure 4-1 Modelling Area at Srinagar (Saph Pani, 2012)

Model construction and run

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

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

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

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

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

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

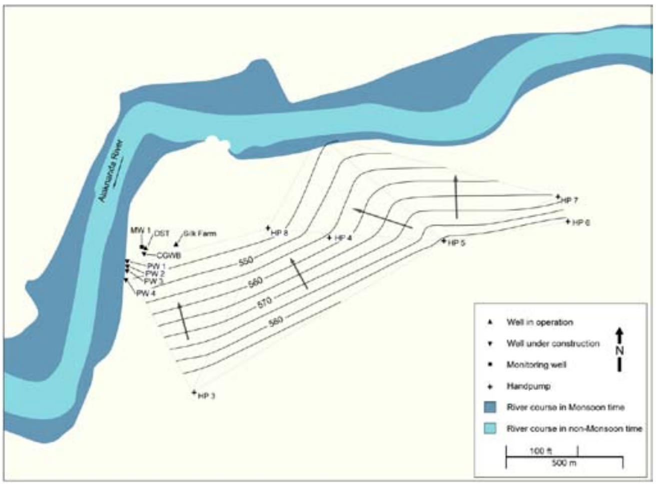


Figure 4-2 Groundwater triangulation to initially assess the groundwater flow regime at Srinagar prior to modelling (HTWD and UJS, 2012b)

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

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

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

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

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

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

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

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

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

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

The effective porosity has been estimated to be 0.3.

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

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

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

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

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

Interpretation of Results

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

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

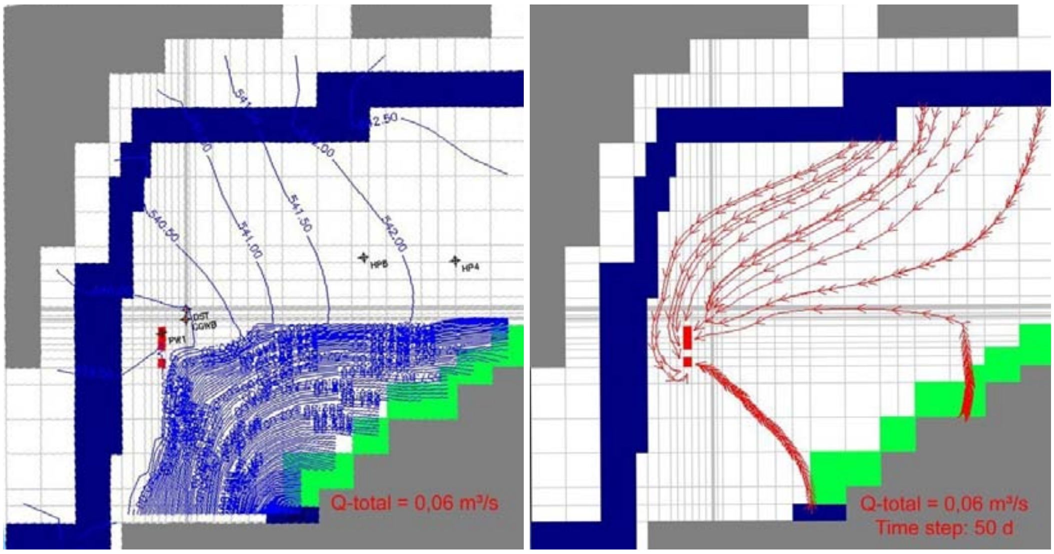


Figure 4-3 Simulated groundwater contours (left) and flow paths (right) at Srinagar - Scenario 1 (Saph Pani, 2012)

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

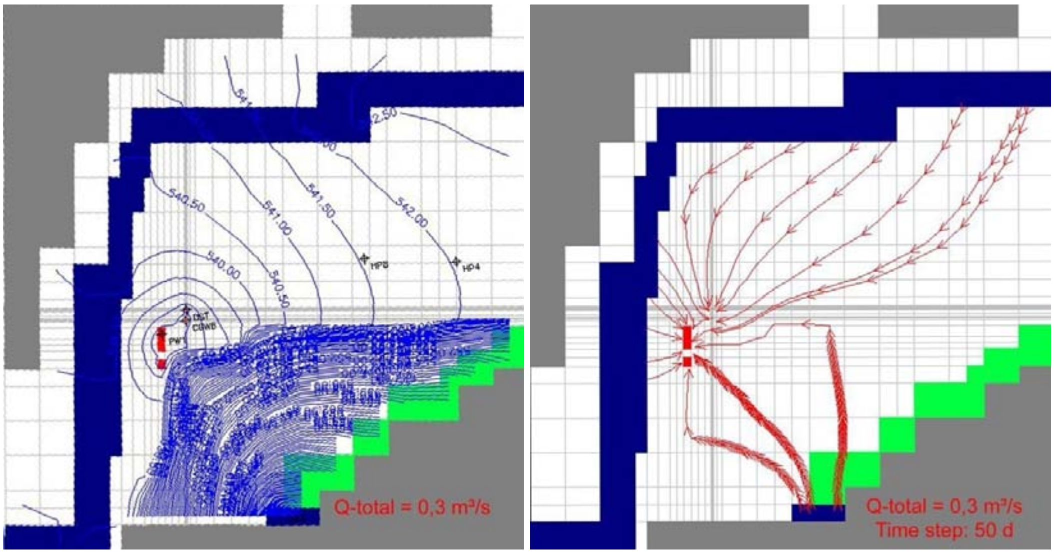


Figure 4-4 Simulated groundwater contours (left) and flow paths (right) at Srinagar – Scenario 2 (Saph Pani, 2012)

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

5 Water quality aspects during bank filtration

5.1 Overview

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

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

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

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

5.2 Removal of Pathogens

5.2.1 History

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

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

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

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

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

5.2.2 Disease causing pathogens

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

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

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

5.2.3 Microbial indicators

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

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

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

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

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

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

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

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

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

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

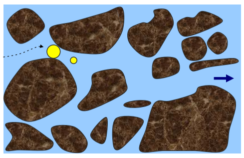
The colony count at 22°C or 20°C represents the number of colonies which can either be detected without a magnifying glass after incubating 1 ml drinking water at 22°C for 72 hours on a nutrient-poor culture medium, or with a magnifying glass after incubating 1 ml drinking water at 20°C for 44 hours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

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

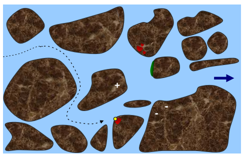
5.2.4 Removing Processing

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

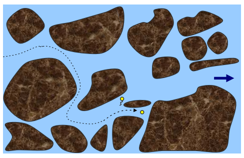
Various environmental factors as well as microbial properties influence the transport and removal processes such as straining, adsorptions, stagnation, grazing and natural decay. Further details are given below.



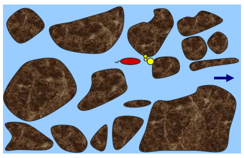
The efficiency of *straining*, i.e. physical filtration depends on the size and shape of the individual microbial pathogen in relation to the particular grain and pore size distribution.



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

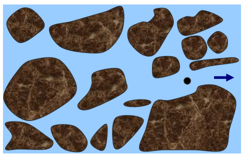


Stagnation In dependence of pore size distribution, flow regime, microbial size and mobility, pathogens can (temporarily) *stagnate* when reaching dead end pores.



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

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



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

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

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

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

5.2.5 Efficiency of pathogens removal at bank filtration sites

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

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

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

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

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

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

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

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

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

5.3 Organic miropollutants

5.3.1 Claimer

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

5.3.2 Introduction

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

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

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

5.3.3 Pesticides

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

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

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

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

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

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

5.3.4 Hydrocarbons

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

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

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

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

5.3.5 Endocrine disruptors

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

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

Table 5-7 Degradation of endocrine disruptors during underground passage

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

BPA = bisphenol A, E2 = 17ß-estradiole, EE2 = 17α- ethinylestradiole, NP = nonylphenol, OP = octylphenol, NPM = nonylphenol monoethoxylate

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

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

5.3.6 Pharmaceuticals

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

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

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

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

Table 5-8 Overview of substance degradability during subsurface passage

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

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

5.3.7 Summary

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

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

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

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

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

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

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

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

5.4 Example – removal of pathogens at Srinagar, India

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

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

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

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

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

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

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

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

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

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

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

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

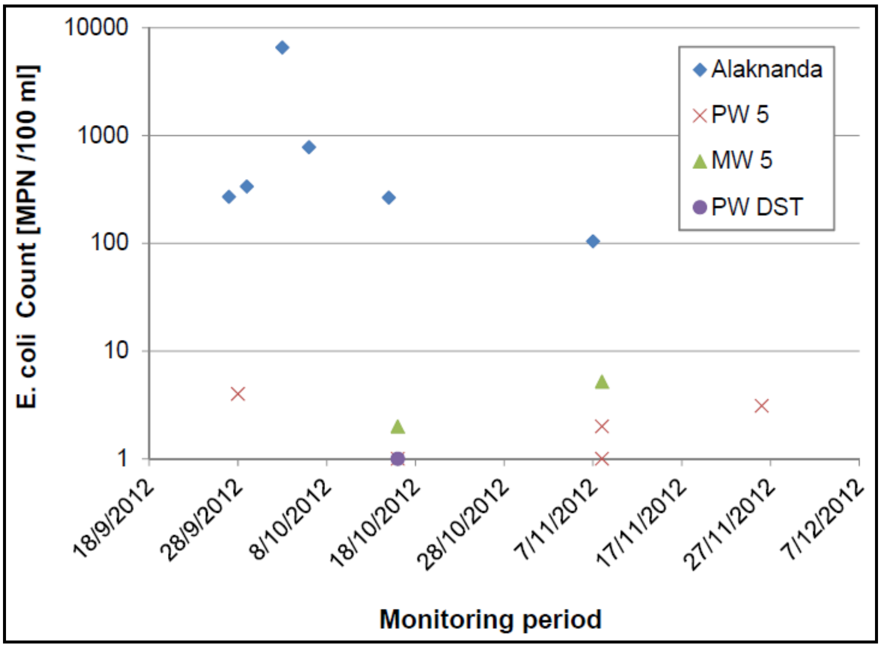


Figure 5-2 E. Coli counts in the Alakanda river and wells at the RBF site in Srinagar during the period September – November 2012 (Saph Pani, 2013)

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

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

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

Removal of particles and turbidity

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

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

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

Equilibration of fluctuating concentrations in the river water

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

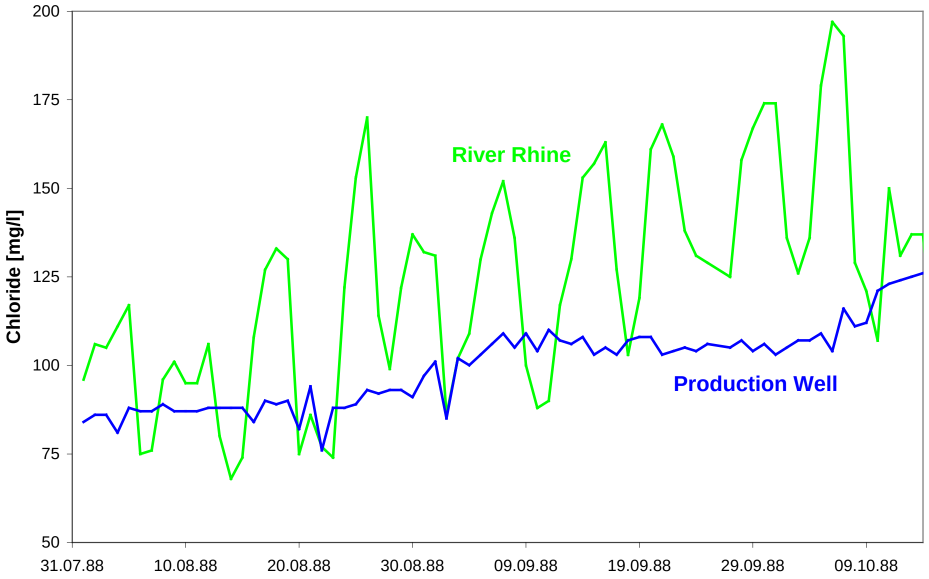


Figure 5-3 Equilibration of chloride fluctuation during bank filtration

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

Removal of biodegradable compounds

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

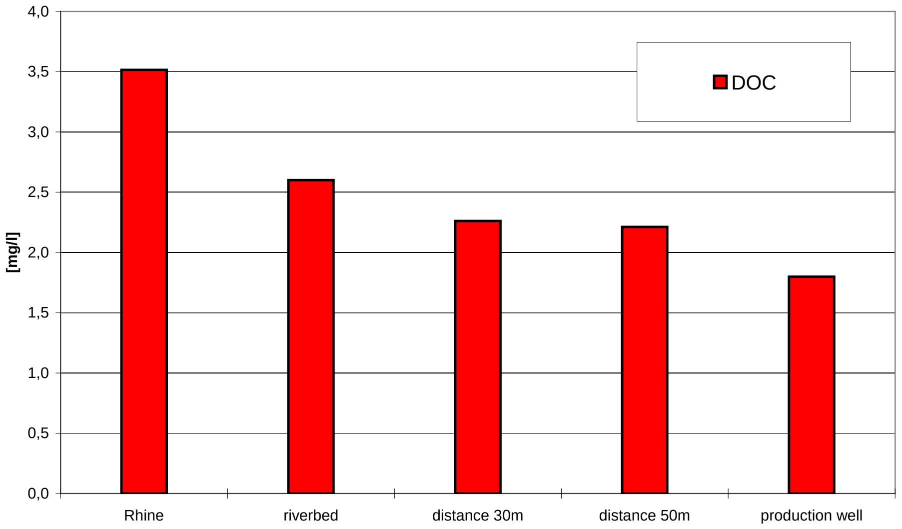


Figure 5-4 Removal of DOC under aerobic conditions

6 Details of case study sites used as examples

6.1 Riverbank filtration site in Srinagar, India

6.1.1 General geography

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

6.1.2 Drinking water production

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

6.1.3 Riverbank filtration scheme

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

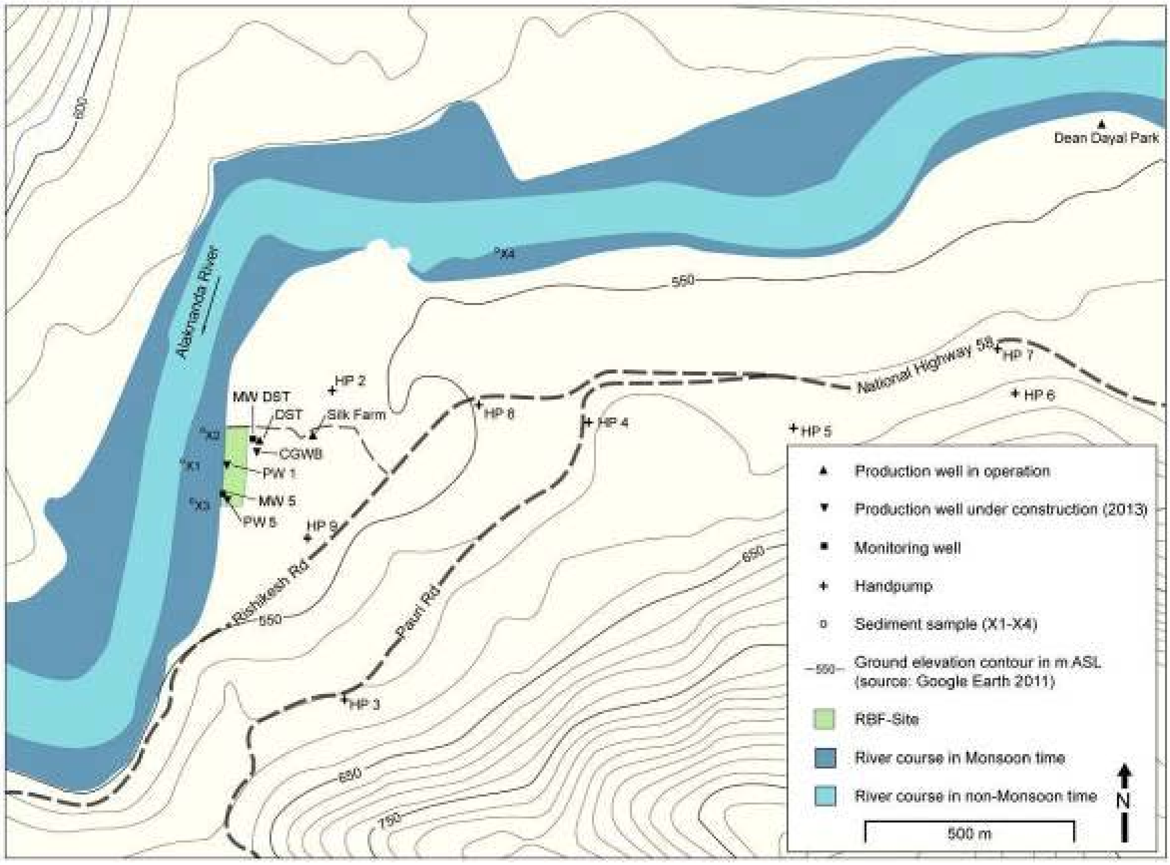


Figure 6-1 RBF well field in Srinagar under development since May 2010 (Saph Pani, 2013)

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

6.1.4 Hydrogeology

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

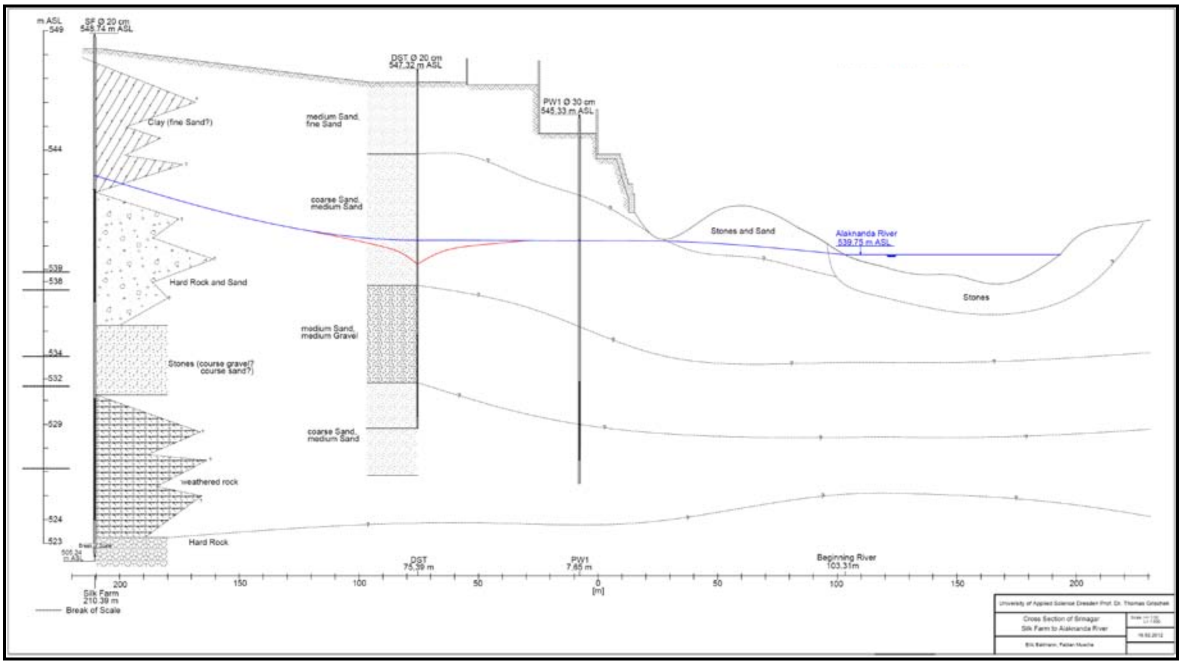


Figure 6-2 Subsurface cross section of RBF site in Srinagar (Saph Pani, 2013)

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

6.1.5 Historic flood event in Srinagar

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

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

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

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

6.2 Riverbank filtration site in Haridwar, India

6.2.1 General geography

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

6.2.2 Religious significance and impact on population numbers

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

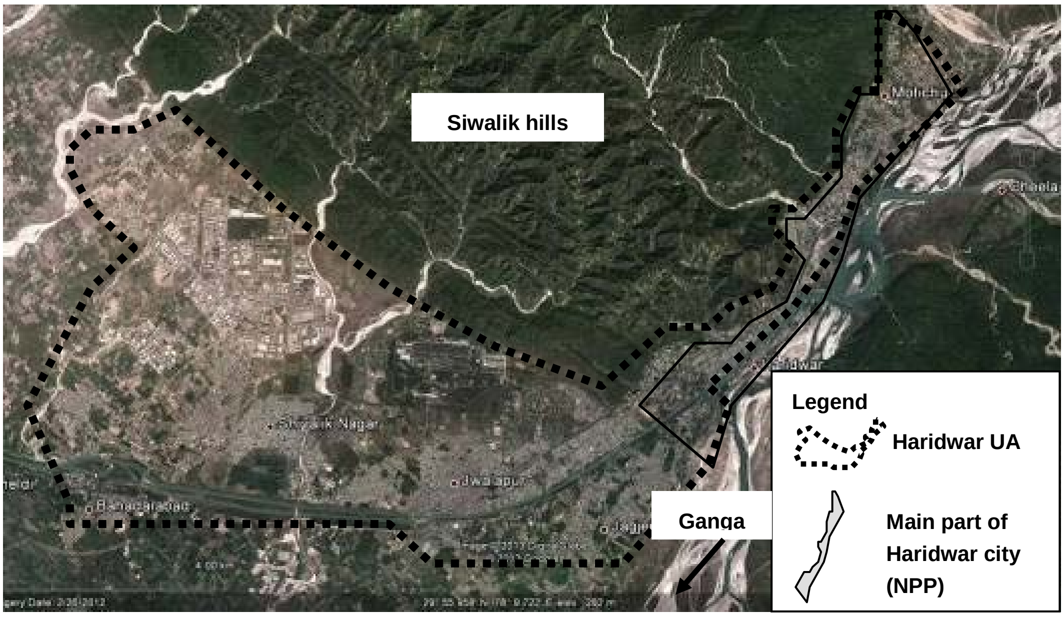


Figure 6-5 Overview of Haridwar (adapted from Google earth © Google, 2013)

6.2.3 Riverbank filtration scheme

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

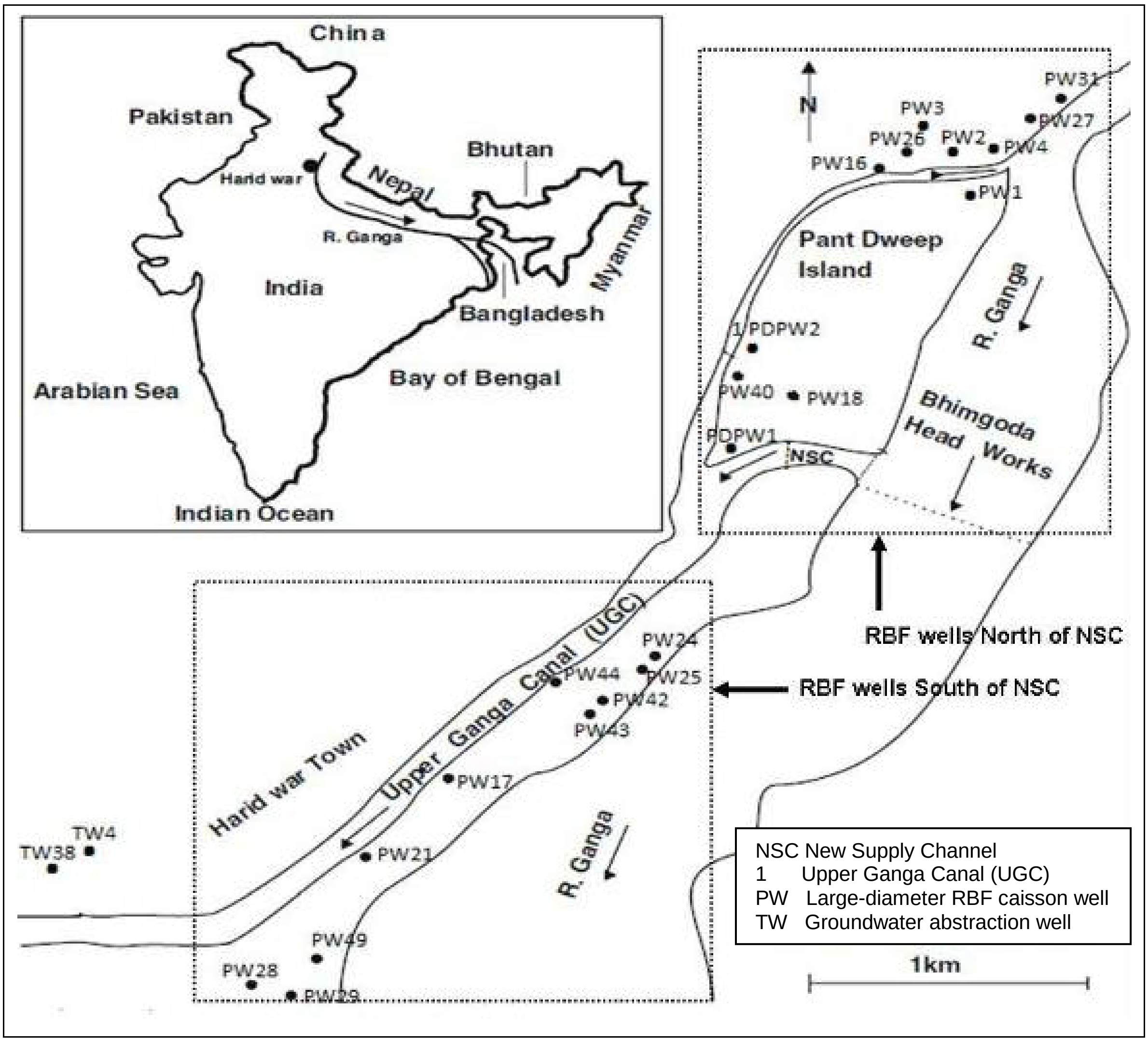


Figure 6-6 Location of large-diameter RBF wells in Haridwar (after Saini 2011)

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

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

6.2.4 Hydrogeology

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

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

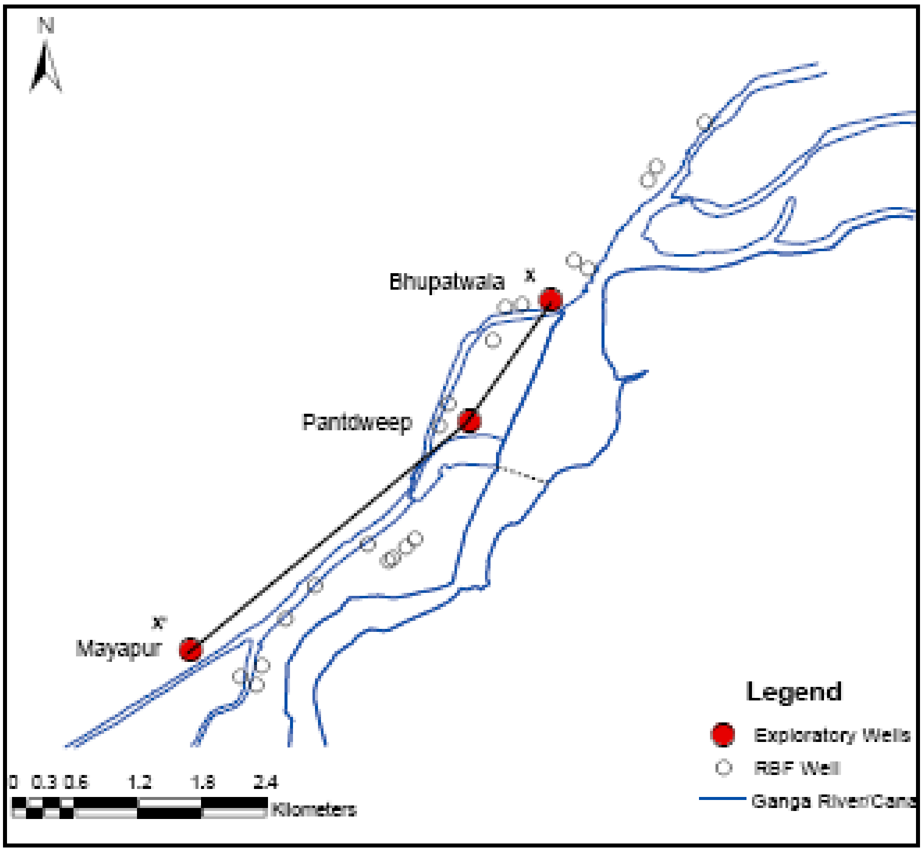


Figure 6-8 Transect X-X' connecting the exploratory wells used for aquifer characterisation (Saph Pani, 2013)

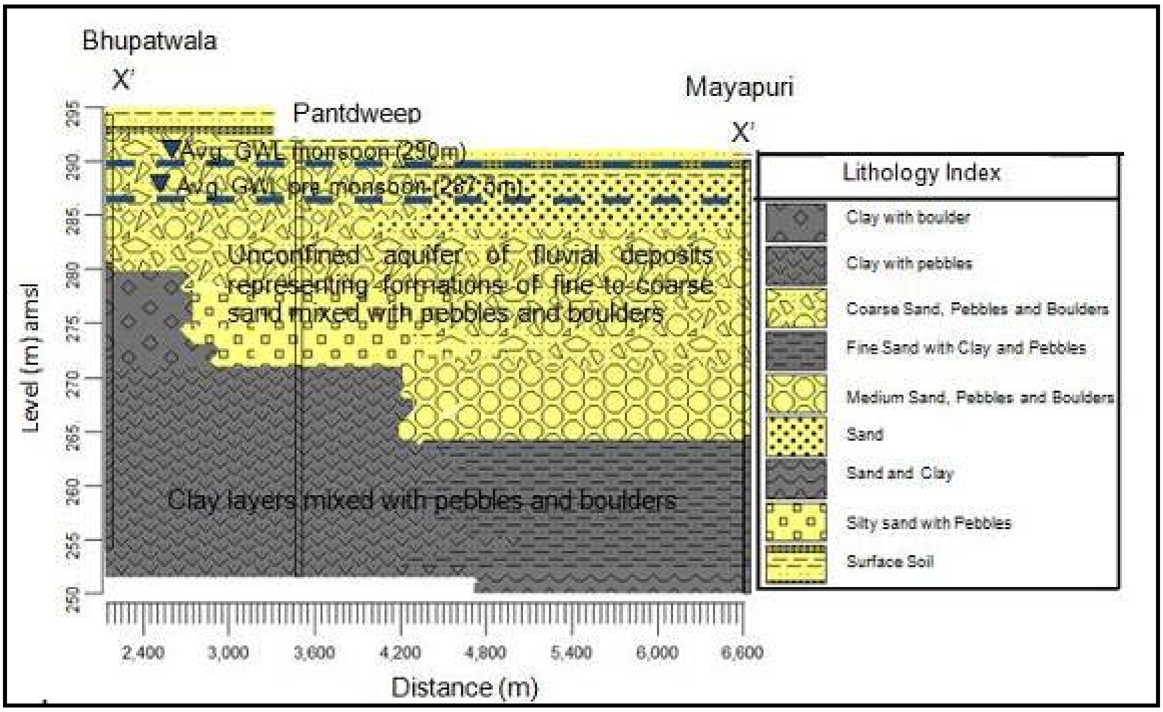


Figure 6-9 Cross-section of the study area along the X-X' transect in Figure 6-8 (Saph Pani, 2013)

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

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

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

6.2.5 Historic flood event in Haridwar

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

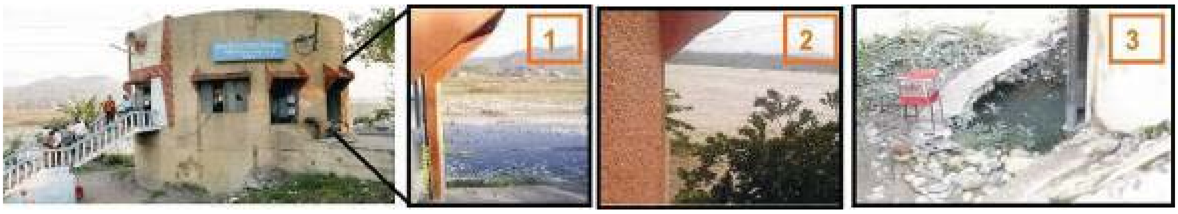


Figure 6-10 RBF well IW 24 in Haridwar (left photo), (1) view of the Ganga River in the background in April 2005 (pre-monsoon), (2) flood-water of Ganga inundates the base of well on 19/09/2010 and (3) damage by scouring to base of well no. 24 (photos from L to R: Schoenheinz and Grischek (2005), Subodh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

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

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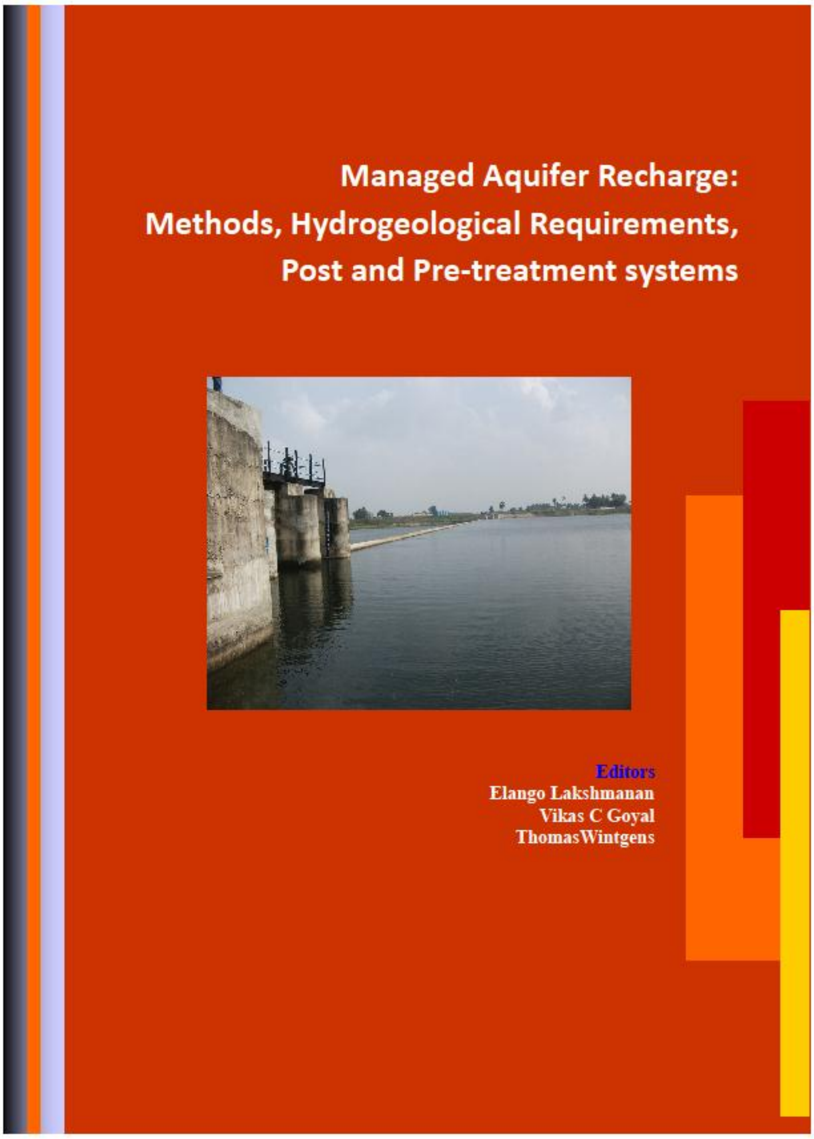
8 Annex-2: Modules for training course on "Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Post and Pre-treatment Systems"



Managed Aquifer Recharge:
Methods, Hydrogeological Requirements,
Post and Pre-treatment systems

Editors
Elango Lakshmanan
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Preface

Increasing demand for water has resulted into over dependence on groundwater, especially in regions where surface water resources are limited and temporal rainfall is uneven. Exploitation of groundwater for various purposes has resulted in depletion of resources and rapid decline in groundwater table in several parts of the world. In order to balance the overdraft of groundwater, it is necessary to increase the rainfall recharge which will result in increase of groundwater storage and improvement in the water quantity.

Managed Aquifer Recharge (MAR) is carried out in many parts of the world including India to increase the rainfall recharge and combat with the present water crisis. Implementation of MAR requires knowledge about the location, quantity and quality of water recharged. In urban areas, MAR can provide effective storage for desalinated seawater, recycled water, storm water. Methods of MAR currently include aquifer storage and recovery (ASR), aquifer storage, infiltration ponds, infiltration galleries, soil aquifer treatment, percolation tanks and check dams. MAR can be used to address a wide range of water management issues, including, storing water in aquifers for future use, stabilizing or raising groundwater levels where over-exploited, impeding storm runoff and soil erosion, improving water quality and smoothing fluctuations, maintaining environmental flows in streams and rivers, managing saline intrusion or land subsidence, disposal or reuse of waste and storm water.

The Saph Pani (Hindi word meaning potable water) project “Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India” aims to study and improve natural water treatment systems, such as river bank filtration (RBF), MAR and wetlands in India, building local and European expertise in this field. The project aims to enhance water resources and water supply, particularly in water stressed urban and peri urban areas in different parts of the Indian sub-continent. This project is co-funded by the European Union under the Seventh Framework (FP7) scheme of small or medium scale focused research projects for specific cooperation actions (SICA) dedicated to international cooperation partner countries.

The objective of this project is to strengthen the scientific understanding of the performance-determining processes occurring in the root, soil and aquifer zones. The removal and fate of important water quality parameters, such as pathogenic micro-organisms and faecal indicators, organic chemicals, nutrients and metals will be considered. The hydrological characteristics (infiltration and storage capacity) and the ecosystem functions will also be investigated since they influence the local or regional water resources management strategies (e.g. by providing buffering of seasonal variations in supply and demand). The project focuses on a set of specific case studies in India. These include a range of natural water systems and engineered treatment technologies investigated by different work-packages including RBF, MAR and constructed wetlands. This book covers the following aspects:

- Introduce the participants to MAR at national and international level;
- Provide knowledge on the basics of artificial recharge by MAR, methods, hydrogeological characterisation ;
- Give an insight into case studies in India and abroad.

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Introduction to Managed Aquifer Recharge (MAR) – Overview of schemes and settings world wide

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Abstract. Managed Aquifer Recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit achieved through injection wells, infiltration basins and galleries for rainwater, stormwater, reclaimed water, mains water and water from other aquifers that is subsequently recovered for all types of uses. The efficiency of MAR systems strongly depends on natural framework conditions like hydraulic conductivity and ambient groundwater flow but can be further enhanced by adjusted design and operation. This paper gives an introduction to the wide variety of systems, elaborates the key parameters responsible for efficiency and introduces typical examples for successful MAR world wide.

Introduction

Managed aquifer recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. Normally, this is achieved through injection wells, infiltration basins and galleries for rainwater, storm water, reclaimed water, mains water and water from other aquifers that is subsequently recovered for all types of uses (Dillon et al. 2009). A schematic diagram illustrating the natural and artificial recharge mechanisms along with bank filtration are shown in Fig. 1.

Objectives

Managed Aquifer Recharge (MAR) has applications in augmenting groundwater quantity, improving groundwater quality and also in environmental management. In detail the objectives of the MAR systems can be given as:

Water quantity objectives

- To store water in aquifers for future use (e.g. water supply), for areas with little surface space and /or high evaporation rates and run-off losses.
- To elevate groundwater levels where over-exploited (for environmental protection of aquifers)

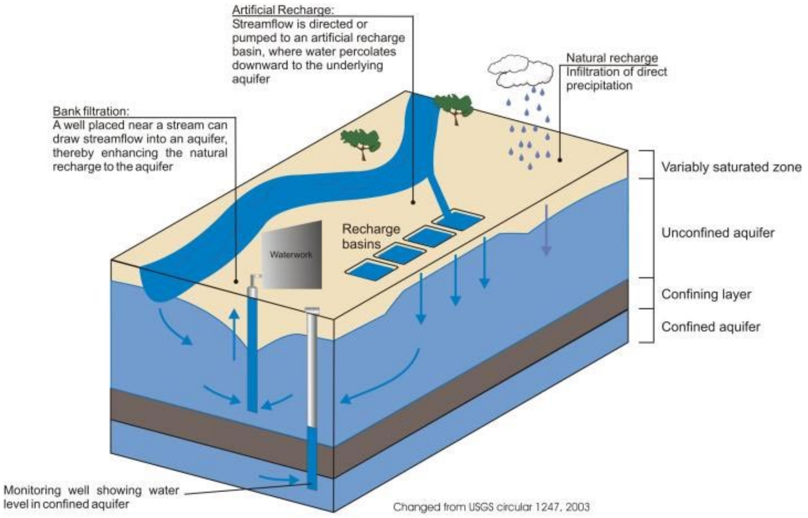

Fig.1. Components of natural and artificial recharge and Bank Filtration techniques (changed from USGS circular 1247, 2003).

Water quality objectives

- Improve water quality in degraded aquifers (e.g. nutrient reduction from agricultural run-off).
- To reduce effort for water treatment (e.g. disinfection byproducts (DBPs) reduction prior to drinking water supply).

Environmental management objectives

- Prevent storm runoff and soil erosion
- Preserve environmental flows in streams/rivers
- Mitigate flood and flood damages
- Control saline intrusion
- Reduce land subsidence
- Hydraulic control of contaminant plumes

Managed Aquifer Recharge (MAR) Structures

A large variety of structures for MAR are available in literature and also in the field, these may broadly classified as surface-spreading, run-off conservation and sub-surface structures (CGWB 2007). Apart from these structures already existing Rain Water Harvesting structures as well as dug wells can be used for aquifer recharge (Fig. 2).

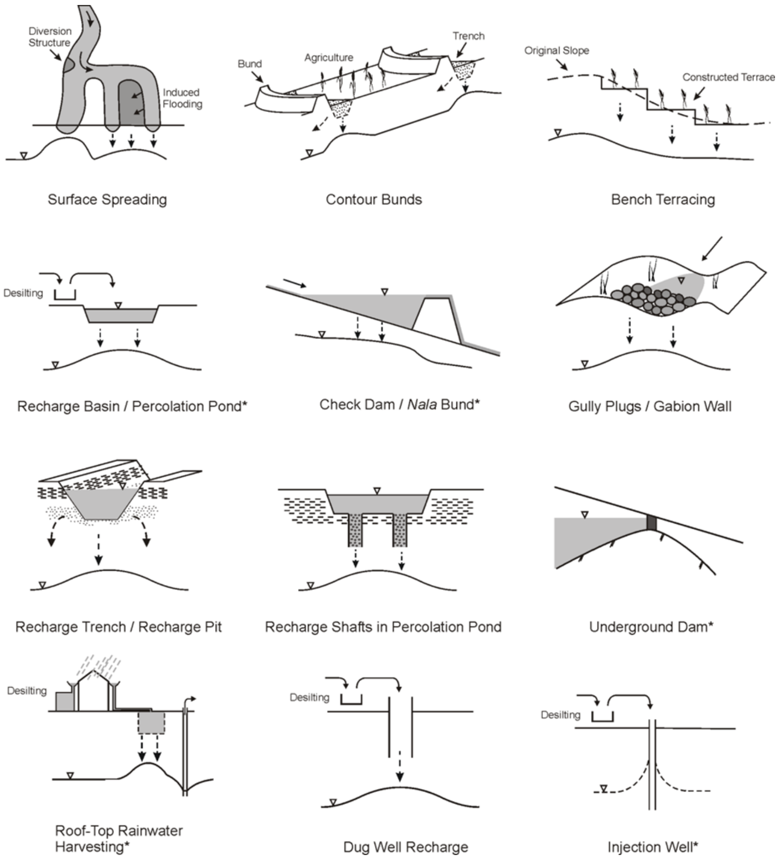

Fig.2. Managed aquifer recharge structures commonly used in India (SAPH-PANI D2.1 (2012), modified from Gale (2005)).

Criteria for initiating MAR projects

The Central Groundwater Board (CGWB 2000) of India has given certain criteria for selecting the potential areas for implementing the MAR structures. These are areas where

- Ground water levels are declining on regular basis.
- The availability of ground water is inadequate in lean months.
- A substantial amount of aquifer has already been desaturated.

- The site is adjacent to a leaky fault or a semi-confining layer containing poor quality water.
- The aquifer contains poor quality water and is highly heterogeneous or has a high lateral flow rate.
- Aquifers show saline intrusion.

Constraints & disadvantages

Although MAR has several advantages, a number of constraints and disadvantages are also reported by various researchers during the implementation. The most commonly encountered problems in MAR, according to Murray (2008) are as follows:

- Clogging
- Uncertainty in aquifer hydraulics
- Uncertainty of complete recovery of stored water
- Uncontrolled recovery by different users
- Regulatory constraints
- Damage to aquifers
- High outlay before feasibility of ASR can be established.
- Operational issues

Factors influencing feasibility and performance of MAR

Hydrogeology

The hydrogeology determines MAR feasibility and is the decisive factor for selecting the optimum location and suitable structure. The aim is to identify aquifers that store large quantities of water and do not release them too quickly. Scientifically, the vertical hydraulic conductivity should be high, while the horizontal hydraulic conductivity should be moderate. However, coexistence of these two conditions is rare case in natural geologic settings.

Detailed investigations on certain parameters, which are inevitable for the successful implementation of a MAR system, are listed below.

- <u>Geological and hydraulic boundaries</u>: data on this parameters are normally available in the regional geology/hydrologelogy maps of the study area
- <u>Inflow and outflow of waters</u>: data regarding these parameters can either be collected from environmental / water authorities or must be measured in the field
- <u>Storage capacity, porosity, hydraulic conductivity, transmissivity</u>: these aquifer parameters must be obtained through pump tests and hydraulic flow models. An overview of hydraulic conductivity val-

ues measured in at BF and AR sites for drinking water production is shown in Fig.3.

- Natural discharge and recharge: recharge estimation may be calculated using the water table fluctuation method or the hydrologic budget method.. Remote sensing-GIS methods can also give valuable information on natural groundwater recharge.
- Water availability for recharge and water balance: source water availability may be calculated from the annual rainfall data, river flow estimation, surface runoff estimation etc.
- Lithology, depth of the aquifer and tectonic boundaries: these datacan be obtained from bore holes, aerial photographs etc.

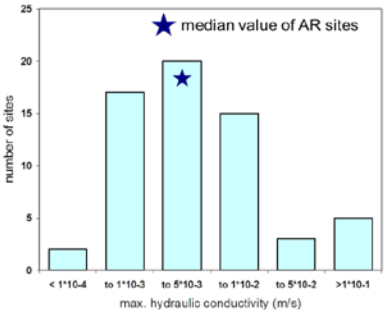

Fig.3. Hydraulic conductivity values observed in the BF and AR sites for drinking water production world wide (n=62).

Different hydrogeological settings and their performance in MAR (Gale 2005)

Alluvium usually consists of highly permeable, unconsolidated sediments ranging from coarse gravel to impermeable silt and mud. Alluvial aquifers are often found in lower reaches of river basins. In most regions with alluvial aquifers, the water table is observed at shallow depths, except in arid regions. MAR structures such as infiltration basins or trenches may be suitable for this geological setting.

Fractured hard rocks act as potential zones for groundwater in many parts of the world. In these rocks the upper weathered zone is responsible for absorbing and storing intermittent rainfall. In the case of hard rock terrains the success of MAR system is mainly dependent on the location of the saturated weathered zone. However, the fractures and lineaments are also may be targeted. However, recharging the deep aquifer can only be done with injection wells.

Consolidated sandstones are one of the favorite geological formations for groundwater storage because of their good storage capacity and transmissive properties. However, if the aquifer permeability is too high, the recharged water may dissipate quickly and is thus lost to the base flow in rivers. A thorough knowledge in aquifer hydraulics is necessary for the successful implementation of MAR in this kind of aquifers. In certain locations, annual overdraft was adopted as a measure to create storage during wet season.

Carbonate rocks are highly dynamic formation in terms of hydrogeochemistry. Due to this high reactivity, groundwaters in these formations often exhibit high hardness. Carbonate aquifers can show high dissipation of recharged water and fast pathways for pollutants. Despite of this behaviour, carbonate aquifers are considered as good water bearing formations all over the world. A considerable modification in the flow patterns can be expected in carbonate aquifers with in a short period. MAR in these formations demands a good understanding of aquifer hydrogeology.

Influence of climate and hydrology on MAR systems

Climatic conditions in the application site have an important role in determining the dimensions and type of structures that need to be implemente:.

- Mean annual rainfall (for determining the size of the structure)
- Number of rainy days
- Shifts in seasonal patterns (alternate dry and wet season, water table fluctuations etc.)
- More frequent high intensity rainfall (storage capacity, pre-treatment capacity and efficiency)
- Variability in temperature (evaporation, freezing, hydrogeochemical reactions etc.)

Hydrology is a key factor in locating the appropriate areas for MAR and also in determining the amount of water available for recharge. Availability of naturally suitable sites is always helpful in bringing down the implementation and operational cost.

The most important hydrological characteristics that influence MAR can be listed as

- Terrain characteristics (topography, elevation, slope etc.)
- Landuse (agriculture, urban areas, barren land etc.)
- Vegetation cover (forest, grass land, etc.)
- Flow availability and rate in streams (perennial, ephemeral, large/small rivers)
- Conveyance system for bringing the water (gravity flow, energized pumping, suitability for canals, pipe networks etc.)

Source water and its requirements

A variety of source waters are used for aquifer infiltration around the world:

- Surface runoff, storm water
- River/Lake water
- Rooftop collected rainwater
- Treated waste water

A case study on MAR systems in India showed that rainwater and surface run-off are most widely used as source water (Fig. 4)

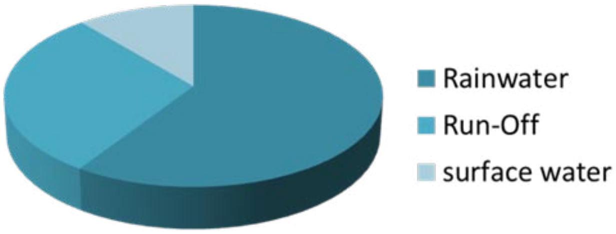

Fig.4. Source water for MAR in India (based on 22 case studies; SAPH-PANI D2.1 (2012).

The selection of specific sources primarily depends up on the local availability, as well as the quality that could be used with least pre-treatment effort. The available raw water must be critically assessed for the following factors (DVGW 2007)

- Sufficient amount (also considering extreme droughts),
- No negative influence on dependent eco-systems (e.g. wetlands),
- Sufficient water table depth to avoid damage to buildings
- No sewage effluent or industry outlet upstream

Raw water quality is important in determining the level of pre-treatment and also to meet the quality of effluents recovered from the MAR systems. The following factors need to be taken into account:

- Low temperatures (< 5°C) retard microbial degradation and infiltration rates (through higher viscosity), temperatures > 10 °C favorable,
- Suspended solids reduce infiltration rate (clogging), pre-treatment may be necessary
- Infiltration of persistent substances (heavy metals, certain trace organic compounds) shoud be avoided
- Avoid strong fluctuations of water quality (biology cannot adapt).

Design and operation

Detailed recommendations for abstraction, pre-treatment, design of infiltration basins and operation are given in DVGW (2007). The following chapters deal with clogging as the most important limiting processes and implications for MAR operation.

Clogging

Clogging is the most widespread problem that causes reduction in hydraulic conductivity of the recharge structures. Numerous projects were abandoned because of the frequent clogging. The following factors result in clogging (Dillon & Pavelic 1996):

- Filtration of suspended solids
- Microbial growth
- Chemical precipitation
- Clay swelling and dispersion
- Air entrapment (or entrainment)
- Gas binding (release of dissolved or generated gases)
- Mechanical jamming and mobilization of aquifer sediments

The major effects that may be imparted by the clogging on the MAR performance can be summarizes as

- Decrease in hydraulic conductivity (decrease in infiltration rate),
- Reduction of the natural treatment efficiency of the aquifer.

Since the efficiency of the recharge systems are negatively affected, clogging must be monitored timely and sufficient treatment should be provided. Proper location of intake structure and judicious design of screens and collection minimize the clogging effect. The adaptation/treatment of clogging may be done by the following techniques.

- Early identification of the problem
- Backwashing of injection wells
- Suitable pre-treatment
- Periodic removal of sediments through scraping

Pre- treatment

A study conducted on the pre- treatment aspects of MAR system in India (SAPH-PANI D 4.1b) showed that different methods are available as listed below:

- Sedimentation: Settling of the suspended materials in the source water under gravity
- First Flush in RWH systems: Elimination of the first flush from the roof tops to remove the impurities due to the interaction between atmosphere and also with the dirty roof tops.
- Filtration: using locally available materials is implemented in many RWH-MAR systems in India. The most common methods are:
    - Sandfilters
    - Metallic filters
    - Slotted PVC pipes wrapped with Coconut Coir

Examples for Successfull MAR World-Wide

Table 1. Case studies on successful implementation of MAR systems to address different objectives.

	Berlin (DE) Greskowiak et al.(2005)	**Orange County (US)** Hammer & Elser (1980)	**Salisbury (AUS)** Page et al. (2009)
Study area and History	RBF had been practiced in Berlin since 1850 for drinking water supply. Since 1960 three infiltration ponds have commenced operation near Lake Tegel to cope with increasing water demand.	Orange County district, CA, USA. Excessive pumping and subsequent seawater intrusion deteriorated the water quality. By 1969, the recharge schemes were proved to be successful in rejuvenating the groundwater basin.	In operation since in 2006
Objectives	Enhancement of groundwater resources for drinking water supply.	To prevent seawater intrusion by creating a hydraulic barrier by injecting the fresh water	To store and treat wetland-treated stormwater for non-potable supply and municipal irrigation
Hydrogeological setting	Quaternary sediments of fluvial and glaciofluvial, medium-sized sand deposits, average range of hydraulic conductivities: 10 to 100 m/d	A deep structural alluvial basin containing a thick accumulation of interbedded sand, silt and clay. The overall hydraulic conductivity of the aquifers is 100 m/d	A confined low to moderate porous limestone, approximately 60 m thick. Brackish groundwater.
Source water characteristics	Surface water from lake Tagel is the source for MAR. The quality of the water is within the permissible guideline values for drinking water. Clogging is encountered in the system due to physical processes and microbial activities. A microstainer is used as pre-treatment	*Rainwater* was used for the infiltration basin. Salinity up to 430 mg/L. *Reclaimed waste water* (treated using lime clarification, ammonia stripping, mixed media filtration, activated carbon sorption and chlorination) is later mixed with fresh *deep groundwater* to achieve permissible Cl level (120 mg/L) before recharging through injection wells.	Urban stormwater derived from Parafield Stormwater Harvesting Scheme. Majority of the parameters are blow the Australian drinking water guidelines. Exceptions: turbidity and *e.coli*.
Design and Operation	Structure: 3 infiltration ponds (area: 8700 m^2; depth: 3 m) Infiltration rate: At the beginning operational cycle about 3 m/d ; after clogging: 0.3 m/d.	The river water is desilted and recharged through percolation tank. Additional extraction wells (*7*), 3 km away from the coast, are pumping the brackish water and return to it to the ocean.	Total catchment area: 1,600 ha. Water harvesting scheme area: 11.2 ha Well system: 4 recharge- ; 2 recovery wells; Wells penetrate the aquifer to a depth of 165 to

	Water quality monitoring: Wells: once per year Purified water (after post treatment): daily Abstraction: >40 production wells	23 recharge wells, located further inland, used for injecting the freshwater. 25 monitoring wells are available for water quality monitoring.	182 m with 50 m spacing in a quadrilateral configuration. This allows for pathogen attenuation in the aquifer. Monitoring: 3 piezometers

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The progression of artificial recharge to ground water in India

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Introduction

Ground water is the major source of fresh water that caters to the demand of ever-growing domestic, industrial and agricultural sectors of India. Ground water provides 70 percent of water for domestic use in rural areas and about 50 percent of water for urban and industrial areas. The significant contribution made for green revolution and also as primary reliable source of irrigation during drought years has further strengthened the people's aspiration in utilizing ground water as a dependable source. As a result, In the last three to four decades, an exponential growth in number of ground water extraction and surface water conservation structures for ground water recharge has been taking place.

The ground water availability in the Indian sub-continent is highly complex due to diversified geological formations, complexity in tectonic framework, climatological dissimilarities and changing hydro-chemical environments. The net result of such diversification has been the non-uniform development of ground water resources. There is intensive development of ground water in certain pockets of India , which has resulted in over-exploitation of ground water resources and led to steep declining trend in levels of ground water.

As per the latest assessment of ground water resources (2004), out of 5723 assessment units(blocks/mandals/ taluks) in the country, 839 units in various states have been categorized as “over-exploited” meaning that annual ground water extraction exceeds the annual replenish able resource. In addition, 226 units are critical with stage of ground water development hovering between 90 % and 100 %. Of annual replenish able resource.

Natural replenishment of ground water reservoirs is slow and is unable to keep pace with excessive abstraction of ground water resources in various parts of the country. In order to augment the natural supply of ground water, artificial recharge to ground water has become an important and frontal management strategy. The efforts are basically augmentation of natural movement of surface water into ground water reservoir through suitable civil structures. This technique of artificial aquifer recharge interrelate and integrate the source water to ground water reservoirs and are dependant on the hydro -geological situation of the area,

The rainfall occurrence in the country is monsoon dependant and in large part of the country, rainfall is limited to about three months period ranging from 20 to

30 days. The natural recharge to ground water reservoirs is restricted to this period only. The artificial recharge techniques aim at increasing the recharge period in the post-monsoon season for about 3 months providing additional recharge. This results in providing sustainability to ground water development during lean season.

The speedy and uncontrolled usage of ground water has also created many problems such as decline in water levels, depletion of ground water resource and ground water quality deterioration. Though, for the individual State as a whole, the availability of ground water resources appears quite comfortable but localized areas have shown the deleterious effects of excessive ground water development. To maintain sustainability of ground water resources, artificial recharge to ground water is being practiced. Artificial recharge is the technique that can revive and sustain development of ground water.

In artificial recharging, subsurface reservoirs are very attractive and technically feasible alternative for storing surplus monsoon run off. The effluence resulting from sub-surface storage at various inter section points emerging in the form of springs or streams, would enhance river flows and improve the presently degenerated ecosystem of riverine tracts, particularly in the outfall areas.

Traditional practices of artificial recharging

India is a vast country with very deep historical roots and cultural traditions. Some of our traditions, evolved and developed by our ancestors thousands of years ago have played important roles in our lives. One of the most important among these is the tradition of collecting, storing and preserving water for various uses.

The tradition probably started at the dawn of civilization with small human settlements on the banks of rivers and streams. When flows in rivers and streams dwindled and/or dried up, they moved away to look for more reliable sources of water. Settlements originally came up along the banks of perennial rivers. As the population had increased, settlements developed in to towns and cities and agriculture expanded. Technique were developed to augment water availability by collecting and storing rain water, tapping hill and underground springs and water from snow and glacier melt etc.,

Water came to be regarded as precious and its conservation and preservation was sanctified by religion. Various religious, cultural and social rituals prescribed purification and cleansing with water. Water itself had many applications in different rituals. Development of water sources such as storage reservoirs, ponds, lakes, irrigation canals etc., came to be regarded as an essential part of good governance. Emperor and kings not only built various water retaining structures but also encouraged the village communities and individuals to build these on their own. Wide ranging laws were enacted to regulate their construction and maintenance and for conservation and preservation of water and its proper distribution and use.

Brick and ring wells for extraction of water were introduced by Satavahanas (1st century B.C- 2nd century A.D.). Tank and well irrigation techniques were developed on a large scale during the time of Pandya, Chera and Chola dynasties in South India during 1st to 3rd century A.D. In the South, the Pallavas expanded the irrigation systems through construction of anicuts such as famous Cauvery Anicut and big tanks such as Dusi- Mamandur tanks for rain water collection during 7th century A.D. The Chola period (985-1205 A.D) witnessed the introduction of advanced irrigation systems and construction of large number of tanks with inter connecting channels.

In the following section, we describe briefly, the various recharge structures used in different parts of India. The trans-Himalayan region of India practiced the traditional recharge structure called Zing. Zings are small tanks which collects melted glacier water, store it and let it out the next day for usage. In the Western Himalayan region, the traditional recharge structure used are called Kul, Naula, and Khatri. Kuls are lined channels sometime lined with stones, which are used to carry water from glaciers to villages and sometimes to irrigate fields. Naula are small wells or ponds in which water is collected by making a stone wall across a stream. Khatris are structures about 10 ftx 12 ft in size and six feet deep carved out in the hard rock mountain. Traditional artificial recharge method practiced in Sikkim, Arunachal Pradesh and Darjeeling is called Apatani. Apatani is a wet rice cultivation cum fish farming system practiced in elevated regions of about1600 m having annual rainfall of 1700 mm with rich water resources like springs and streams. The system harvests both surface and ground water and is practiced by Apatani tribes.

In North Eastern hill region comprising Assam, Nagaland, Manipur, Mizoram, Mehalaya, and Tripura, traditional artificial recharge practiced are theZabo,Cheo-oziihi, and Bamboo-drip irrigation. The Zabo (the word meaning “impounding Runoff”) combines water conservation with forestry, agriculture and animal care. The water collected in pond-like structures are used for cattle –usuage and agriculture. Mehalaya has an irrigation system of tapping of stream and spring water by using bamboo pipes to irrigate plantations. This 200-year old system is used by the tribal farmers of Khasi and Jaintia hills to drip-irrigate their black pepper cultivation. In Brahmaputra valley, dongs and dungs are used as artificial recharge structures. Dongs are ponds constructed by the Bodo tribes while dungs are small irrigation channels linking rice fields to streams.

In the Indo- Gangetic plains, artificial recharge structures practiced are the Ahar-Payne, Bengal’s inundation channels, Digis and Baolis. Digis are step wells used for storing drinking water by individuals in their own houses. On the other hand, Baolis are stepped wells from which all community people can draw water.

Western Rajasthan, Kutch region of Gujarat,Bhatinda and Ferozpur districts of Punjab and most of Hissar and parts of Mahindergarh district of Haryana fall under Thar desert. Many traditional artificial recharge structures such as Khunds,Kuis, Bers, Jharmas,Nadi,Tobas, Tankas, Khadins, Bavadis, Virdas etc., have been practiced. Khund looks like an upturned cup nestling in a saucer.Khund, essentially a circular underground well, has a saucer- shaped catchment area that gently slopes towards the centre where the well is situated. Kuis are

10-12 m deep pit dug near tanks to collect the seepage water. The mouth of the pit is usually made narrow to prevent evaporation from the collected water. Bers are mostly community wells that are used for drinking purposes. Jhalars were human made tanks, often rectangular in design having steps on three or four sides. The Jhalars collect underground seepage of a Talab or a lake located upstream and used for community bathing and religious rites. Nadis are village ponds, used for collecting and storing water from adjoining natural catchment during rainy season. It is planned and constructed by villagers themselves for their use.

Talab is the local name given to a storage structure constructed on a depressed ground with low porosity and a natural catchment area. Tankas (small tank) are underground tanks built in the main house or in the court yard in which rain water was collected for domestic use.

Khadin is an ingenious construction designed to harvest surface run off water for agriculture. Its main feature is a very long(100-300 m) embankment built across the lower hill slopes lying below gravelly uplands. The Khadin system is based on the principle of harvesting rain water falling on the farm land and subsequent use of the land after depletion of storage for crop production. First designed in western Rajasthan by the Paliwal Brahmins of Jaisalmar in the 15th century, this system has great similarity with the irrigation methods ofUr(present Iraq) and later of the Nabateans in the middle east. A similar system is also reported to have been practiced 4,000 years ago in the Negev desert, and in south western Colorado some 500 years ago.

Virdhas are shallow wells built by nomadic Maldharis to skim fresh water floating on top of salt water. These are essentially structures built based on topography to separate salt water from fresh water.

The Central highlands comprising the Eastern Rajasthan, Chambal basin in Rajasthan, north and central Madhya Pradesh and the Narmada region are using the following traditional artificial structures: Talab,Kuva,Johads,Naada, Pat, rapat, Chandela tank and Bundela tank. Talabs are reservoir either man made or natural serving irrigation and domestic purposes. When the water in the reservoir dries up, the talab beds are cultivated with rice and is made to mature with residual moisture stored in the talab bed. Saza Kuva, an open well with multiple owners is the most important source of irrigation in the Aravalli hills in Mewar and Eastern Rajasthan.

Johads are small earthen check dams that capture and conserve rain water, improving percolation and ground water recharge. Naada/ Bhanda are found in the Mewar region of Thar Desert. It is a stone check dam, constructed across a stream or a gully to capture monsoon run off from a catchment. Rapat is a percolation tank with a bund to impound rain water flowing through a watershed and a waste weir to dispose of the surplus flow. Rapats do not directly irrigate a land but recharges wells located as far as 3.5 km downstream.

Chandela tanks were constructed by stopping the flow of water in rivulets flowing between two hillocks by erecting massive earthen embankments. These tanks served to satisfy the drinking water needs of villagers and cattle. Bundela tanks are bigger in size as compared to Chandela tanks. These tanks were constructed to meet the growing water demands in the area of construction and maintenance of these tanks was done by the person employed by the king; but in case of smaller tanks, villagers collectively removed silt and repaired the embankment.

Eastern highlands extending across Bihar, Madhya Pradesh and Orissa were practicing artificial recharge through Katas/ Mundas/ Bandhas. These were the main irrigation sources in the ancient tribal kingdom of Gonds. Most of these structures were built by village headmen.

Decan Plateau constituting themajor portion of South Indian table land occupy large parts of Maharashtra, Karnataka and a small portion of Andhra Pradesh. The traditional structures used for artificial recharging are called Cheruvu, Kohil tanks, Bhandaras, Phad, Kere etc., Cheruvus are found in Chittoor District of AP. They are reservoirs built to store run off water. They are fitted with sluices to draw water and a surplus weir to pass excess flood water. Kohlis are water tanks which constituted the backbone of irrigation in the district of Bahndara, Maharashtra. Bhandaras are check dams or diversion weirs built across rivers to store/ raise water level in the river to make the supply channel flow with water for irrigation. Phad is the community managed irrigation system prevalent in North Western Maharashtra, probably came into existence some 300-400 years ago. The system starts with a Bandhara built across a river. From the Bhandaras, canals branch out to carry water in to the fields. Each canal has a uniform discharge capacity of about 450 litres / second.

Tanks called Kere in Kannada, were the predominant traditional method of irrigation in the central Karnataka plateau, and were fed either by channels branching off from Anicuts(check Dams) built across streams, of by streams in valleys. The outflow of one tank supplied the next all the way down the course of the stream; the tanks were built in series, usually situated a few kilometers apart. This ensured that no wastage through overflow and seepage of a tank higher up in the series would be collected in the next lower one.

The traditional artificial recharge structure practiced in Western Ghats is Surangam.It is horizontal well mostly excavated in hard laterite rock formations. Water seeps into the tunnel and flows out. Surangams are similar to ganats which once existed in Mesopotamia and Babylon around 700 BC and the technology since then spread to Egypt. Iran and India.

The traditional artificial structures practiced in the Eastern Ghats and the Eastern Coastal plains are Korambu, Eris and ooranis. Korambu is a temporary dam stretching across the mouth of channels, made of brushwood, mud, and grass. It is constructed to raise the water level in the irrigation supply channels and divert the water in to the field channels. Eris have played several important roles in maintaining ecological harmony as flood-control systems, preventing soil erosion and wastage of run off during periods of heavy rainfall and recharging the ground water in the surrounding areas. Till the British colonial arrived, local communities maintained Eris. Historical data, for instance, indicates that in the 18th century about 4-5 percent of the gross produce of each village was allocated to maintain Eris and other irrigation structures. Assignment of revenue free lands, called Manyams, were made to support village functionaries who undertook maintenance and management of Eris. These allocations ensured Eri upkeep through regular desilting, maintenance of sluices, inlet channel of Eris and irrigation supply channels. The early British rules enacted and introduced with respect to land tenure system has had disastrous effect on the maintenance of local water bodies due to enormous expropriation of village resources by the State leading to disintegration of the traditional society activities, its economy and policy. Allocations for maintenance of Eris were not adequate and village communities did not provide any support for tank maintenance. These extraordinary water harvesting structures and systems began to decline as a result of neglected maintenance and no involvement of farming community.

Efforts and promotion of artificial recharging in India

The Ministry of water resources, Government of India came out with a model bill for regulation and management of the ground water resources by the States in 1972 and circulated for their comments. Due to changing scenarios of ground water development, the model bill was revised and circulated in 1992,1996 and latest in 2005 in which artificial recharge component was added and it became mandatory for the State Government to include artificial recharge while formulating the ground water regulation act. This was done in view of the over exploitation of ground water taking place in many parts of India and dire necessity to regulate over exploitation of ground water resources and also to augment the depleting ground water resources.

The ministry of Environmental and Forest has constituted the Central Ground water Authority (CGWA) in 1997 with a view to regulate and control, manage and develop ground water resources in the country and to issue necessary regulatory directions for this purpose. In view of the power vested with CGWA, it has issued directions to the Chief Secretaries of the States to adopt rain water harvesting in all the over exploited and critical blocks of the State as well as in urban and other areas of strategic importance. The activities undertaken by the States are being monitored and documented by CGWA.

The Central Ground Water Board (CGWB) which forms part of CGWA has identified 839 over-exploited blocks, 226 critical units and 550 semi-critical units across the country and the CGWA had focused their attention to artificially recharge these blocks. Various methods/techniques have been identified for implementation depending on the local hydro-geological set up for which the following factors were considered:

- The quantum of harvested rain water and recharge to ground water for improving the effects of ground water abstraction.

- Adoption of water conservation measures like technologies used for ensuring water conservation, water audits for ensuring minimal use of water in various sectors.

- Recycling and reuse of effluents conforming to standard norms prescribed by Government of India.

Based on the above, artificial recharge methods pilot tested in India can be broadly grouped as under:

- Spreading Methods
    - -Infiltration ponds and basins
    - -Controlled flooding
    - -Incidental recharge from irrigation
- In-channel modifications
    - -percolation ponds behind check dams
    - -earthen storage dams
    - -sub surface dam
    - -leaky dams and recharge releases
- Well, shaft and borehole recharge
    - -open wells and shafts
- Induced Bank infiltration
    - Riverine and canal bank infiltration
    - Inter-dune filtration
- Rain Water Harvesting
    - -Field bunds
    - -roof-top rain water harvesting

Many recharge schemes such as field bunding and small bunds across ephemeral streams require low levels of technology and are being implemented by farmers themselves with the help of local Non-Governmental Organizations (NGOs). Well digging skills have been developed over generation and diversion of surface flow in to these structures subsequent to settlement of most suspended solids is being practiced in certain pockets of the western semi-arid India.

Institutional aspects of artificial recharging in India

In India, a variety of techniques and approaches are being tried in implementing artificial recharge activities with responsibility resting with Central, State, Local governments, development agencies, NGOs and local community. In implementing these projects, a dominant institutional theme emerged over the last two decades has been decentralization, often in tandem with efforts to promote a more bottom-up participatory planning process. The argument for such decentralized participatory decision making is to improve equity rights and responsibility in resource conservation or in its sustainability which can substantially contribute to the livelihoods of the poor who are disproportionately dependant on common pool resources such as water.

Decentralisation and participatory management are clearly interlinked. It is now generally accepted that to enhance and sustain the productivity of natural resources, those engaged in and affected by managing the resource must participate in its rehabilitation and management. This implies and as the Government of India tries, new ways of managing the watershed development projects by channeling the development funds, managing the implementation process, taking decisions etc., to a new set of stakeholders involved in building the new coalition. Despite its efforts, vested interest and existing power relations are challenging the new ways of developing and managing the watersheds.

Experience in implementing artificial recharge projects indicates that better performing projects engage local people in discussion about what their problems and priorities are (e.g.,reliable drinking water supplies, supplementary irrigation), what different groups value most, adopts flexible approaches to diverse livelihood systems and physical conditions and the project implemented mostly by the beneficiaries. Key issues arising around implementation and management relate to the composition and capacity of local management organizations and the design and operation of cost and benefit sharing arrangements.

Concluding remarks

- Artificial recharging is being increasingly used to conserve and manage harnessed water from different sources. There are many methods that have been pilot tested, depending on source and availability of water, demand, geology, and socio-economic profiles. THE CGWA has come out with guidelines for artificial recharging using current technologies and produced a set of case studies with impact evaluation. However, a systematic approach to evaluate and assess the effectiveness of current technologies are limited.

- Improved understanding of how recharge structures actually work and the impacts they have on water availability, water quality, social and economic sustainability at the local as well as at the downstream need to be investigated and disseminated to promote widespread cost-effective implementation.

- Artificial recharging must be considered as part of integrated water resources management in the context of a watershed and its role will become increasingly important as demand for water increases and the impacts of climate change and variability become more important.

- Promotion of artificial recharge should focus on scientific method of recharging with relevant data base and monitoring, evaluation and lesson learning should form part to provide a feed back loop to improve scientific methods of artificial recharging in the years to come.

- Decentralised water harvesting and artificial recharging should be a bottom up participatory approach in the watershed context to meet the aspirations of the stakeholders in an equitable and cost effective manner.

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Managed Aquifer Recharge Practices in India

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Abstract. 'Managed Aquifer Recharge (MAR)' has a similar connotation as of the 'Artificial Recharge (AR)' commonly known in India, with only difference in consideration of water quality and environmental conditions. The MAR as a tool can be used for replenishing and re-pressurising depleted aquifers, controlling saline intrusion or land subsidence and improving water quality through filtration and chemical and biological processes. India has a long tradition of practicing Rainwater Harvesting (RWH) and AR by employing indigenously developed techniques and methods to fulfill requirements of agricultural and drinking water supply particularly in rural areas. Since last one and half decade, RWH and AR are promoted as the government supported national program for augmentation of groundwater resources in water stressed and groundwater problematic areas. To cope with increasing demands of groundwater, there is an urgent need to conceive large scale strategic promotion of MAR using the knowledgebase and understanding of the existing recharge schemes practiced in India. This article gives an overview of the traditional artificial recharge practices in India along with the government and other organizations initiative taken towards uses of MAR. A general evaluation of MAR implementation has also been presented to help identify the gaps and appreciate usefulness of MAR.

Managed Aquifer Recharge – definition and use

Managed Aquifer Recharge (MAR) describes intentional storage and treatment of water in aquifers for subsequent recovery or environmental benefits (Dillon et al, 2009). The term "artificial recharge (AR)" commonly used in India also describes the similar activity as in MAR without consideration of quality of water resources, however, the term 'MAR' so far has not been as popular as the term 'AR'.

Stating more elaborately, **MAR** is the process of adding a water source including recycled water to aquifers under controlled conditions for withdrawal at a later stage, or used as a barrier to prevent saltwater or other contaminants from entering the aquifer. Water can be recharged by a number of methods including infiltration via basins or galleries or by the use of injection wells.

AR can be defined in many ways. Stating in simple words, AR is a process by which excess surface water is directed into the ground – either by spreading on the surface, by using recharge wells to replenish an aquifer. Except the contemplation on quality of water, MAR and AR have same physical significance and purpose. **MAR** as part of the groundwater manager's tools may be useful for replenishing and re-pressurising depleted aquifers, controlling saline intrusion or land subsidence and improving water quality through filtration and chemical and biological processes. On its own it is not a cure for over-exploited aquifers, but can merely enhance volumes of groundwater. However, it may play an important role as part of package of measures to control abstraction and restore groundwater balance.

MAR can used to address a wide range of water management issues as depicted in Fig 1.

Why is MAR necessary in India?

- India is now the biggest groundwater user for agriculture in the World (Shah, 2009).
- Groundwater has been the most preferred source for drinking water in India, particularly in rural and peri-urban areas.
- Statistics revealed that over the last 50 years, number of groundwater structures have increased manifolds from 3.9 million in the year 1951 to 18.5 million in the year 2001 out of which about 50% accounts tube wells (Fig.2) [Minor Irrigation Census, 2001]. The number of groundwater structures is now expected to be around 27 million (Shah, 2009).
- The poor public irrigation and drinking water delivery, new pump technologies, flexibility and timeliness of groundwater supply, government subsidy on electricity in the rural areas, and lack of groundwater regulation legislation, have given rise to preferential growth of groundwater uses in India.
- The growth in the groundwater structures had also increased the groundwater based irrigation potential, and at the same time, diminished the share of surface water uses for irrigation from 60% in the 1950s to 30% in the first decade of the 21st century (Fig. 3).
- Natural recharge measurements carried out in about 20 river basins suggested that only about 5 to 10 percent of the seasonal rainfall is contributed as annual recharge in the peninsular hard rock regions, and is about 15 to 20 percent of the rainfall in the alluvial areas (Athavale et al 1992). Rapid urbanization and land use changes have reduced drastically the infiltration rate into the soil and are diminishing the natural recharging of aquifers by rainfall. This has created lowering of water table, drying of wells and deterioration in quality.

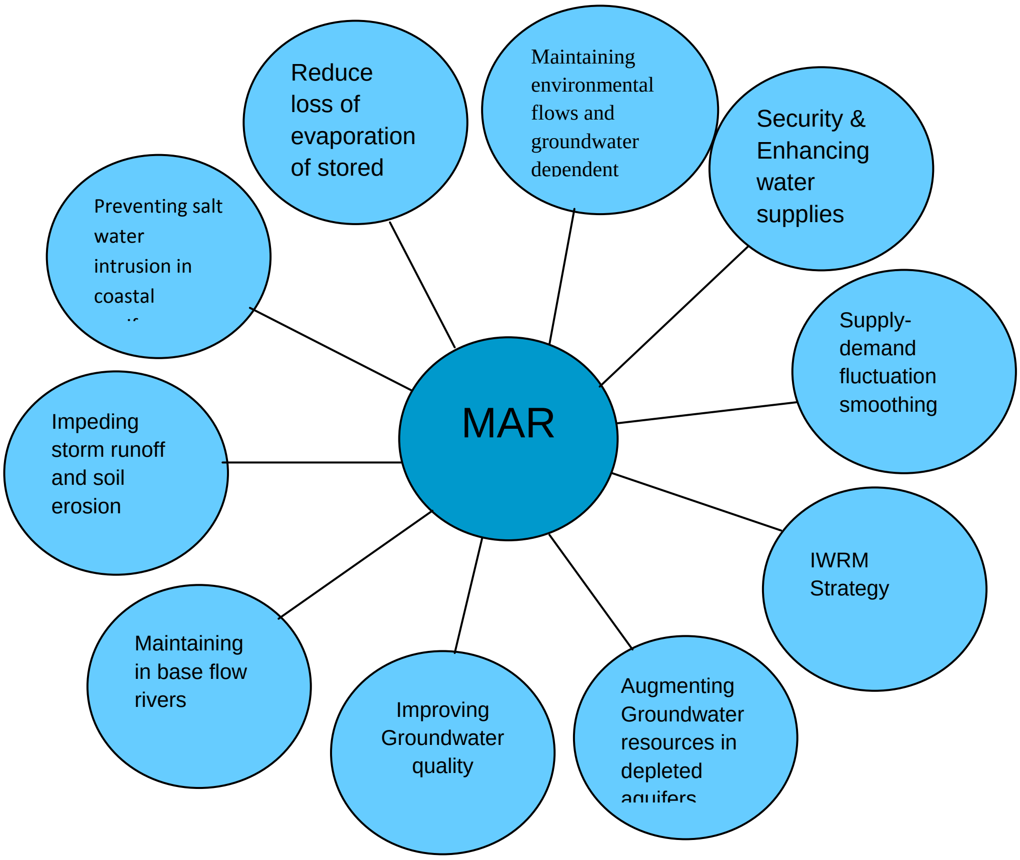


Fig.1. Some important groundwater conservation and management issues, which can be addressed by MAR

- Today, groundwater is the source for more than 85% of India's rural domestic water requirements, 50% of urban water, and about 60% of irrigation demand (CGWB, 2011; Task Force, 2009).
- Groundwater is mostly preferred in rural area primarily because;
  - rural people have a common notation that groundwater is less risk free from pollution than surface sources of water,
  - it is ubiquitous, and can be drawn on demand in any quantity wherever and whenever required.

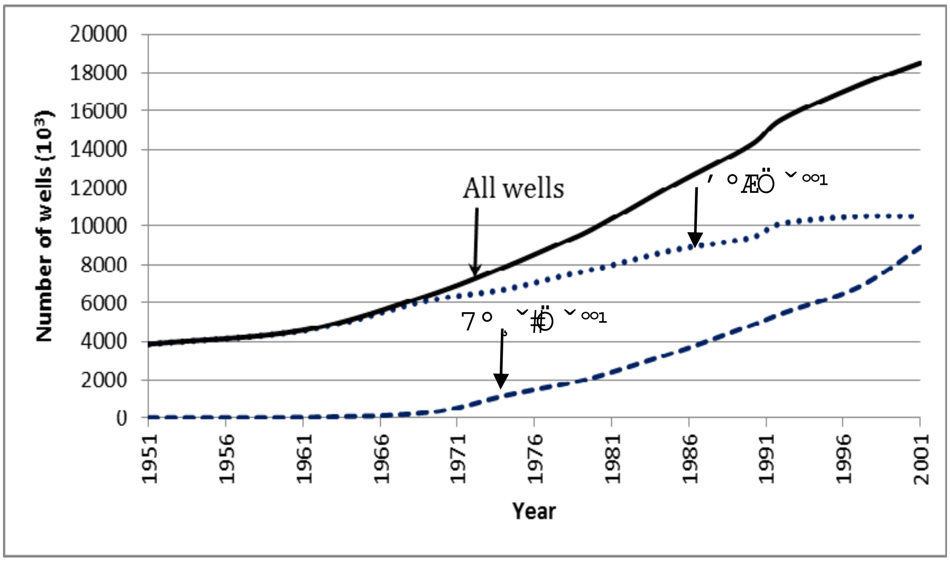
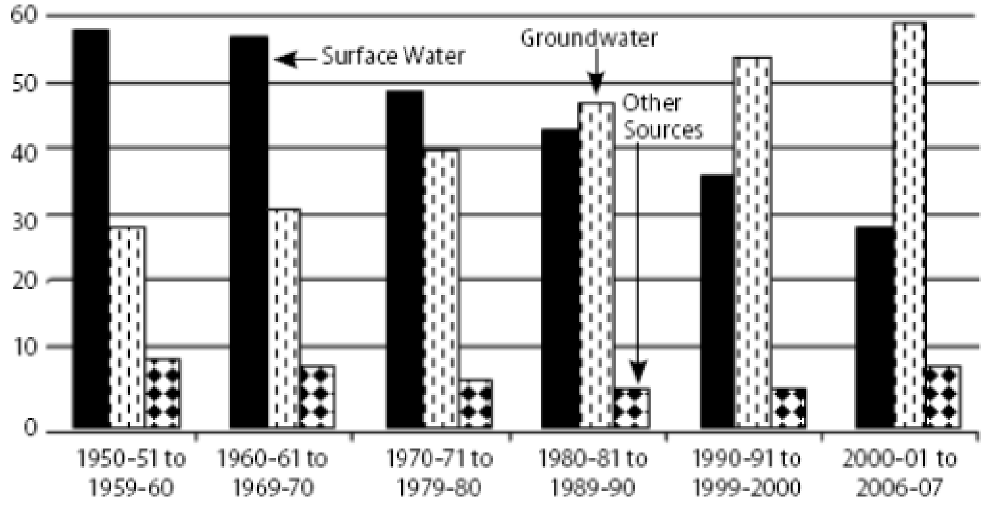


Fig. 2. Growth of groundwater structures in India (1951-2001) [Source : Graph prepared using data of Minor Irrigation Census, 2001 & data compiled by Singh & Singh, 2002] .



Source: *Indian Agricultural Statistics (2008).*

Fig 3. Decade-wise share of surface water and groundwater in net irrigated area in % (adopted from Vijay Sankar et al., 2011) .

- Indiscriminate extraction and development had led substantial ground water table depletion in many parts of India both in the hard rocks and alluvial areas. Long-term decline of ground water table had been reported mostly from the states of Rajasthan, Gujarat, Tamil Nadu, Punjab, Delhi and Haryana.
    - ➢ For example, out of 5723 assessment units (Blocks/Mandals/Talukas) in different states by CGWB(2007), 839 units (15%) had been categorised as 'overexploited' with ground water extraction more than the net annual recharge, and about 4% has been categorized as 'critical', extraction between 90% and 100 % of the net annual recharge. And 30 blocks had been categorized as the saline ground water (CGWB, 2007).
- Groundwater contamination from the sources of geogenic (Arsenic, Fluoride, and Salinity) and anthropogenic origin is another threat to the availability of safe groundwater resources.

There is no reason to believe that the growth of groundwater structures and uses of groundwater are going to slow down in future, unless otherwise controlled by enforcing legislation, rather will continue to rise because of growing concern with quality of public water supply, increasing living standards and socio-cultural dimensions of the rural sector.

Presently, India's irrigation water availability from both surface water storages and groundwater availability is about 541 BCM in which groundwater is 221 BCM. By the years 2025 and 2050, these are projected to be 916 BCM and 1032 BCM, respectively. If the current state of affairs are continued, groundwater availability for irrigation can be increased to 236 BCM (26%) by the year 2025 and 253 BCM (25%) by the year 2050.

On the other hand, runoffs from rainfall are mainly available during four monsoon months and scope for catching runoffs by creating large scale surface water storages is restricted by surface topography; large amount of monsoon surface runoffs of the order of 1548 BCM annually flows out from the basins to sea as unutilized; excess groundwater withdrawal depletes groundwater table and thereby creates more space for aquifer storages, etc.

Therefore, there is need to conserve monsoon runoffs and store them appropriately for subsequent uses during non-monsoon months to meet the growing demands of water for various uses. MAR is one of the ways to conserve excess surface runoffs as groundwater storage and can address the lack of groundwater availability. The main advantages with MAR are; aquifer storages are naturally available and there is no need for additional large scale investment, groundwater moves slowly in the aquifer, therefore, storages are largely available in local scale, etc.

It has been estimated by CGWB (2007) that an area of 4,48,760 km^2 about 14% of total land area of India is suitable for MAR and a volume of 36 BCM of water can be recharged annually. This volume is equal to about 16% of 221 BCM of groundwater that is currently utilised annually for irrigation.

MAR Practices in India

India’s rural villages, in different regions of the country, have a long tradition of practising rainwater conservation, harvesting snow and glacier melt water, and judicious use of groundwater by employing indigenously developed techniques and methods for fulfilling requirements of agriculture and drinking. Although those schemes were known by different names in different parts of the Country, however, their purposes and uses are similar to the MAR.

India’s strong cultural heritage also cites an excellent example of practicing MAR. Temple tanks are part and parcel of many village eco-systems; there are no village without temple and no temple without tank; these tanks act as aquifer recharge structures and help in maintaining groundwater level throughout the year. More than 500, 000 tanks and ponds, big and small, are dotted all over the country and more so in the peninsular India. Some of these tanks were constructed thousands of years ago for catering to the multiple uses of irrigated agriculture, livestock and human use such as drinking, bathing, and washing. Many drinking water wells are located within the tank bed and on tank bund to provide water supply throughout the year with artificially recharged water from the tank water in to these wells.

In addition to those, state and central governments, non-governmental organizations, village community, etc. from time to time had promoted various artificial recharge schemes for conservation and augmentation of groundwater resources particularly in water scarce areas, groundwater table depleted aquifers, and in coastal aquifers to arrest ingress of seawater intrusion.

With the passage of time, the importance of these old age techniques has been realized and presently promoted on large scale as a government supported scheme for conservation of rainwater and groundwater recharge. A compilation of various traditional rainwater harvesting (RWH) and groundwater recharge structures practiced in various places in India is given in annexure I.

Considering the above historical background of MAR practices in India, its spread can broadly be classified under three phases (Sakthivadivel, 2007):

- The first phase relates to the period before the green revolution when limited exploitation of groundwater was taking place, i.e., before 1960,
- The second is the period between 1960 and 1990, where intense groundwater exploitation took place with signs of over exploitation,
- The third is the period from 1990 to date, when water scarcity is increasing alarmingly and the groundwater level is declining in certain pockets.

The First Phase - Period before 1960

Traditional water harvesting methods were given impetus through unorganized movements by the local communities, aided by kings and benevolent persons to meet the local requirement. During this period, there was very little knowledge-based input from the government, non-government organizations and the scientific community to provide assistance for understanding and putting into practice a systematic artificial recharging, and up-scaling. Yet, the local community used their intimate knowledge of terrain, topography and hydrogeology of the area to construct and operate successful artificial recharge structures. Very little understanding existed about the consequences and the knowledge required for artificial recharging of aquifers.

The Second Phase – Period between 1960 and 1990

During this period, both the public and the government had started realizing the importance of recharging of aquifers to arrest the decline in groundwater and maintain the required groundwater levels. As a consequence, pilot studies of artificial recharging of aquifers were carried out by a number of agencies and the technical feasibility of artificial recharging and recovery of recharged water had been established.

The Third Phase – Period from 1990 to date

Water scarcity, continuous droughts in certain pockets and the continuously declining groundwater levels in many parts have forced both the public and the government to become aware and to take up artificial groundwater recharge on war footing. Three major activities took place during this period; one is large scale taking up of artificial recharge scheme by public through dug and bore wells, check dams and percolation ponds, followed by the government joining hands with the local community in implementing such schemes on a mass scale. The second is the action taken by state government such as Tamil Nadu, in promulgating the groundwater regulation act pertaining to metropolitan area and ordering the community to implement rainwater harvesting schemes and artificial groundwater recharge on a compulsory basis in the metropolitan area. The third one is the awareness created among the public by the non-governmental organizations.

Common Techniques Employed for Artificial Recharge in India

Based on a survey carried out between 1980 and 1985, the Central Ground Water Board (CGWB) had identified a number of techniques commonly used and suitable for artificial recharge in India. The suitability of these techniques (Table1) had been identified based on the different hydrogeological and topographic conditions.

Table 1. Artificial recharge structures identified and recommended by CGWB for groundwater resources development purposes**.**

Lithology	Topography	Type of structure
Alluvial or hard rock	Plain area or gently undulating area	Spreading pond, subsurface dike, minor irrigation tank, check dam, percolation tank or unlined canal system
Hard rock down to 40 m depth	Valley slopes	Contour bunding or trenching
Hard Rock	Plateau regions	Recharge ponds
Alluvial or hard rock with confined aquifer to 40 m depth.	Plain or gently sloping of flood plains	Injection well or connector well
Hard rock	Foot hill zones	Farm ponds or recharge trenches
Hard rock or alluvium	Forested areas	Subsurface dikes

Ministry of Rural Department, Government of India (2007) had published a document entitled “Bringing sustainability to drinking water systems in rural India” compiling experiences and studies from all parts of the country on traditional wisdom and best practices in water management with modern technologies and scientific understanding focusing mainly on rainwater harvesting and groundwater recharge. The document provides an excellent state-wise compilation of information on “artificial recharge structures” and their performances.

Pilot Projects on Artificial Recharge by CGWB

A number of reports prepared by different agencies (DFID, 2006;UNESCO-IHP, 2005; BGS,2002) elaborating scope, effectiveness, performances and lesson learned from the case studies of ‘Artificial Recharge’ and MAR schemes implemented in different states of India are available. Recently, the ‘Saph Pani’ has prepared an exhaustive review of ‘MAR’ as one of its project deliverable activities (2012). The following section highlights some parts of the report that elaborates experiences of MAR practices in India.

In the post-independence period, the CGWB first initiated the water harvesting and water conservation programme during the period 1972 to 1984 with UNDP collaboration (Table 2). After an inactive period, pilot projects were taken up again in 1992 to demonstrate the technology for different types of recharge structures. Up to 1997 a total of over 700 pilot structures were constructed.

During the plan period 2007-2012, 82 pilot projects with a total of 1475 structures have been planned for construction in areas which is marked by declining groundwater level, in coastal areas and on islands affected by saline water ingress, in areas of inland salinity, in urban areas showing steep decline in groundwater levels and in sub-mountainous / hilly areas of the country. Since 1972 and increasingly since 1997 all the common types of structures such as check dams, percolation ponds/tanks, subsurface dykes, rooftop rainwater harvesting, recharge wells and shafts and others were financed, documented and evaluated by the CGWB. In the last five years the structures financed by the CGWB are intended for “demonstration of artificial recharge and rain water harvesting techniques in overexploited and critical areas, urban areas and areas affected by water quality” (CGWB, 2012)). The artificial recharge schemes developed in different states of India by CGWB during different plan periods are shown in Fig 4.

Table 2 Artificial recharge studies undertaken by the CGWB during different five year plans (CGWB, CGWB, 2012)

Period and Plan	**Status**	**Cost (in million INR)**
1972-1984	Haryana, Kerala, Gujarat	NA
1984-1992	No rainwater harvesting or groundwater development programs	0
1992-1997, VIII	Maharashtra, Karnataka, Andhra Pradesh, Delhi, Kerala, Madhya Pradesh, Tamil Nadu, West Bengal & Chandigarh (Total States/UT –9)	32.3
1997-2002, IX	Andhra Pradesh, Arunachal Pradesh, Assam, Bihar, Chandigarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkand, Kerala, Lakshdweep, Madhya Pradesh, Maharashtra, Meghalaya, Mizoram, Nagaland, NCT Delhi, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal (Total	331

	States/UT – 25)	
2002-2007, X	Andhra Pradesh, Karnataka, Madhya Pradesh and Tamil Nadu (Total States – 4) Pilot projects 18 ; 197 structures	56
2007-2012, XI	Arunachal Pradesh, Punjab, Tamil Nadu, Kerala, Karnataka, West Bengal, Andhra Pradesh, Uttar Pradesh, Madhya Pradesh, Delhi, Chandigarh, Gujarat, Maharashtra, Jharkhand, Himachal Pradesh, Jammu & Kashmir, Orissa, Rajasthan and Bihar (Total States/UT – 19) Pilot projects 82; 1475 structures	1000

The CGWB in 1996 (CGWB, 1996) had prepared a Perspective Plan for Artificial Recharge to use surplus non-committed runoff. As a sequel to the Perspective Plan, the Master Plan for Artificial Recharge to Groundwater (CGWB, 2002) was prepared and approved by the Ministry of Water Resource on the basis of hydrogeological parameters and hydrological data available for each state. The identification of feasible areas for artificial recharge to groundwater was made on the basis of depth and declining trend of groundwater levels. The plan provides information about area specific artificial recharge techniques to augment the ground water storages based on the availability of source water and capability of subsurface formations to accommodate it. As a part of the Master Plan, a number of demonstration projects were implemented between 2007 and 2012 as mentioned in Table 3.

Table 3. List of Structures proposed under the Master Plan (CGWB, 2002)

[Source : Saph Pani, 2012]

Area Identified for Artificial Recharge	**448760 km^2**
Volume of water to be recharged	36.5 km^3
In rural areas	225000
In urban areas (rooftop rainwater harvesting)	3700000
Total number of structures proposed	3,925,000
Total cost of structures proposed	245000 MINR

Check Dams/Cement Plug/Anicuts	110000
Recharge Shafts and Dug wells	48000
Gully Plugs /Gabion Structures	26000
Development of Springs	2700
Revival of Ponds/Tanks	1000

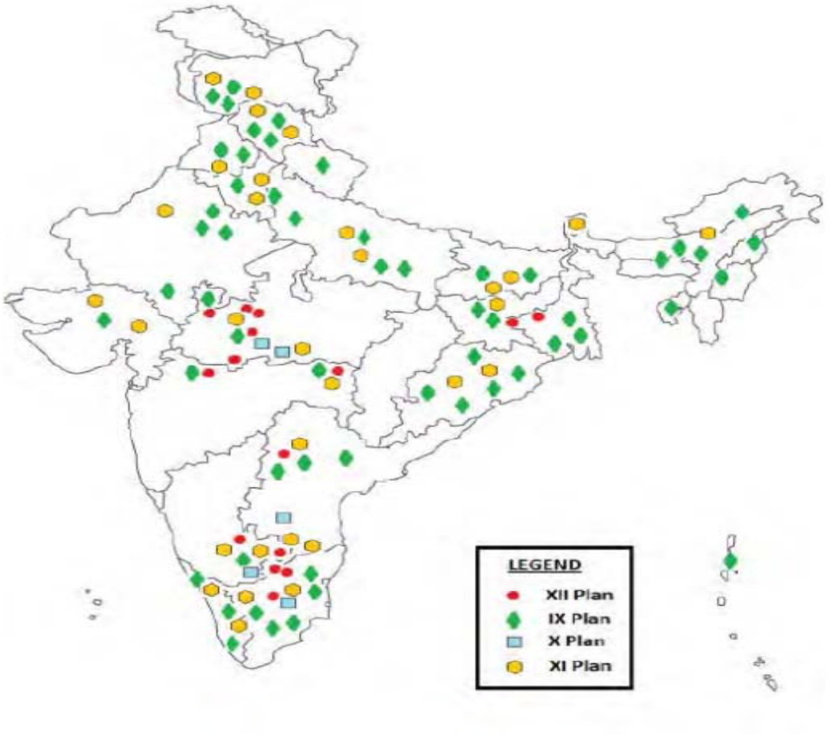


Fig. 4. Artificial recharge schemes developed by CGWB in different states of India under various five year plan (Source : CGWB, 2011)

Rainwater harvesting has now been made mandatory in many states of India with an aim to meet the increasing groundwater needs. The National Bank for Agriculture and Rural Development (NABARD) has launched a project that is aimed at water resource conservation and management by rooftop rainwater harvesting.Table-4 provides some of the important schemes of Government of India which have component involving MAR promotion for augmentation of groundwater resources.

Table 4. Main features of some important programs of the Government of India involving MAR

Year	**Name of the Program**	**Financing Organization**	**Budget**	**Additional Information**
1995-	Integrated Watershed Management Programme (IWMP)	Ministry of Rural Development, Government of India	INR 43,616 million released until 2012.	All states. 1900 projects covering 107,000 km^2 were financed until 2012.
2007-2012	Repair, Renovation and Restoration (RRR) scheme	Ministry of Water Resources, Government of India, Government of India	INR 60,000 million (partly local government	Planned were 23,000 water bodies for irrigation of 17,000 km^2.
2005-2009	Bharat Nirman	Ministry of Rural Development, Government of India	INR 223,992 million	Only a minor part is related to water. 28% of irrigation capacity shall be crated from groundwater and 10% from the RRR scheme mentioned above (out of total of 100,000 km^2). Two investment areas (irrigation and drinking water) out of six are related to Groundwater/MAR.
2008-	Artificial Recharge of Groundwater through Dugwells	MGNREGA (Ministry of Rural Development, GoI)	INR 17,987 million	Seven states are involved. 4.5 million dug-wells proposed.

Experience from Case Studies on MAR in India

Outlining a general view on performances of MAR in India is not a straightforward task, because there are number of unaccounted information on MAR implemented by different bodies including private communities. Baseline data and information in most of the cases are missing. And, there are few case studies on which some information were available. The Saph Pani project (2012), based on the published documents and papers on MAR case studies, compiled some information, which are presented under different perspectives of MAR below:

Hydrological and hydrogeological situations

The considered studies cover a wide variety of natural settings: the average annual precipitation varied between 612 mm (Moga, Punjab: Bassian Drain, Block Nihalsisngh Wala (CGWB, 2011) and 1788 mm (Balasore district + Field Site, Orissa (Hollaender, et al., 2009)), with high inter-annual variations (long-term average minima: 331 mm maxima: 1424 mm reported for Delhi (UNESCO, 2006)). For those case studies, in which hydrogeological information was available (20 studies) 10 were situated in a hard-rock environment (granite, gneiss, basalt) where the aquifer would probably be situated in the weathered/ fractured zone or in alluvial deposits covering the hard-rock. The other hydrogeological settings can be summarized as sedimentary, mainly unconsolidated rocks usually gravel or sand with sections of clay. The information on aquifer thickness, depth of the groundwater level or transmissivities is scarce.Well yields in sedimentary formations vary between 1 and 115 m^3/h with highest values in alluvial aquifers (Bhadrak, Orissa (CGWB, 2011) and Tapi alluvial Belt Maharashtra (Jain, 2009)). Maximum well yields in hard-rock environments on the other hand reach no more than 14 m^3/h (Deccan traps, Maharashtra (Jain, 2009)) and usually lie between 0.8 and 4 m^3/h. These figures give an idea of the hydraulic permeabilities encountered, however, no data on draw-down and well design was available.

Infiltration Rates and Related Issues

The quantification of the recharged water was in the focus of most considered publications. This was either done by small scale observations (measuring water table fluctuations) or on catchment / sub-catchment scale.

Perrin et al. (2010), for example, balanced the volume of different percolation tanks and the evapotranspiration and concluded that between 5 % and 8 % of the monsoon rainfall (20 to 40 mm per annum) was infiltrated from these tanks on a small catchment scale. 71 to 74 % of the rainfall was lost to evaporation, leading to the conclusion, that enhancing infiltration at existing structures (e.g. by desilting or pre-treatment) should be preferred to constructing new ponds.

Both Perrin et al. (2010) and Palanisami et al. (2006) reported that a relevant amount (90 % and more) of the rainfall can be captured by the recharge structures – with potential negative effects for downstream users but beneficial to the water balance inside the (sub-)catchments. The amount of water evaporated in the study by Palanisami et al. (2006) was reported to be around 15 % and thus significantly less than in the case study given in Perrin et al. (2010) (around 73 %, see above), most probably due to higher infiltration rates (percolation efficiency around 85%). For this reason also the residence time of the water in the structures may be considerable: Gale et al. (2006) reports of surface water residence time of 5 months at a check dam in Coimbatore (Tamil Nadu).

Percolation efficiency, as the volume of infiltrated water in relation to the volume of a recharge structure can vary quite considerably. For some case studies, like one on check-dams in Gujarat (Gale, et al., 2006) efficiencies of > 90 % were reported whereas others give efficiencies below 20 % (different structures on catchment scale in Rajastan reported by Glendenning and Verwoort (2010)). This is attributed to two different factors:

- The permeability of the subsurface: infiltrated volumes of up to 1000 m^3/d were observed at gravity injection wells in a canal in Haryana, located in a coarse gravel aquifer (Kaledhonkar, et al., 2003) – corresponding to infiltration rates of > 10 m/d, whereas infiltration rates of a few centimetres per day are common for percolation tanks, check dams or trenches in weathered hard-rock areas (CGWB, 2011; Perrin, et al., 2010; Gale, et al., 2006)
- Clogging of the recharge structure through high amounts of suspended solids (according to Palanisami et al. (2006) de-silting improved the percolation efficiency from 83 % to 87 % in check-dams in Coimbatore and Hollander et al. (2009) give clogging of ASR wells as a major issue, with TSS values of 800 mg/L even after pre-treatment for a field site situated in Balasore).

Generally silting was seen as a problem for MAR, especially for check-dams or similar structures (Gale, et al., 2006; Palanisami, et al., 2006) and percolation tanks (Perrin, et al., 2010). Chakrapani and Saini (2009) found that >75 % of the annual sediment load was transported during the monsoon season. Thus, pre-treatment is widely used, either through sedimentation tanks (UNESCO, 2006), sand filters (Kaledhonkar, et al., 2003; Sivakumar, et al., 2006; Tuinhof & Heederik, 2003) or metal screens (Kanhe & Bhole 2006). Hollaender et al (2009), for example, used different setups of gravel and rice straw to filter monsoon storm water at an ASR site in eastern India. The authors achieved of total removal rate of 70 – 90 %, but TSS was still around 800 mg/L. (Panda, 2002) tested gravel filters and embedded Cocos Matts and achieved concentrations around 180 mg/L. Only one case study was found, in which silting did not seem to pose a problem: In ASR cavity wells in Haryana the high TSS load (900 mg/L) did not result in reduced injection rates. This is attributed to a postulated process of flocculation of silt and particles that may then settle on the surface of the cavity and are then pumped back to the surface once the recovery cycle commences (Malik et al. 2006).

The CGWB (2011) reported a large number of case studies as success stories with respect to their impact on local groundwater level and/ or increased well yield. Annual volumes recharged per recharge structure range from 2 m³ per m trench (Bhubaneswar, Raj Bhawan premises) to 24.000 m³ per well (Bhadrak, Orissa) but are difficult to compare due to diverse hydrogeology, varying precipitation rates and a multitude of regarded structures. Reported increase in groundwater level range from 0.2 to 1 m, but in some cases also the number of abstraction wells has increased considerably (18 additional wells resulting from the installation of 2 trenches and 3 recharge wells in Moga, Punjab (Bassian Drain).

Water Quality Issues

In 11 of the 27 case studies water quality information is given, however, in many cases it is not clear, which issues are attributed to the influence of MAR and which are due to the background hydrochemistry of the groundwater. Stiefel et al. (2009), for example, investigated the qualitative impact of a check dam in Rajasthan and found only positive effects of the infiltrated water on ambient groundwater quality.

Turbidity is mentioned in nearly all of the studies to be an issue with exception of mountainous streams in the Tapi alluvial Belt, Maharashtra (CGWB, 2011), where direct infiltration without pre-treatment is possible. Salinity has been reported to be a problem in the state of Haryana and in Chennai City, Tamil Nadu (UNESCO, 2006). In the first example a clear improvement was observed after the construction of 5 ASR wells (decrease in EC from 9000 to 1500 µS/cm).

In other cases it is clearly stated that the implementation of MAR has lead to an improvement of groundwater quality through dilution (Sivakumar et al., 2006; Sayana et al., 2010; Kaledhonkar et al., 2003). This was indicated by reduced levels of nitrate (112 ppm to 65 ppm (UNESCO, 2006), fluoride (according to (CGWB, 2011) values of >1.8 mg/L were reduced to <1 mg/L), hardness and sulphate.

On the other hand, Dwarakanath (UNESCO, 2006) reports an increase in potassium, chloride and fluoride due to MAR, though still within acceptable limits. Generally, elevated nitrate concentrations seem to be a problem: values above the permissible limit of 45 mg/L were reported in the Satlasana (Gujarat) and Coimbatore (Tamil Nadu) case studies (Gale et al., 2006) as well as in the vicinity of the Raj Bahwan premises (Bhubaneswar, Orissa) according to the CGWB (2011). A connection to MAR is not clear and Gale et al. (2006) postulate agricultural influence. On the other hand, a case study in Hyderabad (rooftop RWH with recharge pit,(UNESCO, 2006)) documents a reduction of nitrate values in the groundwater from 112 to 65 ppm after the installation of MAR.

Generally and as elsewhere, information on mixing ratios between naturally and artificially recharged water as well as travel times or redox conditions were not found. In case of critical parameters like pathogens, fluoride or arsenic this information could support the development of transferable guidelines for the safe implementation of MAR e.g. for drinking water supply.

Experience from Case Studies on SAT in India

Under Indian conditions only few studies of wastewater treatment using SAT technology exist. Primary treated municipal wastewater was used at the Sabarmati River bed in Ahmedabad (Nema et al, 2001). The SAT showed good removal of organic pollutants, nutrients and bacteria and was more efficient and economic than conventional wastewater treatment systems. Based on this pilot study a conceptual design of a 55 MLD (Million Liter per day) SAT system using primary settled domestic water was proposed for the city (CGWB, 2011).

General Evaluation of MAR Implementation in India

The CGWB evaluated the performance of ‘artificial recharge structures’ in different hydrogeological and meteorological contexts based on data from numerous pilot studies. The results were thoroughly documented. Benchmark performances (e.g. 75% percolation efficiency (CGWB, 2002) and suitability of structures for different contexts (CGWB,2000)) were published.

The impact of aquifer recharge in the area, on a watershed level and in India as a whole is dependent on the number of structures and their performance. No systematic inventory of structures exists, a figure of 0.5 Million is mentioned (Sakthivadivel, 2007). From the review of the case studies made in the Saph Pani MAR review, it is seen that the scientific evidence for both positive and negative effects of MAR interventions is scarce. Data on the number, the performance and the effect of the structures would be necessary for future watershed management. Only by making use of evaluation aquifer recharge can be managed.

Evaluation of quantitative performance of recharge structures can show the changes over time. Monitoring of these changes forms the decision basis for the operation and maintenance plans. MAR structures need regular maintenance to ensure stable long-term performance, but this is often lacking (UNDP, 1987; Palanisami et al, 2006; Gale et al, 2006; Glendenning et al, 2012).

Conclusions

Based on the compiled information on experiences of MAR, a general overview of MAR practices in India.' has been presented. Systematic application of MAR in India is still at an initial stage, and the concept of MAR in true sense is yet to gear up. What has been done and is going on is 'artificial recharge' for groundwater augmentation in depleted aquifers and dilution of groundwater quality concentration.

For practicing of MAR, two things are essentially required; one is surplus runoff and the other one is aquifer storage capacity to hold the recharge water. By additional recharge through MAR (as per CGWB's data) only a minor contribution (36 km^3) to the overall water balance can be made. However, it might be a substantial contribution compared to the drinking water consumption and relieve the situation in regions with particular water deficits.

Water quality of recharge water is an area that has received very little attention in MAR practices in India. Most of the case studies of MAR showed lack of water quality measurement of source water.

India's MAR practices are mainly focused on how to plan, construct and operate MAR structures. There is large knowledge gap on social and economic considerations of MAR. These need to be considered parallel to the technical aspects to find out whether an additional MAR structure is desirable, how to best organize the construction and maintenance and how to make the most use of the recharged water.

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Annexure - I

Traditional Rainwater Harvesting (RWH) and Groundwater Recharge structures usages in various places in India.

Name of structures	Place and State in which practices	Region	Features
Zing	Ladhak district in Jammu & Kashmir	Trans-Himalayan Region. Cold deserts.	Traditional water harvesting structure is comprised of a small tank which collect melted glacier water through network of guiding channels.
Kul	Valleys of Himachal Pradesh, and Jammu & Kashmir	Western Himalayan Region. Precipitous mountains.	Traditional rainwater harvesting structure is comprised of water channels which collect precipitated water from glaciers to village valleys.
Naula	Uttarakhand	Western Himalayan Region.	Traditional surface water harvesting structure is comprised of small well or pond in which water is collected by making stone wall across

			a stream.
Khatri	Hamirpur, Kangra, and Mandi districts in Himachal Pradesh	Western Himalayan Region.	Traditional water harvesting structure of about 12 ft.x 10ft x 6 ft in size carve in hard rock mountain, in which rainwater is collected from roof through pipes or through seepage from through rocks.
Kuhl	Himachal Pradesh	Western Himalayan Region	Traditional irrigation system consists of headwall constructed across ravine for storage and diversion of flow through a canal to irrigation fields.
Apatani	Arunachal Pradesh, Sikkim & Darjeeling district in West Bengal.	Eastern Himalayan Region.	Traditional rainwater harvesting system for surface water conservation. In Apatani system, valleys are traced into plots separated by about 0.6 m high earthen dams. These plots are connected to one another by inlet and outlet arrangement located on opposite sides. The inlet of low lying plot acts as the outlet of the adjoining plot. Deeper channels connect the inlet point to the outlet point. Traced plot can be flooded or drained off by opening and blocking the inlets and outlets. Stream water tapped near forest hill slopes is conveyed to the agricultural fields through a channel network.
Zabo (Ruza	Nagaland	Northeaster Hill range	Traditional rainwater harvesting structure like pond in which runoff

system)			passes through terraces are collected in it for forestry, agriculture and animal care.
Bamboo Drip Irrigation	Meghalaya	Northeaster Hill range	About 200 years old traditional system. Bamboo pipes are used to divert perennial streams and springs at the hilltops to lower reaches by gravity for irrigation of plantations. The channel sections, which are made of bamboo, divert and convey to the plot site from where it is again distributed to branches.
Dongs	Assam	Brahmaputra Valley	Traditional artificial groundwater recharge system is comprised of ponds, normally constructed for irrigation. These ponds receive water from surrounding hills.
Dungs and Jampois	Jalpaiguri in West Bengal	Brahmaputra Valley	Small irrigation channels which link rice fields to streams
Dighi	West Bengal	Indo-Gengatic plains	A square or circular reservoir with steps to enter. Each Dighi has its own catchment area and a sluice gate. People are not allowed to bathe and washed clothes on the steps of Dighi, however allowed to take water for personal use. Most of the houses had either their own wells or smaller dighis on their premises.
Kunds/Kundis	Western Rajasthan & Some areas in	Thar Desert	Rainwater harvesting structures look like an unturned cup nestling in a saucer. Essentially a circular underground well in which rainwater is collected for drinking. The sides of the well pits are covered with

	Gujarat		lime and ash. Most of the pits have dome shaped cover or at least a lid to protect water. The depth and diameter of the kund depend on the requirement of water.
Kuis and Beris	Western Rajasthan	Thar Desert	Seepage collecting structures of 10-12 m deep pits dug near tanks. Kuis are also used to harvesting rainwater in areas of meagre rainfall. The mouth of a pit is usually made very narrow to prevent evaporation. Pit gets wider as it burrows under the ground to enable it seep into large surface area.
Baoris/Bers	Rajasthan	Thar Derest	Community wells collect rainwater for use to meet drinking water needs. Baoris can hold water for long time because of almost negligible evaporation.
Jhalaras	Rajasthan & Gujarat	Thar Desert	Man-made community tanks uses for religious rites. Often rectangular in shape and have steps from three or four sides. Jhalaras are groundwater bodies which collect subterranean seepage water of talab or lake located upstream and are built to ensure easy and regular supply of water for bathing and religious rites.
Nadis	Jodhpur, Rajasthan	Thar Desert	Village ponds used for storing water from adjoining natural catchment during rainy season. Sites for nadis are selected by villagers based on natural catchments and their yields.

Tobas	Rajasthan	Thar Desert	Natural ground depression in a catchment having low porosity uses for storing of surface water from rainy season.
Tankas	Bikaner in Rajasthan & Dwarka in Gujarat	Thar Desert	Small underground tanks generally circular in shape & lined with fine polish lime, built in the main house or courtyard to collect rainwater. These tanks' water are used for drinking
Khadin	Jaisalmer in Rajasthan	Thar Desert	A rainwater harvesting system on farmland designed storing surface runoff for agriculture. Its main feature is a long earthen embankment (100-300 m) across lower hill slopes.
Vay/Vavdi/ Baoli/ Bavadi	Gujarat & Rajasthan	Thar Desert	These are step wells known by Vay or Vavdi in Gujarat and Baoli or Bavadi in Rajasthan. Practices of these types of step wells are found non-existence nowadays.
Virdas	Rann area of Kutch in Gujarat	Thar Desert	Shallow wells dug in low depression called Jheels (Tanks).. These structures harvest rainwater. The sites selection of these structures are made such a way that they separate freshwater from unpotable saltwater.
Talabs/Bhandis	Eastern Rajasthan & Bundelkhand in	Central Highlands	Natural or man-made reservoirs. A reservoir area less than five bighas is called talai; a medium sized lake is called talab; bigger lakes are called sagar or samand. These reservoirs serve irrigation and drinking water requirements. When the water in the reservoir

	Madhya Pradesh		dries up just a few days after the monsoon, the reservoir beds are used for rice cultivation.
Saza Kuva	Aravalli hills in Marwar in Eastern Rajasthan	Central Highlands	An open well with multiple owners used for irrigation. It is constructed by digging soil and generally circular in shape.
Johads	Alwar district in Rajasthan	Central Highlands	Small earthen check dams that capture and conserve rainwater, improve percolation and groundwater recharge. It has successfully been used since 1984.
Rapat	Eastern Rajasthan	Central Highlands	Percolation tank with a bund by either masonry wall or earthen, to impound runoff from watershed. It is mainly used for groundwater recharge.
Katas/Mundas/ Bandhas	Orissa & Madhya Pradesh	Eastern Highlands	These were ancient structures used for irrigation purposes. A kata is constructed north to south or east to west of a village by a strong earthen embankment curved at either end and is built on a drainage line to guide drainage water from upland to the irrigation field.
Cheruvu	Chitoor and Cuddapah districts in Andhra Pradesh	Deccan Plateau	Traditional water harvesting reservoirs to store runoff.

Kohlis	Bhandara district in Maharastra	Deccan Plateau	Traditional water tanks which hold rainwater for irrigation of sugarcane and paddy cultivation.
Bandharas	Maharastra	Deccan Plateau	Traditional stream/river water harvesting structures consist of check dams or diversion weirs constructed across streams/rivers to raise water level in the streams/rivers for diversion of water to irrigation fields. Most of the Bandharas are defunct today.
Kere	Central Karnataka	Deccan Plateau	Tanks traditionally used for supply of irrigation water. These tanks are fed either by channels branching off from anicuts (check dams) built across streams or by streams in valleys.
Ramtek model	Maharastra	Deccan Plateau	Surface water runoff harvesting tanks connected in series to catch rainwater from watersheds and supported by high yielding wells and structures like baories, kunds.. The tank located at the upper reaches close to hills are filled up, water flows to downstream to successive tanks through interconnecting channels. This sequential arrangement generally ends to a small watershed to store the remaining water.
Surangam	Karnataka	Western Ghats	Surangam (means tunnel) is a horizontal well mostly excavated in hard laterite rock formations. The excavation is done to a depth till a good amount of water is struck. Underground water seeps out of the hard rock and flows out of the tunnel. This water is collected in an open pit constructed outside a surangam.

Korambu	Kasargod and Thrissur districts in Kerala	Eastern Ghats	Korambu is a temporary dam constructed across mouth of channels by brushwood, mud and grass. It is used to raise water level in the canal and to divert the water into field channels. It is designed in such a way that required quantity can flow to the diversion channel and excess water can overflow through it. Water is allowed to flow from one field to another until all fields are irrigated.
Eris	Tamilnadu	Eastern Coastal Plains	Eris (tanks) are very common in irrigated area of Tamilnadu. They play several important roles: maintaining ecological harmony, preventing soil erosion and wastage of surface runoff, and recharging groundwater in the surrounding areas.

Looking for Suitable Sites for MAR Projects

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Abstract. For sustainability of ground water sources, ground water recharging is considered an important component of aquifer management. The talk presents a brief overview of steps required in locating suitable sites while attempting artificial recharge (MAR) projects. The field studies included in the note include hydrological, geo-hydrological, geo-morphological, soil infiltration, and geophysical investigations. Use of remote sensing and GIS-based technique and ground water prospects map prepared by NRSC is also briefly described.

Artificial Recharge (MAR) Projects

Artificial recharge (or Managed Aquifer Recharge- the term as used in the present context) projects are site specific, and are based on the local hydrogeological and hydrological environments. Artificial recharge is normally taken in areas:

- where ground water levels are declining on regular basis,
- where substantial amount of aquifer has already been desaturated,
- where availability of ground water is inadequate in lean months,
- where salinity ingress is taking place.

The two basic requirements in any artificial recharge projects are:

1. Availability of non-committed surplus monsoon runoff in space and time, and
2. Identification of suitable hydro-geological environment and sites.

Design of an Aquifer Recharge System

Aquifers best suited for artificial recharge are which absorb large quantities of water and do not release them too quickly. This implies that vertical hydraulic conductivity is high, and horizontal hydraulic conductivity is moderate.

The availability of sub-surface storage space and its replenishment capacity further govern the extent of recharge. Upper 3 m of the unsaturated zone is not considered for recharging, since it may cause adverse environmental impact e.g. water logging, soil salinity, etc.

Detailed knowledge of geological and hydrological features is required for adequately selecting the site and the type of recharge structure. It is imperative to plan out an artificial recharge scheme in a scientific manner, and proper scientific investigations be carried out for selection of site for artificial recharge of groundwater. Recharge structures should be planned out after conducting proper hydro-geological investigations. Based on the analysis of this data (already existing or those collected during investigation) it should be possible to:

- Define the sub-surface geology
- Determine the presence or absence of impermeable layers or lenses that can impede percolation
- Define depths to water table and groundwater flow directions
- Establish the maximum rate of recharge that could be achieved at the site

Factors considered useful in selecting the sites are:

- drainage density (immense control on runoff and infiltration)
- lineament intensity (control occurrence and movement of groundwater)
- lineament drainage intersections (drainage pattern is affected by geological structure)
- lineament controlled drainage courses
- lithological and geomorphic set-up
- Hydro-geomorphic units
- soil thickness and channel confluence

Field Investigations

Hydrological Studies

Useful in assessment of availability of source water:

- Precipitation in the watershed
- Surface (canal)supplies from large reservoirs located within basin
- Surface supplies through trans basin water transfer
- Treated municipal and industrial wastewaters

Also useful in deriving the following information:

- quantity that may be diverted for artificial recharge.
- time for which the source water will be available.
- quality of source water and the pre treatment required.
- conveyance system required to bring the water to the recharge site.

Soil Infiltration Studies

Useful in

- assessment of soil and land use conditions which control the rate of infiltration and downward percolation of the water applied on the surface of the soil, and
- deriving infiltration capacity (maximum rate at which water can enter soil at a particular point

Hydro-geological Studies

Useful in

- correlation of topography and drainage to geological contacts
- Identification of promising hydro-geological units for recharge and decide on the location and type of structures to be constructed in field
- Ground water contours to determine the form of the water table and the hydraulic connection of ground water with rivers, canals, etc
- Depths to the water table for the periods of the maximum, minimum and mean annual position of water table
- Ground water potential of different hydro-geological units and the level of ground water development
- Maps showing chemical quality of ground water in different aquifers

Geo-morphological Studies

Geomorphic analyses of a watershed provide quantitative description of the physiographic, topographic and drainage characteristics in the area. Lineaments, landforms and geomorphic units are identified and analyzed in terms of hydrologic characteristics of geologic formation of the study area. This analysis is useful in providing insights on the scope of water storage potential in terms of number, size and prospective locations of the identified recharge structures.

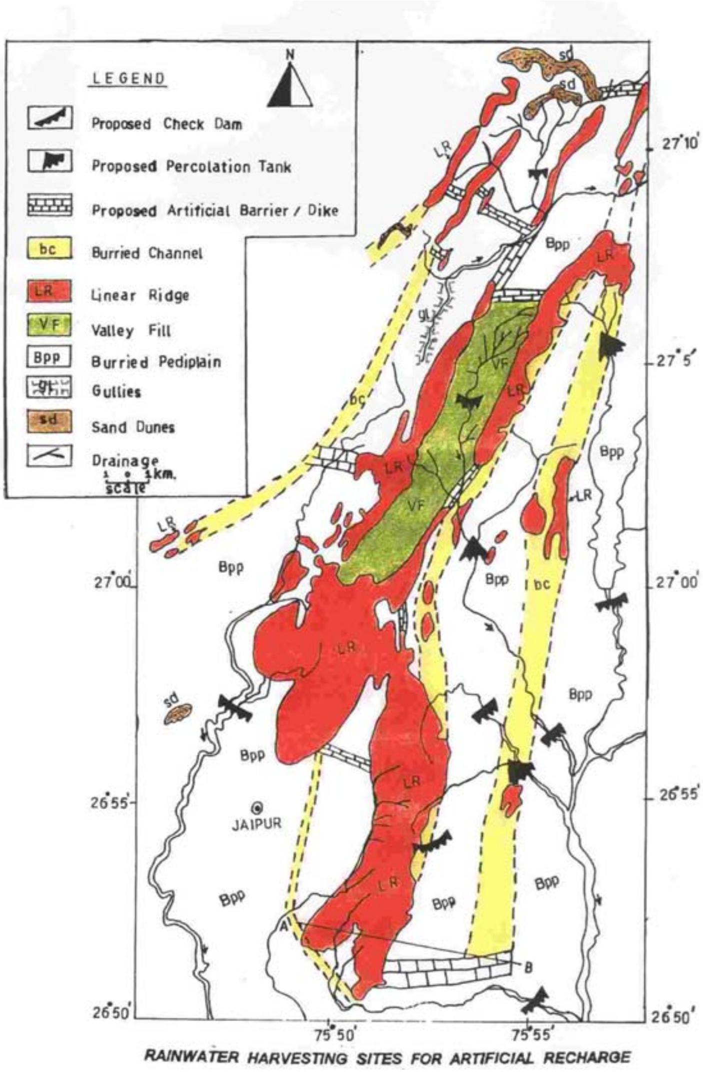


Figure 1 Dhund river basin, Rajasthan

Table-1. Recharge site identification based on hydro-geomorphic analysis (Source: A. K. Sinha; S. P. Yadav and Shyamanuj Dubey, Dept. of Geology, University of Rajasthan, Jaipur)

Geomorphic unit	Lithology	Hyd. characteristics	Recharge status
Burried channel	Sands, alluvium, silts, clays	Low runoff/ high infiltration	Moderately favorable
Linear ridge	Quartzite	High runoff/ low infiltration	Less favorable
Valley fill	Boulders, pebbles, clays, stones	High runoff/ high infiltration	Highly favorable
Burried pediplain	Alluvium, clays, silts, sands	Low runoff/ moderate infiltration	Moderate to less favorable
Gullies	Clays, sands, alluvium	High runoff/ low infiltration	Less favorable
Sand dunes	Clayey sands	High runoff/ low infiltration	Less favorable

Geophysical Studies

Useful in

- Assessment of sub-surface hydro-geological to compliment the exploratory program
- Mostly employed to narrow down the target zone and pin-point probable sites for artificial recharge structure
- Identification of brackish/fresh ground water interface, contaminated zone (saline) and the area prone to seawater intrusion

Use of Ground Water Prospects Maps prepared by NRSC

Under Rajiv Gandhi Drinking Water Mission of the Ministry of Drinking Water and Sanitation (Govt. of India), National Remote Sensing Centre (ISRO), Hyderabad have prepared Hydro Geo-Morphological Maps (HGM) using satellite data for facilitating the State Governments to identify suitable locations of different ground water structures, including recharge structures. These maps are available both in digital as well as hard copy formats. The hard copy format is available in the form of A0 size map (on 1:50,000 scale), and covers an area of approx 700 km^2. The digital ground water prospects maps are made using 19 independent thematic layers, and can be viewed on workstations with Arc GIS software 9.5.1 or higher version.

The ground water prospects map also shows suitable locations for site-specific recharge structures. The location of recharge structures are shown on the upstream side of the habitations so that the drinking water sources located in the habitations are recharged directly. Based on the need for ground water recharge, the hydro-geomorphic units/aquifers occurring in the map area are divided into five priority classes (Table-2).

Table-2. Types of hydro-geomorphic units w.r.t. requirement for ground water recharge (source: GoI, 2011)

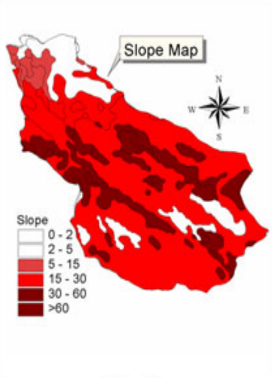
S N	Type	Represented as
1	Hydro-geomorphic units where ground water recharge is required with high priority	High priority
2	Hydro-geomorphic units where ground water recharge is required with medium priority	Medium priority
3	Hydro-geomorphic units where ground water recharge is required with low priority	Low priority
4	Hydro-geomorphic units where ground water recharge is not required	Not required
5	Hydro-geomorphic units where ground water recharge is not feasible	Not suitable

Remote Sensing & GIS-based Technique

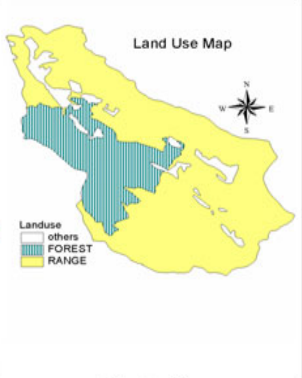
Useful in delineation of various thematic layers such as

- Geology, soil, land use/cover, water table fluctuation, depth to bed rock and slope, and
- Drainage density, lineament density and geo morphology.

Modelling approaches, such as Weighted Linear Combination (WLC) model, are used to derive a suitability index map, which shows probable ground water recharge zones in the area. The figure below shows an example from Isfahan (central part of Iran).

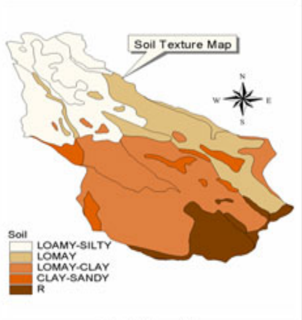


2. Slope Map



1. Land Use Map

4. Stream Map



3. Soil Texture Map

5. Artificial Recharge Map

Sources of Information

- Guide on Artificial Recharge to Ground Water, different States, published by Central Ground Water Board (Govt. of India), 2000
- Ground Water Prospects Maps (of different States), published by National Remote Sensing Centre (ISRO-Govt. of India) and Ministry of Drinking Water and Sanitation (Govt. of India), 2011
- District groundwater maps, published by Central Ground Water Board (Govt. of India)
- Ground water exploration report of different States, published by Central Ground Water Board (Govt. of India) and respective State Governments
- Geological maps of different States, published by Geological Survey of India (Govt. of India) and respective State Governments

Potential of water harvesting structures for groundwater recharge in India

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Abstract. This paper presents the results of a literature review on existing evaluations of managed aquifer recharge (MAR) systems in India. More than 20 papers were studied and the results covered economic, environmental, social and institutional. A SWOT analysis revealed that there are various opportunities and threats related to the implementation of managed aquifer recharge systems that need to be considered for future projects.

Introduction

Managed aquifer recharge (MAR) is the planned, human activity of augmenting the amount of groundwater available through works designed to increase the natural replenishment or percolation of surface waters into the groundwater aquifers, resulting in a corresponding increase in the amount of groundwater available for abstraction (Oaksford 1985). Artificial recharge of groundwater is one of the oldest activities undertaken in India to conserve rainwater both above ground and underground. More than 500,000 traditional tanks and ponds can be found in peninsular India. These ponds (called *khadin, talab, johad, ooranis* or *nadi*) were constructed thousands of years ago for catering to the multiple uses of irrigated agriculture, livestock and human uses. Within the area of influence of these ponds are numerous shallow dug wells that are recharged with pond water (Sakhtivadivel 2007). Since the 1970s numerous watershed development projects (WDP) have been implemented in India.

There are several technical options on how to implement managed aquifer recharge. In general one can distinguish between modern, traditional and hybrid structures. Examples for modern systems are percolation tanks and check dams, examples for traditional systems are *khadins, johads* and *talabs* and hybrid systems are traditional systems improved by modern technologies as for example ooranis where the water is treated in sand filters.

Percolation tanks are artificially constructed surface water bodies that are built by retaining water from a stream with a dam. The water storage induces percolation and replenishes the groundwater (CGWB 2007).

Check dams are constructed across gullies, nalahs or streams to reduce flow velocity of streams and to retain water for longer durations. By reducing flow velocity of the water, also soil erosion is reduced. A series of check dams can be constructed to recharge water on a regional scale (CGWB 2007).

Subsurface dams are intended for stopping groundwater flow in a natural aquifer. They are constructed undergound and consist of an impervious wall which prevents the groundwater from draining (Raju 2006). See figure 1 for schematic drawings.

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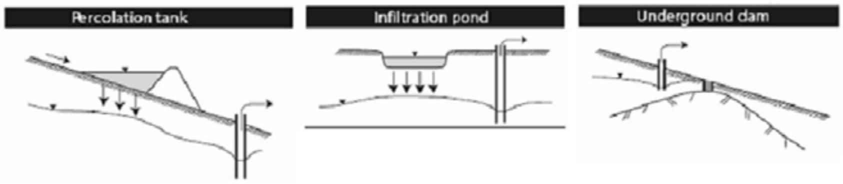


Fig.1. Modern technologies for managed aquifer recharge in India: percolation tank, infiltration pond and underground dam (from left to right) (Source: NRMMC et al. 2009)

A *Khadin*, also called a *Dhora*, is an earthen embankment built across the general slope, which conserves the maximum possible rainwater runoff within the agricultural field. *Khadin* is an ancient water harvesting mechanism of the desert environments of Western Rajasthan. The run-off from the catchment area is stored in the valley enclosed by earthen bund. Surplus water if any passes out through spillway sluices (Agarwal and Narain 2003, Barah 2003)

Johads are small earthen check dams that capture and conserve rainwater, improving percolation and groundwater recharge (www.rainwaterharvesting.org). They recharge groundwater and improve soil moisture in vast areas, mostly downstream (WSP 2011)

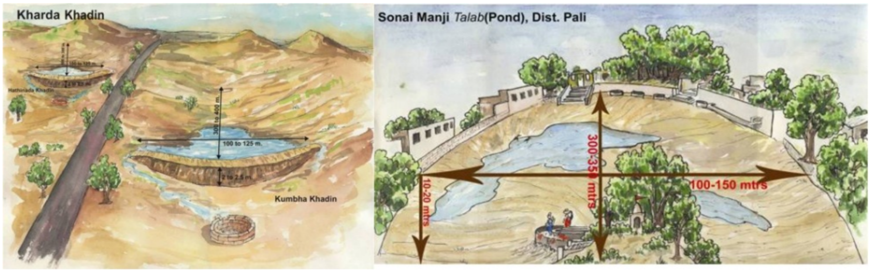


Fig.2. Traditional technologies for managed aquifer recharge in India: *Khadin* (left) and *Talab* (right) (Source: Bishnoi and Gupta 2011)

Talabs are reservoirs which serve irrigation and drinking purposes. This is the most commonly used method to collect and store rainwater. Where the catchments are too small to provide enough water, water from nearby streams or irrigation channels is diverted through open channels to fill the ponds. (http://www.rainwaterharvesting.org)

This paper aims at assessing the potential of MAR structures in India with a focus on environmental, economic, social and institutional aspects, based on previous experiences with such structures in India.

Experiences in India

India has a long tradition of implementing MAR structures and consequently a large number of reports and studies on MAR structures in India are available. The following section summarizes some of these available reports and studies with a focus on non-technical information and structures the available information in environmental&health, social, institutional and economic impacts.

Environmental and human health impact

An important aspect to consider would be the impact of the recharged water quality on groundwater quality and quantity. However, no documentation of the impact on groundwater quality could be found. With respect to the specific impacts of MAR on the groundwater table, considering the high number of implemented systems, there are few studies available where the real impacts on the groundwater levels were quantified as field investigations are difficult and expensive (Glendenning et al. 2012). The following studies could be identfied:

A recent study (Glendenning and Vervoort 2010) indicated recharge efficiencies of around 7% of total rainfall in a case study watershed in Rajasthan. A similar value was obtained by Sharda et al. (2006a) for a case study in Gujarat, where various recharge schemes were constructed. The recharged water in the years 2003 and 2004 corresponds to 7.3 and 9.7% of the total annual rainfall.

Another study of three WDP in Gujarat, Tamil Nadu and Maharashtry by Gale et al. (2006) shows that recharge is about 4-12 mm corresponding to 0.6-1.4% of the total rainfall, which is much lower than the estimation of 80 mm over 14% of the entire land area of India by the Central Ground Water Board (CGWB 2002).

Raju et al. (2006) report a rise of groundwater level of up to 1.8 meters in the Swarnamukhi River basin in Andhra Pradesh after the installation of subsurface dams.

The different results show that there is a high variability of aquifer response to MAR system. The measurement of the recharged amounts is usually done by analysis of water-level fluctuations in observation wells, which can over-estimate the recharged amount if the measurement is done near the recharge structure (Glendenning 2012).

With respect to health impacts, especially in traditional systems, where water is not only recharging the aquifer, but is directly used from the recharge structures, some risks were highlighted. For instance, Pangare (2003) analysed 16 samples from *ooranis* in Tamil Nadu and found that the water from the *ooranis* needs to be treated to reduce turbidity and biological pollutants prior to its use. Another study where *khadins* were evaluated came to the same result: analyzed samples of hand pump water near the *khadin* fulfill the standards for drinking water, but water taken directly from the *khadin* needs treatment before use (Bishnoi and Starkl 2011). That shows the importance of the soil passage during which the water is filtered.

Social impact

MAR structures provide an alternative water source to humans and therefore the social impact has to be considered. Two types of social impacts are relevant: On the one side social impact on the users, mainly acceptance, benefit sharing and financing/affordability of the users of the alternative water sources. On the other side, a MAR structure may affect the water source of downstream users which can cause important social impacts on the downstream users. With respect to user acceptance, different studies (Pangare 2003, Bishnoi and Starkl 2011) have shown that the water from the systems is highly accepted or even the preferred water source. Concerning benefit sharing, the study of Gale et al. (2006) of three WDP showed that in all case studies, recharge was assumed to provide community-wide benefits, and hence structures were generally viewed as community assets, to be financed and managed by the community. Nevertheless, land owners are the ones who are benefitting most from the interventions. With respect to downstream impact no studies about the social impact have been conducted so far.

Institutional impact

Water has been traditionally managed by local institutions in India. As the review of MAR project documentations has shown, most of the documented systems are implemented in rural areas and operated by designated committees which are also responsible for collecting user fees. Therefore, the local institutional arrangements are important for ensuring long term sustainability of the MAR structures.

The evaluation of six modern water development projects in Andhra Pradesh (LNMRI 2010) has shown that the programmes remained weak with regard to community organization for maintaining the assets created as well as continuing the programme through user groups and people's involvement. The study recommended that efforts should be made to strengthen the participation of user groups in the programme in terms of obtaining their consent before taking up works and involving them in executing these works. Building up proper awareness and constant persuasion and motivation to make them take active part would ensure further effective contribution and sustainability of the programme. Similar results have been obtained in another study by Gale et al. (2006) where three watershed development projects in Maharashtra, Gujarat and Tamil Nadu have been evaluated.

Similar experiences were reported by AFPRO (2010) which studied a project in Rajasthan. It showed that the organisational structures of traditional recharge technologies are similar and therefore the same challenges concerning operation and maintenance have to be handled. Users were satisfied with the work of the committee, but there can be risks related to long-term sustainability if the members of the committee do not fully recognise their role during operation and maintenance of the systems.

Economic impact:

Implementing MAR structures needs capital and operational costs.Capital costs of MAR systems are documented. For instance, the government of India (GOI 2007) has published information on construction costs. The numbers are based the information of 4 – 16 case studies per technology. The table below shows investment cost and the costs per m³ recharged water. The costs per m³ vary between 2.5 -455 INR depending on the type of structure applied. This shows that the costs are highly dependent on the local situation and average unit costs are difficult to determine

Table 1. Costs of recharge structures (Source: GOI 2007)

Type of structure	Investment costs (lakh INR)	Costs / m³ recharged water (INR)
Percolation tank	1,55 – 71	20 – 193
Check dam	1,5 – 1050	73 – 290
Recharge well	1 – 15	2.5 – 80
Sub-surface barrier /dyke	7,3 – 17,7	158 – 455

Raju et al. (2006) reported construction costs of subsurface dams in a range of US$ 18000 – 74000 US$. The construction costs of the traditional *johads* built in Rajasthan are in the range of USD 1,000 – 2500 (WSP 2011).

Only little information is documented about operation and maintenance costs. Only in one study (Bhagwat et al 2011) operation and maintenance costs of a water conservation project basically encompassing check dams for 16 villages in Madhya Pradesh, could be identified. Users pay 70-100 INR per month for the operation and maintenance of the water supply systems which are supplied with recharged groundwater (personal communication with A.M. Singh 2012).

Potential for India

To assess the potential of water harvesting structures for groundwater recharge in India, a SWOT-analysis was conducted. SWOT analysis was initially developed for business management, but has also been used in natural resource management (e.g. Srivastava 2005, Terrados 2007, Mainali 2011). The SWOT analysis provides a framework for analyzing a situation by identifying strengths and weaknesses, but also recognises challenges and developes strategies for the future (Srivastava 2005). Thereby, strengths are advantages that support the decision to implement MAR systems; weaknesses show what can be improved or what needs to be investigated before implementing MAR systems. Opportunities refer to possible chances and positive improvements of MAR systems, whereas threats show risks and obstacles for the future. The following text discussed the SWOTs of MAR structures building up on the previous section.

Strengths

MAR systems provide communal assets, from which local communities are benefiting. Higher agricultural yields increase the income resulting in higher quality of life. Water provided in the recharge structures is well accepted by the affected population and sometimes even preferred over other sources. Recharge amounts of ~10% of the total annual rainfall were documented.

Weaknesses

Concerning benefit sharing it became evident in the existing studies that the benefits are not distributed evenly among the whole community, but that those who own land benefit more than landless people.

The soil passage where the water is filtered before use is important to ensure good quality. The practice of using water directly from recharge structures is common for traditional systems, but this water turns out to be contaminated as it collects surface runoff and people step into the water to collect it.

Opportunities

Systems for aquifer recharge have been implemented for centuries but many of them have been replaced by centralised system relying on surface and groundwater. A study about the potential of traditional recharge sytems in Rajasthan showed that there have been successful attempts in reviving kunds in Churu district of Rajasthan and also *khadins* have a high potential to solve drinking water problems as there are 118,600 hectares of land that could be used for construction of these systems (Babu 2008). The combination with modern technologies (e.g. sand filters, disinfection) can improve the water quality of traditional systems.

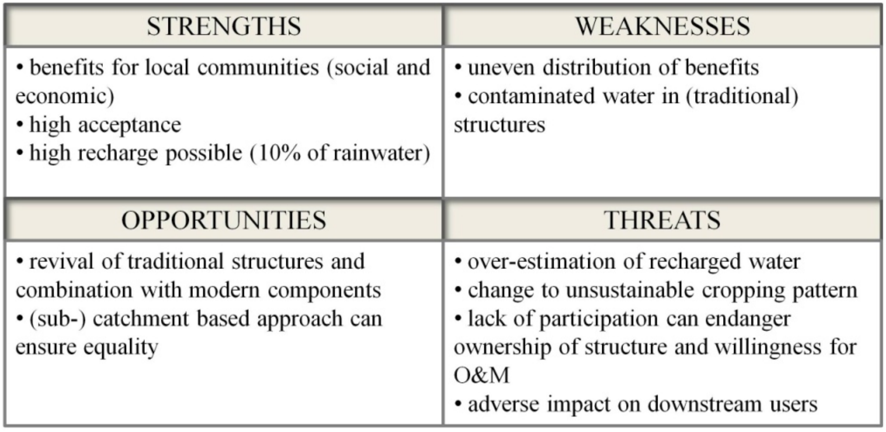
A possibility to minimise the adverse impacts for downstream users is the implementation of small scale systems at sub-basin level. Sharda (2006b) proposes decentralised systems instead of centralised schemes to meet the water demand of communities in water scarce areas. Considering the possible impacts of MAR systems, this approach may be a possibility to mitigate the negative effects. The water conservation project presented by Bhagwat (2011) is based on this approach: within a sub-basin of a river, small check dams were implemented and 16 villages in the watershed benefit from the project.

Threats

Concerning the threats related to MAR systems, various issues have been raised. More available water motivates farmers to change to new crops which can lead to unsustainable farming systems as groundwater replenishment is not as big as expected (Gale et al. 2006). Another problem often not considered is that the water which is locally recharged could have been a source of water for downstream users who can experience water shortage as a consequence (Kumar et al. 2008). There are few basin-wide studies on that consider the trade-offs between upstream and downstream use (Sakthivadivel 2007, Glendenning et al. 2012).

The general public opinion of MAR systems is positive as they are considered to result in economic benefits through increased crop production. Bouma et al. (2011) come to the result that the downstream impacts are considerable and that net benefits are insufficient to pay back investment costs. The study showed that the benefits gained in the upstream region can compensate downstream losses as long as investments are kept low. If the investments increase, the net benefit of the MAR systems can become negative as downstream users lose more than upstream users gain.

A summary of the main SWOTS can be seen in Figure 3.



STRENGTHS	WEAKNESSES
• benefits for local communities (social and economic) • high acceptance • high recharge possible (10% of rainwater)	• uneven distribution of benefits • contaminated water in (traditional) structures

OPPORTUNITIES	THREATS
• revival of traditional structures and combination with modern components • (sub-) catchment based approach can ensure equality	• over-estimation of recharged water • change to unsustainable cropping pattern • lack of participation can endanger ownership of structure and willingness for O&M • adverse impact on downstream users

Fig.3. SWOT analysis based on existing evaluation results

Conclusions

The government of India has put strong emphasis on the implementation of watershed development programms. There are many national programs under which several hundreds watershed development projects (WDP) have been implemented. The most relevant ones are the National Watershed Development Programme for Rainfed areas (NWDPRA), Desert Development Programme (DDP), Integrated Wasteland Development Programme, Drought Prone Areas Programme (DPAP) and the Rajiv Gandhi Mission on Watershed Development (RGMWD).

The existing literature on managed aquifer recharge is very extensive and showed that MAR systems provide various benefits. The following recommendations resulting from the SWOT analysis can be made:

Detailed investigations at the beginning of projects are necessary to predict the response of the aquifers on the planned measures. As a general recommendation, the investigation of the basin-wide effects should be integral part of new MAR projects.

India has a large number of traditional systems which have been abandoned and their revival in combination with modern treatment systems has a huge potential to mitigate water scarcity (Starkl and Bishnoi 2011, Sharda 2006b).

Many different watershed development projects have been implemented all over India in the last decades and those including a participatory component proved to be more sucessful than their technocratic counterparts. Also organisational arrangements have been studied and a well organised operation and maintenance scheme proved to be an important pillar for well working systems. Therefore participatory components should be integral part of every watershed development project.

Acknowledgements

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Mitigation of seawater intrusion by Managed Aquifer Recharge

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Abstract. There are several methods to mitigate seawater intrusion. Managed aquifer recharge is one of the best suited methods for water supply and other potable services. Seawater intrusion has been identified along the coastal aquifers o Chennai by geoelectrical, geochemical and isotope studies. Groundwater modeling has been done to find out the effect of pumping on sea water intrusion. A pilot pond is constructed as a part of managed aquifer recharge at Andarmadam, Thiruvallur district of Tamil Nadu and studied the effect of the pilot pond. The improvement of groundwater potential by a check dam over the Arani River shows that check dam have considerable effect on increasing the quality of groundwater.

Introduction

Seawater intrusion is defined as the migration of salinewater from the sea into aquifers that are hydraulically connected with the sea. Seawater intrusion thus leads to the salinization of fresh water aquifers along the coastlines. In highly populated coastal regions with greater dependence on groundwater, the withdrawal usually exceeds the recharge rate which causes seawater intrusion. Seawater generally intrudes upward and landward into an aquifer and around a well, though it can occur ‘passively’ with any general lowering of the water table near a coastline. The transition zone (the interface where freshwater naturally mixes with seawater as it is discharged to the sea) naturally descends landward as a wedge within aquifers along the coastline.

Causes of seawater intrusion

The density of seawater is marginally higher than that of fresh water. Hence the intruded salinewater settles at the bottom of the aquifer and fresh water floats on the top of it. However the boundary between saltwater and fresh water is not distinct but characterised by the dispersion zone. The rate of depletion of aquifers is directly related to the position of zone of dispersion.

One of the most important causes of seawater intrusion is the reversal of groundwater gradients in coastal aquifers, where over pumping of wells disturbs the hydrodynamic balance. Potential saltwater intrusion occurs wherever a natural hydrodynamic equilibrium exists between fresh and salinewater; under natural conditions, the groundwater gradient along coastal areas is from the elevated land to the coast, following the topography of the terrain. Over pumping of fresh water aquifers results in the development of a cone of depression and the reversal of groundwater gradient. This causes the entry of saltwater to the original fresh water zones.

Seawater intrusion also results from the destruction of natural barriers that separate freshwater and salinewaters. Saltwater may infiltrate into freshwater zones where coastal water way dredging causes the exposure of low permeable materials and transverse fault zones. Oil exploration or deep mining practices infringe the confining layer between freshwater and saltwater aquifers and increases the possibility of intrusion.

Salinewater intrusion results from the subsurface disposal of waste salinewater such as into disposal wells, landfills or other waste repositories. Saline wastes depositing into streams or unlined evaporation pits have a potential to infiltrate down the fresh water zone. In some areas, the structural reliability of the zone of dispersion is inadequate due to natural fracturing, thus permitting vertical intrusion.

Saltwater intrusion also results from the degradation of groundwater through continuous use without sufficient out flow, degradation through lateral or upgrade migration of brines or degraded waters from the formations to underlying the groundwater basin, degradation through the downward seepage of sewage or industrial waste or mineralised surfacewater from streams, lakes and lagoons to the groundwater table and degradation through migration of salinewater from one water bearing formation to another, either through the natural breaks in impermeable layers or through improperly constructed wells (Ramakrishnan1998).

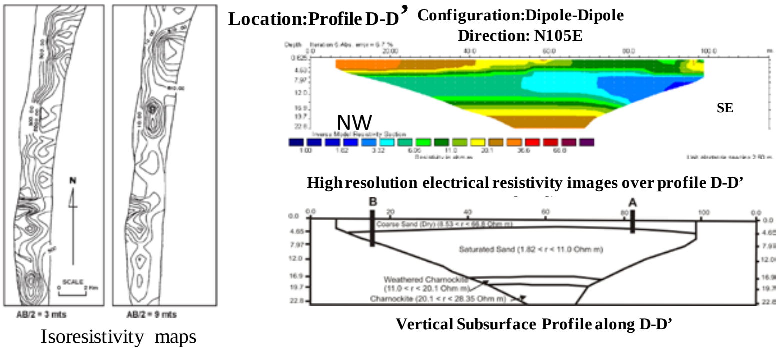
Identification of seawater intrusion

Groundwater level measurements

Reversal of hydraulic gradient is major cause for seawater intrusion. If the groundwater head is below the local sea level, then seawater intrusion is certain. Hence, measurement of groundwater head in vicinity of coast will indicate about whether the region is affected by seawater intrusion.

Geoelectrical studies

Geoelectrical measurements are very well useful for the investigation of extent of seawater intrusion and also to assess the groundwater salinisation. Vertical Electrical Sounding was conducted using Schlumberger configuration in a rectangular grid pattern consisting of seventeen traverses and five profiles along the coastal region near Chennai, India (Gnanasundar and Elango, 1999; Senthilkumar et al. 2001). This study clearly indicated the presence of a fresh water ridge in the central portion of the study area. Very low resistivity values existed along the eastern and western margins. The saline groundwater in the eastern margin was due to seawater intrusion and in the western margin was because of the influence of Buckingham canal which carries contaminated water (Sathish et al, 2011).


Location:Profile D-D' Configuration:Dipole-Dipole Direction: N105E

High resolution electrical resistivity images over profile D-D'

Vertical Subsurface Profile along D-D'

Isoresistivity maps

Fig.1 Vertical subsurface profile along the Chennai coastal aquifer

Geochemical studies

The dominant cations and anions present in groundwater of Chennai costal aquifer is in the order of Na+ >Ca2+ >Mg2+ >K+> and Cl->, HCO3--> SO4-> NO3-> F- respectively. Sodium chloride type water was dominant in most part of the aquifer (Sivakumar, 2008; Sathish and Elango, 2011). The concentration of the major ions showed an increase from west to east. The hydrochemical data indicates that the deep wells in the east are saline. It is clear from the geochemical analysis that saline groundwater is fairly distributed in coastal part of this region. Thus the geochemical data was also used to understand the influence of seawater intrusion in this area.

Isotope studies

Isotope studies can be used for a variety of environmental and hydrological studies. Such a study was carried out near Chennai to study the impact of December 2004 tsunami on groundwater resources (Sivakumar, 2008). The relation between oxygen 18 and deuterium of the groundwater samples show that excluding six groundwater samples, all samples plot near the meteoric water line, indicating that they are of meteoric origin. Oxygen-18 and Deuterium relationship in the groundwater indicate the evaporation process.

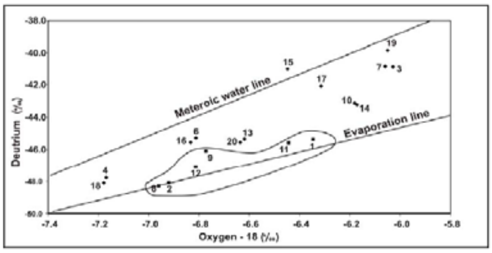
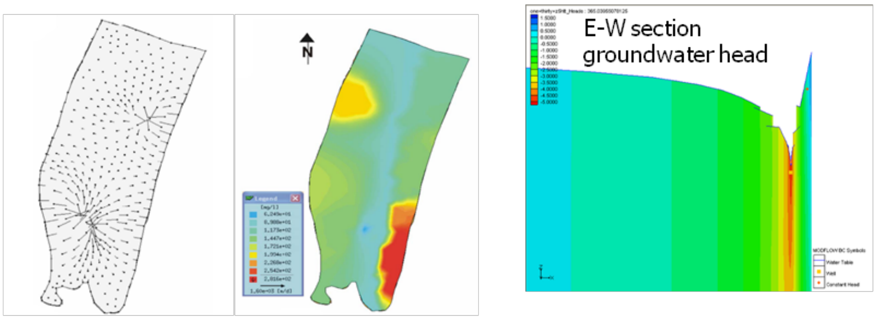


Fig.2 Correlation of groundwater Oxygen-18 & Deuterium

Groundwater modeling

Groundwater modeling was carried out using MODFLOW and FEFLOW for the coastal regions of Chennai (Sivakumar and Elango, 2010; Sivakumar et al. 2006; Gnanasundar and Elango, 2000). This aquifer was found to be under stress due to pumping of groundwater to meet the city's increasing water needs. Groundwater modeling was carried out to assess the seawater intrusion under various scenarios of abstraction. Modelling was also used to assess the impact on the groundwater system by the proposed pumping by the desalination plant. The possibility of having a horizontal well to pump seawater for the desalination plant was assessed.



Regional groundwater flow vector

Simulated chloride ion concentration of groundwater in January 2007

Fig.3 Groundwater model or the coastal regions of Chennai

Thus geoelectrical, geochemical, isotopic and groundwater modelling studies were carried out to understand the influence of seawater intrusion on fresh water aquifers.

Mitigation measures of salt water intrusion

Considerable attention has been focused on alternative methods to mitigate salinewater intrusion. Reduction in pumping of existing wells and changing the locations of pumping wells to inland areas can reestablish stronger seaward hydraulic gradient. Such a condition would tend to slow down the inflow of salinewater towards the fresh water aquifer. Another way of mitigation of salt water intrusion is the construction of an impermeable subsurface barrier parallel to the coast and the prevention of inflow of seawater into the basin. The construction of physical structures composing of sheet piling will sufficiently prevent the inflow of seawater into the freshwater strata. The injection of emulsified asphalt, plastics and other materials can also reduce the permeability which can retard seawater intrusion. Fresh water ridges, artificially constructed near the sea can also control seawater intrusion. This method requires a continuous maintenance of a fresh water ridge in the principle water bearing deposits along the coasts through the application of artificial recharge techniques. By applying an injection barrier, the pressure ridge along the coast will be maintained by means of line of recharge wells; an extraction barrier maintains a continuous trough with a line of wells adjacent to the sea. Groundwater levels in the over pumped aquifer can be maintained by artificial recharge methods for confined aquifers and surface spreading and injection wells for unconfined aquifers. Artificial groundwater recharge is a process by which the augmentation of groundwater reservoir takes place at a higher rate than that under natural conditions of replenishment or it refers to the intentional replenishment of groundwater bodies. Managed Aquifer Recharge is the most environment friendly and cost effective method of mitigation of seawater intrusion. Several studies have shown that MAR can be very effective in raising groundwater levels (Athavale et al. 1992; CGWB 2000; Karanth and Prasad 1979, Muralidharan et al. 2007; Parthasarathi and Patel 1997; Raju 1998; Shivanna et al. 2004). Effective improvement in groundwater head by the construction of subsurface barriers was also studied by Elango and Senthilkumar (2006) in Tamil Nadu, India. These studies demonstrated that MAR is a very effective solution to overcome water scarcity.

Managed aquifer recharge (MAR)

Managed Aquifer Recharge (MAR) is the process of adding water source to aquifers under controlled conditions for withdrawal at a later date, or used as a barrier to prevent saltwater or other contaminants from entering the aquifer. Water quality issues of the area and transmissivity of the soil would be evaluated before the commencement of the recharge method. Preliminary soil analysis is generally carried out to find out the infiltration rates and to check the permeability of unsaturated zone between land surface and the aquifer. Pretreatment of water is carried out to manage clogging layers. The sources of groundwater recharge may be natural such as precipitation, stream ad lake seepage, irrigation return flow from canals and fields, inter aquifer flows and urban recharge or artificial such as reclaimed water, mains water, desalinated seawater. The source of water that is used depends on what is available, the conditions of the aquifer and the uses of recovered water.

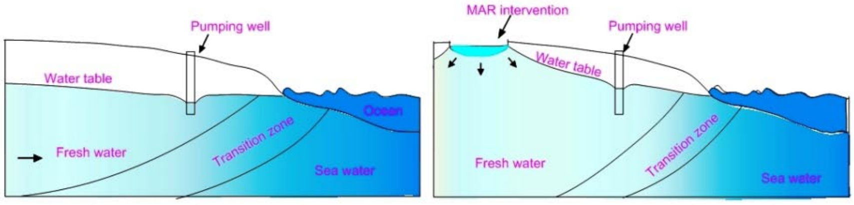


Fig. 4 Conceptual cross section showing (a) seawater intrusion due to overpumping and (b) MAR intervention for mitigation

MAR structures can improve the quality of coastal water and groundwater, enhance the water supply, mitigate floods, facilitate urban landscape improvement and assist in harvesting abundant water in urban areas. Drinking water supplies are aided by industrial water, irrigation, toilet flushing, and sustaining ecosystems with appropriate pre treatment and sometimes post treatment on recovery. MAR structures controls the entrance of salt water into the coastal aquifers, reduce the evaporation of stored water and maintain the environmental flows and groundwater dependant ecosystems. MAR increases water storage in the aquifer which can make more water available for irrigation and other uses and also to preserve water levels in wetlands that are maintained by groundwater. The important methods of MAR, used to mitigate seawater intrusion involve percolation tanks or spreading basins, check dams, Gabion structure, village tanks, injection wells, induced recharge and rain water harvesting.

Percolation tanks Percolation tanks collect the surface run off, which would get percolated though the aquifer and thereby recharges the groundwater table. This method is feasible in geologic formations with considerable permeability. Preliminary investigations on regional rainfall and other hydro geologic conditions of the area are necessary. This method needs continuous monitoring and maintenance after each rainy season to avoid clogging. Village tanks and temple tanks are also used to recharge the groundwater table. The topographical conditions of the area play a major role in the quantity of water that can be recharged into the aquifer.

Check dams Check dams involve bunds built across small rivers with gentler slopes in such a way that water flowing through the river is baffled for a long time. The stored water percolates down the permeable strata underneath and thereby recharges the aquifer. Gabion structures involve check dams constructed across small streams, whereby the stream flow will be blocked by the structure.

Dug well recharge Water sources such as storm water, canal water and tank water can be diverted to damaged dug wells to recharge the aquifer. In this method moisture loss during the passage of water through the soil is reduced. Problems face when the recharge water is saturated with contaminants, pollutants and other suspended particles.

Injection wells Treated surface water is injected into the subsurface through structures called injection wells in order recharge confined aquifers. The dissolved contaminants and suspended particles of the water should be removed prior to the injection of water. Factors such as pumping rate, groundwater hydraulic gradient, permeability of geologic stratum and the type well are to be considered for this method. In urban areas, the most feasible method of recharging aquifer is rain water harvesting which is the process by which rain water is accumulated and stored before it reaches the aquifer in such a way that it can be reused.

MAR is actively and successfully used in the USA, Europe, South Africa, India, China and the Middle East. In southwest Florida, the Southwest Florida Water Management District established the Southern Water Use Caution Area to mitigate saltwater intrusion, caused by the over pumping of the Floridan Aquifer. The Water Management District's Recovery Strategy includes reduction of groundwater pumping from the Floridan Aquifer. California and San Luis Obispo County implemented a strategy that uses treated wastewater to recharge the aquifers to mitigate saltwater intrusion.

The efficacy of MAR has been experienced all over India, for the last few decades. Gale et al. (2006) tested the impacts of MAR during 2002 to 2005 at three locations – Satlasana in Gujarat, Kodangipalayam in Tamil Nadu and Maheshwaram in Andhra Pradesh. The construction of four major check dams and the interventions of several rain water harvesting projects could halt the lack of groundwater over the foothills of Aravally, at Satlasana, where overpumping of water for irrigation caused a decline in water level. The introduction MAR techniques could increase the recharge of the aquifer by 3 to 13% and the irrigation production during droughts by 30 to 80%. At Kodangipalayam in the Coimbatore district of Tamil Nadu, MAR practices could increase the recharge by 23% by check dams and other impoundments. 13 tank structures supplement natural recharge in the Maheshwaram water shed, which covers an area of $53Km^2$, situated on a granitic terrain. Dewandel et al. (2007) reported that several socio economic problems will arise due to the over groundwater pumping in the area and half of the pumping wells will be dried after three years; this can be overcome by implementing several rain water harvesting structures and changes in crop pattern.

The Chennai case study

Chennai, in the southeastern part of India, is one among the vulnerable areas of salt water intrusion. The rate of hydrological pollution along the coastal zones of Chennai has been increasing day to day by the uncontrolled disposal of wastewater and pollutants due to human activities. Several studies have been carried out on the extent of seawater intrusion along the coastal aquifers of Chennai (Gnanasundar and Elango 1998, 1999; Sathish et al. 2011a, b). Seawater intrusion was identified earlier in the Panjetti- Ponneri- Minjur areas of Chennai in 1986 (Elango and Manickam 1986, 1987). Later, Elango (1992) identified that groundwater in most parts of Arani- Korattalaiyar river basin is enriched with sodium chloride. The major geochemical processes controlling the groundwater chemistry of the area are dissolution and deposition of minerals, ion exchange, changes in carbonate chemistry and sulphate reduction. The trace/toxic metal concentrations are found to be significantly higher than the permissible limit of international standards at several locations (Shanmugam et al. 2006, Giridhar 2001; Das 2011; Rengaraj 1996). Sivakumar and Elango (2010) studied the role of 2004 tsunami on aquifer salinisation along the coastal regimes of Chennai. After the 2004 tsunami that inundated the coastal regions of Chennai, solute transport modelling was carried out to understand the salinisation processs caused by the 2004 tsunami and the time required for remediation using neumerical modelling. Anuthaman (2009) proved practicability of controlling the excess run off in enhancing the augmentation of the groundwater resources in the Arani-Korattalaiyar basin. Studies made by UNDP (1987) concludes that the Chennai water supply system can meet the city water needs by diverting the water in Arani River to the Korattalaiyar River through a canal and by recharging the Arani- Korattalaiyar groundwater basin artificially through infiltration ponds. Although several conventional treatment facilities are available to reduce the content of suspended solids, oxygen-demanding substances, dissolved inorganic compounds, and pathogens in these areas, the treated wastes still contain high concentrations of several polluting substances.

The study area forms a part of Arani- Korattalaiyar river basin located north of Chennai, Tamil Nadu, India. The eastern side of the study area is bounded by Bay of Bengal. The Arani River runs in the northern part of the area while the Korattalaiyar River runs in the southern region. These two rivers are non perennial and normally flow only for a few days during north east monsoon from October to December. Near the eastern boundary, the Buckingham Canal runs parallel to the coast and this carries salinewater. After monsoon, the river usually becomes dry and the salinewater from the sea enters the river. Ennur harbour is situated on the south eastern part of the study area. Seasonally the concentration of Na-Cl ions in groundwater varies according to the water level fluctuations. The groundwater is not suitable for irrigation at few places due to salt water intrusion, salt pan activities and backwaters. Both salinewater and seawater is pumped for salt pan activity towards the eastern part of the area near to the coast. The hottest and driest period of the year in this region is April-May, when the temperature rises above 40° C. Winter is mild during November-January, when the average temperature is around 25° C.

The average rainfall calculated using 40 year’s data (1950-1990) is around 1200 mm, 60% of which is contributed by north east monsoon (October – December) and 35 % by south west monsoon (June September). 70-80% of this area is cultivated by paddy. The average farm sizes vary between 1 and 2 acres. The main cropping season is from September to January which coincides with north east monsoon when paddy is grown in about 80% of the available cultivated land.

More importance has to be given for the selection of appropriate remedial measures in order to make the water useful for humans. This work is focused on the construction of a MAR structure in the form of a pilot pond near to north of Chennai, specially emphasized to mitigate salt water intrusion, in collaboration with Saph Pani. In connection with this, a pilot pond was constructed at Andarmadam, Thiruvallur district of Tamil Nadu. The study site (Fig. 5) lies within the latitudes 13º 10' N to 13º 25' N and longitudes 79º 55' E to 80º 20' E. The pond is located within the premises of a school at Andarmadam and the choice of suitability of the area relied on the safety of instruments, slope of the land and groundwater quality of the area.

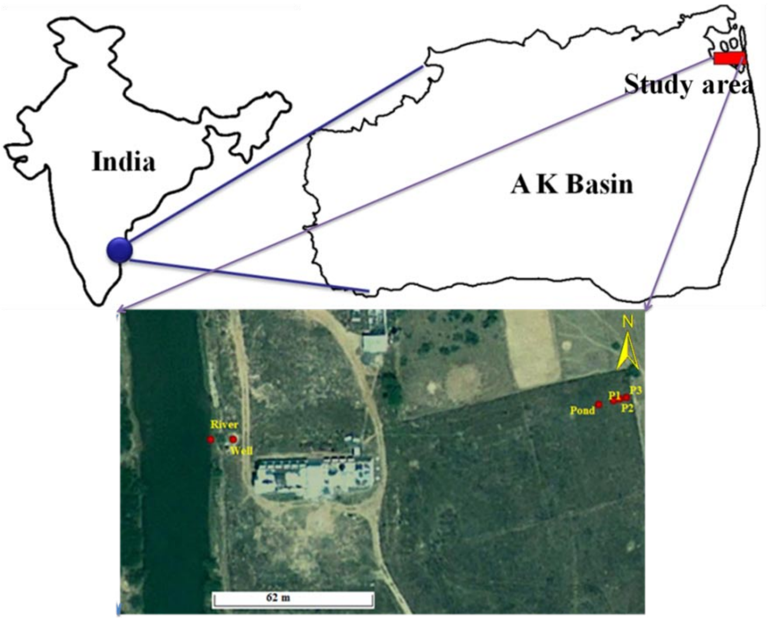


Fig. 5 Location of the pilot pond

For the detailed lithological investigations of the study site, bore holes were drilled at four corners of the school ground with the aid of hand auger and soil samples were collected at every one feet depth. These textural parameters of the soil samples were analyzed in the laboratory and fence model was prepared (Fig. 6). More than 50 % of the fence model is constructed by sand and this will aid the proper functioning of the pilot pond. Ground penetrating radar (GPR) with 50 MHz antenna was used to capture the subsurface geophysical signatures of the area and the processed data were compared with the existing litholog data of the region.

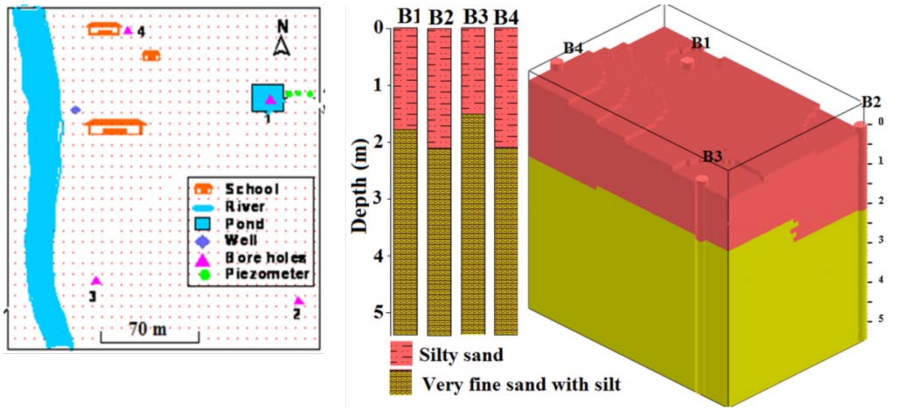


Fig. 6 Lithologic fence model of the study area

Three observation wells at different depths were constructed to measure the groundwater levels (marked as ‘P1’, ‘P2’ and ‘P3’) and are marked in fig. 3. These peizometers are constructed in such a way that the bottom of the pipe is netted for 0.5 to 1 m depth for water filtration and are properly sealed. Peizometer design is shown in fig. 7. Water level indicators are installed inside the peizometers and in the pond in order to allow continuous monitoring of groundwater level fluctuations of the area, along the flow direction. Water level indicator is set up so as to measure the water level fluctuation in every 30 seconds. Rainfall, wind speed, wind direction, outdoor temperature, pressure and humidity will be automatically measured and stored by the rain gauge and anemometer attached to the automatic weather station, which is installed in the study area. Field parameters such as pH, EC, salinity, TDS, temperature and DO are being measured once every month using CyberScan Series 600 water proof portable meter.

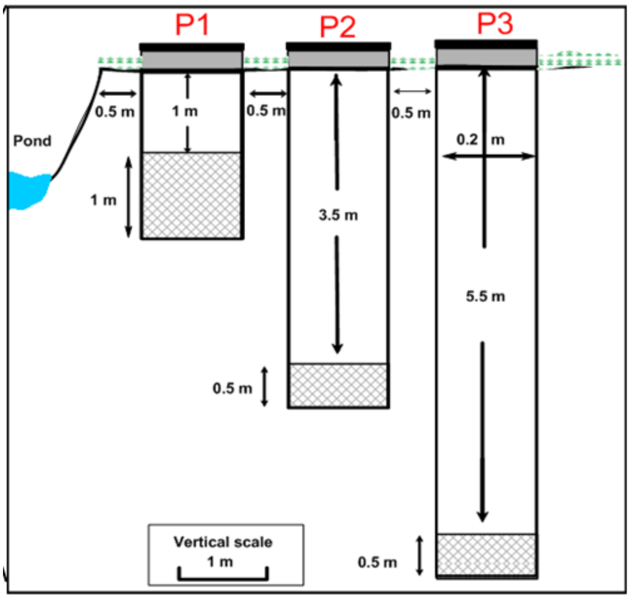


Fig. 7 Schematic design of peizometers constructed near the pond

The preliminary results from the field visits carried out in July and August 2012 show that EC in Arani River is between 25000 µS/cm and 70000 µS/cm. Salinity in the Arani River has been mainly attributed to the entry of seawater from the Bay of Bengal through the Pulicat Lake towards the land. EC of groundwater at different depths at the pilot site were measured and were 12000 µS/cm at 2 m, 37000 µS/cm at 4 m and 68000 µS/cm at 6 m depths showing an increase in EC with increase in depths.

The groundwater quality of Arani River, school well, pond, and the peizometers for the last four months were compared and it was found that the effect of pond in diluting the salinity in the peizometers is negligible. This is mainly due to the clogging of fine suspended particles and also due to the low hydraulic conductivity of upper lithologic layers of the area. Electronic conductivity of ground water samples collected from different peizometers shows no much positive correlation even after heavy rain fall and a revised design was proposed for the Pond and peizometer (fig. 8).

A vertical shaft of diameter 8 inches and depth 10 m (from pond bottom level) is planned to be drilled at the centre of the pond. The exposed portion of the shaft should be slotted except for the bottom part (nearly 10 cm). The shat should be perfectly closed with a lid. An impervious layer with natural material should be kept around the shaft at the pond bottom. A slotted drum which is covered by a cloth or sack bag will be placed over the shaft and the purpose of the cloth is to prevent the entry o contaminants. The drum should be fixed in such a way that it could be easily remove and clean. The contaminants and other fine grained particles in water will be deposited and clogged on the pond bottom and are to be removed after drying up the pond and can be used for farming. The shaft below surface will be slotted except for 1 m below the pond bottom level. Water in the pond will enter the shaft through the drum after infiltration and will low laterally to the aquifer. Peizometers are to be drilled with depths 10m and 8 m and water level indicators are to be installed. Shrubs such as Tulsi, ixora should be planted around the pond to prevent soil erosion. Also water stagnation in the pond is expected only for 45-60 days. If stagnation is expected to be for more days, care to be taken to prevent bacterial contamination of water in the pond. If bacteria or other contaminants start in the pond, cloth or sackbag screen can be replaced by plastic sheets to prevent infiltration.

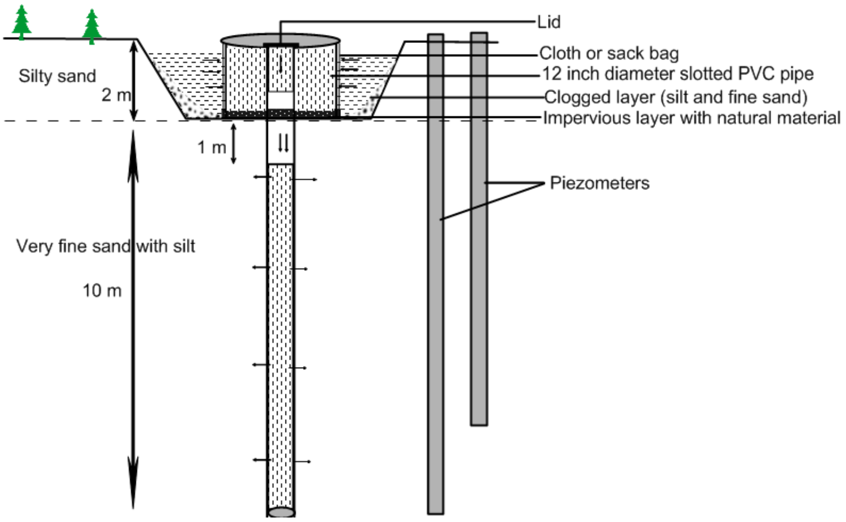


Fig. 8. Proposed diagram of the pond and peizometers

Check dams

Artificial recharge of coastal aquifer by check dams, recharge ponds/tanks, spreading channels will be the alternate solution to improve the groundwater balance. In order to improve the groundwater potential and to mitigate the seawater intrusion in the Chennai’s coastal aquifer, certain long-term water management measures such as construction of check dam across A-K rivers have been proposed by the Government to augment the groundwater resources is shown in Fig.9. This study shows the improvement on groundwater potential obtained through the check dam constructed across Arani River.

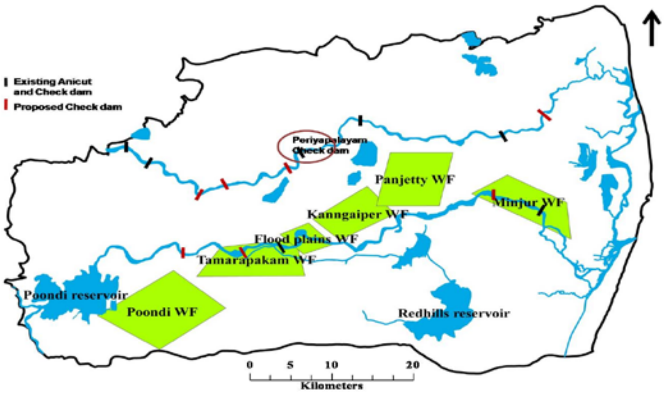


Fig. 9 Check dams across Arani and Karattlaiyar rivers

The electrical conductivity against chloride plot is shown in fig. 10 indicates that the water in the check dam is having the lowest electrical conductivity value of 551 µS/cm and lowest chloride value of 128 mg/l.

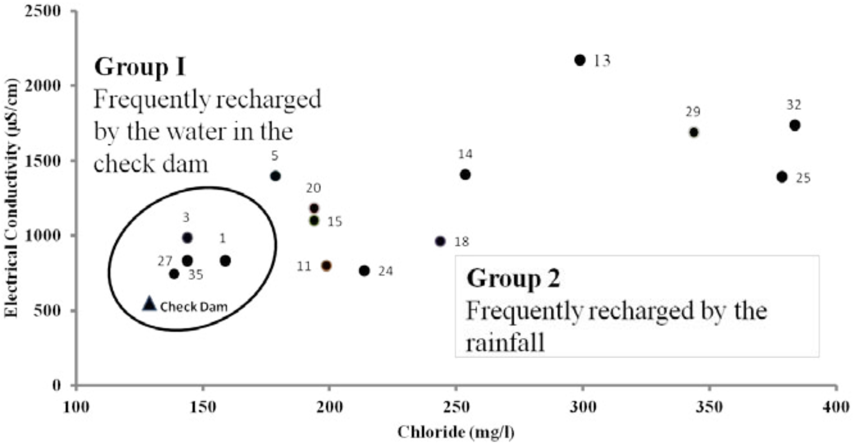


Fig. 10 Plot on electrical conductivity and Chloride concentration for water in the check dam and groundwater

Further this plot divides the wells into two groups based on the groundwater quality. The group 1 wells are having low electrical conductivity values varied from 746 µS/cm to 987 µS/cm and low chloride concentration varied from 135 mg/l to 156 mg/l is due to the most frequent recharge by the water in the check dam.

Whereas group two wells are having high electrical conductivity values varied from 800 µS/cm to 2100 µS/cm and high chloride concentration varied from 180 mg/l to 380 mg/l which indicates that these wells are more frequently recharges by the rainfall or rarely receive recharge from the water in the check dam. This study indicates that series of check dam constructed across this A-K river will improve the groundwater quality by the recharge from this structure.

Limitation

Through MAR in/ near agricultural areas, there is also the possibility of fertilisers and pesticides used in agriculture to leach through the unsaturated zone and reach the groundwater table. Also in developing countries, disposal of wastewater inappropriately on the surface without proper drainage system may lead to contamination of groundwater. Thus the choice of location for MAR recharge should take into consideration these negative factors in order to successfully implement the system and benefit the society.

Surface water, which contains soil particles, nutrients, micro organisms and other pollutants is infiltrated through MAR directly into the aquifer. Besides quality problems of the stored water the infiltration of polluted water leads to clogging of the well screen and the aquifer near to MAR structure. The biological clogging process has the largest influence on the reduction of the aquifer conductivity when using untreated surface water for infiltration. Organic and inorganic suspended matters and adsorption of silt and clay particles may be accumulated.

Methods used and the effectiveness of these inventions is controlled not only by physical but also by social and economic drivers. Knowledge gained through experience, including unsuccessful schemes is often poorly disseminated and the effectiveness of the schemes is often poorly assorted. Key issues around implementation and management relate to the composition and capacity of local management organisations, and the design and operation of cost-sharing arrangements. It is not always easy to predict the impact of MAR on groundwater conditions, and people’s access to water, in a specific area.

Conclusion

The causes, methods of identification and mitigation measures of seawater intrusion were described in this chapter. Some of the studies carried out that are relevant to this in and around Chennai was discussed. Some of the research outcome of studies on mitigation measures by managed aquifer recharge in the form of check dams and percolation ponds where presented.

Acknowledgements

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Role of temple tanks in MAR

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Abstract. Managed Aquifer Recharge helps largely to water harvesting and reuse. Temple tanks in India are also rainwater harvesting and storage structures contributing to local groundwater recharge. The methodology of the study of the impact of infiltration through some selected temple tanks in Chennai city on groundwater quality taken up under Saph Pani is presented in this paper.

Temple tanks

There are numerous temples in India which are several centuries old and temple tanks have been important socio-cultural structures. Temples usually had a tank constructed nearby its front entrance. The tank is basically a pond dug in the earth and its sides protected from falling. The depth of tank depended on the ground water table conditions. Normally there is always inhabitants living in the streets around the tank.

Temple tanks have been considered by the religious minded as sacred as the temple itself. Water from the tank is used for temple rituals and by the common man for a bath or washing hands and feet before entering in to the temple. The public used the temple tank water in some places for drinking also in olden days. However as urbanization increased the demand and brought protected water supply,the use of temple tank as drinking water source ceased.

Temple tanks were constructed in different shapes and sizes near major temples. Different geometry and other elements such as entrance, rainwater inlets, and a central Mandapam in contemporary architecture were incorporated in some of the large tanks while many others were plain rectangular water storage structures with simple steps and protection for sides. But the unique feature has been that the tank bed has always been just left as unpaved earth indicating that it is designed to permit percolation to enable recharging the wells around the Tank.   The temple tanks in India are known by different names such as Pushkarni, Kund, Kulam etc. in different regions and in different languages.

There is always an arrangement to collect rainwater in to the tank from the sprawling temple complex as well as streets around. There was an outlet also to drain any surplus over its storage capacity. The stored water usually lasted till the next rainy season. There is no large scale direct extraction from the tank. The loss of water in the tank is only due to evaporation and percolation of stored water in to the aquifer. Thus the temple tank served as a natural recharge structure.

Over the years, lack of proper maintenance and encroachments around temple tanks chocked the rain water inlet with the result the tank does not get filled to sufficient capacity and hence dries out quickly in summer.

Managed Aquifer Recharge

Aquifer recharge is an important function in hydrogeology and groundwater studies. Now recycled water is found have huge potential as new source of water. Managed Aquifer Recharge helps in augmenting groundwater sources by introducing water, preferably recycled water in to the aquifer under controlled conditions to ensure quantity as well as quality. Managed Aquifer Recharge also plays a central role in water harvesting and reuse (Peter Dillon).

Water harvesting and recharge

The importance of temple tank as a recharge structure has been realized in Chennai only very recently at a time when urbanization put enormous pressure on the local ground water sources and when monsoon failed to bring enough rainfall.

With periodical insufficient storages in the major water supply reservoirs of Chennai city due to failed monsoons resulting in scarcity and decreased public supply the only option open was to look for increasing the recharge of ground water aquifers, including at local level. Thus Rain water harvesting initially became compulsory at household level in Chennai and later became mandatory in the entire Tamil Nadu .Simultaneously the Government of Tamil Nadu took the task of introducing rainwater harvesting in all temple tanks.

Temple tanks in Chennai

There are 2324 temple tanks in Tamil Nadu. Out of this 64 are in Chennai and its suburbs (Times of India, Chennai, June 18, 2011).Prior to the recent expansion of Chennai city there were 39 temple tanks in the City. Four of these tanks have been selected for the study of the impact of infiltration through temple tanks on groundwater quality development under Saph Pani .The tanks are:

1) Adipuriswarar- Adikesava Perumal Temple Tank (Chindadripet).
2) Kurungaleeswarar-Vaikundavasa Perumal Temple Tank (Koyambedu).
3) Agatheeswarar-Prasanna Venkatesa Perumal Temple Tank (Nungambakkam).
4) Suriamman Temple Tank (Pammal, Pallavaram).

The first three are twin temples adjacent to each having a common Temple Tank. The tanks are referred by the first named temple.

One of the temple tanks namely Agatheeswarar- Prasanna Venkatesa Perumal Temple Tank (Nungambakkam) is shown in the Figure 1.

Fig. 1 Agatheeswarar- Prasanna Venkatesa Perumal Temple Tank (Nungambakkam)

The locations and dimensions of the tanks are furnished in the following table:

Name of the temple tank	Location	Dimensions in m Length x breadth x depth
Adipuriswarar Temple Tank	Chindadripet Lat:13°4'34.90"N Long: 80°16'4.73"E	35 x 33 x 3.43
Kurungaleeswarar Temple Tank	Koyambedu Lat: 13° 4'25.41"N Long: 80°11'52.26"E	50 x 50 x 4.8
Agatheeswarar Temple Tank	Nungambakkam Lat: 13° 3'36.13"N Long: 80°14'30.82"E	45.72 x 30.48 x 3.01
Suriamman Tample Tank	Pammal, Pallavaram Lat: 12° 58'21.69"N Long: 80°07'58.29"E	188 x 100 x 3

The indicative location of the above Tanks in Chennai is shown in Figure.2

Fig.2 Locations of the Tanks in Chennai

Lithology in the vicinity of the first three tanks has been ascertained by drilling bores using hand bore set and analyzing the soil samples collected at different strata. Bore wells were also constructed at these sites for observation purpose.

Adipuriswarar Temple Tank at Chindadripet is located in coastal alluvial sub- stratum.

Agatheeswarar Temple Tank at Nungambakkam has sub stratum consisting of alluvium of fluvial origin.

Kurungaleeswarar Temple Tank at Koyambedu is in a clayey sub stratum.

Suriamman Temple Tank falls in hard rock terrain consisting of weathered and fractured rock (Charnockite) as sub stratum.

Periodical water level monitoring in the Tanks and an Observation well each near the tank is being done.

Water samples from the temple tank (stored surface water) and observation well (groundwater) at each location collected periodically were analyzed at a reputed Laboratory for Physical, Chemical and Bacteriological parameters as per the relevant BIS (Bureau of Indian Standard). Analysis was done for about 36 parameters including heavy metals. Three sets of sample taken on the following dates have been analyzed so far.

Location	**First set**	**Second set**	**Third set**
Adipuriswarar Temple -Chindadripet	21.11.2011	03.04.2012	20.07.2012
Kurungaleeswarar Temple - Koyambedu	19.11.2011	03.04.2012	20.07.2012
Agatheeswarar Temple - Nungambakkam	19.11.2011	05.04.2012	20.07.2012
Suriyamman Temple-Pammal	24.12.2011	09.04.2012	20.07.2012

The study is in progress.

Sustainability of groundwater abstraction structures in hard rock through MAR

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Abstract. Sustainibility of groundwater abstraction structures in hard rocks is a challenge due to erratic variations of the Transmissivity and Storativity within small distances. As the sustainability of the dugwells and borewells imparts confidence amongst farmers which in turn assures food security of the region, effective management of the aquifer is so vital. Successful implementation of Managed Aquifer Recharge (MAR) ensures the sustainability of the abstraction structures provided sincere exercise on the details of the source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use and selection of suitable artificial recharge structures based on the hydrogeological set up is carried out.

Introduction

Groundwater development and management is a major challenge because of the occurrence of heterogeneous and low yielding hard rocks. It's is no longer a case of locating water or identifying a site to dig a well/tube well but understanding the resource that feeds the well and reasons for depletion or deterioration of the resource. The expansion in irrigated area in India was possible because of the dramatic rise in the number of irrigation wells since 1970. In order to effectively manage groundwater resource, it is much important to know the quantum of resource, the hydrological relationships to recharge and discharge.

Groundwater has huge impact on the economy of the region and the livilihoods of the people around especially farmers. About 70 % of irrigated agriculture is by groundwater in India, the groundwater abstraction structures (Dugwell/Borewells) almost dictates the agricultural ouptut. Sustainibility of the abstraction structures in hard rocks is a challenge due to the complex hydrogeological setup. Sustainable groudwater abstraction sturctures in hardrocks imparts confidence to the farmers which in turn assures food security. Managed Aquifer Recharge thus enhances the recharge to the aquifer which in sustains the dugwells for a longer period.

Managed Aquifer Recharge in Hard rocks

Groundwater management is all about an integrated effort of understanding aquifers, managing demand and effectively implementing supply. Aquifer systems are different and so as the societies that depends upon them and uses them. Detailed aquifer mapping exercise is required in order to customize the broad regional Hydrogeological setting to local situations. Successful exercise of MAR in hard rocks requires the details on source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use. These components need to be quantified and put in the over context of natural recharge and discharge including abstraction so as to assess the impact to MAR in relation to the amount invested towards recharge structures. The knowledge on the stage of development of groundwater and the information on the variation of the aquifer parameters is must to select suitable recharge techniques.

The development of groundwater irrigation has not largely been policy driven as it has emerged out mostly through private activity (Fig.1). Free and low cost electricity has further encouraged groundwater development in the irrigation sector to a greater extent. The groundwater development in the 1950s was dominated by traditional dug wells extracting groundwater with depths generally not beyond 30 – 40 feet. During early 1970s, groundwater development was by dug-cum-borewells and the wells increased upto 100 feet and the wells were energized mostly by centrifugal pumps. The groundwater abstraction for irrigation phenomenally increased by late 1970’s due to construction of more wells. On contrary, tanks became unusable for irrigation in many cases due to poor maintenance and this resulted in greater dependence on groundwater. With the advent of submersible pumps during mid 1980’s the depth of wells increased to beyond 400 feet in many areas of the country and groundwater extraction increased rapidly since then mainly influenced by the subsidy made available on electricity. This led to rapid decline in the ground water level and to some extent deterioration in groundwater quality mostly in coastal areas.

Rapid changes have occurred in the past four decades in groundwater irrigation economy of the hard rock areas. The increased number of wells, the greater depth of the wells, failure of wells and higher cost per unit of water extracted, high density of wells per unit area and more irrigated area under commercial crops. MAR should address these sensitive issues in hard rocks for better irrigated agriculture by groundwater. The demand for water increased in line with the green revolution which has put greater focus on agriculture in order to increase food production. Groundwater abstraction for irrigation is totally governed by private as the farmers are the owners of the groundwater abstraction structures. Lack of surface waters invited the farmers to rely on groundwater. Groundwater from deep borewells paved way for reliable and equitable exploitation of water to sustain the crops. In

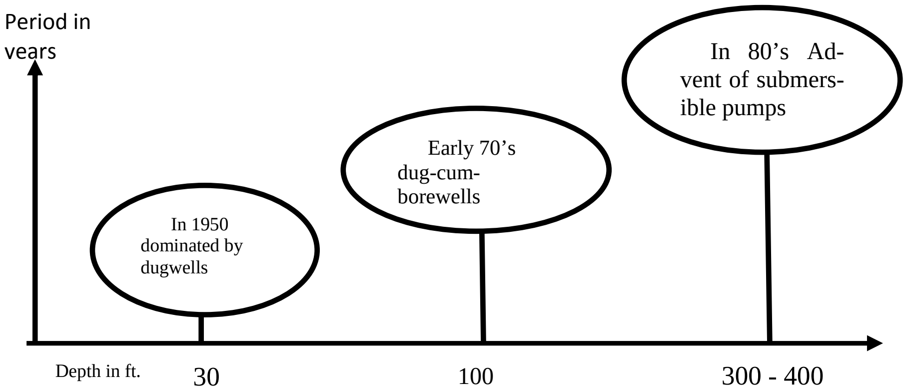


Fig.1 Stages of Groundwater development in Hard rock areas.

this process, the yield of the dugwells and dug-cum-borewells declined drastically while investments in deep borewells increased manifold. MAR addresses these issues.

For efficient and successful MAR in hard rocks, it is necessary to understand the transmission capacity and the storage capacity of the aquifer. Aquifer parameters like Storativity (S) and Transmissivity (T) often show erratic variations within small distances in hardrock aquifers. The saturated portion of the mantle of the weathered rock overlying the hard fractured rock often makes a significant contribution to the yield of the wells. When a well in pumped in hard rocks in many cases, the drawdown in a pumping dugwell or borewell is often almost equal to the saturated thickness of the aquifer (Fig.2).

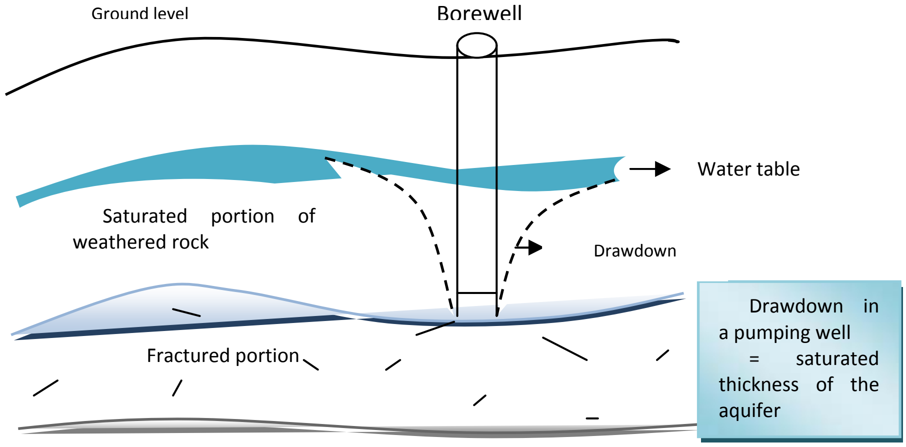


Fig.2. Schematic Sketch showing the drawdown in hardrocks

The recharge to groundwater takes place during the rainy season (monsoon) through direct infiltration into the weathered portion and also into the exposed portions of the network of the fissures and fractures. The ratio of rainfall recharge to rainfall in hardrock (Tamilnadu) ranges between 3 to 12 %. After monsoon, the recharged hard rock aquifer gradually loses its storage mainly due to abstraction and effluent drainage by streams and rivers. The annual recharge to the aquifer is thus a sizable part of the total storage of the aquifer and the whole system is sensitive to the availability of recharge during the rainy season. Artificial recharge structures like percolation ponds would be a source of sustained recharge to the aquifer even after the rainy season ceases.

The enhanced recharge facilitated by artificial recharge structures increases the pumping hours of the abstraction structures in a day. The continual recharge induced by the recharge structures enhances the pumping days. Numerous recharge structures are to be constructed for good results. The horizontal boreholes drilled radially outward from a dugwell (Fig.3), at various level below the water table do act as a recharge structure since it not only connects the fractures that increases the yield to the dugwell but would facilitate further recharge when the recharge structures like percolation pond or recharge shaft which in turn enhances the yield of the dugwell. In areas where vertical fractures, joints occur near to the dugwell, horizontal bores are more successful

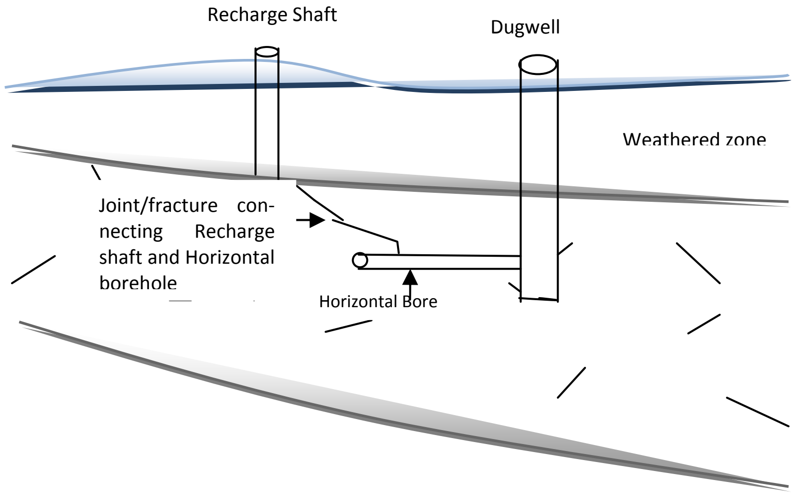


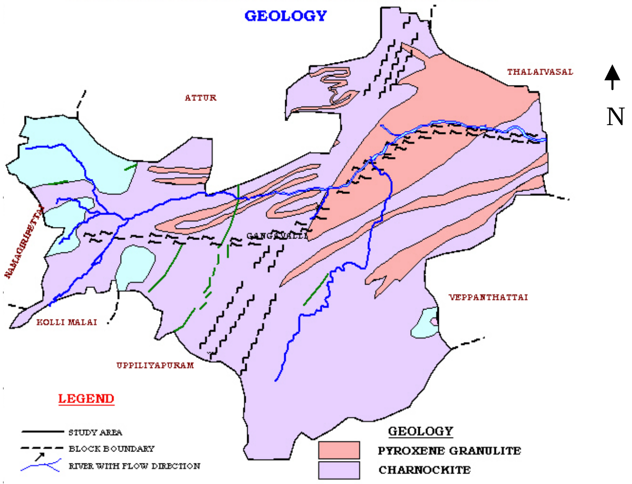
Fig.3. Sketch depicting the MAR structure

Summary

Sustainability of wells in hard rock regions through MAR-case studies by CGWB

The Central Ground Water Board has carried out Managed Aquifer Recharge in the hard rocks of Tamilnadu state. In the western ghats of Tamilnadu, even though the rainfall is substantially high, scarcity of water exists in the hard rock aquifer even during the post-monsoon season . The reason is attributed to moderate to steep gradient wherein the water at large quantity flows out to the low lying areas as surface runoff. The other important factor is the less residence time of groundwater within the hard rocks. The major concern of the farmers in these region is that the wells do not sustain for a longer hours in a day.

Gangavalli Block in salem district of Tamilnadu state area of 410 sq.km. This region has complex geological and hydrogeological environment. Charnockite and pyroxene granulite occur as bands trending NE-SW (Fig .4). The area receives rainfall during southwest (June – August) and northeast monsoons (October to December). The normal annual rainfall varies from about 800 mm to about 1600 mm. The mean daily maximum temperature varies from 19.2° C to 30.2°C.



Source: CGWB

Fig.4. Geology of Ganagavalli region,Tamilnadu

The occurrence and movement of ground water are controlled by rainfall pattern, weathered thickness and fracture pattern, which in turn depends on physiography, climate, geology and structural features. The aquifer system can be considered as two layered aquifer system. (Weathered and deeper Joints/fractures).Ground water occurs under phreatic conditions in the weathered mantle and under unconfined to confined conditions in the deeper fracture zones. The thickness of weathered ranged between 1 and 28 m. Fracture down the depth of 42 to 57 meters yields exists. The dugwells are the major groundwater abstraction structures with the depth ranging from 10 to 30 m bgl. The yield of the dugwells ranged between 40 to 140 lpm and sustains for 60 to 90 minutes of pumping. The yields of dug wells are improved at favorable locations by construction of horizontal bores of 50 to 60 m in length. The rocks have wide transmissivity (1 to 250 m^2/day) and the specific capacity of the large diameter wells ranged between 60 and per meter drawdown.

The groundwater abstraction increased in early 90's due to the advent of numerous bore wells drilled by the farmers. This led to declining groundwater levels and reduction in yield of the dug wells. As per the groundwater resources estimation – 2004, the stage of groundwater development is 221% inferring that the groundwater extraction is twice than the annual replenishment. Artificial recharge was done to supplement the natural recharge to the groundwater so as to maintain the prevailing groundwater utilization and to prevent further impact on the crop yield. A total of 41 artificial recharge structures (check dam, check dam with recharge well, percolation pond, percolation pond with recharge well) were constructed under the central sector scheme during 2006 – 2008 (Subburaj A). In addition, desilting of the existing tanks was taken up to augment the storage capacity of the tanks so as to increase the recharge to the aquifer. The schematic representation (Fig.5) of the Gangavali region exhibiting the recharge structure is given as below;

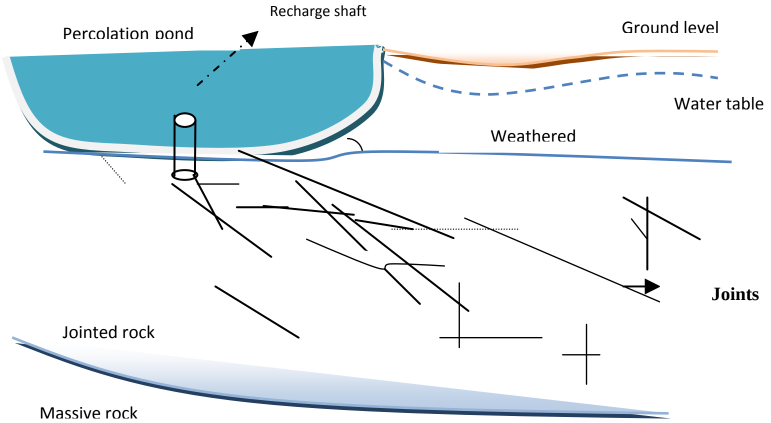


Fig.5.Schematic representation showing recharge structures in Ganagavalli region.

The tanks were expected to have three to five fillings annually depending upon the rainfall and the run off generated from the catchment. Only 50% of the water harvested in the tanks/ponds has been considered as water that could be recharged into groundwater system.

The recharge structures had remarkable impact on the groundwater regime which was reflected by the sustainability of the dugwells and borewells even during lean periods. The dugwells that existed near to the recharge structures registered rise in water level. The dugwells existing at distance from the recharge structure though has not shown rise in water level, but the wells sustained for more days than earlier. The wells either had longer duration of pumping or increase in number of pumping days. The impact on pumping hours of the dugwell before and after the MAR is given as figure.6. The pumping hours increased by 60 to 90 minutes in most of the dugwells existing within the benefit zone. The MAR in Gangavalli has inferred that the desilting of tank is most economical structure and recharge wells with percolation pond was much economical compared to the check dam. However, the checkdam was effective in preventing soil erosion and for regulation flow in the nalas. Also, for the sustainability of the abstraction structures, the number of fillings and its percolation is the controlling factor in many the structures. The recharge structures with short water retention period were more effective in enhancing the yield of the dugwells since the percolation rate was high. The maintenance of the recharge structures is vital for the continuous sustainability of the groundwater structures.

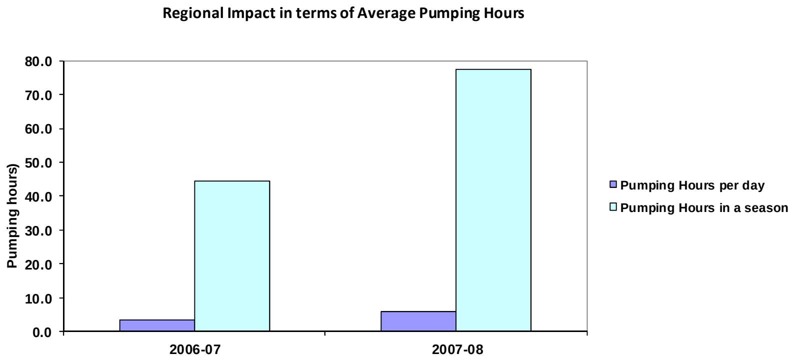


Fig.6. Impact on pumping hours due to MAR structures

Summary

Sustainability of the groundwater abstraction structures in hard rocks greatly depends on the replenishable groundwater recharge annually by rainfall and the erratic variations of the transmissivity and storativity within small distances. Successful implementation of Managed Aquifer Recharge (MAR) ensures the sustainability of the abstraction structures provided sincere exercise on the details on the source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use and selection of suitable artificial recharge structures based on the hydrogeological set up is carried out.

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Managed aquifer recharge with reclaimed water

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Abstract. In the current paper, the concept of managed aquifer recharge (MAR) with reclaimed water is introduced. The benefits as well as requirements of MAR are illustrated generally. In order to achieve the infiltration requirement as well as maintain a sustainable operation, pre-treatment for the purpose of water reclamation must be taken into consideration. Pre-treatment methods includings flocculation/filtration, dual membrane systems and chemical oxidation processes are presented generally covering the design parameters and application examples.

Introduction

Many countries and regions of the world are facing water scarcity and deterioration of groundwater quality caused by climate change and a continuous population growth especially in coastal areas. The acute or chronic water stress triggers the need for integrated water cycle management and the supplementation of the available freshwater resources. In this context, the exploitation of available surface or reclaimed water to promote the conservation or replenishment of groundwater levels *i.e.* through Managed Aquifer Recharge (MAR) has long been advocated (Bouwer, 2000). The main purposes of MAR schemes can be summarized as: to reduce, stop, or even reverse the decline of groundwater levels; to protect underground freshwater in coastal aquifer regions against saltwater intrusion; and to store water for future use (Abiye et al., 2009; Committee on Ground Water Recharge, 1994; Drewes, 2009; Furumai, 2008; Georgopoulou et al., 2001; Holländer et al., 2009; Li et al., 2006; Oron et al., 2007; Sheng, 2005). Municipal wastewater including storm water can be considered as an alternative water source if treated appropriately for the intended use. This is highlighted by the Urban Wastewater Treatment Directive (91/271/EEC) and by the Water Framework Directive (2000/60/EC) encouraging "reuse measures" and "artificial recharge" as supplementary measures that can be applied to reach the fixed environmental objectives for surface and groundwater bodies.

MAR usually evolves in response to local needs and hydrological conditions. Hence, there is an increasing variety of methods for MAR. Most commonly employed methods include bank filtration, soil aquifer treatment, infiltration ponds, etc (DAFF, 2010).

Bank filtration – extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovery (Bixio and Wintgens, 2006).

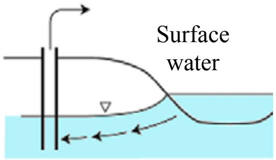

Figure 1 Scheme of bank filtration (DAFF, 2010; Dillon and Jimenez, 2008)

Soil aquifer treatment (SAT) – pre-treated infiltration water *e.g.,* surface water, storm water, or treated sewage effluent, is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the aquifer (Bixio and Wintgens, 2006).

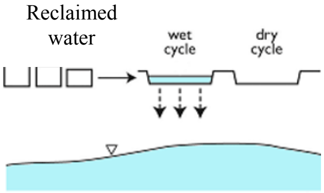

Figure 2 Scheme of soil aquifer treatment (SAT) (DAFF, 2010)

Infiltration ponds – ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate (generally through an unsaturated zone) to the underlying unconfined aquifer (Bixio and Wintgens, 2006; Dillon and Jimenez, 2008).

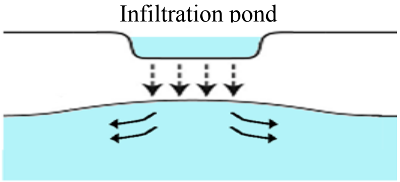

Figure 3 Scheme of infiltration ponds (DAFF, 2010)

These methods take the advantage of the purification ability of primarily the unsaturated zone (also called vadose zone) in the soil-aquifer system and are capable to produce high quality abstracted groundwater. Main processes during soil-aquifer passage treatment are dispersion, filtration, biodegradation, sorption, and mixing with ambient groundwater (Høgh Jensen, 2001) . Mechanical filtration removes suspended solids, while a relatively high microbial activity can lead to mineralization or transformation of organics under aerobic conditions at the beginning of the infiltration flow path. Organic compounds can also sorb onto aquifer material to a certain extent depending on the properties of the compounds and solid material (Brady and Weil, 2002; Schwarzenbach et al., 2003; Worch et al., 2002). Microorganisms are adsorbed, strained out or die because of competition with other soil microorganisms. Nitrogen concentrations are reduced by denitrification meanwhile phosphate, fluoride and heavy metals are sorbed, precipitated or immobilized in the soil.

Examples of managed aquifer recharge projects

One of the most famous MAR practices for water reclamation purpose is the Shafdan project in Israel. WWTP effluent reclamation by SAT for agricultural irrigation has been practiced in the Dan Region, Israel, for half a century. The Dan Reclamation project (known by its Hebrew acronym Shafdan) is the largest wastewater treatment and reclamation project in Israel. It treats more than 140 million m^3 of WWTP effluent per year (approximately 0.4 Mm^3/d), serving a population of about two million, from the Greater Tel-Aviv area and produces high quality abstracted groundwater (Bixio and Wintgens, 2006; Mekorot, 2003; Pettenati et al., 2008).

In Shafdan, the effluent from the Dan Region WWTP is delivered into four recharge basins covering a total area of 80 ha as the infiltration water without further treatment. The effluent percolates vertically through 15 to 30 m of the unsaturated zone, and spreads horizontally through the aquifer. A series of recovery wells located 300 to 1,500 m from the recharging basins pump the recharge water from a depth of 100 to 200 m. The hydraulic loading to the basins varies between 80 and 150 m/yr, depending on the infiltration capacity of the basins (le Corre, 2009).

Table 1 General information of Shafdan SAT process

Test Site	ISRAEL, Shafdan, Negev
Source water	Secondary effluent
Pre-treatment method	-
Recharge method	Soil Aquifer Treatment (SAT)
Additional treatment	Intermediate chlorination
Recharge rate	339,000 m^3/d
Retention time (days)	180-360
Reuse purpose	Agriculture irrigation

The treatment efficiency of MAR at Shafdan in terms of basic water parameters and microorganisms is illustrated in Table 2. The long-term quality monitoring has shown that the system is performing with high reliability. Water recovered from the SAT system is of high quality and can be used for unrestricted agricultural irrigation (Bixio and Wintgens, 2006).

Table 2 Performance of MAR at Dan Region water reclamation scheme, Israel (Bixio and Wintgens, 2006; Mekorot, 2003)

Parameter	**Unit**	**Before SAT**	**Well 1***	**Well 2***	**Well 3***	**Well 4***	**Removal %**
TSS	mg/L	11	0	0	0	0	100
pH	-	7.41	7.3	7.4	7.3	7.4	-
Alkalinity	mg/L	268	275	290	300	293	-
BOD	mg/L	12	< 0.5	< 0.5	< 0.5	< 0.5	> 95
COD_f	mg/L	36	4.5	5	4	4.5-5.0	87.5
DOC	mg/L	12	1.5	0.8	1.2	1.1	90
UV254 absorbance	$cm^{-1}x10^3$	223	38	36	42	38	82.7`
Ammonia, as N	mg/L	6.53	0.2	< 0.02	< 0.02	< 0.02	> 99
Nitrate, as N	mg/L	1.0	2.64	6	6.5	6.75	
Nitrite, as N	mg/L	1.237	0.02	0.004	< 0.01	< 0.004	> 99
Phosphorous	mg/L	3.0	0.03	0.03	0.06	0.02	99
Total bacteria	No./mL	8.0E+05	454-455	2	22	7-8	3 log
Coliforms	MPN/100mL	4.1 E + 05	< 2	< 2	< 2	< 2	5 log
Faecal Coliforms	MPN/100mL	2.8E+05	< 2	< 2	< 2	< 2	4 log
Strept. Faecalis	MPN/100mL	9.0E+05	< 2	< 2	< 2	< 2	3-4 log

* Observation wells bored after the SAT.

Various MAR practices across the world using reclaimed water and/or storm water for infiltration were investigated in the RECLAIM WATER project (Reclaim Water, 2005). Table 3 gives an overview on the treatment technologies, recharge systems and end-uses relevant to the different case studies.

Table 3 Water reclamation schemes investigated in RECLAIM WATER (Le Corre et al., 2012).

Site location & capacity	Scheme description
Sabadell 30 km from Barcelona, Spain	Secondary treated wastewater effluent discharged into a river bed where it infiltrates and is recovered. The water is then disinfected (UV) and distributed for parks irrigation.
Nardò Salento Region, south of Bari, Italy	Secondary treated municipal effluent is transported to aquifer injection. Recharge acts as a salt intrusion barrier and resource is also used as drinking water source.
Shafdan Negev, Israel	Secondary wastewater from the Tel-Aviv area is recharged to an aquifer via a soil aquifer treatment (SAT) system. Recovered water is primarily used for irrigation but has accidental drinking water quality.
Gaobeidian Beijing, China	Tertiary effluent is used for aquifer recharge. Treatment is provided by coagulation, filtration and ozonation (in test) prior to infiltration and recharge.
Adelaide Salisbury, South Australia	Wetland treated urban stormwater injected into a brackish aquifer. Water recovered via separate recovery wells. Recovered water intended for drinking supplies, and until proven will be used for irrigation.
Torrele (Wulpen) Belgium	Tertiary treated municipal effluent is upgraded by Microfiltration and reverse osmosis, and then infiltrated via an infiltration pond to prevent salt intrusion and to recharge an aquifer used for drinking water production.
Mezquital Valley (State of Mexico)Mexico	Wastewater mixed with stormwater and surface water is discharged to an irrigated area of more than 76,000 ha. About 40 % of the irrigation water infiltrates into the aquifer. The water is recovered via separate wells and springs. 206 well systems, 31 springs, and 63 waterwheels are in operation. Recovered water is chlorinated and distributed for drinking water supply, industrial use, irrigation and other purposes (bathing, swimming, washing).
Atlantis (Cape Town) South Africa	Urban stormwater run-off, is collected via a series of detention basins and blended with secondary treated domestic wastewater and recharged up-gradient of the production well field for augmenting the water supply. The blend of natural groundwater and recharged water abstracted from the well field is used as potable water supply for the town of Atlantis.
NEWATER Singapore	NEWater is treated used water further purified using dual-membrane (microfiltration and reverse osmosis) and UV treatment. Four NEWATER factories are in operation supplementing Singapore’s water supplies, part of the product water is use to augment drinking water reservoirs.

Removal of microorganisms was one of the most important parameters measured in the Reclaim Water project. Based on results presented in Table 4, the SAT in all selected locations exhibited high removal capacity. Intensive pre-treatment can ensure zero detection of total coliforms e.g. in Torrele, Belgium site. On the other hand, more than 99% removal was also achieved in the Mezquital, Mexico site where the mixture of raw wastewater and rain water was used as injectant.

Table 4 Total Coliforms (average values) measured in respectively the source, the injectant and the abstracted water selected sites in the Reclaim Water project (Le Corre et al., 2012).

Total Coliforms (CFU/100mL)			
Site	Source	Injectant	Abstracted water
Shafdan, (Israel)	9.8×10^5	9.8×10^5	4.0
Torreele (Belgium)	1.3×10^5	9.1×10^2	0
Gaobeidian (China)	6.0×10^2	7.0	1.0
Adelaide (Australia)	4.6×10^2	3.6×10	0
Mezquital (Mexico)	7.7×10^6	7.7×10^6	Well water 8.0 – 69 (depends on sample locations)

Organic trace pollutants in MAR schemes

In the last decade the occurrence and fate of organic pollutants (e.g. pesticides, pharmaceutical residues and industrial chemicals) in the aquatic requirements received growing attention. Particular in water reclamation these parameters are relevant as the compounds often pass conventional wastewater treatment plants. presents the observed concentrations of organic pollutants in the extracted groundwater from the observation well after the SAT at the Dan Region.

Table 5 Comparison of drinking water standards for specific organics and results obtained in Dan Region SAT observation well. The residence of the MAR at the observation well is approximately 12 months (Bixio and Wintgens, 2006; Mekorot, 2003).

Compounds [μg/L]	**Observation well**	**Drinking water std.**
Alachlor	< 0.1	20
Atrazine	0.1	2
Benzene	0.1	10
Benzopyrene	< 0.1	0.7
1,2 dichlorobenze	< 0.2	1000
1, 4 dichlorobenze	< 0.2	300
Carbon tetrachloride	< 0.2	5
Chlordane	< 0.1	2
Chloroform	< 1	100
DDT	< 0.1	2

Numerous studies have been carried out to characterise the occurrence and fate of various types of pollutants in MAR systems with a recent focus on wastewater originated trace organic contaminants. It is revealed that the subsurface soil-aquifer passage is only capable to attenuate a subset of trace organic compounds especially when reclaimed WWTP effluent was used for MAR.

One of the most representative and systematic investigations about the occurrence of trace organic compounds in SAT is from the MAR applications in the city of Berlin in Germany. In Berlin, the groundwater based public water supply is strongly dependent on bank filtration and groundwater recharge. Nearly 70% of the 220 million m^3/year originate from these sources, ≈56% from bank filtration and ≈14% from groundwater recharge, with the remainder from natural groundwater recharge (Berliner Wasser Betriebe, 2003). At some bank filtration sites the surface water is strongly influenced by treated domestic WWTP effluent (e.g., 15-30% in Lake Tegel) (Ziegler et al., 2002). The bank filtration system is providing high-quality water, which is distributed without chlorination. Iopromide was detected at an average concentration of 151 ng/L in groundwater monitoring wells located at the Lake Tegel bank filtration site. Similar concentrations were also observed in the extracted groundwater at an artificial groundwater recharge basin receiving lake water. The antibiotic drug sulfamethoxazole was detected in the abstracted groundwater at the groundwater recharge site with an average concentration of 151 ng/L (Grünheid et al., 2005). Benzotriazole was found in abstracted groundwater from production wells located in Lake Tegel and Lake Wannsee bank filtration sites. Concentrations of benzotriazole ranged between 0.2 – 0.3 μg/L in the groundwater samples (Reemtsma et al., 2009). Phenazone-type analgesic pharmaceutical residues were also detected between 0.1 – 0.3 μg/L in abstracted groundwater from the Lake Wannsee bank filtration site in Berlin (Massmann et al., 2008). Other trace organic compounds such as bezafibrate, carbamazepine, clofibric acid, diclofenac and pimidone were detected in monitoring wells of shallow bank filtrates with concentrations ranging from 50 to 250 ng/L in Berlin (Heberer et al., 2004b; Massmann et al., 2004; Schittko et al., 2004). The occurrence of trace organic compounds in the SAT was also reported across the world. For example, nineteen pharmaceuticals including erythromycin, fluoxetine, and diphenhydramine were detected in soil samples which were irrigated with reclaimed water derived from urban wastewater in Colorado, USA (Kinney et al., 2006). In the south of France, trace organics, most frequently paracetamol, caffeine, and diclofenac, were detected in drinking water wells where recycled wastewater constitutes 20-30% of the drinking water (Rabiet et al., 2006). Partial removal of pharmaceuticals, including naproxen, ibuprofen, diclofenac, and propyphenazone, have been observed in laboratory and full-scale sand filtration, while other substances including carbamazepine, primidone, sulfamethoxazole, clarithrymycin, and erythromycin are inert to soil passage treatment (Nakada et al., 2008; Nakada et al., 2007).

Engineered pretreatment processes

The main objectives of reclaimed water pre-treatment prior to MAR are to protect the hydraulic capacity of the aquifer, to maintain the treatment ability of soil-aquifer system, ensure the quality of recovered water, and to prevent jeopardising of groundwater quality as well as adverse geochemical reactions. Contaminations with pathogens as well as inorganic and organic pollutants should be avoided in the recharge water. Nowadays, a wide range of water purification techniques are available and therefore the production of reclaimed water of any desired quality is technically feasible. According to the pre-treatment objectives the main quality aspects to be considered for municipal wastewater after centralized biological treatment are according to the report of the EU project Aquarec; Bixio and Wintgens, 2006:

- Bulk organics and macro nutrients (N and P)
- Salinity
- Organic micropollutants represent contamination due to their specific biologic activity
- Pathogens and viruses
- Toxic metals
- Soil clogging potential

Engineered treatment processes are normally designed to attenuate specific species or constituents with particular attributes within a defined range of source water flow rates and water quality characteristics. Therefore a series of treatments is usually required. Table 6 lists pre-treatments that have been used for aquifer recharge projects or research projects with a view to achieving the water quality requirements for effective aquifer treatment.

Table 6 Pre-treatments and their relative effectiveness for MAR with reclaimed water and storm water (Dillon et al., 2008)

Treatment	**Reclaimed water**	**Storm water**	**Suspended solids removal**	**Labile organics removal**
Roughing filter		Y	*	
Rapid sand filtration		Y	*	
Biofiltration		Y	***	**
Activated carbon filtration	Y	Y	*	***
Chemical coagulation and filtration		Y	**	*
Dissolved air flotation and filtration	Y		***	*
Membrane bioreactor	Y		***	*

Microfiltration		Y	***	
Reverse osmosis		Y	***	***
Activated sludge digestion	Y		*	**
Settling/aeration ponds	Y	Y	*	*
Wetland ponds		Y	**	*
Reedbeds		Y	**	*

Y = treatment has been widely applied for this type of source water. Treatment effectiveness: blank = ineffective. * = only partially effective. ** = moderately effective. *** = very effective

Conclusions

The paper generally demonstrates that well designed and operated MAR with reclaimed water can be used as a water stress mitigation option, but issues around site selection, pre-treatment, clogging prevention, geo-hydrchemistry, pollutant attenuation and appropriate post-treatment for a particular use have to be considered. Results from the EC FP6 research project RECLAIM WATER underline that managed groundwater recharge can be a save and reliable climate change adaptation method. Technologies and methods can be tailored to the different socio-economic contexts. In developing and emerging countries' context de-intensified natural systems, in particular MAR, can also provide a decent water quality at very low costs

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Towards Indian Water Quality Guidelines for Managed Aquifer Recharge (AusAID project)

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Abstract. The current extensive program of artificial recharge projects in India augment natural recharge thereby sustaining groundwater supplies for drinking water, agriculture, industry and for environmental protection. This paper describes the background and scope of a current AusAID project that aims to enhance groundwater quality protection wherever artificial recharge is undertaken through the development of guidance at national level. The project will help to ensure that recovered water is fit for all its planned uses. Recharge projects that follow this guidance and effectively manage both the quantity and quality of groundwater replenishment will be known as managed aquifer recharge (MAR) projects. Guidance will draw on recent Australian experience, but engagement with Indian experts and adaption based on Indian experience at selected demonstration projects will be needed to ensure these are relevant and useful.

Artificial Recharge in India

Much of India is monsoonal and has a very long intervening dry period. Water is at a premium in the dry season for drinking, stock and irrigation supplies. Monsoonal rains are heavy, eroding top soil, and flooding turbid streams. Much of the terrain has low relief, unsuited to dams, and there is only minor storage capacity in its hard rock aquifers. As a result, Indians have become highly inventive in detaining water close to where if falls as rain, in order to increase soil moisture and recharge both alluvial and hard rock aquifers as a buffer against the oncoming dry (Chadha, 2002).

Farmers and city dwellers and National and State Governments understand what is needed and the potency of stored water for social and economic resilience. A national plan for artificial recharge was produced by the Central Ground Water Board (CGWB 2005) which has invested in developing recharge projects in all states where there has been a need, generally working in partnership with State and Local governments and non-government organizations towards achievement of the plan. This has been accelerated in recent years by a range of on-ground works to recharge groundwater implemented at village scale throughout India as a part of the government's Mahatma Gandhi National Rural Employment Guarantee Act 2005 (NREGA) to enhance livelihood opportunities while developing a durable asset base. Of the A$8.6B committed in 2010/11 a large proportion (estimated at 70%) was invested in construction of small-scale structures to conserve water via soil and aquifers. Since 2008, a dug well rehabilitation program has supported farmers in cleaning out wells that had run dry due to aquifer overdraft, and recharging them with available sources of surface water. About 4.5 million wells are intended to be recharged in this program, albeit in the current absence of water quality guidance for groundwater replenishment. In urban areas of some states, new houses are required to recharge their roof runoff to sumps and wells so as to contribute to groundwater supplies and not to urban stormwater. In Gujarat there is even a greenhouse gas abatement program that provides carbon credits to industries that recycle water, including stormwater and their groundwater pumping is metered to ascertain the credits.

The uptake of recharge enhancement has been phenomenally successful in volumetric terms and has supported much agricultural production and many communities that otherwise would not be sustainable Government of India (2010b) and Table 1). However to date water quality aspects have tended to be subjugated and there are opportunities to enhance existing guidance documents; the Indian Guidelines for Artificial Recharge (CGWB 2000) and Manual for Artificial Recharge of Groundwater (CGWB 2007), to take more specific account of groundwater quality protection. When both water quantity and quality are effectively managed the term "managed aquifer recharge" may be applied. India is beginning to make huge strides in the development of water resources management policies, which may include account of the groundwater replenishment and its role in sustaining supplies from aquifers.

Managed Aquifer Recharge in Australia

In contrast, Australia, is slow in taking up managed aquifer recharge, and these advances have been stimulated by the Commonwealth Government. The Water Smart Australia (A$2B) program of the National Water Commission, supplemented by the Stormwater Harvesting Fund (A$200M) has helped local government and water utilities in urban areas to recycle water sewage and stormwater, and a proportion of this has been stored in aquifers. In Adelaide stormwater storage in confined aquifers will account for 20Mm^3/yr by 2014 and is planned to reach 60Mm^3/yr by 2050. The rural areas have been almost untouched by managed aquifer recharge since pioneering work in the Burdekin Delta that since the mid 1970s has resulted in 40Mm^3 annual recharge in a successful effort to prevent aquifer salinisation and protect crops. One exception is the Fortescue Metals mine water management project where reinjection of 20 Mm^3/yr groundwater is being undertaken in the North West of Australia to sustain aquatic ecosystems otherwise impacted by dewatering and also to create reserves of water for future mineral processing. Even so the accumulated groundwater replenishment from all Australian projects is less than 2% of India's.

Table 1. A profile of managed aquifer recharge in India and Australia

/ Country	India	Australia
Estimated quantity of recharge enhancement (Mm^3/yr)	>4,000*	80 #
Potential quantity of recharge enhancement (Mm^3/yr)	36,200*	500 #
Guidance on hydraulics and design of recharge enhancement	CGWB (2000, 2007)	ongoing research on clogging and recovery efficiency
Water allocation policies for groundwater and MAR	in progress. Government of India Draft Water Act (2012)	uptake at State level in progress following Waterlines#38 (Ward and Dillon 2011)
Water Quality Guidance for Managed Aquifer Recharge	to be developed	NWQMS #24 (NRMMC-EPHC-NHMRC 2009)

* derived from CGWB (2005) # Parsons *et al* (2012)

The Raising National Water Standards Program under the National Water Initiative, overseen by the National Water Commission was used to develop Guidelines for Managed Aquifer Recharge (NRMMC-EPHC-NHMRC 2009) to protect health and the environment. This is now an integral part of the National Water Quality Management Strategy series of documents. Accompanying this was a compendium of example risk assessments for nine demonstration projects produced according to the Guidelines (Page *et al* 2010). Groundwater quality protection is now accounted for explicitly in the formation of new recharge projects and in re-evaluating historical practices. Australia was the first country to adopt risk-based guidelines for managed aquifer recharge, just as it has for water recycling and drinking water supplies. These all follow the same principles adopted internationally in the World Health Organisation's Water Safety Plans (WHO 2010).

Much work has been done to evaluate the consequences of introducing a new source of recharge water into an aquifer already in geochemical equilibrium (eg. Vanderzalm *et al* 2009) and to study the fate of species introduced into an aquifer (eg. Dillon and Toze 2005). Kazner *et al* (2012) also studied the combination of engineered pre-treatments with aquifer treatment processes for producing safe water supplies in a number of case studies.

A framework for water resources policies accounting for MAR has also been developed in consultation with states (Ward and Dillon 2011). This allows account of entitlements to harvest, recharge, recover and use water. Giving a tradeable entitlement to recover, related to the volume and quality of water recharged, protects the benefits of those who recharge aquifers. This framework has now been adopted in two states and there are plans in other states to also adopt these.

Hence Australia has much to learn from India on project mobilisation and implementation at small to medium scale and it is likely that India can benefit from the water quality perspective that Australia now brings to protecting health and the environment under the National Water Quality Management Strategy. AusAID is assisting in this process. It is expected that closer ties between these two countries under science linkages programs will yield significant mutual benefit in the field of replenishing aquifers to secure safe water supplies.

Are Australian MAR Guidelines Useful for India?

A fuller description of the Australian Guidelines for Managed aquifer Recharge is given in a companion paper by Page and Dillon (2012). The application of Australian MAR Guidelines to various MAR projects in other countries, including developing countries, was tested and the utility and constraints in applying them was reported in more detail by Dillon *et al* (2010b). The guidelines were applied to case studies in China (2), India (2), Jordan, South Africa and the United States of America by researchers or water utility managers actively involved in those projects. Indian sites were a dug well recharge scheme in Gujarat, India (Jain 2010); and a check dam (percolation tank) at Kodangipalayam in Tamil Nadu, India (Gale *et al* 2006; Dillon *et al* 2009).

Those applying these guidelines for the first time reported that they found the entry level assessment (Stage 1) easy. The assessment did not reveal any issues that the proponents had not already considered, nor did it fail to address any issues that the proponents had considered. Several proponents reported that the entry level assessment and the maximal risk assessment provided check lists that they thought would be useful for assessing future projects. No proponents recorded any difficulty in undertaking the entry level assessment, which is in keeping with the objective in developing the guidelines to provide a very simple starting point based on minimal information.

However, completing the maximal risk assessment (Stage 2) revealed that all project reviewers had difficulty in assessing risks to human health, particularly from pathogens that were likely to be present in source water for recharge. There were several reasons for this. Firstly, there is a lack of data on the viral content of source waters originating from streams, urban stormwater or water reclamation plants. In every case, viruses were the most critical of the microbial pathogens.

Furthermore, proponents generally did not feel confident in their ability to perform a reliable quantitative microbial risk assessment, or in making conservative assumptions about source water quality.

Possibly because all the sites had hydrogeological investigations data available, the level of uncertainty in the fate of recharged water was relatively well defined, with the exception of recharge to the karstic or fractured rock aquifers. Factors affecting the relevance of the guidelines were predicted to be:

1. the ability to establish accepted environmental values for an aquifer and hence water quality requirements for aquifer protection
2. variability of source water quality and the capability to measure water quality parameters important for risk assessment (including human pathogens and micropollutants)
3. ability to acquire information on aquifer hydraulic and geochemical properties
4. ability to measure attenuation rates in the soil-aquifer system for the hazards of highest concern
5. reliability of power supplies, preventive measures and controls
6. ability to invest in monitoring and reporting

Development of MAR guidelines for India

Clearly it is important that guidelines are pragmatic and easy to use. Preliminary results suggest that the Stage 1 of the Australian MAR Guidelines could find immediate and useful applications in India, however more widespread testing would be useful, and adaptations made where necessary. Simplification of Stage 2 risk assessments will be required that can protect human health and the environment but reduce the associated investigations and analysis costs. It is likely that use of surrogate and indicator organisms that are much more easily and cheaply measured than rotavirus, C*ryptosporidium* and *Campylobacter* (the reference pathogens in the Australian Guidelines, Page *et al* 2012) could provide a useful pathway forward as has been applied elsewhere in the world (Drewes 2008, Schijven *et al* 1998; Schijven and Hassanizadeh 2000). Similarly these could also be applied for organic chemicals, along with a reconnaissance in the catchment for pesticide and herbicide use, industries likely to use hazardous chemicals, and for presence of sewage and indicators of sewage organic chemical constituents in India.

Salinity, nutrients and inorganic chemicals from source water or aquifer origin will still need to be assessed. In addition to meeting water quality targets required for the recovered water use, nutrients can act as a stimulant to microbiological activity. This can lead to clogging of infiltration wells and basins and can alter the reduction-oxidation potential of the aquifer and hence influence the geochemistry and microbiology of the aquifer, thereby changing the rates of contaminant attenuation or pathogen inactivation. A basic decision tree to determine the likelihood of arsenic release (Figure 1) could be used directly or with adaptation to suit information likely to be available in India.

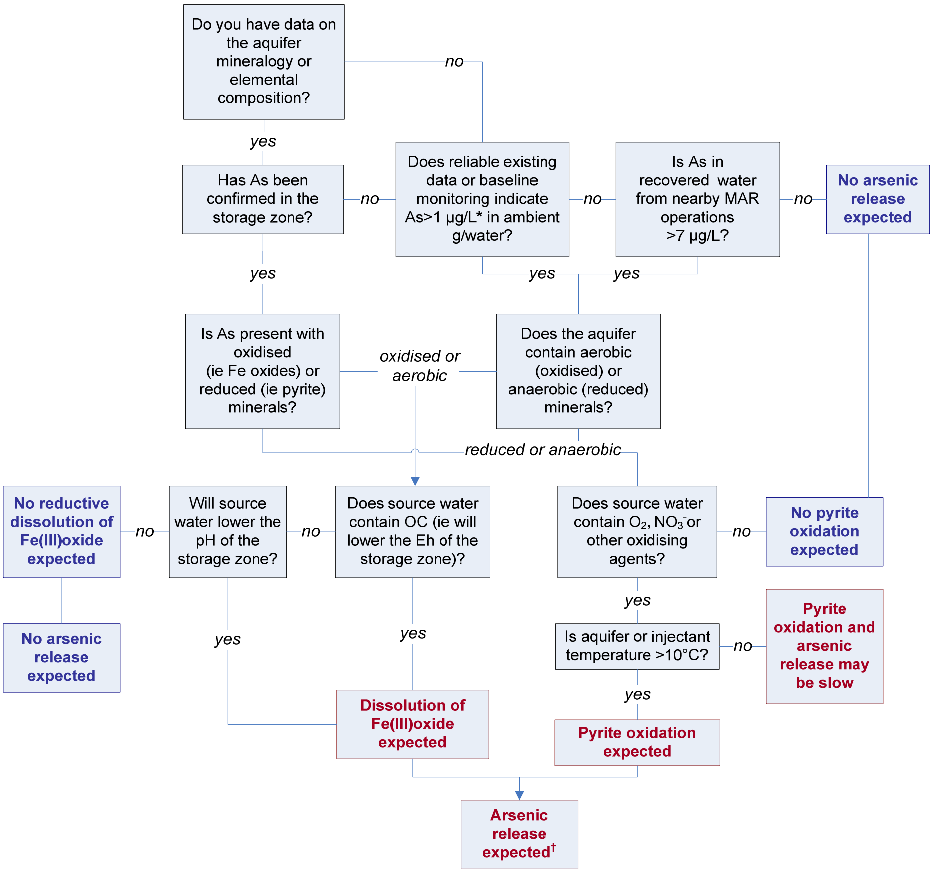

Figure 1. Decision tree for identifying arsenic mobilisation in aquifer storage and recovery

*Arsenic (As) concentrations should be reported to 1 µg/L.

†Other trace metals may be released concurrently.

Turbidity and particulates also require some consideration, in order to mitigate the potential for clogging of recharge facilities, and also for their role in assisting migration of pathogens in aquifers (Šimůnek *et al.* 2005; Wall *et al.* 2008). Radionuclides are unlikely to exceed drinking water guidelines from MAR operations unless they are already present in native groundwater at unacceptable concentrations.

Due to extensive areas of fractured rock aquifers, contaminant migration in fractures does need to be taken into account, especially as travel times along fractures can be very fast in comparison with equivalent primary porosity media. This reduces the amount of time for inactivation of pathogens in transit from a recharge location to any well in the vicinity used as a drinking water supply. Hence water supply wells in proximity to recharge sources need to be protected using simplified approaches such as buffer distances, and safety verified by monitoring of appropriate indicator organisms.

CGWB is giving consideration to the possibility of including a chapter on water quality to update the Indian Guidelines for Artificial Recharge (CGWB 2000) or Manual for Artificial Recharge of Groundwater (CGWB 2007). Demonstration sites are needed where information is available to help with development and testing of this chapter. An AusAID project entitled '*Guidance on water quality in managed aquifer recharge (MAR)*' will provide support for this task.

Success of MAR operations is important and for the immediate future, it is suggested that monitoring for water quality be undertaken at a number of case studies sites and used to form an evidence-based approach to determining circumstances where it is possible with less effort in investigations to reliably protect health and the environment commensurate with local standards (as proposed by Anderson *et al* 2000).

Conclusions

Managed aquifer recharge in India is crucial to the sustainability of many groundwater supplies. A science-based approach to assure protection of public health and the environment is warranted when establishing new managed aquifer recharge operations, and to evaluate the safety of existing artificial recharge operations, especially for those in close proximity to drinking water supply wells. As a general principle, MAR should not be used to experiment with public health, but with adequate safeguards it may provide a low cost means of protecting the safety of drinking water. Central Ground Water Board is considering developing a chapter on water quality issues for updating the current Indian Guidelines for Artificial Recharge. Such a chapter could incorporate some of the fundamentals of the current Australian Guidelines for Managed Aquifer Recharge, after ground-truthing by monitoring at some selected Indian managed aquifer recharge sites.

Australian MAR Guidelines allow for logical and efficient stage-wise development of projects commensurate with risks, account for water quality changes in aquifers, provide for water quality and pressure effects in aquifers and connected ecosystems, address greenhouse gas emissions and allow for monitoring to inform continuous improvement in their application. Test applications of the Australian Guidelines on several sites including two in India suggest that the qualitative first stage is likely to be useful and corresponds with the undocumented approaches by existing project proponents. However the quantitative second stage of these Guidelines is currently impractical in India because it relies on quantitative analyses of water quality, including for pathogens and trace organic chemicals, which are unlikely to be available at Indian sites.

Hence it is proposed that the Indian Guidelines take better account of costs of investigations and incorporate more information on surrogates and indicators for pathogenic microorganisms and organic chemicals in order to reduce the costs of investigations and analyses. There would also be value in obtaining improved characterization of water quality of classes of source water used in India with a view to providing an initial estimate of the log removals required for pathogens and trace organics (and their surrogates) within the aquifer before recovery. Greater reliance will need to be placed on published experimental data, interpreting its relevance via aquifer environmental conditions. It is intended that a simplified version of the guidelines be produced, especially if this can be correlated with the Australian Guidelines by examining more data for several selected sites.

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Pre-treatment and post-treatment for MAR systems

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Abstract. Pre-treatment and post-treatment are integral parts of the managed aquifer recharge (MAR) systems to facilitate the enhanced functioning of these systems and to ensure that the extracted waters subsequently meet the water quality requirements for intended applications. Depending upon the source water quality, type of MAR system used and its operation, and local water quality guidelines or standards, the type of the pre-treatment and post-treatment system requirements vary considerably. Sedimentation, filtration and disinfection are some of the common pre-treatment systems applied for MAR systems. Commonly used post-treatment for MAR systems include disinfection, aeration-rapid sand filtration, ozonation-activated carbon filtration and membrane filtration aiming at removal of the contaminants present in the source water that were not sufficiently removed during MAR and new contaminants that are introduced during the soil passage.

Introduction

Natural treatment systems namely bank filtration (BF), artificial recharge and recovery (ARR) and soil aquifer treatment (SAT) are managed aquifer recharge (MAR) systems that are robust, reliable, capable of removing multiple contaminants and are sustainable (Ray 2008; Dillon 2005; Amy and Drewes 2007). In addition to replenishing groundwater aquifers, depending upon the quality of the water source used for recharge (river or lake water, stormwater, wastewater treatment plant effluents) and local hydrogeological conditions, these MAR systems can serve at least as a pre-treatment or sometimes even as a total treatment system (Schütz, 2008; Sharma *et al.*, 2012). Comprehensive analysis of the source water quality as well as quality of the water currently present in the aquifer to be recharged must be done prior to design of MAR system. Very often the "treated water" from the MAR systems may not meet the required local water quality guidelines or standards for intended use and thus require additional post-treatment.

Furthermore, some contaminants present in the source water may pollute the aquifer or influence the performance of MAR systems and therefore, often pre-treatment of source water is done before the recharge. Pre-treatment and post-treatment thus form an integral part of the MAR systems. Depending up on the raw water quality, local hydrogeological conditions, process conditions applied and intended use of the extracted water, a MAR system can have pre-treatment or post-treatment or both. Figure 1 shows a schematic of MAR system components from water quality and treatment perspectives.

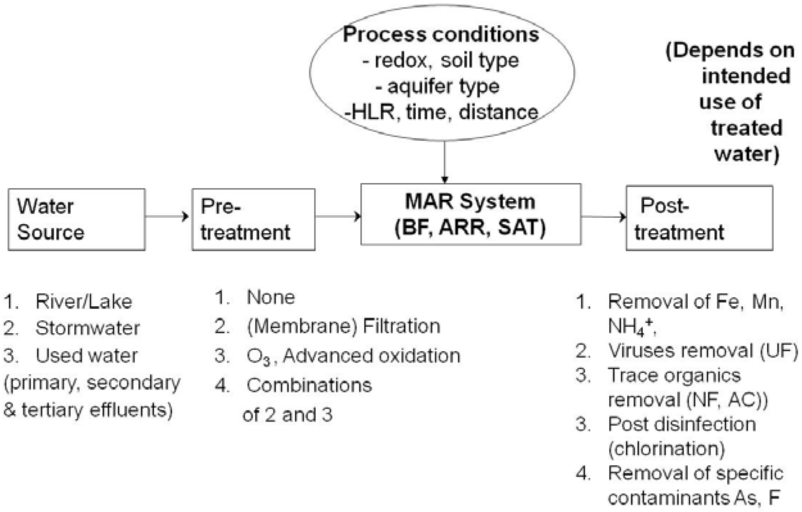

Fig.1. MAR system components from water quality perspectives

Need for pre-treatment and post-treatment

The following are some of the main reasons to employ pre-treatment and post-treatment in MAR systems aiming at water and wastewater treatment and reuse.

i) Some contaminants present in source water may seriously affect the performance of a MAR system (e.g. clogging or contamination of the soil layer and aquifer) and reduce its efficiency for removal of certain contaminants

ii) Some contaminants in source water are not removed or only partially removed by MAR systems (e.g. bulk organics, nutrients and organic micropollutants)

iii) Some new contaminants may be introduced during the MAR due to local hydrogeological conditions (e.g. iron, manganese, ammonium, arsenic, fluoride, colour, nitrate, natural organic matter etc.)

iv) Some treatment may be needed to meet local water quality guidelines and standards for artificial recharge and intended reuse of the reclaimed water

v) Additional treatment may be required to ensure "multiple barrier treatment system" in the context of deteriorating quality of source waters, increasing water demand, emerging contaminants and climatic change

Pre-treatment for MAR systems

Pre-treatment refers to removing some of the critical contaminants in source water to enhance the performance of subsequent MAR systems. Pre-treatment may be required to avoid clogging and contamination of the aquifers, and to enhance the removal efficiency of different contaminants during soil passage. Sedimentation, filtration (roughing or rapid sand), and disinfection are some of the common pre-treatment applied for MAR systems. Some pre-treatment filters also incorporate additional layer of adsorbents for the removal of heavy metals or other specific contaminants from source water before recharge. Furthermore, some water supply companies apply comprehensive water treatment employing advanced processes before using this water for infiltration (van der Hoek, 2000; Balke and Zhu, 2008)

Where river or lake water of low turbidity is diverted to infiltration basins for enhancing irrigation supplies, no treatment may be necessary. Dillon *et al.* (2009) reported that constructed wetlands may be suitable as pre-treatment when urban stormwater is being used to recharge a brackish limestone aquifer with recovery of water for irrigation without any requirement for post-treatment. Furthermore, they mentioned that microfiltration (MF) and granular activated carbon (GAC) filtration were needed at an artificial storage and recovery (ASR) site with a very fine-grained aquifer to prevent clogging of the well and that this requirement was more stringent than those to protect groundwater quality and for recovered water to be fit for use. On the other hand, when wastewater treatment plant effluent is used for recharge aiming at indirect potable reuse, there is need for high degree of pre-treatment before recharge. Again, the pre-treatment requirements may vary depending upon whether surface infiltration (basins), vadose zone wells or direct injection wells are employed for MAR. Table 1 summarizes the main water quality concerns and commonly used pre-treatment options for different types of source water used for MAR.

Often some type of pre-treatment is applied before the wastewater treatment plant effluent is applied for aquifer recharge or treatment using SAT. The objective of the pre-treatment is to improve removal efficiencies for different contaminants, increase run time and to reduce clogging (Sharma *et al.*, 2011). Pre-treatment operations and processes can include fine screening, primary treatment, lagoons or ponds, constructed wetlands, biological treatment, membranes, and disinfection. Primary sedimentation or the equivalent is the minimum recommended pre-treatment for all SAT systems. This level of treatment reduces wear on the distribution system, prevents unmanageable soil clogging, reduces the potential for nuisance conditions, and allows the potential for maximum nitrogen removal. For small systems, a short-detention-time pond is recommended. Long-detention-time facultative or aerobic ponds are not recommended because of their propensity to produce high concentrations of algae. The algae produced in stabilization ponds will reduce infiltration rates significantly (NAP, 1994).

Table 1. Main water quality concerns and pre-treatment options for different types of water used for MAR

Source water	Main water quality concern for MAR	Pre-treatment options
Rainwater (from roofs)	Suspended solids, turbidity (fines)	Sedimentation, sand filtration
Urban runoff	Suspended solids, turbidity, nutrients, heavy metals	Sedimentation, sand filtration, adsorption, constructed wetlands
River water	Suspended solids, turbidity, bulk organic matter, colour, pathogens	Sedimentation, sand filtration, coagulation, adsorption, disinfection
Wastewater treatment plant effluents	Depends on the degree of wastewater treatment (pathogens, suspended solids, nutrients, bulk organic matter, colour, organic micropollutants)	Depends largely on the MAR method employed (Sedimentation, sand filtration, coagulation, adsorption, disinfection, constructed wetlands, membrane filtration, advanced oxidation and their combinations)

The following are some examples of different pre-treatment processes applied before MAR of different types of water:

(i) India: Artificial recharge of the groundwater using the rainwater from the roofs or stormwater (urban runoff) is a common practice in India. The commonly used common pre-treatment systems before recharge of rainwater or stormwater (urban runoff) include sedimentation tanks (desilting basins), sand filters, wrapped PVC pipes and metallic filters (CGWB, 2007; Hollander *et al.*, 2009). Very often these pre-treatment units are constructed as a part of recharge structures.

(ii) Salisbury (Australia): In stormwater reuse system of City of Salisbury Australia, stormwater from Parafield and Ayafield catchments are pre-treated in storage tanks (for settling of fine sediments) and constructed wetland (for filtration, aerobic degradation, phytoremediation and volatilization) before artificial recharge (direct injection for ASTR) (Rinck-Pfeiffer *et al*., 2010).

(iii) Amsterdam (The Netherlands): The Leiduin water treatment plant is one of the two plants of Waternet (Amsterdam Water Supply Company) supplying water to the city of Amsterdam, The Netherlands. The raw water from Lekkanaal (a man-made side branch of the Rhine River) is pretreated at Nieuwegein and transported via pipelines for a distance of about 50 km to dune areas near the Leiduin water treatment plant. The standard pre-treatment process employed at the Nieuwegein pre-treatment plant is coagulation (with ferric chloride), sedimentation, rapid sand filtration, and pH correction with caustic soda. After pretreatment, the water is transported to the nearby dune area for infiltration. The system consists of 40 infiltration ditches with a total length of 24.6 km and an average width of 35 m. The dune area used by Waternet is about 36 km^2, of which 10 km^2 is taken up by actual infiltration areas (van der Hoek, 2000; Tielemans, 2007).

(iv) Wulpen (Belgium): The water reclamation plant of Wulpen/Torreele water plant in Belgium, operating since July 2002, reuses municipal wastewater effluent to produce 2,500,000 m^3/year of infiltration water (after treatment with ultrafiltration, reverse osmosis and UV) for an artificial groundwater recharge in St-Andre dune water catchments. The recharged water is recaptured from wells located a distance of 35 to 120 m infiltration ponds after a minimum residence time of 40 days in the dune aquifer and then further treated for drinking water supply (van Houtte and Verbauwhede, 2005).

(v) California (USA): Groundwater Replenishment System (GWRS) in Orange County, California is the world's largest wastewater purification or reclamation system for indirect potable reuse. At this state of the art facility, the secondary effluent is further polished employing microfiltration, reverse osmosis and advanced oxidation (UV/H_2O_2) treatment before using it to recharge the aquifer and to create salt water intrusion barriers (GWRS, 2010).

Post-treatment for MAR systems

Post-treatment refers to upgrading the quality of the "treated water" produced by different MAR systems so that it meets the water quality requirements for different applications. Requirements for post-treatment of "product water" from MAR systems vary from simple disinfection to complete full-scale treatment depending upon on the quality of the source water used for natural treatment (recharge), type, design and operation of MAR system utilized, process conditions applied and applicable water quality guidelines or standards for intended use (Sharma and Amy, 2010).

In general, two main water treatment requirements after MAR systems include (i) removal of contaminants like bulk organics, nutrients and organic micropollutants that are not removed or only partially removed by natural treatment systems like BF, ARR and SAT and (ii) removal of contaminants like iron, manganese, arsenic, fluoride or color that are introduced into the water in different layers of aquifer during the soil passage due to changes in redox conditions, ion-exchange and dissolution of the minerals.

Generally, conventional water treatment (coagulation, rapid sand filtration, ozonation, activated carbon filtration and disinfection) or advanced treatment (membrane filtration, advanced oxidation) or their combinations are applied as post-treatment. Very often designs of these post-treatment systems are site specific. Commonly, used post-treatment methods include (i) disinfection/chlorination to ensure microbial safety and disinfectant residual in the water distribution system, (ii) aeration/chemical oxidation-rapid sand filtration to remove common groundwater contaminants like iron, manganese and ammonium, (ii) ozonation for oxidation of bulk organics and organic micropollutants, (iv) activated carbon filtration (with or without pre-ozonation) to remove the organic micropollutants and colour/taste and odour present in the water, (v) softening and pH correction to remove the hardness and to ensure that there is no scaling or corrosion of water distribution system. Table 2 presents the main water quality concerns for water extracted from a MAR system and commonly applied post-treatment methods.

Post-treatment of water from natural treatment systems will be more crucial in the future to ensure safe water supply in the context of increasing water demand, deteriorating source water quality, emerging contaminants and climate variability. With the proper design of the MAR systems for a given water quality and hydrogeological condition and with the provision of appropriate pre-treatment where applicable, the requirements for post-treatment (including energy and chemicals) can be minimized. Therefore, it is important that pre-treatments and post-treatments are considered from the planning, design and implementation of MAR systems as this has direct consequence on the overall cost of water treatment and on the long-term sustainability of applying MAR systems for water and wastewater treatment and reuse.

Table 2. Common water quality concerns for water from MAR systems and post-treatment options

Water quality concern	Pre-treatment options
Pathogens	Disinfection (Chlorination, ozonation, UV disinfection)
Iron, Manganese, Ammonium	Aeration/chemical oxidation - rapid sand filtration
Fluoride, Arsenic	Coagulation - sedimentation, rapid sand filtration, adsorption-based processes using specific adsorbents
Nitrate	Ion-exchange, biological-denitrification, membrane filtration
Hardness	Chemical softening, ion-exchange, membrane filtration
Organic micropollutants	Ozonation, activated carbon filtration, advanced oxidation, membrane filtration
Salinity (from brackish groundwaters)	Membrane filtration (reverse osmosis)

The following are some examples of different post-treatment process applied after the ARR and SAT of different types of water:

(i) India: Limited information is available on the post-treatment of water obtained from MAR systems utilized for municipal or industrial (re)use in India. Majority of the rainwater MAR systems in India do not employ any specific post-treatment for reuse of the extracted water for irrigation purposes. Disinfection (often chlorination) is applied as the only treatment, if water from the MAR system is used for drinking purposes. Presence of iron, manganese in groundwater is a common in water quality problem in India, for which normally aeration/chemical oxidation followed by rapid sand filtration is applied. Some groundwaters in India have elevated concentration of arsenic and fluoride for which coagulation-sedimentation-filtration or adsorption-based processes using specific adsorbents are employed as treatment at household or community level.

(ii) Berlin (Germany): After bank filtration and artificial recharge, only aeration and rapid sand filtration is employed at Berlin Waterworks to increase oxygen concentration and to remove iron and manganese present in the extracted water. This water is then distributed to the consumers without disinfection (Grunheid *et al*., 2005).

(iii) Amsterdam (The Netherlands): After the average residence time of about 100 days (ranging from 60–400 days) in the dunes, the infiltrated water is abstracted through the drains and collected in an open basin. This ARR water then is further treated at the Leiduin water treatment plant by employing cascade aeration, rapid sand filtration, ozonation, pellet softening, two-stage biological activated carbon filtration, and slow sand filtration to achieve drinking water. No final disinfection is applied before supplying the water to the city of Amsterdam (van der Hoek, 2000; Tielemans, 2007).

(iv) Israel: The Dan Region Project, the largest wastewater reclamation and reuse scheme in Israel, employs SAT for further polishing of secondary/tertiary effluent, which is then used for irrigation. MEKOROT, the national water company of Israel, is conducting pilot studies on alternative hybrid SAT system employing sand filter and ultrafiltration as pre-treatment and nanofiltration as post-treatment for SAT in order to increase infiltration rates and removal efficiencies for different contaminants (Ideolovitch *et al*., 2003; Aharoni *et al*. 2011).

(v) Colorado (USA): The Prairie Waters Project of the City of Aurora uses an innovative natural purification process (combination of bank filtration and artificial recharge) to perform initial treatment of water from the South Platte River. After the natural purification process, water is piped 54.7 km south using a 1.5 m pipeline to the Aurora Reservoir Water Purification Facility. The new treatment facility uses multiple treatment processes that include chemical softening (to reduce hardness, iron, manganese, and scaling potential), advanced oxidation using ultraviolet (UV) light and hydrogen peroxide (to inactivate pathogens and oxidize remaining trace organics), rapid sand filtration (to remove remaining particles and pathogens), and activated carbon adsorption (to adsorb remaining trace organics and improve taste) (Ingvoldstad, 2007).

Summary and Conclusions

MAR systems like BF, ARR and SAT are robust and have high potential to improve the quality of different types of source waters during soil passage. These systems often require some pre-treatment and/or post-treatment to avoid detrimental effect on the aquifer system, improve their removal efficiencies, and to meet the water quality guidelines or standards for intended applications. Type of the pre- or post-treatment system that should be used together with a MAR system depends on its design and operation, source water quality, size of the recharge system, process conditions applied as well as treated water quality requirements.

Some of the common pre-treatment methods include sedimentation and filtration while disinfection, aeration/chemical oxidation followed by rapid sand filtration, activated carbon filtration with or without ozonation, advanced oxidation as well as membrane filtration systems have been applied for post-treatment. Proper design of a MAR system with appropriate pre-treatment will reduce the need for extensive post-treatment and make the MAR technology more cost-effective and offer a sustainable solution for integrated water resources management.

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MAR risk assessment and water quality considerations

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How to establish a MAR project using a risk assessment framework

Potential proponents need to know first whether they have the five essential elements (Stage 1 assessment) of a MAR project outlined below before proceeding further. If the project looks potentially viable at this first stage, the Australian MAR Guidelines (EPHC, 2008) lead proponents through the investigations (Stage 2) and commissioning trials (Stage 3) to an operational project (Stage 4).

Stage 1 - Five essential ingredients

The five critical elements for a successful MAR project are:

- a sufficient demand for recovered water
- an adequate source of water for recharge
- a suitable aquifer in which to store and recover the water
- sufficient land to harvest and treat water
- capability to effectively manage a project

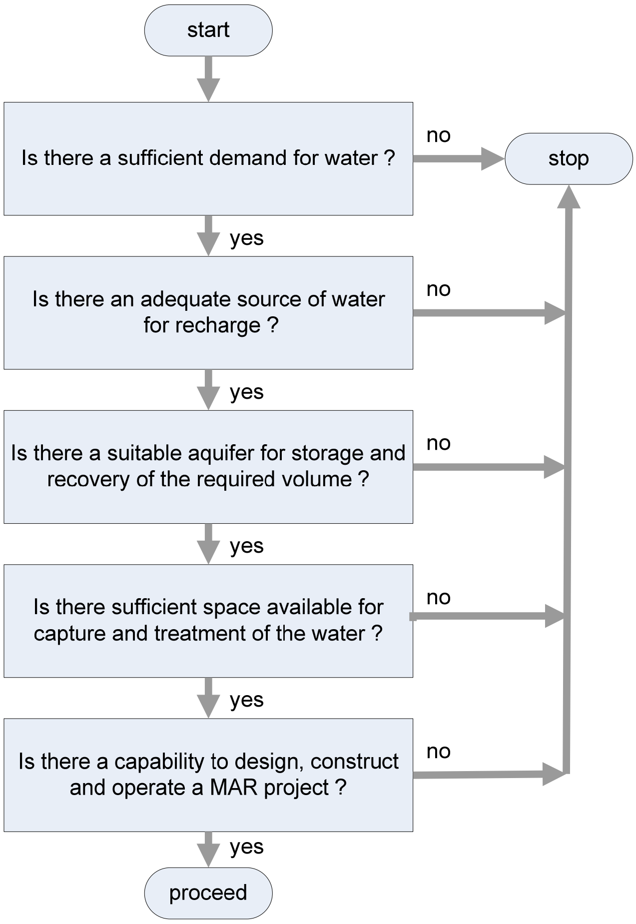

Fig.1. A checklist for considering whether to undertake a managed aquifer recharge project.

Demand: The volumetric demand for recovered water (within an economic scale) or a clearly defined environmental benefit of recharge is essential for MAR. The purposes for which water will be recovered also need to be defined (Figure 1). Generally this will provide the revenue stream to pay for the water supply cost elements of the project. In urban areas demand for stormwater detention for mitigating floods, improving coastal or receiving water quality and enhancing urban amenity and land value may also contribute revenue streams for MAR projects. For reclaimed water projects the decline in discharge of treated effluent to sea may provide a motivation for investment in MAR.

Source: Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand with sufficient excesses to build up a buffer storage to meet reliability and quality requirements. In an over-allocated catchment it is unlikely that an entitlement to surface water would be available.

Stormwater and reclaimed water are usually abundant resources in urban areas but require treatment and storage before reuse. The availability of stormwater or reclaimed water to make useful contributions to city water supplies is not a constraint. The primary limitation to stormwater harvesting and use is the ability to store the water from runoff events for subsequent use as drinking water supplies or as irrigation, industrial supplies or other non-drinking uses. MAR can provide an economic means of storing water in urban areas.

Sewage effluent requires extensive treatment before placement in either dams or aquifers prior to reuse. Aquifers have advantages with respect to ongoing passive treatment of the water and allowing longer assured residence times before recovery for drinking.

Aquifer: A suitable aquifer is critical for MAR. It needs to have an adequate rate of recharge, sufficient storage capacity and be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred so that mixing with fresh recharge water should still allow recovered water to be fit for use.

Local hydrogeological knowledge is needed to identify the presence of aquifers and their suitability for MAR. Basic stratigraphic and hydrogeological information existing wells can serve as valuable background information before drilling new wells and can be used to determine potential sites for MAR. Hydrogeological reports generally provide some indication of the level of knowledge of the local aquifers and their degree of uniformity. Aquifer properties vary spatially so it is not generally reliable to extrapolate from one site to predict viability or performance at a nearby site.

At any given location there may be several aquifers stacked on top of each other interleaved with low permeability layers. This allows choice of one or more with the most favourable characteristics for water storage. Depending on their degree of inter-connection, it may be possible to store water of different qualities in different aquifers at the same location.

Detention Storage: There should be open space, or dams, wetlands, ponds or basins to detain sufficient water without causing flood damage to enable the target volume of recharge to be achieved. Similarly there needs to be space available for whatever treatment process, if any, is subsequently determined to be required. In established urban areas space for capture can be a major impediment to stormwater water harvesting and ASR wells are commonly used to avoid land requirements of infiltration systems. For recycled water from a sewage treatment plant generally no additional detention storage will be required at the recharge facility.

Management capability: Hydrogeological and geotechnical knowledge, as well as knowledge on water storage and treatment design, water quality management, water sensitive urban design, hydrology and modelling, monitoring and reporting are all required to meet governance requirements. Such expertise will be required from Stage 2 and a growing number of consultants are experienced in investigations and design of MAR projects.

Identify the degree of difficulty

Appendix 1 gives an example of a checklist to understand the degree of difficulty associated with a conceived project. This serves as a guide to the amount of effort required in project investigations and commissioning trials in order to manage human health and environmental risks in accordance with the relevant water quality management guideline (for example, National Water Quality Management Strategy). This consists of 13 questions with commentary on information required to answer and the consequences of the answer on the need for further information during the investigation stage (Stage 2).

The questions address the water quality of the source water in relation to environmental values of the aquifer, of intended uses of recovered water, potential for clogging and potential for mineral reactions. They ask about groundwater quality in relation to recovered water uses, and whether groundwater needs to be protected for drinking supplies or high conservation ecological values, or is highly saline. They also ask whether there are nearby groundwater users or ecosystems, is the aquifer confined or artesian, fractured or cavernous, are if there similar projects with similar source water in the same aquifer and whether the proponent or his consultant or intended operator has experience with MAR or water quality management.

Costs of MAR investigations and trials are not trivial and having completed this checklist the proponent should know whether their proposed project has a low or high degree of difficulty and the types of information which will be of most value in the investigation stage. Because of the costs of these investigations it is normal to first seek assurance that at least the core approvals for MAR are likely to be obtained, before investing in such investigations.

Approvals required

Approvals that may be needed for a MAR project to proceed include:

- an entitlement to a share of the source water, such as stormwater, reclaimed water or other source, taking account of environmental flows and other users of the source water
- a permit to construct wells for investigations, ASR or recovery
- planning approval for a water impoundment, covering geotechnical safety, amenity, insect and pest nuisance and danger of drowning

- a declaration of environmental values of an aquifer, accounting for ambient groundwater quality and current uses
- approval to recharge water to an aquifer, to protect an aquifer’s environmental values, prevent excessive changes in the hydraulic head, and to protect human health and the environment as a result of the recovery of stored water for intended uses.
- an entitlement to a share of the aquifer storage space, recognising that this is finite, and may be smaller than the harvestable volume of source water
- an entitlement to recover water from an aquifer, possibly as a proportion of the cumulative recharge that may depend on the degree to which the aquifer is over-exploited and will take account of other groundwater users and water bankers so as not to cause them adverse impacts
- transfer of water entitlement, endowing the recharger with an ability to transfer their entitlement to a third party, subject to hydrogeological constraints and not into locations where piezometric heads are already depressed
- a permit for the use of recovered water, to ensure that usage conforms with catchment management plans and that the water quality is fit for intended uses

Next steps

Assuming that the entry level assessment (Stage 1) indicates that the project is apparently viable, the degree of difficulty does not deter the proponent, and the regulator has not identified other impediments, the next stage is to undertake investigations on source water, pre-treatment methods and the aquifer to determine if the project will demonstrably protect human health and the environment, notably the aquifer.

Stage 1 was a rapid qualitative assessment but Stage 2 is quantitative, using existing information supplemented by site-specific investigations that were foreshadowed in Stage 1. Information to confirm that the project is operating as intended will not be available until commissioning of a pilot project, or the full-scale project after it is constructed. A staged approach (Figure 2) to project development helps avoid wasting time and money, and can improve the design of the project by tailoring it to the aquifer. It also allows investment appropriate to the MAR project in relation to alternative or complementary projects.

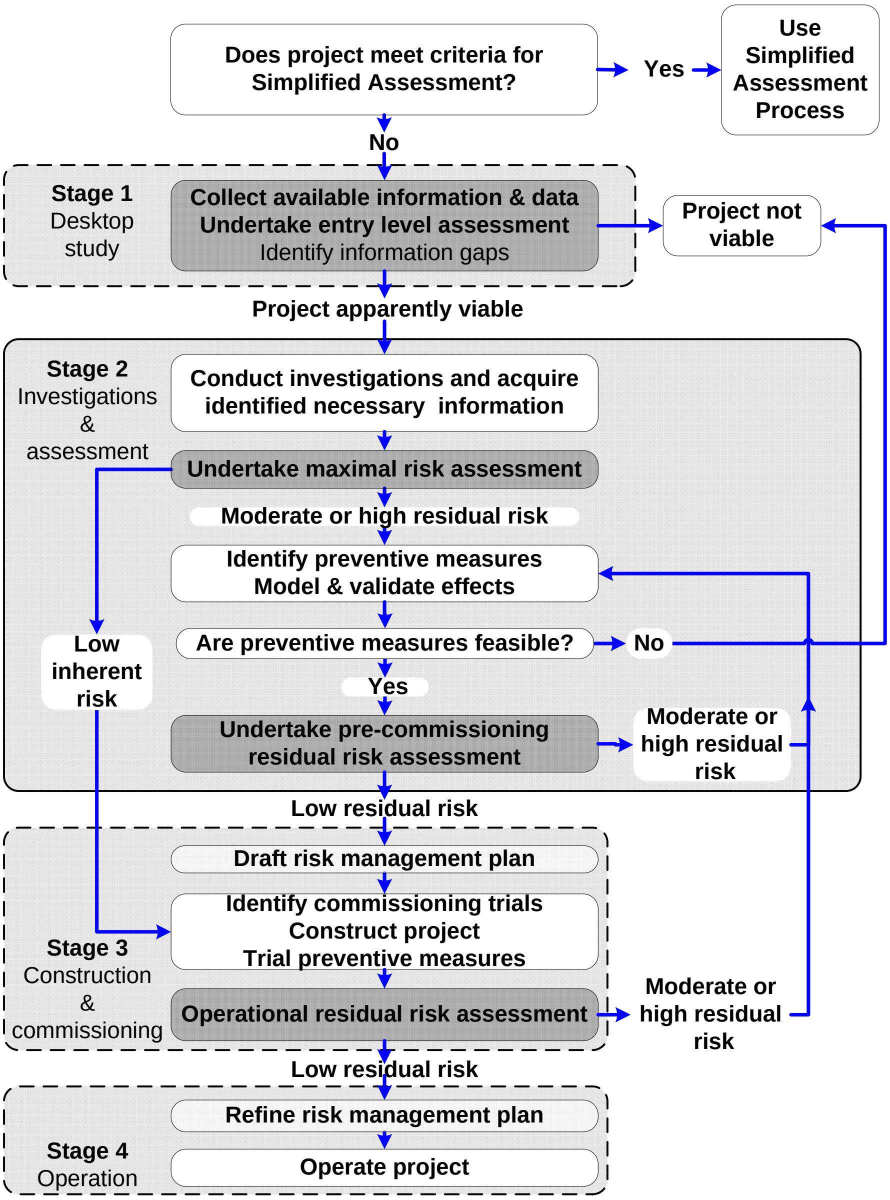

Fig.2. Risk assessment stages in managed aquifer recharge project development

Stage 2 investigations enable risks to be assessed and the preventative measures by which they can be managed to be indentified. This requires information describing the source water quality, infrastructure and proposed operations of the project, and characterisation of the hydrogeology to demonstrate that all hazards have been addressed with sufficient supporting information for a management plan. Where further information is needed, a pilot project might be required.

At this point the risks of success will be better defined and a decision would be made on whether to invest in constructing the MAR project or in alternative water supplies. Such a decision would account for the full range of costs and benefits of all projects.

For many MAR projects the level of some risks cannot be known before implementation, accompanied by suitable monitoring. Known as commissioning trials, Stage 3 monitoring provides a basis for ongoing operation of the MAR scheme. It also provides for the development of management plans for the ongoing operation of the project, Stage 4, which will require ongoing monitoring to ensure that risks to human health and environmental health are controlled.

A risk assessment framework for health and environmental protection

The risk management framework for MAR operations comprises 12 elements (Figure 3) that fall into four main categories:

- commitment to responsible use and management of recycled water
- MAR system analysis and management, such as risk assessment and a series of preventative measures
- supporting requirements, such as employee training, community involvement, research and development, validation, and documentation and reporting systems; and
- review, including evaluation and audit processes.

All 12 elements need to be implemented for the risk management approach to be successful.

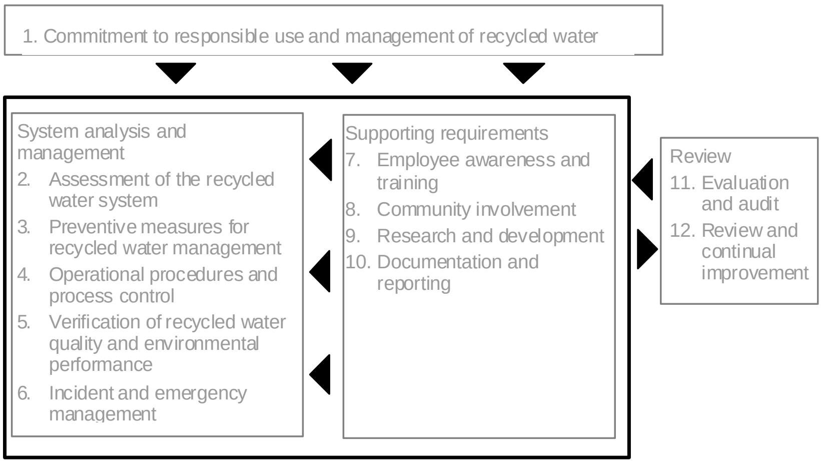

Fig.3. Elements of the framework for managing water quality and use (EPHC, 2008).

This approach aims to protect the environmental values of all intended uses of recovered water and of the aquifer beyond a transient attenuation zone, and to prevent adverse impacts. This is done by assessing potential hazards and the risks associated with each, and identifying preventive measures to manage the risks.

A simplistic view that treating water to near drinking standards before recharge will protect the aquifer and recovered water is incorrect. For example chlorination, to remove pathogens that would sustainably be removed in the aquifer, can result in water recovered from some aquifers containing excessive chloroform. In some locations, drinking water injected into potable aquifers has resulted in excessive arsenic concentrations on recovery due to reactions with pyrite containing arsenic. Source water that has been desalinated to a high purity dissolves more minerals within the aquifer than water that has been less treated.

Hence a scientific approach is recommended that takes account of three ways that aquifers interact with recharged water:

1. Sustainable hazard removal - allowing for attenuation during passage through soil and aquifer within an attenuation zone (Figure 14), (eg pathogen inactivation, biodegradation of some trace organics, a limited amount of nutrient assimilation)
2. Ineffective hazard removal –- these hazards need to be removed prior to recharge because they are either unremoved (eg salinity) or removal is unsustainable (eg adsorption of any metals and organics that are not subsequently biodegraded, or excessive nutrients or suspended solids)

3. New hazards introduced by aquifer interaction (eg metal mobilization, hydrogen sulphide, salinity, sodicity, hardness, or radionuclides) - there is a need to change the quality of recharge water to avoid these (eg change acidity-alkalinity, reduction-oxidation status or reduce nutrients)

The response of an aquifer to any water quality hazard depends on specific conditions within the aquifer including temperature, presence of oxygen, nitrate, organic carbon and other nutrients and minerals, and prior exposure to the hazard.

The zone of aquifer in which water quality may be measurably affected by MAR may be larger than the attenuation zone, but in this outer domain the water quality should continuously satisfy the initial environmental values of the aquifer The effects of MAR operations on hydraulic heads (pressures) may be measurable over a much larger area, especially in confined aquifers, and may extend several kilometres. If the aquifer is originally too saline for the uses of recovered water, a storage zone can be identified that contains water which when recovered is fit for its intended use (Figure 4).

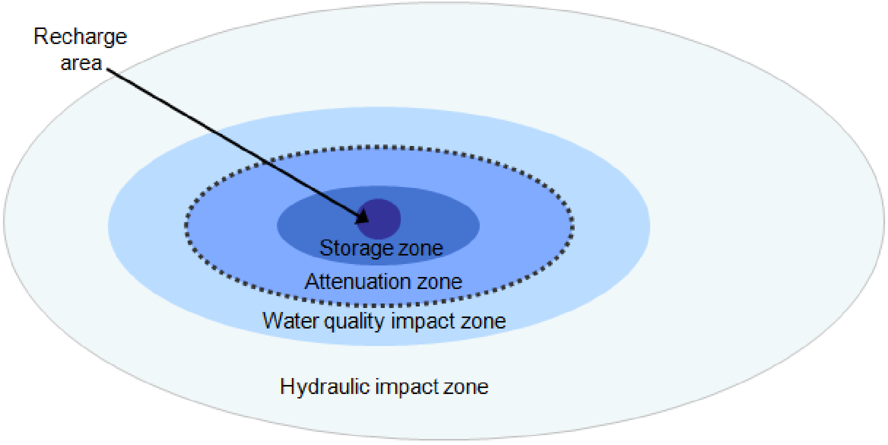

Fig.4. Schematic showing zones of influence of a MAR operation.

The dotted line in Figure 4 marks the outer boundary of the attenuation zone. This represents the maximum separation distance between the MAR recharge structure and well(s) for verification monitoring to ensure that the ambient groundwater quality is protected. As the attenuation zone defines sustainable attenuation only, on cessation of the MAR operation this will shrink and disappear as ultimately the whole aquifer will meet all its initial environmental values.

Water quality considerations

Applying the system analysis and management components (Elements 2–6) of the framework for water quality management to MAR reveals a number of water quality hazards (Table 1). Hazards to human health or the environment may originate from:

- the source water for recharge
- native groundwater
- aquifer minerals reacting with recharge water
- byproducts of treatment processes or maintenance practices.

Table 1. Summary of key water quality hazards in source water, groundwater and aquifer materials for MAR projects, with examples of specific hazards and preventive methods.

Hazard	Origin[a]	Examples	Preventive measures
Pathogens	S, (G)	Viruses	Adequate aquifer residence time
Inorganic chemicals	G, A, S	Arsenic	Control Eh during recharge (avoid mobilisation)
Salinity and sodicity	G, (S)	Salinity	Increase volume of freshwater recharged
Nutrients	S, (G)	Nitrogen	Pretreat water (eg activated sludge)
Organic chemicals	S, (G)	Pesticides	Exclude prone sub-catchments
Turbidity and particulates	S, (G)	Suspended solids	Pretreat water (eg wetland)
Radionuclides	G, A, (S)	Alpha-radiation	Aquifer selection (avoidance)

A = aquifer minerals, G = groundwater, S = source water for recharge

[a] Brackets show possible secondary source; Eh = a measure of redox potential, the propensity for oxidation and reduction reactions.

These key hazards impact on:

- the aquifer beyond the attenuation zone (and hence other groundwater users and groundwater dependent ecosystems)
- the uses of recovered water
- situations where the byproducts of MAR water treatments and operations are reused or discharged (see Table 2).

Table 2. Examples of hazardous byproducts of managed aquifer recharge operations.

General hazard	Example of specific hazards
Water treatment byproducts	Any process with reject water (eg reverse osmosis) or byproduct (eg coagulation, filtration, backwash water) may produce water with elevated concentrations of suspended solids, pathogens, inorganic chemicals, nutrients, salinity and organic chemicals
Purge water	Suspended solids, pathogens, metals, nutrients and organics in recharge water may be concentrated in water purged from an aquifer storage and recovery well during maintenance
Basin scrapings	Pathogens, metals, nutrients and organics in recharge water may be concentrated in scrapings produced by infiltration basin maintenance. If they meet quality criteria, scrapings may be reused in agriculture as a component in soil conditioner

Note: The waste management hierarchy should be invoked in the priority order of: avoid, reduce, reuse, recycle, treat and dispose.

Proponents developing a MAR project should engage specialist consultants to identify and quantify health, environmental (eg hydrogeological and geotechnical) and management risks. The next step is to develop preventive measures to mitigate risks and appropriate monitoring methods to assess each hazard, including critical control points where applicable. Hazard preventive measures may include one or more of the following barriers:

- source water selection
- recharge control system (eg recharge shut down if the monitored indicator variable is outside critical control limits)
- aquifer selection
- project location (away from sensitive groundwater-dependent ecosystems or end uses)
- treatment of recharge water to remove hazards or precursor(s) to their formation or occurrence
- adequate detention time for passive treatment within the aquifer
- treatment of recovered water before distribution to end uses
- incident response plans, including feedback from real-time monitoring.

In many MAR operations, multiple barriers may be needed, so that if any one barrier fails, human health and the environment will still be protected. Table 3 summarises preventive measures, many of which apply to more than one hazard. Depending on the particular project, other critical control points and preventive measures may be more appropriate. Education and training are important components of implementing and maintaining prevention measures.

Table 3. Summary of preventive measures and critical control points for MAR.

Preventive measures	Description	Critical control point
Exclusion barriers — preventing entry		
Hazard source control	Selection or management of water sources before recharge (eg catchment, recycled water, roof runoff, stormwater)	No
Intake levels	Exclusion of floating hazards by maintaining intake levels below the water surface	No
Exclusion of water that does not meet critical limits	Continuous monitoring of indicator variable, to provide feedback to divert water flow or stop recharge when critical limit is exceeded	Possibly: depends on the hazard, associated risk prevented and monitoring system
Exclusion barriers — removing hazards		
Residence time in the soil or aquifer	Attenuation of all human pathogens and selected organic chemicals	Yes: system needs to provide required residence time. Recovery rate is restricted to ensure adequate time between recharge and recovery
Travel distance in aquifer	Travel distance (between recharge and recovery) chosen to provide a minimum residence time under the range of operating conditions	No: component of system design
Treatment processes	Concentration of specific hazards decreased before recharge or on recovery	Possibly: at the point of recharge and/or recovery; depends on the hazard and effect on the specific environmental endpoint
Preventive measures to manage risks in commissioning and validation monitoring (Stage 3)		
Operate early warning feedback system	Monitor near-recharge wells for early warning of treatment effectiveness and to allow corrective actions to be implemented	Yes: detection exceeding critical limit trigger corrective action
Recover recharged water and re-treat	Recover contaminated water to prevent exposure	No: however, volume to be recovered would be reduced by use of an early warning system
Prevent distribution of recovered water to unacceptable end uses	If recovered water does not meet water quality requirements for intended uses, stop recovery (to allow longer residence time), divert to acceptable uses or re-treat	Possibly: surrogate parameter correlated with water quality concern may be used
Post-treatment of recovered water	Treat recovered water to remove identified hazards	Yes: direct or surrogate parameters exceeding critical limit trigger corrective action
Reduce rate of recharge or recovery	Modify flow rates to increase residence times, reduce pressure gradients across thin aquitards, or reduce MAR-induced flow and level variations	No: subject to validation monitoring

Pathogens

In confined aquifers, sources of enteric pathogens (ie intestinal pathogens) are limited to those present in the recharge source water. However, in unconfined aquifers, other sources of such pathogens may exist. Potential water sources for managed aquifer recharge (eg wastewater, greywater, stormwater) can contain a wide range of enteric pathogens that pose a risk to human health.

Public health and environmental risks associated with pathogens in relation to managed aquifer recharge are identical to those described in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

Fate and behaviour of pathogens in MAR

Pathogen survival in groundwater is affected by physical, chemical, and biological processes (Toze and Hanna 2002, Gordon and Toze 2003). The inactivation of pathogens in aquifers highlights their potential use as robust treatment barriers in the multi barrier approach. Pathogen presence and survival in aquifers is highly variable and is influenced by a variety of factors, including:

- pathogen type
- recharge water source type
- temperature
- redox state and oxygen concentrations
- activity of indigenous groundwater microorganisms
- aquifer geochemistry.

Further information on the effects of these parameters on pathogen survival in aquifers is given by Dillon and Toze (2005) and NRC (2008). Although all of these parameters (either independently or collectively) may influence pathogen survival, different pathogens can also vary in their environmental stability (eg between different locations), depending on local groundwater conditions. Enteric viruses are generally accepted to be the most resistant to decay (ie have the highest potential for survival); followed by protozoa and then bacteria.

Little is known about the fate of helminths during MAR. In Australia (except for the tropical northern regions), helminths pose minimal risk. They can be controlled by suitable pretreatment, and are effectively removed from water by simple treatment systems such coagulation, flocculation and sedimentation in stabilisation ponds (Jimenez 2003). Even if a helminth egg was able to pass through treatment systems, their small size (40–90 µm) means that simple filtration processes in more consolidated and sand aquifers would be likely to remove them.

Managed aquifer recharge projects relying on aquifer treatment to remove pathogens before recovery for drinking water supplies will always require validation. The efficiency of pathogen removal depends on site-specific conditions; uncertainties can be resolved by monitoring to validate attenuation rates. In terms of log removals, aquifers are conceptually much like other natural and engineered water treatment processes for pathogens (NRMMC–EPHC–AHMC 2006). Log-removals in aquifers are primarily related to the residence time of the recharge water, the redox state of the aquifer and the temperature; they are typically expressed in terms of the number of days required for a 1-log reduction in pathogen numbers.

As a rule of thumb, the most reliable assessment of pathogen attenuation at a given site is measurement of pathogen survival in situ using inoculated diffusion chambers. Due to temporal variations in pathogen numbers in source water, detecting no pathogens in groundwater samples sheds little light on the aquifer’s actual pathogen inactivation rate. Relevant laboratory-derived attenuation data must be obtained at a temperature and redox status relevant to the aquifer, using chambers inoculated with microorganisms from the aquifer.

As validation data from MAR sites accumulates, greater precision in estimating pathogen attenuation rates in aquifers is expected. Verification monitoring involves attempting to detect microbial indicators and targeted enteric viruses in the recovered water. This is done by monthly sampling of observation wells within the attenuation zone and of the recovered water.

Secondary treated effluent does not appear to affect the numbers of indigenous pathogens in an aquifer. Laboratory evaluation of the effect of secondary treated effluent on the abundance of indigenous opportunistic pathogens in aquifer material did not result in any significant difference in comparison with controls (S. Toze CSIRO Land and Water, pers comm, 2007).

Recent studies (Reed 2007, Reed et al 2007) have documented the changes in native microbial populations near the Bolivar (South Australia) reclaimed water ASR trial and the Floreat Park (Western Australia) reclaimed water infiltration galleries. These studies confirmed trends in populations related to proximity to nutrient-rich recharge water and changes in redox status. In distal water, where water quality indicated presence of reclaimed water, microbial community populations, biodiversity and activity were unchanged. Although the evidence is not conclusive, it suggests that MAR is unlikely to stimulate recovery of higher numbers of indigenous opportunistic pathogens (eg Pseudomonas, Aeromonas) than would be recovered by pumping native groundwater.

Management of pathogens via MAR

Preventive measures to reduce the risk of pathogenic hazards and achieve performance targets include:

- source control (eg catchment management for stormwater sources)
- removing pathogens using treatment processes (eg engineered or natural treatment processes to achieve the required log removal rate of the reference pathogens)
- reducing exposure through preventive measures on-site (eg controlling public access during irrigation with recovered water).

These three measures are described in Sections 3.4.1–3.4.3 and Appendix 3 of the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

The concept of tolerable risk is central to the management of enteric pathogens via managed aquifer recharge. These guidelines adopt a tolerable risk of 10^{-6} disability adjusted life years (DALYs) per person per year (NRMMC–EPHC–AHMC 2006).

Given the potentially large numbers of pathogenic hazards in source waters, three reference pathogens — rotavirus, Cryptosporidium and Campylobacter — have been selected to represent viral, protozoan and bacterial hazards respectively. For a detailed description of DALYs, and the calculation of microbial health-based performance targets for the reference pathogens, refer to Appendix 2 of the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006). The unique feature of MAR is the consideration of the aquifer's effects on pathogens.

Inorganic chemicals

This section is applicable to the major ions (calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate, bromide and fluoride); metals (aluminium, cadmium, chromium, copper, iron, manganese, nickel, lead, strontium and zinc); metalloids (arsenic, boron and silicon); and gases (hydrogen sulfide and methane). Nitrogen and phosphorus are discussed separately below.

Unlike pathogens, there is insufficient information on chemical parameters to support DALYs. Tolerable risk is therefore defined in terms of guideline concentrations (ANZECC and ARMCANZ 2000; NHMRC–NRMMC 2004; WHO 2006; EPHC–NHMRC–NRMMC 2008a).

The key inorganic hazards resulting from aquifer storage are:

- increased arsenic, iron, manganese, trace species or hydrogen sulfide, producing recovered concentrations in excess of the beneficial use guideline value
- increased iron in recovered water, which impacts on water supply infrastructure (eg irrigation)
- changes to major ion chemistry alter the sodicity or nutrient balance of the recovered water, affecting its suitability for potential uses (eg irrigation).

When elevated metal concentrations exceeding the beneficial use guideline value occur in backwash water from injection wells, or in the initial water recovered from an aquifer storage and recovery well, care should be taken in the treatment, use and disposal of this waste stream.

Sources and fate of inorganic chemicals in MAR

The chemistry of water stored in an aquifer during MAR is affected by chemical reactions, driven by the aquifer's conditions (eg pH, redox state, minerals, organic matter, microbial activity). Reactions can occur between the source water and the native groundwater, and between the source water and the aquifer material. This can change water quality and aquifer permeability. The key risks related to subsurface reactions are described below.

Arsenic increase

Mobilisation of arsenic from the aquifer sediments can occur when pyrite in the storage zone is oxidised, or iron (III) oxides are dissolved (see decision tree in Appendix 3). This is a key issue for confined target zones in which reduced minerals are present, despite starting with source water at acceptable arsenic concentrations (Arthur et al 2003), and may lead to concentrations of arsenic greater than the drinking water guideline value.

Iron increase

Release of iron from the sediments in the storage zone occurs mainly when organic matter in the source water reacts with iron (III) oxyhydroxides and oxides (ie goethite, hematite). It can also occur from pyrite oxidation or by changing the pH of the storage zone (see decision tree in Appendix 3). Iron release is generally an aesthetic water quality concern, potentially causing an elevated colour; but, it can also contribute to aquifer clogging. Iron increases can be associated with the release of other hazards such as arsenic and radium.

Manganese increase

Dissolution of manganese from manganese oxides and oxyhydroxides in the sediments occurs by reaction with organic matter in the source water, or by changing the pH of the storage zone (Ibison et al 1994). Like iron, manganese may contribute to the colour of the recovered water.

Trace ion increase

The ion species affected include: aluminium, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, fluoride, iron, lead, manganese, molybdenum, nickel, vanadium, uranium and zinc. All of these can cause health or environmental concerns. Increases in trace constituents frequently coincide with an increase in iron, manganese or arsenic.

Mechanisms for trace ion release include:

- oxidation of sulfide minerals, such as pyrite, due to presence as trace elements within the mineral (similar to arsenic, although arsenic is generally more mobile than cations)
- iron (III) oxide dissolution under changing pH or Eh, as these surfaces often contain adsorbed trace species
- exchange or displacement from the solid surface by another species (eg cation exchange)
- mineral equilibrium, when water in the storage zone is not in equilibrium with the dominant mineral phases
- dissolution of mineral phases or accumulated particulates under changing pH or Eh.

Hydrogen sulfide increase

Hydrogen sulfide gas is produced when organic matter, introduced to an anoxic storage zone, reacts with dissolved sulphate. In the sequence of microbial-mediated redox reactions, iron mobilisation is likely to precede the production of hydrogen sulfide. Hydrogen sulfide contributes an aesthetic hazard by imparting taste and odour to the recovered water.

Changes to major ion composition

Mixing of the source water with saline groundwater, or ion exchange between the source water and the solid phase exchange sites, can significantly affect the contribution of sodium, calcium and magnesium. This is an important consideration if the recovered water is to be used for irrigation, because it can alter the risk of soil sodicity.

Excessive dissolution of carbonate minerals

Excessive dissolution of carbonate minerals can:

- lead to injection well and aquitard stability concerns
- increase production of sand in recovered water
- extend preferential flow paths, which may reduce the residence time available for hazard attenuation.

Carbonate mineral dissolution may also expose reactive surfaces such as sulfide minerals, and increase the potential for release of metal and metalloid species.

The source water used in a MAR scheme is unlikely to be in equilibrium with the minerals present in the storage zone. As a result, some dissolution of minerals will occur when the source water comes into contact with minerals in the aquifer. The degree of dissolution depends on the solubility of the mineral in the given conditions (eg pH, temperature, pressure, ionic strength, contact time). Mineral equilibrium can also be altered during subsurface storage by other reaction processes; for example, barium can be released by the dissolution of barite (BaSO4) in aquifer sediments, after dissolved sulfate concentrations have been reduced by bacterial sulfate reduction (Zhou and Li 1992).

Carbonate minerals can be a major influence on the quality of water recovered, because carbonate dissolution is a rapid reaction. In contrast, silicate dissolution is a very slow buffering reaction between pH 6 and 8 (Appelo and Postma 1999), and has minimal impact on water quality over the timescale of a managed aquifer recharge scheme. Dissolution of carbonate minerals will increase aquifer permeability, and the impact on the stability of injection wells and the aquitard must be considered.

Mineral dissolution can increase the salinity and hardness of the water available for recovery, and also increase minor constituents such as barium or fluoride (fluorite dissolution). Solubility controls may limit the dissolved concentration of some hazards, such as barium (barite solubility), phosphate (apatite solubility) or iron (iron oxyhydroxides or oxides), but mineral precipitation can lead to clogging concerns. The tendency for mineral dissolution or precipitation can be examined through the saturation index of a solution.

The redox state within the storage zone alters the inorganic chemistry of the recovered water. Redox reactions in MAR will often be induced by addition of source water that contains oxygen to an anoxic aquifer, or by addition of organic matter to an aquifer. Redox zones, and the resulting water quality, can vary spatially and temporally during a managed aquifer recharge operation. A highly reactive zone often develops near the point of injection or infiltration, resulting in water quality that differs from the bulk of the stored water. For example, if source water high in organic matter is used, the reactive zone can become anaerobic. This can lead to dissolution of iron (either present in the aquifer sediments or accumulated around the injection well from filtration of particulate matter in the source water) or in situ generation of hydrogen sulfide.

Changes in redox conditions and water quality can also occur:

- over time under different flow rates (eg injection or infiltration versus storage)
- where degree of saturation changes (eg wetting and drying cycles in soil aquifer treatment)
- in flow reversal during recovery in an aquifer storage and recovery operation.

Sorption to clay minerals, organic matter or iron oxide surfaces can act as an attenuation mechanism for trace metals and metalloids. However, sorption is not permanent. It can be reversed by preferential sorption of another species, or by pH–Eh-dependent changes in the surface properties that alter the number of available sorption sites. In addition, the sorption capacity of an aquifer may be limited, delaying breakthrough of the hazard to a downstream monitoring or recovery location.

Mixing is an important influence on the quality of recovered water, if the native groundwater is brackish or contains hazards that exceed target values for the specific beneficial use. Mixing of two waters can produce a solution that is more aggressive toward the aquifer minerals (Runnels 1969). If an inorganic constituent in the groundwater exceeds water quality targets, dilution may not be sufficient to ensure water quality targets are met if additional processes, such as mineral dissolution, release that species from the aquifer sediments. The effect of mixing should be considered in relation to salinity targets or operational constraints.

Metals in source water are largely in particulate form, and thus will accumulate in the subsurface, close to the point of entry (ie well face or basin floor). Accumulated metals may be removed permanently from the system by operational maintenance, such as well redevelopment or basin scraping. Some in situ dissolution may occur, producing a localised increase in soluble metal concentration. This is most likely to affect the first water recovered from an aquifer storage and recovery well.

Management of inorganic chemicals

Source control may include limiting the contribution from hazardous activities (eg catchment management, trade waste discharge agreements), and diversion of flow outside water quality criteria (eg pH, conductivity).

Pretreatment measures include:

- source water treatments (eg filtration, coagulation, flocculation)
- pH adjustment (eg prevention of manganese release from sediments) (Ibison et al 1994)
- redox control to limit reaction within the aquifer (eg limiting organic carbon in source water, deoxygenating to prevent arsenic release).

Residual risk assessment management of inorganic chemicals within the aquifer requires validation of the conceptual understanding of geochemical processes and of the preventive measures necessary to manage the human health and environmental risks. Validation monitoring (Stage 3) is necessary because the presence of trace amounts of some minerals can cause problems. Drill core and groundwater samples collected in Stage 2 cannot be relied on to detect all minerals present in the aquifer that recharged water will come into contact with.

Upon recovery and (where necessary) for high-value use, the major ions contributing to salinity can be removed. This can be achieved by post-recovery treatments such as aeration and filtration, or other techniques (individually or in combination) including oxidation, precipitation, coagulation, sorption, ion exchange, lime softening and filtration (NHMRC–NRMMC 2004).

Salinity and sodicity

The public health and environmental risks associated with salinity and sodicity (the abundance of sodium relative to calcium and magnesium) in relation to MAR include:

- salinity values exceeding the beneficial use value for total dissolved salts or sodium content
- osmotic effects on plant health and yields, due to irrigation with saline water
- rising watertables, due to leaching requirements to remove excessive salinity
- sodicity-related decline in structure of agricultural soils
- salinity effects on infrastructure and other assets (eg excessive corrosion or scaling in pipes, fittings and appliances; salt damp in stone and masonry structures).

The mixing of recharge water and ambient groundwater in MAR will cause the salinity of recovered water to differ from that of the recharge water. In general, the salinity of ambient groundwater within aquifers targeted for managed aquifer recharge should be similar to or higher than the source water (in keeping with the principles outlined in the Groundwater Protection Guidelines, ANZECC-ARMCANZ 1995). Therefore, native groundwater will represent an additional source of salinity (and sodicity) in recovered water. The environmental risks of salinity and sodicity and their effects on soil structure and agricultural production are discussed in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

Sources of salt in MAR

All source waters for MAR contain natural salinity levels, derived from inorganic salts, minor amounts of dissolved organic matter and small colloidal material. The inorganic constituents of source waters may be characterised by measures such as conductivity, total dissolved salts and sodicity. Typically, the salinity of roof runoff is lower than stormwater runoff. Stormwater runoff, in turn, has lower salinity than water recycled from sewage effluent. This is because the enrichment or addition of salts from natural or anthropogenic processes in water transported through a rural or urban catchment increases its salinity levels.

Salinity levels in groundwater range from fresh to highly saline. Infiltration of shallow saline groundwater into leaky sewers can substantially increase the salinity and sodicity of sewage effluent, rendering it unfit for recycling via managed aquifer recharge unless it is treated or blended.

Management of salinity and sodicity

Management controls include preventive measures such as:

- catchment water quality management and source control (to minimise salt export and remove or mitigate point sources of salinity, where viable)
- source water selection
- site selection to target aquifers that minimise risk
- pretreatment or post-treatment (desalination)
- shandying of recovered water with alternative, lower salinity sources (shandying is the addition of one water source to another).

Nutrients: nitrogen, phosphorus and organic carbon

This section discusses nitrogen and phosphorus — recognised as environmental hazards for water recycling (NRMMC–EPHC–AHMC 2006) — and organic carbon, an important nutrient in relation to microbial processes in the subsurface.

Nitrogen and phosphorus are identified as key environmental hazards due to their potential for causing nutrient imbalance in irrigation water, soil eutrophication and toxic effects on terrestrial biota (NRMMC–EPHC–AHMC 2006). While subsurface storage is likely to reduce nutrient concentrations, the overall nutrient balance of the recovered water still needs to be considered in relation to its beneficial use. Nutrients (predominantly organic matter) in the source water will stimulate microbial activity in the subsurface. In turn, this alters the concentration of inorganic and organic chemicals in the water and affects aquifer permeability.

Sources and fate of nutrients in MAR

The level and variability of nutrient loads in source waters is largely affected by pretreatment measures. Recycled water potentially contains high nutrient loads that may vary with seasonal effects on microbial treatment processes. Nutrient concentrations in stormwater are generally likely to be lower than in recycled water, but will vary with catchment type (eg industrial areas).

Removing organic carbon and nitrogen is a passive water quality treatment provided by MAR operations (Dillon and Toze 2005). Organic matter can be removed by biodegradation, microbial assimilation, filtration, sorption or precipitation. Biodegradation occurs through redox processes that influence the mobility of inorganic chemicals and the fate of organic chemicals. Colloidal organic matter can also facilitate the transport of other chemical hazards. The amount of organic matter removed by biodegradation depends on its character; the easily biodegradable portion can be removed within days of introduction to the subsurface, while less reactive material may degrade over a longer time (Fox et al 2001). Reactive organic matter present in the sediments may also be degraded. Microbial assimilation occurs when the nutrient rich source water is introduced to the subsurface, leading to the development of a biofilm near the point of entry (ie well face or basin floor). The biofilm forms a reactive zone that can have distinct redox chemistry from the rest of the storage zone, and is largely responsible for subsurface water quality treatment. Filtration of particulate organic carbon provides an additional energy source to sustain microbial activity, and can produce soluble degradation byproducts.

Nitrogen can exist in various forms in source waters, including organic nitrogen (predominantly proteins), ammonium, nitrate, nitrite and gaseous nitrogen. The dominant nitrogen species in recycled water are organic nitrogen, ammonium and nitrate. The fate of nitrogen depends on its form and the redox conditions encountered. Under aerobic conditions, nitrification will convert ammonium to nitrate; under anaerobic conditions, ammonium can be adsorbed to mineral surfaces by ion exchange until the exchange capacity is exceeded. Nitrate can be removed by reduction to nitrogen gas (denitrification) or ammonium. In the unsaturated zone, some partitioning of ammonium to gaseous ammonia and loss through volatilisation at the air–water interface may occur.

Management of nutrients

Source control may include limiting the contribution from hazardous activities, and diverting flow when water quality indicators (eg colour and turbidity) exceed pretreatment or discharge criteria.

Pretreatment measures include:

- inline filtration on source water delivery infrastructure (for particulate organic carbon)
- biofiltration
- passive treatment through wetlands.

The effectiveness of natural treatments systems such as wetlands for nutrient removal depends on their maintenance. Monitoring is necessary to assist with managing wetland treatment systems.

Removal of subsurface organic carbon and nitrogen relies on treatment through redox processes (eg Soil Aquifer Treatment; Fox et al 2001; Amy and Drewes 2007). Validation would need to be supported by evidence of declining concentrations and physiochemical conditions. Phosphorus removal would also need evidence of declining concentrations, supported by mineralogy (iron, aluminium oxides) or mineral saturation calculations. Organic carbon can be recovered from recovered water by granular activated carbon and membrane filtration, if necessary, for high-valued use (NHMRC and NRMMC 2004). Biological clogging of recharge wells and infiltration basins and galleries should also be considered.

Organic chemicals

This section discusses trace organic compounds (often referred to as micropollutants) including:

- pesticides
- hydrocarbons
- polycyclic aromatic hydrocarbons (PAHs)
- emerging chemicals of concern
- endocrine disrupting chemicals
- personal care products
- pharmaceuticals
- flame retardants.

Trace organic compounds are predominantly anthropogenic in origin (eg PAHs are a combustion product of carbon fuels); however, some may be naturally occurring (eg algal toxins).

Organic chemicals can pose health risks (NHMRC–NRMMC 2004) and environmental risks (NRMMC–EPHC–AHMC 2006). There are numerous emerging chemicals — for example, endocrine disrupting chemicals, pharmaceuticals and personal-care products, and some disinfection byproducts (eg N-nitrosodimethylamine, NDMA) (NRMMC–EPHC–AHMC 2006). If an established water quality guideline value does not exist for a specific chemical, EPHC–NHMRC–NRMMC (2008a) provides methods for determining guideline values for any chemical with respect to drinking water uses; it also provides guidance on dealing with mixtures of chemicals.

Environmental toxicity testing may be required to provide additional information on the impacts of MAR projects on sensitive environments. Guidance on environmental toxicity testing is provided in Chapter 3 of Aquatic ecosystems of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000a).

Sources and fate of organic chemicals in MAR

Determining the presence of organic chemicals in source waters, and carrying out the associated risk assessment can be difficult, due to intermittent loadings and analytical detection capabilities for these substances. However, the origin of the source water should allow the likelihood and nature of organic chemical presence to be estimated. The effort taken to characterise organic constituents of source water must be proportionate to the risk posed to public health and the environment.

In general, subsurface storage provides a treatment step for organic chemicals (Dillon and Toze 2005). However, formation and attenuation of trihalomethanes (a group of disinfection byproducts) has been reported during storage (Pavelic et al 2005, 2006b). The potential for disinfection byproduct formation can be lowered by reducing the amount of organic matter in the source water, or altering the disinfection regime to reduce residual chlorine (Jimenez 2003).

Subsurface removal of organic chemicals can occur through volatilisation (in the unsaturated zone) and biodegradation (in the unsaturated and saturated zones). Degradation rates vary with pH, temperature, redox state and the presence of cosubstrates such as dissolved organic carbon. Sorption will also retard organic chemical movement, but the sorption removal capacity may be limited. However, sorption does provide additional residence time for degradation to occur. No allowance should be made for attenuation in the aquifer due to sorption alone for chemicals that do not degrade under the redox conditions and temperature relevant to the aquifer’s storage zone.

The availability of environmental fate data for organic chemicals varies considerably. The fate of hazards such as benzene, for example, is reasonably well documented (Howard 1991); but there may be little information on emerging chemicals of concern. It is critical to ensure that existing environmental fate data was determined in a similar physiochemical environment to that expected in the MAR scheme under consideration. In the absence of relevant field data, laboratory studies can predict the fate of the hazard under the expected conditions (Oliver et al 1996, Ying et al 2003).

If the storage zone is an unconfined aquifer, organic chemicals may be present from point sources (eg industrial activities) and diffuse sources (eg pesticide use).

Mixing between the source and native groundwater may therefore affect the recovered water quality.

Management of organic chemicals

Source control may include limiting the contribution from hazardous activities to trade waste or stormwater discharge, and improving hazard management for high risk activities in order to reduce source concentrations or prevent against shock loadings from spills.

Pretreatment and post-treatment measures include biofiltration, passive treatment through wetlands and advanced tertiary treatment, such as membrane filtration.

Reliance on attenuation of organic chemicals in the aquifer requires validation of the reduced concentration with time and distance, supported by details of the residence time in the aquifer and its physicochemical and redox conditions.

Indicators may be selected for monitoring to focus effort on species that will give the most sensitive indicator of effective system performance (Drewes et al 2008).

Turbidity and particulates

The public health and environmental risks associated with turbidity in relation to managed aquifer recharge include:

- recovered water having turbidity in excess of drinking water guidelines (where drinking is an intended end use) which if not removed, can impact on pumps and irrigation infrastructure
- reduced disinfection performance, leading to increased risk from microbial pathogens
- increased risk of transporting a range of contaminants that can sorb to particles
    - heavy metals
    - phosphorus
    - various organics
    - microbial pathogens
- discharge of backwash water during redevelopment (backwashing) of injection wells, impacting on the stormwater catchment downstream.

Sources of turbidity in MAR

All source waters for managed aquifer recharge contain natural levels of particulates — measured as turbidity or suspended solids — derived from inorganic silt, clay-sized particulates and organic matter. Stormwater runoff usually contains highly variable turbidity levels, as a result of factors related to climate, catchment geomorphology, and land use and management. Secondary or tertiary treated sewage effluent typically contains lower concentrations of particulates, and a higher organic content, than stormwater. Roof runoff is typically low in particulate matter, but can be high due to deposition of vegetation debris or poor management. Groundwater turbidity levels are generally low, but can be high in wells that are inappropriately designed or inadequately developed.

Managed aquifer recharge practices can generate particulate hazards as a result of mineral dissolution and particle remobilisation within the soil or aquifer, and through the standard practice of backwashing injection wells to maintain recharge rates.

Management of turbidity

Turbidity management controls include preventive measures such as:

- source selection
- catchment water quality management and source control to
  - minimise particulate export
  - remove or mitigate point sources of turbidity (where viable)
- pretreatment or post-treatment before recharge through
  - settling tanks
  - wetlands
  - coagulation
  - filtration.

Radionuclides

Radioactive materials (eg uranium, thorium, potassium-40) occur naturally in the environment, and risk of human exposure to radiation is predominantly from natural sources. Additional exposure can occur through anthropogenic activities such as medical (radiopharmaceuticals) and industrial use of radioactive materials.

The main radionuclide concern is recovery of water posing a risk to human health by ingestion of drinking water or foods via crop irrigation, stock watering, or food chain accumulation (radium and radon), or inhalation of gas released from the water supply (radon).

Radioactivity is measured in becquerel (Bq), where 1 Bq= 1 disintegration per second. Health considerations are based on the effective dose of radiation, measured in sievert (Sv), which takes into account the equivalent dose received by all tissues or organs, weighted to account for their different sensitivities to radiation. The acceptable radiation dose via the ingestion of water should be <1 mSv/year (NHMRC–NRMMC 2004). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 from the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004).

Sources of radionuclides in MAR

Recycled water or stormwater may contain radionuclides if they receive water from medical and industrial uses. Groundwater may contain naturally occurring radium and radon isotopes (radium 226, radium 228 and radon 222). Mining activities may also concentrate naturally occurring radionuclides (eg processing mineral sands, producing phosphate fertiliser).

The major source of radionuclides in MAR will usually be from the interaction of stored water with the aquifer matrix during aquifer storage. Native groundwater radioactivity is a useful indicator of the minimum level of radiation in the recovered water. Natural concentrations of radionuclides vary considerably, and depend on the properties of the aquifer, which are (Dillon and Toze 2005):

- geology
- porosity
- grain size
- redox state
- major ion chemistry.

In general, high radionuclide concentrations are found in granitic fractured rock (crystalline) aquifers and near rich organic coal deposits (Herczeg and Dighton 1998). Leaching of uranium from carbonate aquifers has also been reported (Williams et al 2002).

Radon concentrations in recovered water and the native groundwater before managed aquifer recharge will be similar, because equilibrium between radon in the aquifer material and the source water is reached in less than three weeks (Dillon and Toze 2005).

Iron or manganese oxyhydroxides can adsorb substantial amounts of radium. Thus radium concentrations can increase through a MAR scheme if oxidation of organic matter leads to dissolution of these iron or manganese oxyhydroxide surfaces. Radium concentrations can also increase through the dissolution of radium-bearing minerals such as phosphates (Dillon and Toze 2005).

Management of radionuclides

The radioactivity of native groundwater in the storage zone can be screened by measuring gross alpha and beta activity (excluding potassium-40), followed by analysis of individual radionuclides, if the gross alpha or beta exceeds the target value (NHMRC–NRMMC 2004).

If the target aquifer is a potential source of radium, geochemical modelling is warranted to evaluate the potential for additional release through mineral dissolution or oxidation of organic rich deposits. Modelling would also define acceptable values for pH, oxygen, nitrate and organic carbon within the source water, to minimise the potential for geochemical reactions that could release radium during aquifer storage.

Potential pretreatment and post-treatment includes aeration for radon-222, and lime softening, ion exchange or reverse osmosis for radium-226 and radium-228 (NHMRC–NRMMC 2004).

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Appendix 1. Entry-level risk assessment —degree of difficulty

	Information required for assessment	Questions and indicators of degree of difficulty
1	**Source water quality with respect to groundwater environmental values**	
	• Where multiple samples are available, the highest concentration of each analyte should be used in the evaluation; unless there is justification that events resulting in those values will be prevented when the MAR project is established • Alternatively, in the absence of water quality data from actual source water, data may be used from existing similar MAR projects using the same type of source water and recharging the same aquifer • In the absence of either data source above, generic data from AGWR guidelines may be used: – for stormwater; the Phase 2 guidelines (EPHC–NHMRC–NRMMCb, in progress) gives generic data on concentrations of selected hazards in stormwater from roof catchments (Table 5.1) and urban catchments (Table 5.2). In the absence of other information, use 95 percentile data – for reclaimed water; maximum concentrations detected in secondary treated sewage may be used as a starting point and the Phase 1 guidelines (NRMMC–EPHC–AHMC 2006) gives generic data (Table 4.10). These data range from sewage that has been treated in water reclamation plants (min value) to raw secondary treated effluent (max value) • Assessment of quality variability and factors affecting quality are deferred to the maximal risk assessment	Q1. Does source water meet the water quality requirements for the environmental value of ambient groundwater? (Note: environmental values of water are listed in Table A1.1 along with a reference to water quality criteria for each) If Yes — low risk of pollution is expected. This is a necessary condition, but not a sufficient condition for low risk. If **No** — high maximal risk is likely. Expect Stage 2 investigations to assess preventive measures to reduce risk of groundwater contamination beyond attenuation zone (and size of attenuation zone).
2	**Source water quality with respect to recovered water end use environmental values**	
	• If the source water does not meet the water quality requirements for the environmental values of intended end uses of recovered water, then there is a reliance on attenuation of hazards within the subsurface	Q2. Does source water meet the water quality requirements for the environmental values of intended end uses of water on recovery? If Yes — low risk of pollution of recovered water is expected. However, this is not a sufficient condition for low risk due to aquifer reactions. If **No** — high maximal risk is likely. Expect Stage 2 investigations to assess this risk.

	Information required for assessment	**Questions and indicators of degree of difficulty**
3	**Source water quality with respect to clogging**	
	• Where source water quality is poor and soil or aquifer are fine-grained, clogging of the infiltration basin and gallery or recharge well is likely to occur, unless the water is pretreated before recharge • Clogging is most prevalent when water contains moderate or high levels of suspended solids or nutrients, such as nitrogen or labile organic carbon • Clogging can also occur when oxygenated water is introduced into an aquifer that contains iron. If the soil or aquifer are coarse grained or contain macropores, clogging with such waters is less likely, but the risk of pollution of groundwater is high (as covered in Q1 and Q2) • Lack of evidence of clogging is insufficient to indicate that risk of pollution is low, even in fine-grained media.	Q3. Does source water have low quality, for example: • total suspended solids >10 mg/L • total organic carbon >10 mg/L • total nitrogen >10 mg/L? And is soil or aquifer free of macropores? If **Yes** — high risk of clogging of infiltration facilities or recharge wells. Pretreatment will need consideration regardless of answers to Q1 and Q2. If No — lower risk of clogging is expected. However, this is not a sufficient condition for low risk, due to dependence of clogging on aquifer characteristics that would be revealed by stage 2 investigations.
4	**Groundwater quality with respect to recovered water end use environmental values**	
	• Where samples are available, the highest parameters detected in each sample should be used in the analysis; unless there is justification that events resulting in those values will be prevented when the MAR project is established • Alternatively, in the absence of data on groundwater quality from the proposed site, data from nearby wells in the same aquifer may be used	Q4. Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery? If Yes — low risk of inadequate recovery efficiency is expected. If **No** — some risk of inadequate recovery efficiency is expected. See Table A1.2 for degree of difficulty expected.

	Information required for assessment	Questions and indicators of degree of difficulty
5	**Groundwater and drinking water quality**	
	• The environmental values of the aquifer need to be defined by the relevant authority. These will depend on the ambient groundwater quality and any groundwater-affected ecosystems, and as identified in the NWQMS *Groundwater Protection Guidelines* (ANZECC–ARMCANZ 1995) • Setting these values involves a stakeholder consultation process, and in practice will possibly be related to groundwater allocation planning processes • In the event of an absence of defined environmental values (for entry-level assessment purposes), all environmental values that are met by the native groundwater quality need to be protected. Such environmental values may include: – raw water for drinking supplies – irrigation – aquaculture, recreation or livestock water – support of aquatic ecosystems with various conservation values • The water quality requirements for these environmental values are referenced in Table A1.1.	Q5. Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer? If **Yes** — high risk of groundwater pollution if recharged by water if answer to Q2 is No. If No — low risk of groundwater pollution is expected. However, this is not a sufficient condition for low risk. For a broader view on this topic for the spectrum of environmental values, see Table A1.2.
6	**Groundwater salinity and recovery efficiency**	
	• If native groundwater has high salinity, its proportion that can be present as a mixture with source water in recovered water is limited • At such sites, density affected flow may also occur. Fresh recharge water can form a lens above the native saline groundwater, making recovery difficult and reducing recovery efficiency (ie the volume of recovered water meeting the environmental values for its intended uses as a proportion of the volume of recharged water)	Q6. Does the salinity of native groundwater exceed (a) 10 000 mg/L or (b) the salinity criterion for uses of recovered water? If **Yes** to both — high risk of achieving only low recovery efficiency. Aquifer hydraulic characteristics, especially layering within the aquifer will need careful examination in Stage 2. If Yes to only (b) — moderate risk of low recovery efficiency is expected. However, this is not a sufficient condition for low risk (eg in brackish aquifers with high rates of ambient lateral flow). If No to both — low risk of low recovery efficiency.

	Information required for assessment	Questions and indicators of degree of difficulty
7	**Reactions between source water and aquifer**	
	• Reactions between source water and aquifer minerals may result in deterioration of water quality for recovered water, and possibly for water in the aquifer beyond the attenuation zone; or cause excessive clogging or dissolution of the aquifer • A full evaluation may be undertaken in Stage 2, but a simple indicator of the likelihood of potential problems at entry-level stage is to note the extent of contrasts between quality of source water and native groundwater	Q7. Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water? If Yes — low risk of adverse reactions between source water and aquifer is expected. However, this is not a sufficient condition for low risk. If **No** — high risk of adverse reactions between source water and the aquifer is possible, and will warrant geochemical modelling in Stage 2 (refer to sections 5.2, 5.4 and 6.1).
8	**Proximity of nearest existing groundwater users , connected ecosystems and property boundaries**	
	• Proximity of nearest existing groundwater users and groundwater-connected ecosystems is likely to influence the extent of investigations required in Stage 2 • Typically, attenuation zones will have aquifer residence times of up to a year • If property boundaries are close to the MAR site, then the attenuation zone may extend beneath a neighbouring property • Groundwater pressure effects in confined aquifers due to MAR may propagate over considerably longer distances than water quality effects	Q8. Are there other groundwater users, groundwater–connected ecosytems or a property boundary near (within 100–1000 m) the MAR site? If **Yes** — high risk of impacts on users or ecosystems is possible, and this will warrant attention in Stage 2. If No — low risk of impacts on users or ecosystems is likely. However, this is not a sufficient condition for low risk.
9.	**Aquifer capacity and groundwater levels**	
	• Groundwater mound height induced by MAR depends on aquifer hydraulic properties, size of recharge area and recharge rate • Mounding is normally calculated in Stage 2 when aquifer properties are measured. However, excessive mounding can cause: – waterlogging – soil heave – flooding of below-ground infrastructure – salt damp – soil salinisation • Hence, unconfined aquifers with shallow watertable sites are generally unsuitable as storage targets for large-scale recharge projects • For confined artesian aquifers, care needs to be taken against overpressurisation, and to seal existing wells that might otherwise start to flow	Q9. Is the aquifer confined and not artesian? or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas? In either case: If Yes — low risk of water logging or excessive groundwater mound height is expected. However, this is neither a necessary nor a sufficient condition for low risk. If **No** — high risk of water logging or excessive groundwater mound height is expected. However, Stage 2 investigations may reveal that risk is acceptable.

	Information required for assessment	Questions and indicators of degree of difficulty
10	**Protection of water quality in unconfined aquifers**	
	• If the aquifer is unconfined and the intended recovery is for drinking water supplies, then overlying land and waste disposal (including intensive horticulture and septic tanks) should be managed carefully or precluded from the groundwater capture zone	Q10. Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies? If **Yes** — high risk of groundwater contamination from land and waste management. If No — lower risk of groundwater contamination from land and waste management.
11	**Fractured rock, karstic or reactive aquifers**	
	• If the aquifer is fractured rock or karstic, the ability to recover stored water will require evaluation, especially if the ambient groundwater is saline, or hydraulic gradient is steep • Provision will also need to be made for a larger attenuation zone, due to more rapid migration of recharge water from the recharge area	Q11. Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals? If **Yes** — high risk of migration of recharge water is expected. There is a need for an enlarged attenuation zone, beyond which pre-existing environmental values of the aquifer are to be met. Dissolution of aquifer matrix and potential for mobilisation of metals warrant investigation in Stage 2. If No — low risk of the above is expected. However, this is not a sufficient condition for low risk.
12	**Similarity to successful projects**	
	• A founding principle of MAR is that all validation and verification monitoring data should be in the public domain, and include sufficient operational data to enable accurate interpretation • This information is of value for future MAR projects, for improving design and operation and reducing costs and further refinement of these guidelines • A national or state repository for these data should be accessible for proponents	Q12. Has another project in the same aquifer with similar source water been operating successfully for at least 12 months? If Yes — take validation and verification data from the existing project(s) into account when designing the current project and the Stage 2 investigations and subsequent risk assessments. If **No** — expect that all uncertainties will need to be addressed in the Stage 2 investigations.

	Information required for assessment	Questions and indicators of degree of difficulty
13	**Management capability**	
	• A proponent new to MAR operation needs to gain appropriate expertise in parallel with Stage 2 investigations, to demonstrate a low level of residual risk for the precommissioning risk assessment.	Q13. Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty (see Table A1.2), or with water treatment or water supply operations involving a structured approach to water quality risk management? If Yes — low risk of water quality failure due to operator experience. If **No** — high risk of water quality failure due to operator inexperience. The proponent is recommended to gain instruction in operating such systems (eg a MAR operator's course or aquifer storage and recovery course) or engage a suitable manager committed to effective risk management in parallel with Stage 2, to reduce precommissioning residual risks to low.
14	**Planning and related requirements**	
	• Proximity of nearest neighbour • Provision for safe public access or exclusion • Dimensions and slopes of water holding structures • Location and dimensions and design of any buildings or engineering structures, • Method by which power will be brought to site and water connections • Nuisance insect abundance before and after construction and proposed control measures • Noise emissions of any mechanical plant and abatement measures • Earthmoving and construction plans and measures for dust and noise control • Provision of information to neighbours concerning the development • Information to address other provisions of planning and development regulations within the relevant jurisdiction •	Q14: Does the proposed project require development approval; is it in a built up area; built on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health or safety issues (eg falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (eg from waste products of treatment processes)? If Yes – Development approval process will require that each potential issue is assessed and managed. This may require additional information and steps in design. If No – Process for development approval, if required, is likely to be considerably simpler.

MAR = managed aquifer recharge

Assessment of impact of MAR structures by hydrogeological methods

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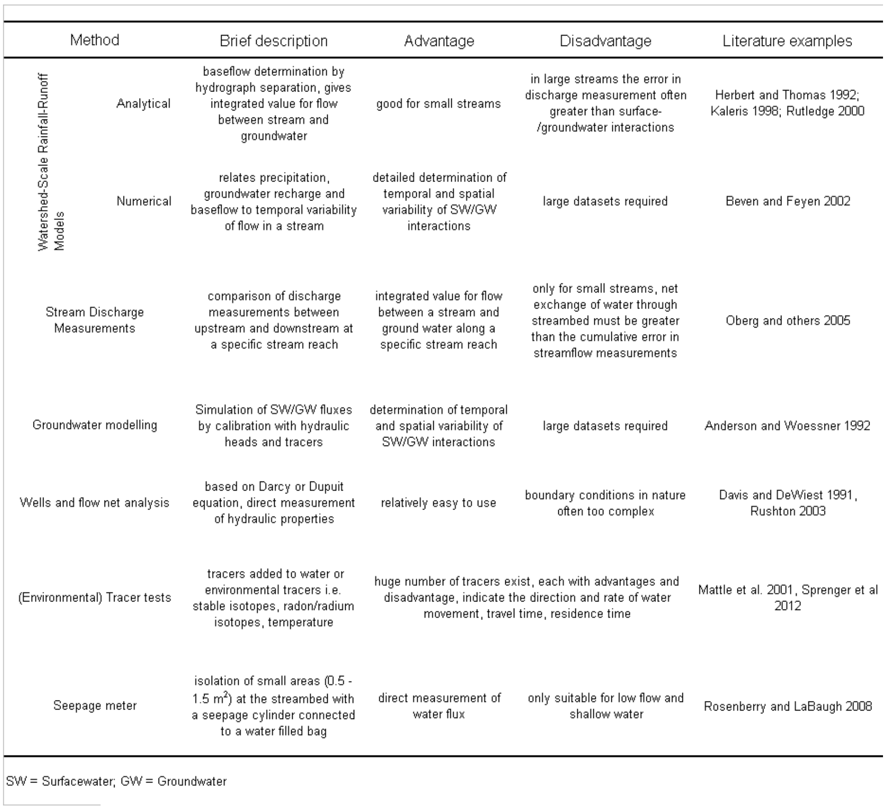
Abstract. Managed aquifer recharge (MAR) is commonly used in India and elsewhere. Quantitative and qualitative impact of the MAR structure can be investigated by an appropriate set of hydrogeological methods. Field measurements and observations are the essential basis for any further empirical based study and require careful planning and accurate conduction on site. This text tries to give an overview of methods/techniques and highlights tips and tricks during field work. In the second part, examples from a check dam site in Tamil Nadu are given.

Introduction to hydrogeological methods

Managed aquifer recharge (MAR) comprises a wide range of technical structures of different purposes (Dillon 2005). One common feature of many MAR structures is the infiltration/injection/percolation of surface water into an aquifer. Therefore, estimation of water fluxes between surface- and groundwater is an important key to understand the impact of MAR structures. A methodological overview with a short description of each method along with advantages and disadvantages is given in table 1. It is clear that several other methods exist and this overview is certainly not complete, but it tries to highlight the most important methods and techniques.

Table 1 Summary of methods and techniques for estimating water fluxes between surface- and groundwater



Method		Brief description	Advantage	Disadvantage	Literature examples
Watershed-Scale Rainfall-Runoff Models	Analytical	baseflow determination by hydrograph separation, gives integrated value for flow between stream and groundwater	good for small streams	in large streams the error in discharge measurement often greater than surface-/groundwater interactions	Herbert and Thomas 1992; Kaleris 1998; Rutledge 2000
	Numerical	relates precipitation, groundwater recharge and baseflow to temporal variability of flow in a stream	detailed determination of temporal and spatial variability of SW/GW interactions	large datasets required	Beven and Feyen 2002
Stream Discharge Measurements		comparison of discharge measurements between upstream and downstream at a specific stream reach	integrated value for flow between a stream and ground water along a specific stream reach	only for small streams, net exchange of water through streambed must be greater than the cumulative error in streamflow measurements	Oberg and others 2005
Groundwater modelling		Simulation of SW/GW fluxes by calibration with hydraulic heads and tracers	determination of temporal and spatial variability of SW/GW interactions	large datasets required	Anderson and Woessner 1992
Wells and flow net analysis		based on Darcy or Dupuit equation, direct measurement of hydraulic properties	relatively easy to use	boundary conditions in nature often too complex	Davis and DeWiest 1991, Rushton 2003
(Environmental) Tracer tests		tracers added to water or environmental tracers i.e. stable isotopes, radon/radium isotopes, temperature	huge number of tracers exist, each with advantages and disadvantage, indicate the direction and rate of water movement, travel time, residence time		Mattle et al. 2001, Sprenger et al 2012
Seepage meter		isolation of small areas (0.5 - 1.5 m^2) at the streambed with a seepage cylinder connected to a water filled bag	direct measurement of water flux	only suitable for low flow and shallow water	Rosenberry and LaBaugh 2008

SW = Surfacewater; GW = Groundwater

After a brief description of selected methods from table 1, water sampling techniques will be discussed. Water sampling, either from surfacewater or groundwater is the basis for any qualitative study. Standard methods for water sampling and techniques will be presented and discussed. Additionally, tips and tricks for field sampling and field observations will be given.

Check dam is one MAR structure which is being constructed across the non perennial rivers and it is one of the suitable methods for unconfined aquifers. Various hydrological measurements will be helpful to evaluate the efficacy of check dam to understand the improvement on water level and water quality. Many research work is been carried out by using hydrological measurements such as water level measurements, water quality parameters and isotopic analysis.

Calculating evaporation losses due to evaporative enrichment

Fractionation caused by evaporation can be considered as a non-equilibrium process (Dansgaard 1964). Gonfiantini 1986 describes the kinetic fractionation in relation to humidity with the following equations:

$$\varepsilon\ {}^{18}\mathrm{O}_{\mathrm{kinetic}} = 14.2\ (1-h)\ \ (\times 10^{3}‰)$$

$$\varepsilon\ {}^{2}\mathrm{H}_{\mathrm{kinetic}} = 12.5\ (1-h)\ \ (\times 10^{3}‰)$$

where h is the humidity (100% = 1). The total fractionation between the water body and the open air is then the sum of the fractionation factor for equilibrium water-vapour exchange ($\varepsilon_{\text{ equilibrium}}$) and the kinetic factor ($\varepsilon_{\text{ kinetic}}$). For δ^{18}O according to:

$$\delta^{18}\mathrm{O}_{\mathrm{l}} - \delta^{18}\mathrm{O}_{\mathrm{v}} = \varepsilon^{18}\mathrm{O}_{\mathrm{equilibrium}} + \varepsilon^{18}\mathrm{O}_{\mathrm{kinetic}} = \varepsilon^{18}\mathrm{O}_{\mathrm{total}}$$

The indices l and v are for liquid and vapour, respectively. Since atmospheric water forms under about 85 % humidity a displacement of the evaporation line towards a d-excess (or intercept) is observable. If now evaporation rates are high due to high temperatures and low relative humidity in the atmosphere at the initial formation of water vapour, a strong kinetic effect takes place. Evaporation rates were calculated, according to a Rayleigh enrichment, in relation to temperature and humidity and plotted in δ^{18}O vs. δD diagrams (Fig.2.5), according to

$$\delta = \delta_{\mathrm{o}} + \Delta\varepsilon_{\mathrm{total}} * \ln\,(f)$$

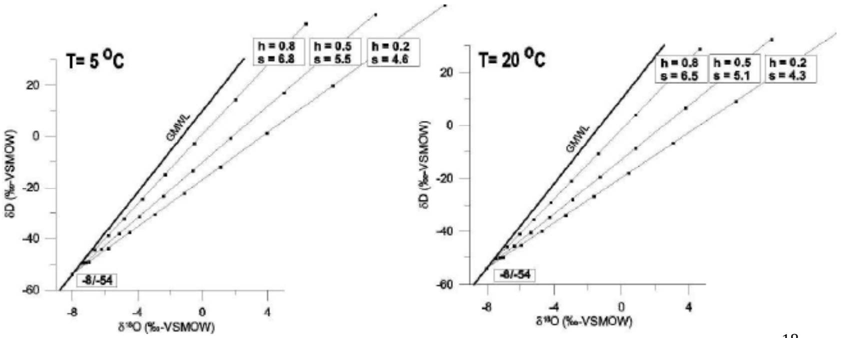


Fig. 1. Differences in evaporation rates in relation to humidity (h) in a δ^{18}O vs. δD (‰-VSMOW) diagram for 5°C and 20°C showing the predominating ex-

change fractionation process at values for f from 1 to 0.1. (s = slope of evaporation line)

where δ_0 is the initial value (here $\delta^{18}O$= -8 ‰; δD= -54 ‰) and δ is the resulting value. The resulting graphs (Fig. **1**) are useful to estimate the conditions during evaporation and the proportion of fractionation with factors *f* from 1 to 0.1. According to the above mentioned equations strong kinetic fractionation, due to low humidity (h = 0.2) and high temperatures (T = 20 °C), result in more shallow slopes around 4.3. Higher humidity (h = 0.8) and lower temperatures (T = 5 °C) results in evaporation lines which are closer to the GMWL and have slopes around 6.8.

Assessment of check dam at the Aranyar River in Tamil Nadu

Chennnai basin is spread across Thruvallur, Kancheepuram and Vellore districts of Tamil Nadu. Araniar, Kosasthalaiyar, Cooum and Adyar are the four important rivers draining the basin. The city also gets its groundwater supply from well fields in the Araniyar-Koratlaiyar (A-K) basin and southern coastal aquifer. Though contribution of groundwater is very less, this quantity of groundwater is given greater importance during lean period. Fast rate of depletion of groundwater level in A-K basin is due to the continuous pumping of groundwater for city’s water supply, extraction of groundwater by farmers and insufficient water management. Hence, in order to maintain the yield of the aquifers and to supply assured water supply to the city as well as native community certain long-term water management measures such as construction of check dam across A-K rivers have proposed by the Government to augment the groundwater resources. One such check dam constructed across Arani river is considered for the present study. This check dam is of 260m length with the crest height of 3.5m used to store 0.8 Million cubic meter of water is constructed across Arani River near Paleshwaram village. Assessment of impact of MAR by using the water level measurements, electrical conductivity and chloride/stable isotope measurements discussed in the following sections.

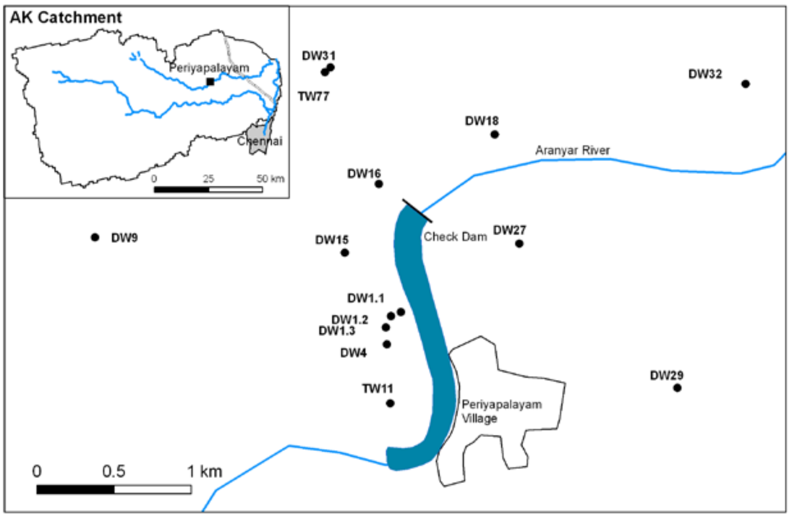


Fig. 2. Location map of check dam close to the Periyapalayam village and sampling stations. (DW = dug well, TW = tube well)

Groundwater levels

Groundwater level measurement is a good indicator to identify the efficacy of MAR structures. Groundwater fluctuation for a particular year is depended upon the amount of groundwater recharge, which in turn depends on, among other parameters, rainfall. Comparison between water level measured before construction of the check dam and water level measured after construction of check dam will help in identifying the impact of this structure on groundwater level improvement. Zone benefited by the recharge structure can also demarcated using the water level measurements.

Electrical conductivity measurement

Electrical conductivity is one of the field measurements used to identify the efficacy of the check dam. In the present study, the measurement on electrical conductivity is made between July 2010 to July 2011. Fig. 3 shows the variation in minimum and maximum electrical conductivity values with respect to distance from the check dam.

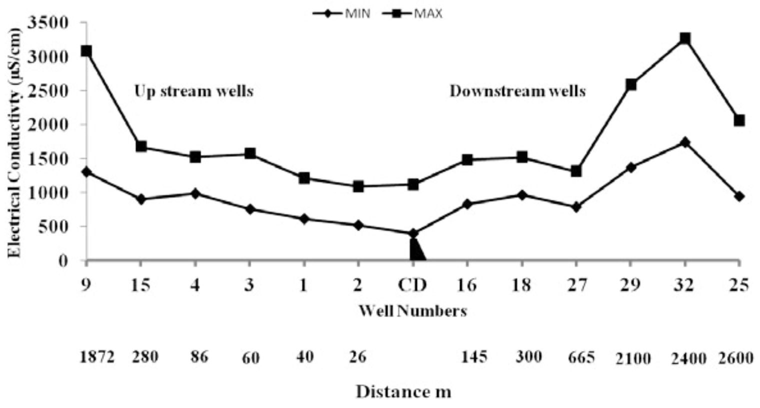


Fig.3. Minimum and maximum electrical conductivity of water samples.

Electrical conductivity values in the check dam varied from 400µS/cm to 1117 µS/cm. Electrical conductivity values of groundwater samples varied from 514 µS/cm to 3270 µS/cm. Electrical conductivity values gradually increases as the distance of wells increases from the check dam. The wells located within 60m in the upstream of the check dam and the wells located 665m in the downstream of the check dam are highly benefitted by the recharge from check dam. The electrical conductivity values of the wells located within distances are having similar electrical conductivity values of the water in the check dam.

Evaporation from check dam water

The surface water samples from the Periyapalayam check dam show, as expected under the climatic conditions, an evaporative enrichment with time (Fig. 4). At the beginning of the monsoon November 2011 isotope values are on the LMWL with -3.7‰/-18.6‰ and the following samples show a successive enrichment with a composition of -0.19‰/-1.2‰ in March 2012 leading to overall enrichment in δ^{18}O of 3.51‰. Regression line calculated with the 5 samples is $\delta D = 4.8 \times \delta^{18}O - 1$, the slope of 4.8 is very typical for evaporation from open water bodies. The evaporative enrichment can be calculated with the equations given in the methods section. Mean annual temperature is 28.6°C, humidity during Oct – Nov-Dec – Jan – Feb – Mar approx. 0.5 resulting in 20% losses by evaporation in March 2012.

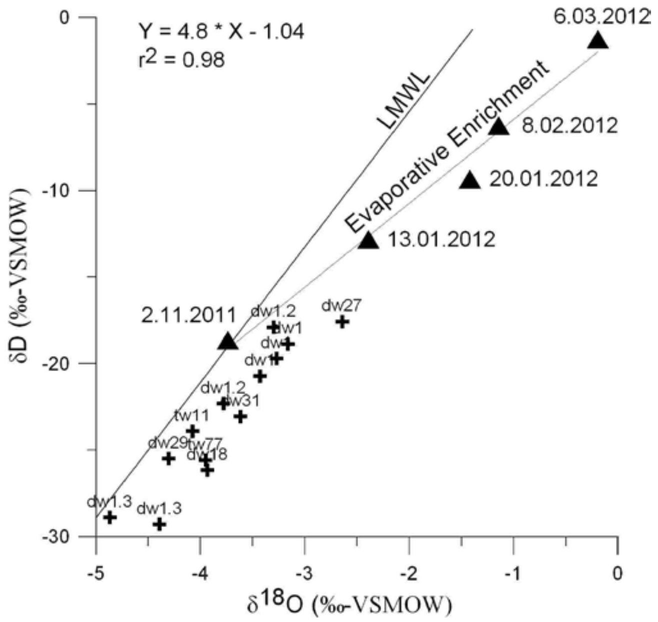


Fig. 4. $\delta^{18}O$ against δD plot of surface water from the check dam and groundwater

Chloride and stable isotopes as tracers

Chloride and stable isotopes of water ($\delta^{18}O$, δD) are used as tracers to indicate recharge and mixing of ambient groundwater (not influenced by the check dam) with recharge water from the check dam. Isotopic composition and chloride concentration of surface water from the check dam and groundwater is shown in Fig.5. Surface water from the check dam is characterised by low chloride concentration (<120 mg/l) and enriched isotopic composition. Isotopic composition of the surface water shows increasing evaporative enrichment with time as discussed in the earlier section. Ambient groundwater is characterised by high chloride concentrations (80 – 600 mg/l) and depleted isotopic composition. Samples of groundwater which is influenced by check dam infiltration can be found in between the composition of ambient groundwater and the recharge water composition (5). Mixing of ambient groundwater with recharge water takes place with water from the beginning of the recharge period between November 2011 and January 2012. It can be concluded that recharge is limited or absent during February to March 2012.

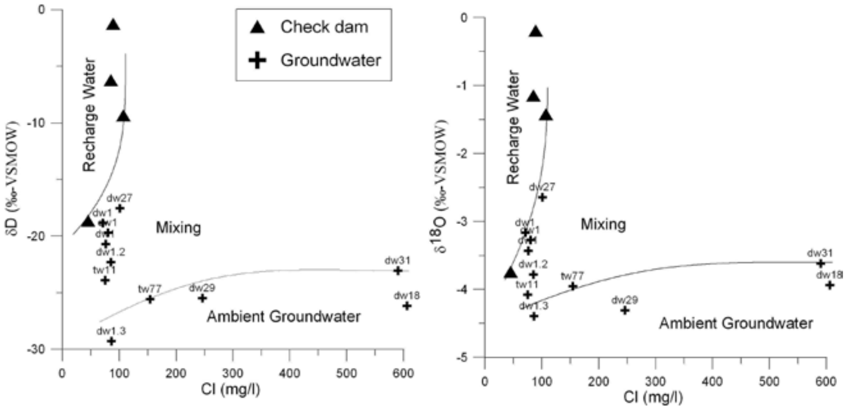


Fig.5. Chloride and stable isotopes of water ($\delta^{18}O$, δD) in check dam (Recharge water) and groundwater.

Conclusions

- Water levels measurement is a good indicator to identify the improvement on groundwater level before and after constructionmof MAR structure
- Electrical conductivity of surface water in check dam and groundwater indicate the positive impact of check dam recharge on groundwater quality
- Losses due to evaporation from the check dam water are indicated by the evaporative enrichment of stable isotopes
- Main recharge period of the check dam is from November to January

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Integrated modeling for assessment of impact of MAR structures

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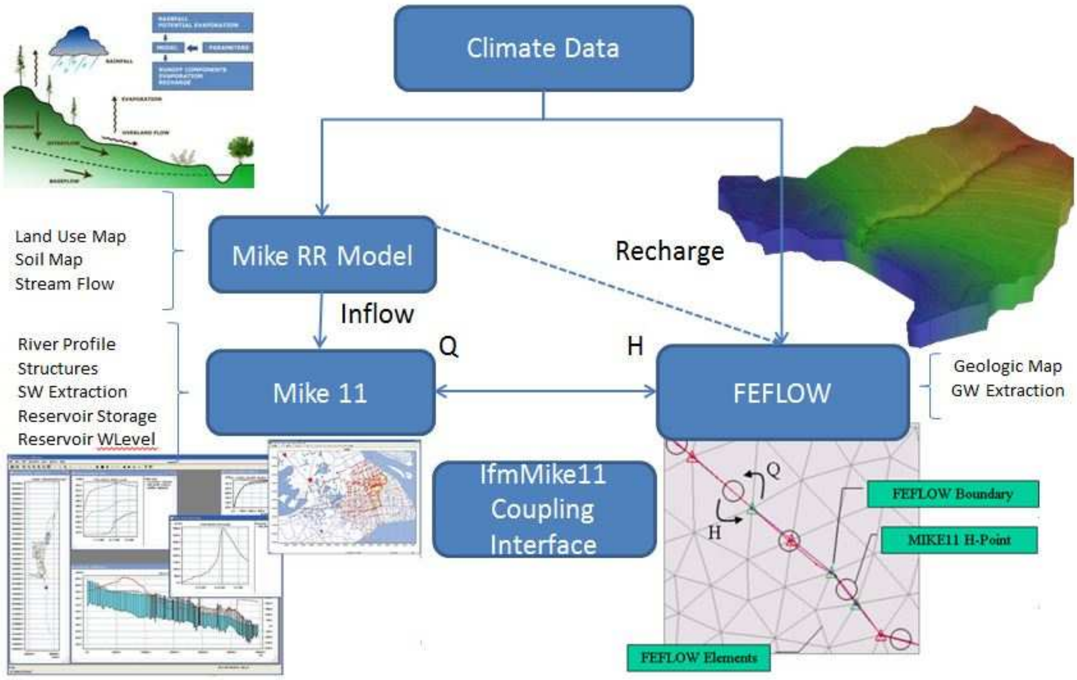


Introduction

In this workshop document a brief introduction to a modeling approach for an impact assessment of MAR structures to counteract saltwater intrusion problems is provided. This approach is based on the software products FEFLOW (groundwater) and MIKE11 (surface water). As FEFLOW is the main component a short description of this software is given in the next section. After that the basic coupling concept, a short overview of the theoretical background of density dependent modeling as well as a basic example are described.

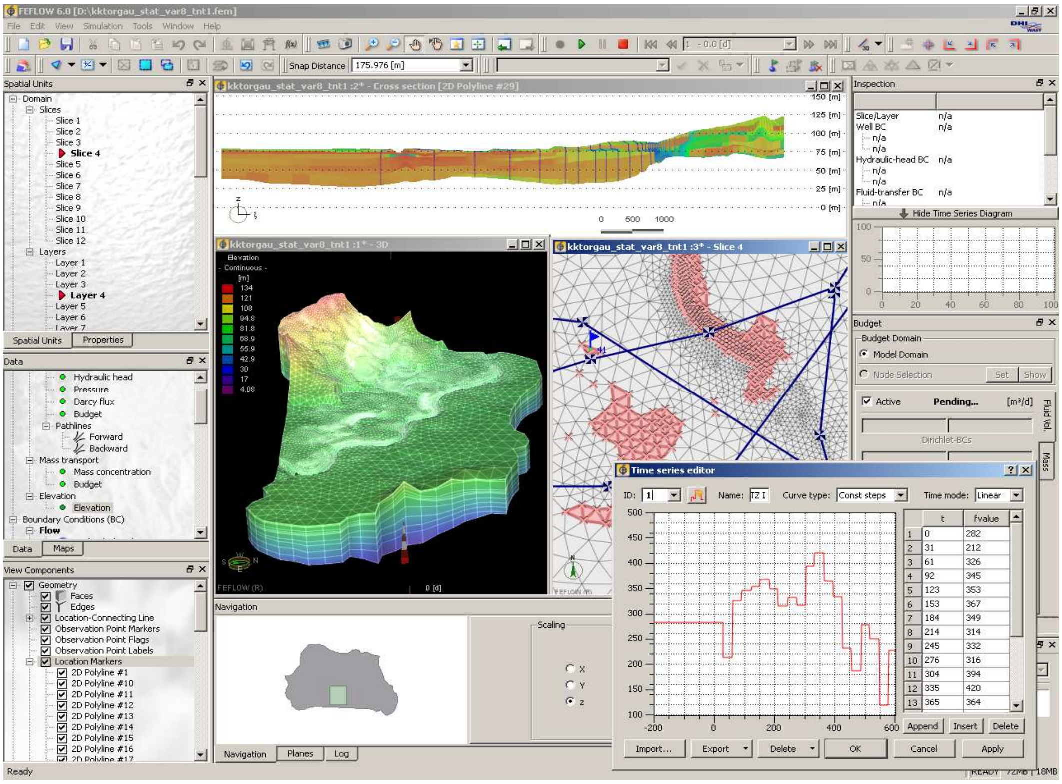
Groundwater Model FEFLOW

DHI-WASY as a daughter of DHI is also responsible for the development of the groundwater model FEFLOW. FEFLOW provides an advanced 3D graphically based modeling environment for performing complex groundwater flow, contaminant transport, and heat transport modeling. Regarding contaminant transport both multiple species as well as kinetic reactions between the species can be modeled. Both saturated and unsaturated flow regimes can be modeled. It uses a Galerkin-based finite element numerical analysis approach with a selection of different numerical solvers and tools for controlling and optimizing the solution process.

FEFLOW is a completely integrated system from simulation engine to graphical user interface including also a public programming interface for user code. FEFLOW is widely recognized as the most complete software package for subsurface porous media simulation and is used by leading research institutes, universities, consulting firms and government organizations all over the world. Its scope of application ranges from simple local-scale to complex large-scale simulations.

Special features like chemical reactions and particularly salt water interaction areimportant for the project under consideration.

Furthermore, FEFLOW offers an integrated Interface Manager (IFM) which allows for external interaction with other source code. In this way new modules can be provided and important coupling routines to other modeling software can be implemented.



Time series editor

ID: 1 Name: TZ I Curve type: Const steps Time mode: Linear

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3	61	326
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5	123	353
6	153	367
7	184	349
8	214	314
9	245	332
10	276	316
11	304	394
12	335	420
13	365	364

Snap Distance: 175.976 [m]

Fig. 1: FEFLOW Example

Coupling concept

Since 2005 the coupling interface IfmMIKE11 has been available. The interface module couples FEFLOW to MIKE11 (DHI 2010, 1D hydrodynamic model) using the FEFLOW InterFace Manager (IFM). From 2006 to 2009, the coupling module was successfully extended for the coupling of polder areas and forelands (Monninkhoff & Li, 2009; Monninkhoff & Kaden, 2007).

Quantity modeling

In FEFLOW rivers can be described by boundaries of the 1st kind (Dirichlet-type) or boundaries of the 3rd kind (Cauchy-type). The latter boundary type is the only type supported by the coupling module IfmMIKE11. At the end of each FEFLOW time step the discharges to these FEFLOW boundary nodes are calculated by the module within FEFLOW. The resulting values are transferred to the MIKE11 calculation points (h-points) as single point source inflow boundary conditions. Then, MIKE11 calculates as many internal time steps as needed to reach the actual time of FEFLOW. This process is ended by transferring the calculated water levels at the end of the FEFLOW time step from the MIKE11 h-points to the FEFLOW boundary nodes. The internal time step of MIKE11 is controlled by the interface. This time step can be constant or adaptive to the dynamics of the model. The time step of the groundwater model is controlled by FEFLOW. The spatial overlay of both meshes is automatically integrated within IfmMIKE11. The exchange discharges (Q) between the ground- and surface water can be calculated within FEFLOW for each single boundary node of the 3rd kind separately. The main parameter to control this discharge is an elemental parameter called transfer coefficient [d^{-1}]:

$$Q = \phi_h A(h_{ref} - h_{gw})$$

In which:

Q Discharge [$m^3 d^{-1}$] of fluid (positive from river to groundwater),

A nodal representative exchange area [m^2] of the boundary node and

h_{ref}, h_{gw} heads [m] in the river and groundwater respectively.

The nodal representative exchange area depends on the finite-element stratigraphy within the model in FEFLOW. Moreover, the stratigraphy is subject to changes using the free and movable option in FEFLOW. In that case, the top slice of a 3D model is located exactly on the position of the head of the first slice and all remaining slices are moved accordingly. To avoid an uncontrolled and unrealistic exchange area in this case, an additional boundary option has been implemented. Using these integral boundary conditions the exchange area of the boundary nodes is determined only once just before the simulation is started. Nevertheless, in most cases, the exact exchange area between the river and the groundwater cannot be described by the stratigraphy of the mesh.

From the stratigraphy point of view, rivers can be defined in FEFLOW by a typical vertical (also areal) or horizontal (or lateral) infiltration scheme. In the first case boundary nodes are only set to the 1st slice of the FEFLOW model and in the latter case boundary conditions are located in more than one slice but within a single slice only as a line element.

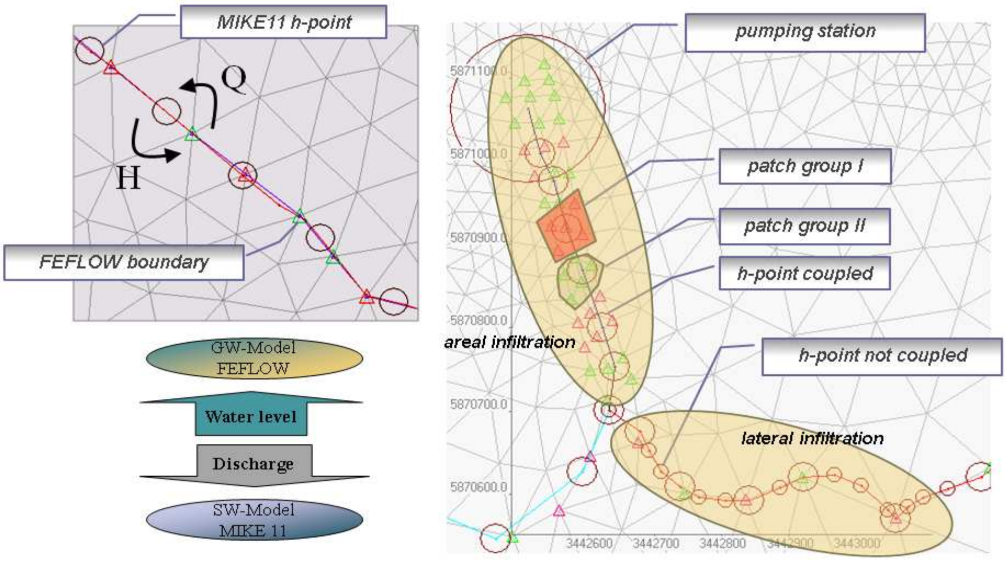

Fig.2: Basic principle of the coupling

In case that the groundwater level drops below the bottom of a river, the above equation indicates that the calculated discharge will continue to increase. Brunner et al. (2009) show that this is not the case in reality and the discharge is limited to a certain maximum. In FEFLOW additional constraints can be set to approximate this process. Using these constraints, a user-defined minimum for hgw is introduced in the above equation, usually equal to the bottom of the river.

Monninkhoff &Hartnack (2009) showed a third mechanism to describe rivers in FEFLOW which is only available within the FEFLOW internal programming interface (IFM). In IfmMIKE11 these boundaries are called special boundaries. It is basically the same as a 3rd kind boundary, but both the exchange area and the transfer coefficient can be defined externally and for each single node. Using this function IfmMIKE11 could be improved by updating the exchange areas according the actual water levels and the profile data available in MIKE11. It was shown that both for triangular and rectangular cross river sections this approach gives results which fit reasonably with analytical solutions of the same problem.

Quality modeling

In 2011, the coupling between MIKE11 and FEFLOW was extended also for mass transport. The numerical solution of the transport equation of MIKE11 (AD simulation) requires, like FEFLOW also, a temporally varying background flow field. With respect to the FEFLOW coupling, the hydrodynamics and the transport equations in MIKE11 are solved in a coupled mode i.e. MIKE11 calculates the river flow field and the concentrations within the same time step. The coupling between FEFLOW and MIKE11 is explicit i.e. FEFLOW completes a time step and then exchanges values with MIKE11 which in turn takes a time step. The exchange of water and mass is calculated by FEFLOW based on values from the previous time step. This approach in turn requires that every time a MIKE11 time step is calculated FEFLOW must pass the following values for each coupling point:

- Flow (in- and outflow to the river in separate parameters)
- Mass flux (kg/s) for each chemical species (in case there is inflow to a river h-point)

In return MIKE11 passes

- Water level at the h-points
- Concentrations (kg/m^3) for each chemical species at the h-pointsback to FEFLOW.

Like the flow boundaries also the mass boundaries can be set as different types in FEFLOW. From these, only the 1st (defined concentration) and 4th (defined mass) kind are useful for mass coupling processes.

IfmMIKE11 automatically generates mass boundary nodes at those FEFLOW nodes which also have coupled flow-boundary conditions. It is therefore not necessary to set mass boundary conditions to the coupled nodes at the beginning of the simulation. The type of boundary is defined by the user settings. Both single and multi-species processes can be coupled. Despite the fact that the mass coupling is mostly automatically, it is useful to be familiar with the basics of mass transport in FEFLOW to be able to couple MIKE11 and FEFLOW also for mass-transport processes.

In that context it is important to know that FEFLOW can run a mass-transport problem applying one of two different formulations of the transport equation; the convective or the divergence form. In Diersch (2009) the difference between the divergence and convective form of a mass-conservation equation is explained in detail. The main difference lies in the convective terms in the transport equations applied to both forms. Both transport equations are physically equivalent, but they lead to different formulations of boundary conditions. When using the divergence form of transport, the mass fluxes prescribed at a boundary denote the sum of both advective and dispersive fluxes. Using the convective form, only the dispersive part of the flux is prescribed. In that case the total flux will be calculated internally as a result of the governing concentration at a node and the fluid flux across the flow boundary located at the same node.

In general it can be stated that the convective method ensures a higher degree of stability, especially at outflow boundaries. This form, however, is rather unsuitable for using mass boundary conditions of the 4th kind in case that there is also a flow boundary condition at the same node (inflow into groundwater). So, if mass-boundary nodes of the 4th kind will be used for the coupling, it is obligatory to use the divergence form, accepting possibly less stability at outflow boundaries. To ensure stability, the mesh discretization around the boundary conditions should then be rather dense and using well-shaped finite elements. The main advantage of this method, however, is that the mass balance is guaranteed. Mass-boundary nodes of the 1st kind (boundary values are defined as concentrations) on the other hand are ideal to use with the convective form. The model is more stable and the resulting parameters of the MIKE11 time step can be transferred directly to the FEFLOW model (both concentrations). This would however imply that the finite-element volume represented by a mass boundary node of the 1st kind would get the same concentration as the concentration at the coupled h-point of the river. The original groundwater concentration within this volume would be neglected and a discrepancy in the mass balance is automatically generated. This error can be reduced by ensuring that the elements around the mass-boundary nodes of the 1st kind are small.

Besides these two options, also an IFM internal option has been implemented, similarly to the special boundaries available for quantity coupling, which can be accessed by the function IfmSetCoupledMassTransBndNodes(). This function enables the definition of a new boundary-condition type which has two main parameters; (1) surface-water reference concentration (c_{ref} [mg/l]) and (2) a parameter representing the product of the mass-transfer rate in [m/d] and the exchange area in [m^2]. This parameter is called PHI [m^3/d]. Using suitable parameters, the result of a special boundary in the convective form will give the same results as a 4th kind boundary in the divergence form. The value of a 4th kind boundary [g/d] for inflow into groundwater can be calculated by multiplying the fluid flux with the concentration in the river. Using this fluid flux [m^3/d] for PHI and setting the river concentration as c_{ref} [mg/l] for the special boundary in the convective form, an equivalent boundary condition will be defined. The practical consequence is that input mass-flux boundary conditions can also easily be simulated by using the standard convective form without resorting to the more complex divergence form of the transport equation.

The quality coupling routine has successfully been tested in a similar project as the one under consideration. In that project the objective was also to analyze the effect of MAR techniques to counteract salt water intrusion in the coastal zone. In the next section a brief overview of the theoretical background of density dependent processes is given after which an example using the coupling mechanism described above will be provided.

Theoretical Backgroundof density dependent flow in FEFLOW

In continuum fluid mechanics, the density ρ of a fluid is found to be dependent of pressure p, temperature T and a partial density ρ k, which is described by the equation of state (EOS). For the groundwater flow equations in FEFLOW, the pressure is defined by the hydraulic head h and the density at a known salinity concentration Cs, thus the EOS can be defined as:

$$\rho = \rho(h, C_s, T)$$

For the purpose of saltwater intrusion, temperature variations will be neglected. Through the linear expansion of the EOS, it can be derived that:

$$\rho = \rho(\mathbf{p}, \mathbf{C}) \approx \rho_0 \left[1 + \gamma(\mathbf{h} - h_0) + \frac{\alpha}{((C_s - C_0))(\mathbf{C} - C_0)}\right]$$

where ρ_0 is the reference fluid density, h_0 is the reference head, C_0 the reference concentration, γ is the expansion coefficient for the hydraulic head term, and α the expansion coefficient (or density ration) for the concentration.

The principles of mass conservation, momentum and energy are the basis of the density-dependent flow and transport models. After several approximations the velocity can be derived by the relation of the pressure and gravity-induced flow:

$$q_z = -K(\nabla h + \alpha)$$

Where K is the conductivity (m/s). The density ratio α , relates concentrations in the model to density differences and is described by:

$$\alpha = \frac{\rho(\mathrm{Cs}) - \rho_0}{\rho_0} \approx 0.\frac{7\mathrm{Cs}}{\rho_0}$$

Considering that freshwater has a reference concentration of 0 g/l, with a density of 1000 Kg/m³Considering that freshwater has a reference concentration of 0 g/l, with a density of 1000 Kg/m³ and seawater has a concentration of 35 g/l with corresponding density of 1024.5 Kg/m³, the α -Value in FEFLOW is defined as 0.0245.

As described in the velocity formula, denser saltwater settles underneath lighter freshwater, which results in a stable density stratification and flow conditions. In coastal areas intensive extraction of groundwater can lead to the progression of the saltwater front into the aquifer (see next figure).

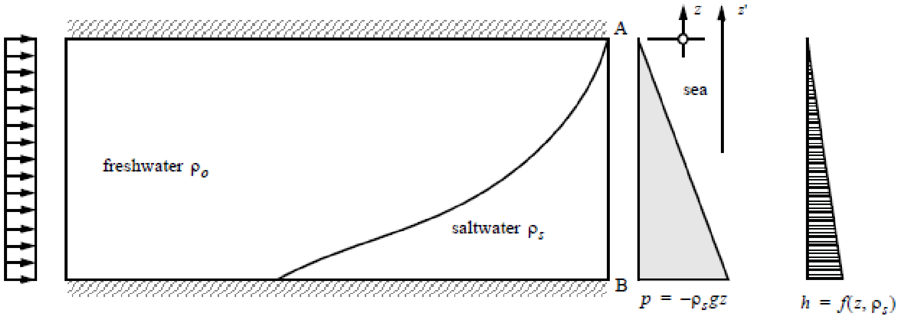

Fig. 3: Saltwater intrusion in a coastal aquifer

Example

Objective

The test case shows how FEFLOW can be used together with MIKE11 to model saltwater-intrusion processes and implements MAR techniques to counteract the effects of excessive pumping.

Problem Setting

A 3D confined, flow and mass-transport box-model was setup in FEFLOW. The North and South flow boundaries were defined as Dirichlet kind and the east and west boundaries were set as no flow boundaries. A mass concentration of 35000 mg/l was assigned to the southern sea side boundary. For simplicity the material properties were maintained homogenous.

First, the FEFLOW model was run without coupling to obtain the initial concentration in the domain. Mass transport was initiated with pure advection using the head gradient and the model was run for a period of 145 days.

In a second step, the model was coupled to MIKE11 model using the interface IfmMIKE11. In the MIKE11 River model, fresh water solute with mass concentration of 20 mg/l was transported from north to south, bringing the fresh water in the domain. On the upstream boundary, the fluid inflow was kept constant at 0.25 m^3/s. The water level downstream was assigned constant at sea level. Initial water level was given a global value, higher than the FEFLOW water level to insure the outflow condition (MIKE11 to FEFLOW). The next figure shows the mass concentration of the intersection along the river for t=0 (result from the uncoupled model) and t=15 days. The figure shows that the saltwater front at t=0 behaves as explained in the previous section; the dense saline water predominantly intrudes along the bottom of the aquifer. The fresh water from the river counteracts this and at t=15 the salinity front has clearly being reduced. It has to be noticed that the parameters in the model have been chosen in such a way, that concentrations can change rapidly in time to save time consuming simulations. In reality changes in salt water concentrations can take much longer.

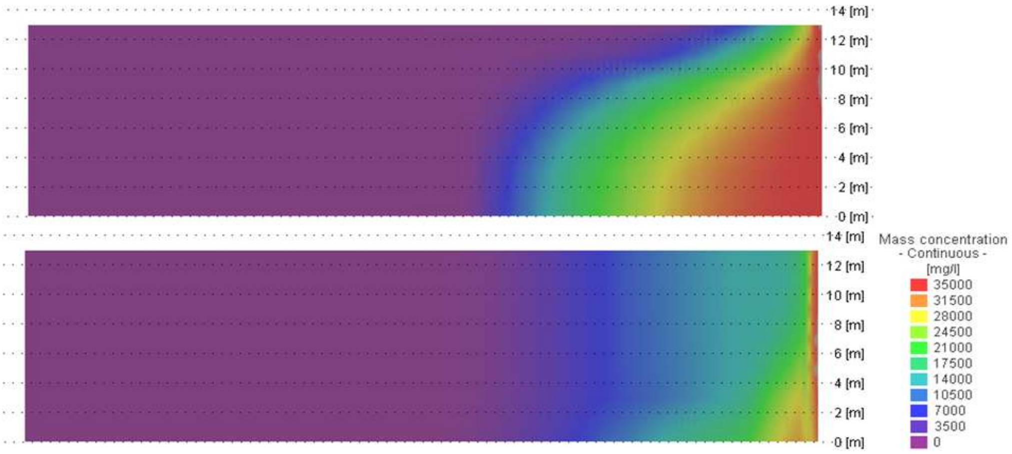

Fig. 4: Mass Concentration Initial Condition (top) and results after 15 days (bottom)

Based on this model, in a first scenario a pump was installed in the FEFLOW model extracting at a rate of 1000 m^3/d from all 7 slices and the effect of the pumping on the concentrations was observed. The next figure shows the mass concentration distribution in the domain caused by the pump. The local concentration at pump location was increasing from a value of 0 to 650 mg/l over a period of 15 days and the blue plume towards the pump shows that this water is attracted by a much higher velocity than the surrounding areas.

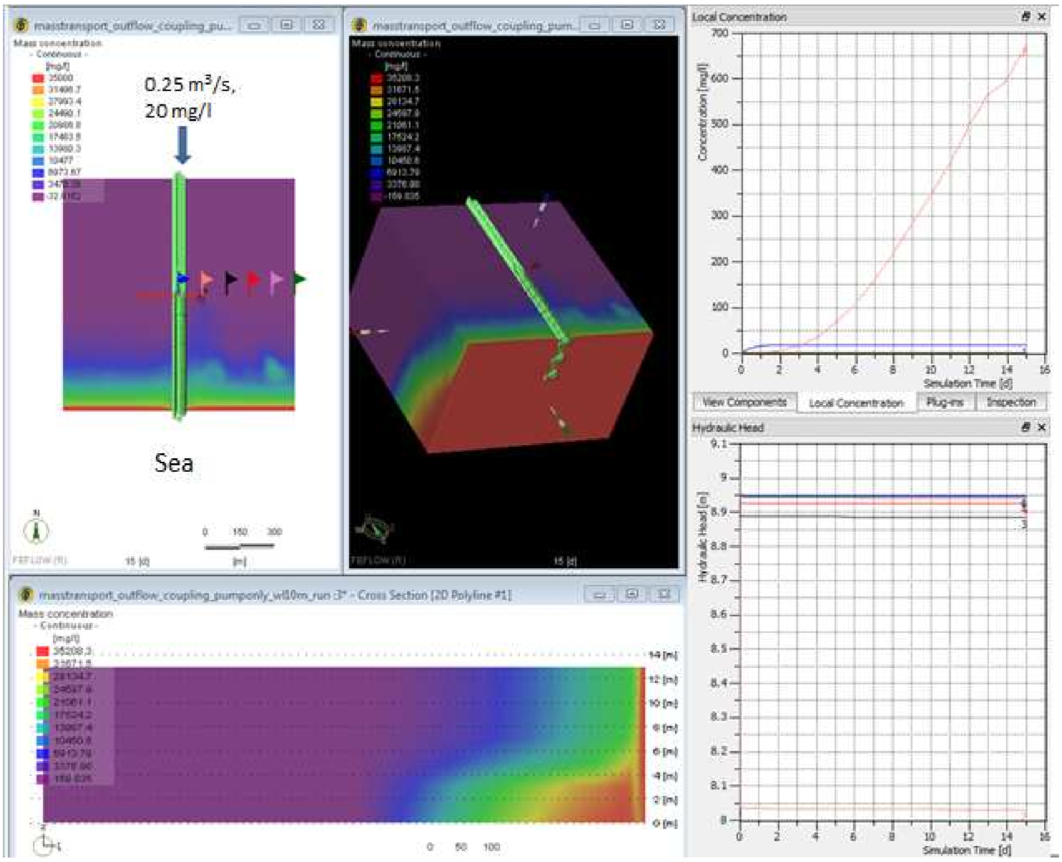

Fig. 5: Simulation using an extraction pumpafter 15 days.

In the second scenario, a weir was installed at the confluence of the river into the sea in order to increase the water level in the river and to increase the effect of artificial recharge. The next figure compares the hydraulic head at a FEFLOW node close to the weir and shows that due to the implementation of the weir the groundwater level is rising (result in an increase of fresh water in the domain).

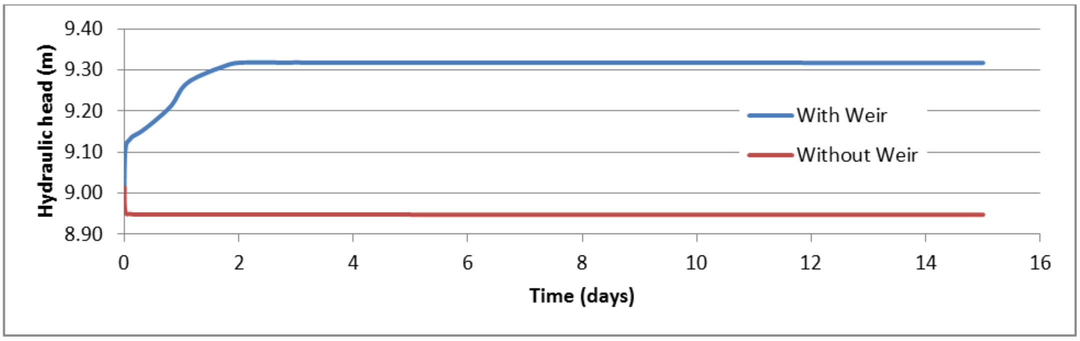

Fig. 6: Comparison of groundwater headsclose to the river for 2 Scenarios.

This can also be seen in the next figure, where negative values represent an increase of groundwater level caused by the implementation of the weir. The strongest increase is in fact located along the river at the location of the well.

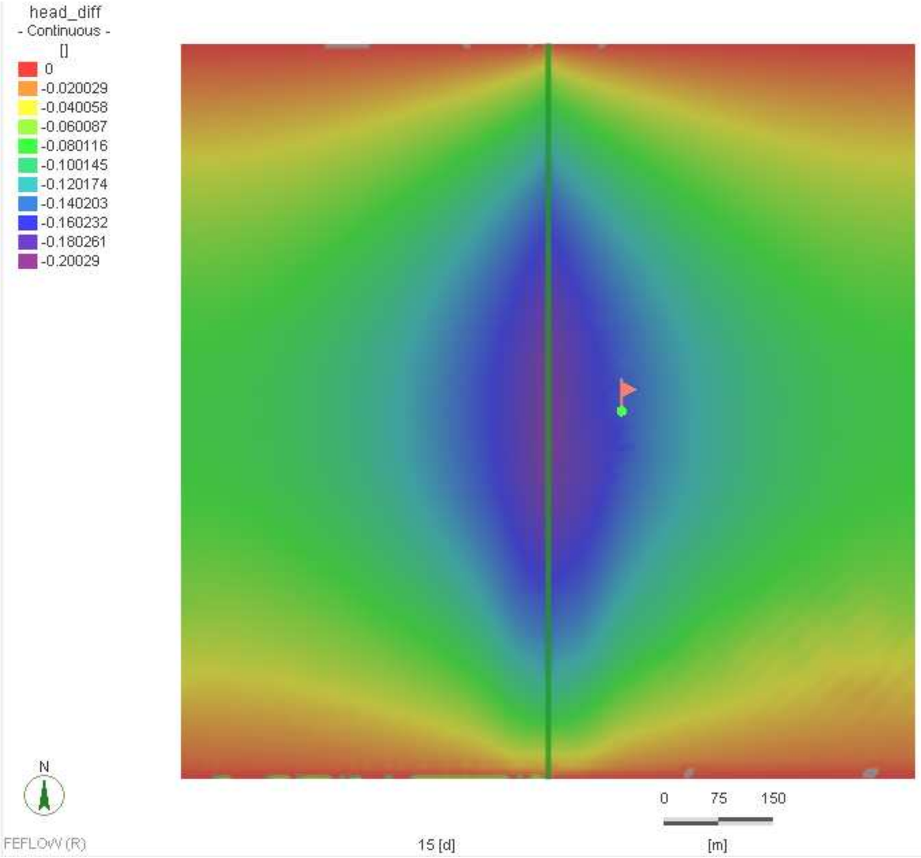

Fig.7: Difference of hydraulic head for 2 Scenarios (heads without weir minus heads with weir).

In the next figure these two scenarios are compared in respect to the concentrations at the well. The second scenario clearly has lower concentrations proving the positive effect of this MAR facility on a potential drinking water well.

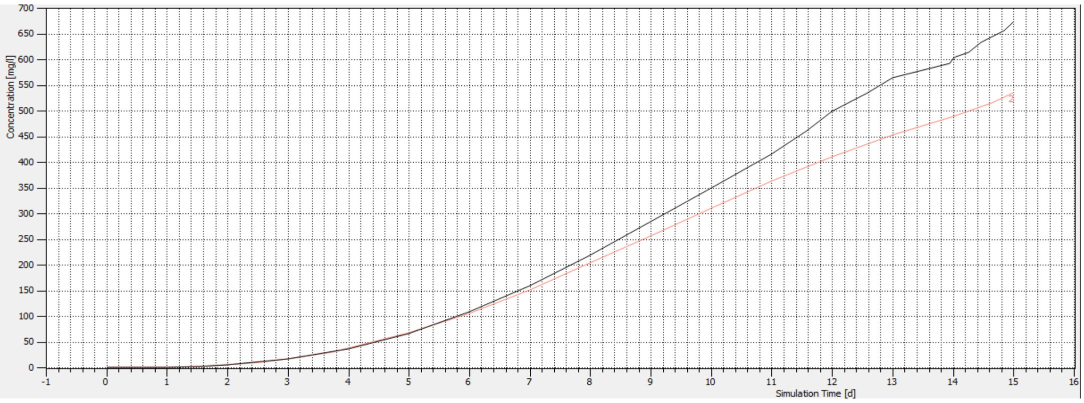

Fig.8: Comparison of concentrations at the well for 2 Scenarios (line 1: scenario without weir, line 2: scenario with weir).

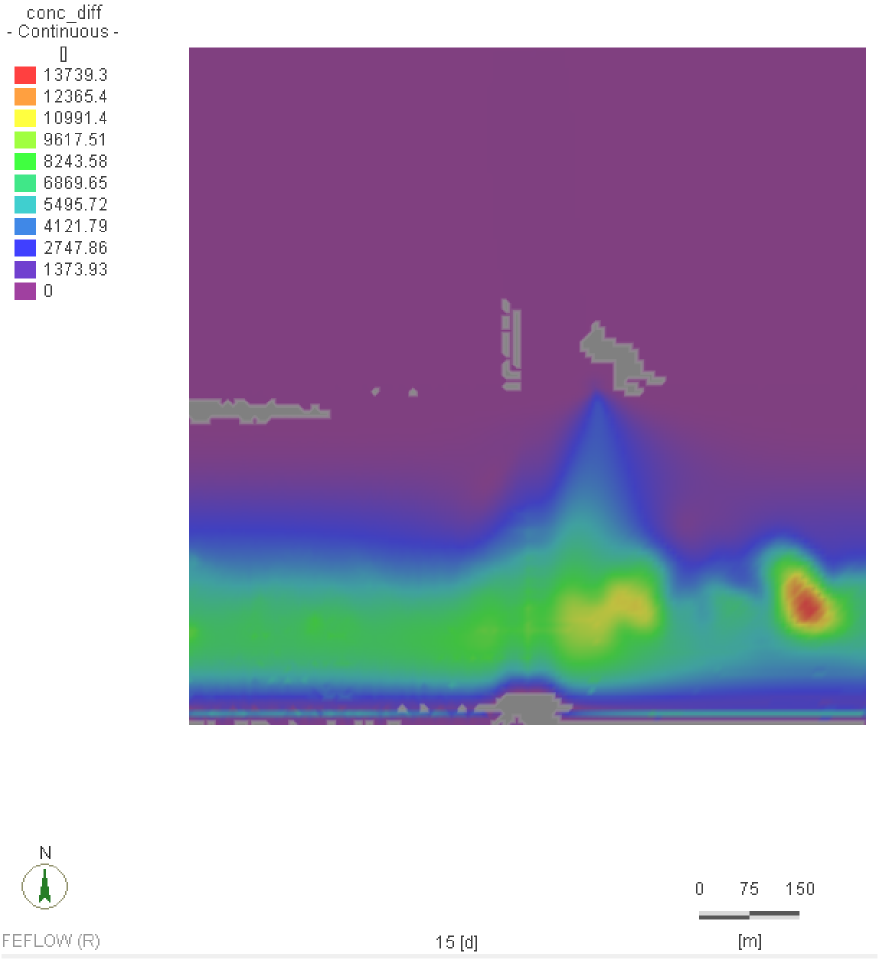

Fig. 9: Comparison of concentration for 2 scenarios.

Finally, the above figure shows the differences in concentrations between the wells. Positive values indicate a reduction of concentration caused by the implementation of the weir. The figure also shows that this basic example still has some numerical instabilities which might be optimized during the next weeks: in some locations further away from the river the differences in concentrations are relatively high and at some locations even negative (grey areas).

Nevertheless, these examples show that the coupling concept presented in this document can be flexibly applied to a wide range of potential MAR facilities, also for the project under consideration.

Acknowlegdements

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