Chapter 5

Overview of Managed Aquifer Recharge in India

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5.1 INTRODUCTION

5.1.1 Scope

Groundwater exploitation in India has increased rapidly over the last 50 years as reflected by the growth of the number of groundwater abstraction structures (from 3.9 million in 1951 to 18.5 million in 2001) and shallow tube wells (from 3,000 in 1951 to 8.5 million in 2001) (Singh & Singh, 2002). Today, groundwater is the source for more than 85% of India's rural domestic water requirements, 50% of urban water and more than 50% of irrigation demand. The increase in demand in the last 50 years has led to declining water tables in many parts of the country. For example, 15% of the assessment units (Blocks/Mandals/Talukas) have groundwater extraction in excess of the net annual recharge (Central Ground Water Board (CGWB), 2007). According to Rodell *et al.* (2009), the extent of groundwater depletion between 2002 and 2008 was 109 km^3, which is about half the capacity of India's surface-water reservoirs.

One way to address the dwindling groundwater resources is through the use of Managed Aquifer Recharge (MAR). It is estimated that about 29% of the total land area in India is suitable for additional MAR and that a volume of 86 km^3 is available for additional groundwater recharge annually. This is equivalent to an average depth of 90 mm over the suitable area and the volume that could be recharged equates 27% of the 231 km^3 of groundwater that is currently utilized annually (CGWB, 2013).

This chapter presents an inventory of the MAR applications in India, performed as a starting point for the work in Saph Pani. It focuses on the technical aspects associated with MAR, discussing the state-of-the art with respect to the techniques used and to the amount of water being artificially recharged. This chapter does not consider, or only tangentially touches, on the socio-economic impacts of MAR. These aspects will be treated in chapter 17: Rapid assessment and SWOT analysis of non-technical aspects of natural wastewater treatment systems. The goal of this chapter is to give a comprehensive overview of the potentials and limitations of MAR techniques for natural water treatment in India and derive ideas for action.

5.1.2 Definition of Managed Aquifer Recharge (MAR)

MAR has been defined as intentional storage and treatment of water in aquifers (Dillon *et al.* 2009; Sharma *et al.* 2011). Dillon *et al.* (2009) and Sharma *et al.* (2011) included the techniques Soil Aquifer Treatment (SAT), Aquifer Storage and Recovery (ASR), Aquifer Storage Transfer and Recovery (ASTR), Subsurface groundwater treatment (SGT) and Bank filtration (BF) in the wider frame of MAR. The term Artificial Recharge commonly used in India denotes recharge of the aquifer for later use. Artificial Recharge is practiced in order to increase water quantity without reference to recharged water quality. It is similar to the term Aquifer Recharge and Recovery used by Sharma *et al.* (2011) and encloses ASR and ASTR.

In the Saph Pani project, MAR denotes the replenishment of the aquifer with the intention to compensate for prior use and/or to store for future use. ASR, ASTR and SAT all fall under this definition of MAR (Table 5.1)

Table 5.1 Characterization of techniques for MAR with respect to the intention and the water flow.

Technique	ASR Aquifer Storage and Recovery	ASTR Aquifer Storage Transfer and Recovery	SAT Soil Aquifer Treatment	SGT Subsurface Groundwater Treatment	BF Bank Filtration
Intention	Mainly storage	Storage and treatment	Storage and treatment	Treatment	Treatment
Water flow	Infiltration, subsequent abstraction	Infiltration, subsequent abstraction	Infiltration, subsequent abstraction	Small quantity infiltrated in order to cause treatment	Abstraction leading to infiltration

Table 5.1 ASR being practiced mainly for storage of water, whereas ASTR and SAT also have the intention to improve quality by controlled underground treatment. Subsurface groundwater treatment and bank filtration are exclusively intended for treatment and consequently do not fall under the definition of MAR in Saph Pani. BF is the subject of a separate work package in Saph Pani.

5.1.3 Structures for MAR

MAR can be performed by a multitude of structures (Figure 5.1) which capture and store the water and enable it to infiltrate into the underground. Thereby the flow of water is better controlled, limiting flooding and erosion. Both new structures and modification of existing structures (e.g. rooftop rainwater harvesting and dugwell recharge) are possible. Because of India's long tradition of water harvesting and its many languages, there are many traditional structures and also different names for similar structures. The following list of structures is thus not exhaustive, but covers the main types. More detailed information is given by CGWB (2007) and Dilllon *et al.* (2009).

Surface spreading

Surface spreading structures (Figure 5.1) aim to increase the area which is in contact with surface water and also the time over which this contact takes place. In this way infiltration is improved and evaporation decreases. This can be achieved through managed flooding between constructed canals or streambeds or by constructing a system of ditches and furrows.

Contour bund and contour trench

A bund is an embankment of earth. Contour bunds and trenches (Figure 5.1) break the flow of water and thus increase infiltration and limit erosion. They are constructed along contours of equal land elevation. Between two contours, agriculture can be practiced and tree plantation on the bund is possible. Bunds trees/plants can help to fix nitrogen in the soil for the crop plants. During rainfall the contour bund acts as a barrier to the water flow, reducing the speed of run-off water and thus also the washing out of nutrients.

Bench terracing

Bench terracing (Figure 5.1) is practiced in hilly areas where the original slope is levelled stepwise by cutting and filling. Under suitable conditions the structure helps to reduce surface run-off and enhances soil moisture conservation, crop production and aquifer recharge.

Percolation or infiltration pond or tank and recharge basin

Percolation tank or pond (Figure 5.1) is a term used in India to describe harvesting of water in storages built in ephemeral streams or off-stream where water is detained and infiltrates through the permeable base to enhance storage in unconfined aquifers. Recharge basins differ from percolation ponds in that they are designed to accommodate a flow through a series of basins not retaining the whole amount of water in a single basin like in a percolation pond. For both types of structures the water is usually desilted to prevent clogging.

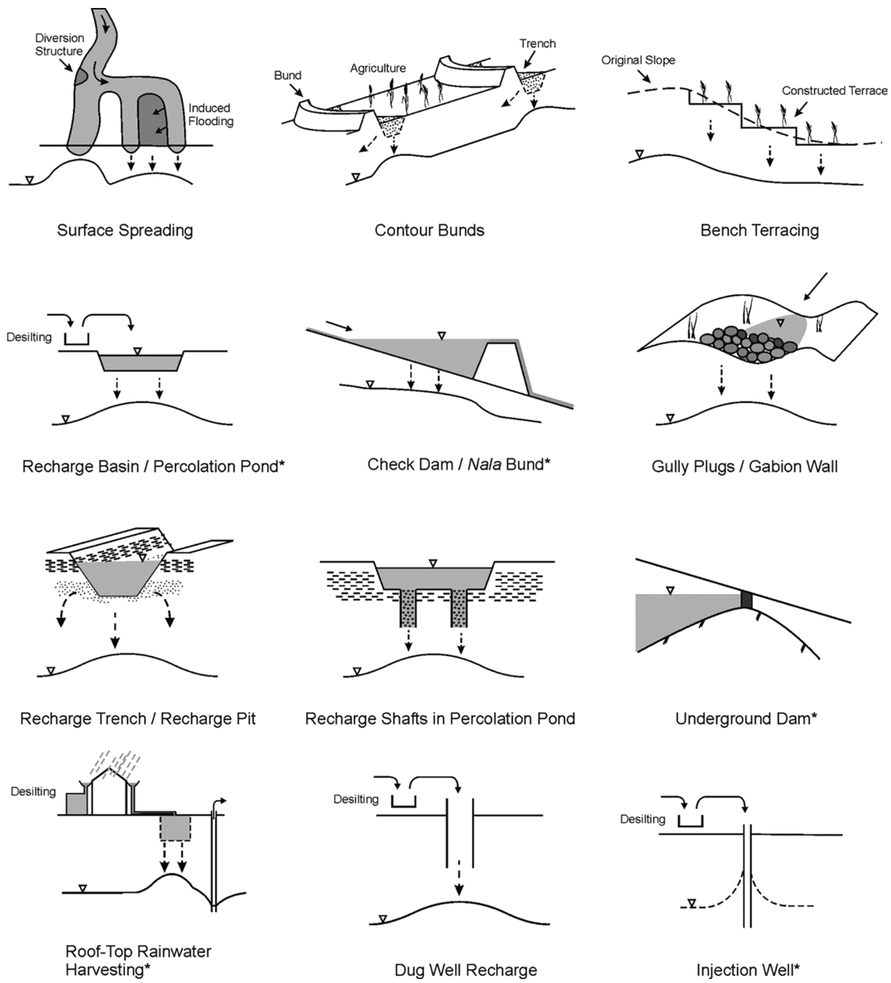

Figure 5.1 Sketches of managed aquifer recharge structures commonly used in India. *Modified from Gale (2005).

Check dam, nala bund

Check dams (Figure 5.2) or Nala bunds (Figure 5.3) are barriers built across the direction of water flow in rivers. These dams retain part of the water flow during monsoon rains in the area upstream of the structure. The increased accumulation of water in the reservoir area increases the infiltration rate.

Figure 5.2 Check dam in Araniyar River in Tamil Nadu (*Source*: Christoph Sprenger).

Figure 5.3 Nala bund (*Source*: Lakshmanan Elango).

Gully plug and gabion wall

Gullies are formed due to erosion of top soil by the flow of rain water. Gully plugs are built with local stones, sand, clay and plants. It is a simple technique for conservation of soil and moisture by reducing the speed of run-off water during floods. Gabions are wire mesh baskets filled with rocks and have a permeable, flexible structure (Figure 5.1). Gabions walls are used often for erosion control, bank stabilization, channel linings and weirs. They are also constructed to protect the bank of lakes and rivers against erosion due to water and waves. Sludge and small stones deposit in the interstices, leading to growth of vegetation and ultimately a natural reservoir is formed. It retains water for dry periods to serve agriculture and also replenishes groundwater.

Recharge pit

Recharge pits (Figure 5.4) are dug out pits and trenches, which have been dug through a layer of low permeability to improve infiltration to a shallow phreatic (unconfined) aquifer (Figure 5.1). They differ from percolation ponds and recharge basin in that they are deeper and frequently recharge takes place through the sides of the pit as well. Abandoned mine shafts and quarries are often converted to recharge pits if they are in contact with an underlying aquifer.

Figure 5.4 Recharge pit at Raipur Municipal Corporation headquarters (*Source*: Raipur Municipal Corporation).

5.1.3.8 Recharge shaft

Recharge shafts like recharge pits (Figure 5.1) are recharge structures which penetrate an upper layer of low permeability into the underlying phreatic aquifer. They are constructed at the bottom of surface structures (ponds/tanks/channels) which do not connect to the permeable layer. In contrast to injection or recharge wells they are backfilled with coarse sand and stones thereby creating columns of porous, permeable soil which connect the recharge pit to the aquifer.

Injection well or recharge well

Injection wells (Figure 5.1) are tube wells constructed for the purpose of recharge. Injection wells are primarily used to recharge deep lying aquifers and the water is injected under pressure or using gravity alone. Many of them are constructed with slotted PVC pipe and surrounded with some kind of clogging protection.

Underground dam

Underground dams (Figure 5.1) are built in ephemeral streams where basement ridges constrict flows. A trench is dug across the streambed keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use.

Rooftop rainwater harvesting structure

Rooftop Rainwater harvesting (Figure 5.1) collects and infiltrates the roof run-off from buildings. Most commonly injection takes place through dug or bore wells, but recharge through percolation ponds is also possible.

Dug well recharge

Dug wells (Figure 5.1) which have run dry can be adapted for use as recharge structures. This is done by diverting surface water into the well. It is normally desilted before infiltration to avoid clogging.

5.2 HYDROLOGIC CYCLE OF INDIA

5.2.1 Current overall situation

The main features of India's hydrologic cycle are shown in Figure 5.5 and given in Tables 5.2 and 5.3. The availability and use of water and the interactions between surface and groundwater are shown, allowing an appraisal of the role of MAR in the Indian water supply.

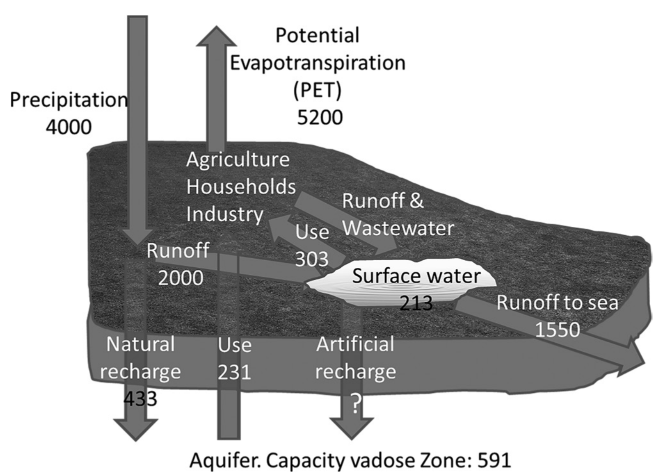

Figure 5.5 Water cycle of India with flows in km³/year and capacities in km³. Values and literature references in Tables 5.2 and 5.3.

Potential Evapotranspiration is the maximum amount of water evaporated and lost by transpiration from vegetation (Allen, 1998). India's potential evapotranspiration (5,200 km³) is higher than its rainfall (4,000 km³). In other words, the amount of irrigation needed to keep the Indian landmass moist all year, exceeds the water available through rainfall. Today approximately half of the rainwater (2,000 km^3) flows as run-off into natural or manmade surface water bodies and 39% of the rainwater (1,550 km^3) flows into the sea, mainly during the monsoon period.

Table 5.2 Water balance of India.

	[km^3]	[mm][a]
Annual precipitation	4,000[b]	1,200
Annual potential evapotranspiration	5,200	1,580[c]
Annual run-off to surface water	1,890[d]–2,440[e]	570–740
Annual run-off to sea	1,548[f]	470
Annual surface water use	Irrigation: 228[g] Other: 75	Irrigation: 69 Other: 23
Surface storage	213[h]	65

[a]In general the average number of mm was recalculated from the volume using the area of India (3,288,000 km^2); [b]Central Water Commission (2005), Water Resources Information System Data Book-2005; [c]India Meteorological Department (1971); [d]Chaturvedi(1976); [e]Zade *et al.* (2005); [f]Parikh *et al.* (2007); [g]Central Water Commission (2005), Water Resources Information System Data Book-2005: Data for year 2000; Central Ground Water Board (2006), Dynamic Ground Water Resources of India: Difference between total and groundwater use; [h]Central Water Commission (2005), Water Resources Information System Data Book-2005: Data for 2002.

Table 5.3 Indian groundwater balance. Values for natural recharge, groundwater use and annual balance are largely confirmed in the revised master plan for artificial recharge to groundwater of CGWB (2013).

Groundwater Balance	[km^3]	[mm]
Annual natural recharge	433[a]	132
Annual groundwater use	Irrigation: 213[a] Other: 18	Irrigation: 65 Other: 6
Annual natural discharge non-monsoon	34[a]	10
Annual balance	168[a]	51
Unsaturated aquifer deeper than 3 m below ground	591[b]	180

[a]Central Ground Water Board (2006), Dynamic Ground Water Resources of India; [b]Central Ground Water Board (1996), National Perspective Plan for utilization of surplus run-off for augmentation of groundwater resources in India.

Approximately 11% of the rainwater (433 km^3) is naturally recharged to the groundwater, either directly in the rainfall area or from the surface water bodies, whereas abstraction for irrigation and other uses from groundwater represents 6% and abstraction from surface water bodies represents 8%. Part of the water evaporates during use and part of it returns to the groundwater table and surface water bodies.

There is no official figure for the total volume of water harvested by MAR in India (see section 5.3.2). The statistical data on surface water bodies also includes the volumes of MAR structures. Often structures are used conjunctively for irrigation and infiltration. The extent of infiltration in that case depends on whether a passage to the vadose zone has been freed and whether silt has accumulated since then. The total volume (83km^3) to be recharged in the structures suggested in the Master Plan of the CGWB (2013) is 2% of the total rainfall. This gives an idea of the potential importance of MAR in India's water cycle. It is a small fraction of the total rainfall, but could make a sizeable contribution (62km^3, 27%[1]) to the amount of groundwater used (231 km^3). Large volumes of water (213 km^3) are used for irrigation and consequently demand side management (Dillon *et al.* 2009) influencing the type and the number of crops and the irrigation methods also has a large potential for attenuating the groundwater scarcity.

[1]The amount of infiltrated water is calculated from the amount of recharge water (85 km^3) and the efficiency of the structure (75% was assumed).

5.2.2 Spatial and seasonal variation

The parameters of the Indian water cycle (Figure 5.5, Table 5.2 and 5.3) are average values. India has high spatial variability of rainfall across the country, ranging from 150 mm in the west to 11,690 mm in the northeast (Indian Meterological Department, 2004). Thus the water availability and the possibilities for MAR are very different in different parts of the country.

India has an average precipitation comparable to many European countries (European Environment Agency, 2012). However, the seasonal variation is much more pronounced in India, which makes MAR and water storage in general more important.

The period of rainfall in India, the monsoon, comes either from the southwest or the northeast. All states are subject to the southwest monsoon that accounts for about 74% of the annual rainfall in the country (Guhathakurta & Rajeevan, 2006), while some stretches in the peninsular India are also subject to the north-east monsoon which accounts for about 11% of the annual rainfall. Whereas the eastern part of the peninsular India receives most of the rainfall (over 60%) during the north east monsoon.

The rain period can be characterized by recording the shortest period in which 10% and 90%, respectively, of the annual rain falls. "The 10% wet period occurs in the months of July/August with an average duration of 1–3 days and rainfall intensity varying from 44 to 89 mm/d. The duration of the 90% wet period varies from 112 days in the central part of the country to 186 days in the north." (Deshpande & Singh, 2010, p. 561).

The rivers are fed by the monsoon and to some extent by snow melt and experience high seasonal variations. The Ganges peak flow during monsoon in the Himalayan foreland was measured to be 17 times higher than during non-monsoon (Chakrapani & Saini, 2009). In the Indo Gangetic plains, the average dry season to monsoon discharge ratio is about 1 to 6 (Qader, 2005). In the southern part of the country, streams dry out during non-monsoon season.

5.2.3 Future water demand

The water demand in India is expected to increase by some 15% between 2010 and 2025 (0.9%/year) (Kumar *et al.* 2005) (Table 5.4). India Infrastructure Research (2012) predicts an increase in yearly demand of 68 km^3 for irrigation and 28 km^3 for domestic purposes between 2000 and 2025. This would correspond to an increase of 0.6% per year for these two major sectors. The total Indian consumption reported by Kumar *et al.* (2005) and India Infrastructure Research (2012) is above 600 km^3/year in 2010, which is somewhat higher than the values given by CGWB (2006) and CWC (2005) (total of 534 km^3 in 2005 in Table 5.2). Thus, although absolute values and growth rates vary considerably, the sources indicate an increasing water demand. This is attributed among other things to rising population and living standards.

Table 5.4 Expected increase in total water consumption (Kumar *et al.* 2005).

	1997/1998	2010	2025	2050
Total consumption [km^3]	629	694–10	784–843	973–1180
Increase [%]		12	29	71

5.3 COORDINATED ACTIONS FOR PROMOTING ARTIFICIAL RECHARGE

5.3.1 Pilot schemes of the Central Ground Water Board (CGWB)

The CGWB, a subordinate office of the Ministry of Water Resources, Government of India (GoI), is entrusted with the responsibilities of providing scientific inputs for management, exploration, monitoring, assessment, augmentation and regulation of groundwater resources of the country (CGWB, 2012).

The Central Ground Water Board undertakes macro/micro-level groundwater management studies, exploratory drilling programs and also monitoring of groundwater levels and water quality through a network of groundwater observation wells. Periodic assessment of replenishable groundwater resources of the country is carried out by the Board jointly with the concerned State Government agencies. Geophysical studies, remote sensing and GIS studies and groundwater modelling as well as special studies on groundwater sector such as aquifer mapping, groundwater depletion, seawater ingress, groundwater contamination, conjunctive use of surface and groundwater and water balance are also part of the CGWB activities. In addition, the CGWB organizes internal and external capacity building activities as well as mass awareness campaigns on the importance of water conservation and judicious groundwater management (CGWB, 2012).

In the post-independence period, the CGWB first initiated the pilot programme for water harvesting and water conservation during the period 1972 to 1984 with the UN Department of Technical Cooperation for Development collaboration (Table 5.5).

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 recharge structures were constructed.

Table 5.5 Artificial recharge studies undertaken by the CGWB during different five year plans (Chadha, 2012; CGWB, 2012).

Period and Plan	Status	Cost* [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 States/UT – 25)	331
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	1,000

*Costs in [Million EUR]: VIII Plan = 0.39; IX Plan = 3.97; X Plan = 0.67 and XI Plan = 12.30. (Average currency exchange rate of year 2014: INR EUR = 0.0123; Online Currency Converter, 2015).

During the plan period 2007–2012, 82 pilot projects with a total of 1,475 structures were to be constructed in areas which are 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 (Table 5.5) all 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 with the purpose of "demonstrating artificial recharge and rain water harvesting techniques in overexploited and critical areas, urban areas and areas affected by water quality" (CGWB, 2012).

Based on the experience acquired in the pilot programs the CGWB strives to contribute to large scale implementation of MAR. The CGWB Perspective Plan for Artificial Recharge (1996) estimated the non-committed surplus monsoon run-off available for recharge in India by adding data from different basins (872 km^3). Furthermore the sub-surface storage potential available on saturation of the vadose zone up to 3 meters below ground level was calculated (590 km^3). By selecting the lowest of those two values for each basin the "feasible groundwater storage" was calculated (234 km^3). This is the amount of water which is available in the basin and for which there is also storage potential in the basin.

A 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 the capability of subsurface formations to accommodate it. As a part of the Master Plan of 2002, a number of demonstration projects were implemented between 2007 and 2012 as mentioned above. In 2013 a revised Master Plan was published (CGWB, 2013). The revised master plan of 2013 identifies more than twice as much water to be recharged as the original Master plan of 2002 (Table 5.6). It remains to be seen if the huge amounts of funds needed for this plan (see section 5.3.2) can be raised and whether the volumes of the revised plan of 2013 or only those of the Master plan of 2002 can be recharged.

Table 5.6 List of structures proposed under the master plan of 2013 (Values of 2002 in brackets) (CGWB, 2002; and 2013).

Structures Proposed under the Master Plan of 2013	Values
Area Identified for Artificial Recharge [km^2]	942,000 (449,000)
Volume of water to be recharged [km^3]	85.6 (36.5)
Number of structures in rural areas	2,283,000 (225,000)
Number of structures in urban areas (rooftop rainwater harvesting)	8,799,000 (3,700,000)
Total number of structures proposed	11,082,000 (3,925,000)
Total cost of structures proposed [Million INR]	792,000 (245,000)*

*Costs in [Million EUR]: 9,741.6 (Master Plan 2013) and 3,013.5 (Master Plan 2002). (Average currency exchange rate of year 2014: INR EUR = 0.0123; Online Currency Converter, 2015).

5.3.2 Implementation schemes

Right from the ancient days, canals, ponds, anicuts and reservoirs have been dug and constructed in India to improve the water availability. There are numerous examples and stone inscriptions from as early as 600 A.D. citing that ancient kings and other benevolent persons considered construction of small ponds to collect rainwater which also assisted increasing groundwater recharge. Traditionally each village had a pond to store surface run off and to augment groundwater recharge. Most of the temples had a tank which also serves as a structure for groundwater recharge.

Over the last few decades several initiatives have been taken to improve the groundwater potential by increasing the rainfall recharge. By now India counts innumerable structures mainly in peninsular India (0.5 Million) (Sakthivadivel, 2007) or even 1.5 Million (Pandey *et al*. 2003). Several agencies in India provide financial support for constructions which facilitate improvement of groundwater conditions. These agencies are from both government and non-governmental sectors. Several Departments/Boards under the Ministry of Water Resources and Ministry of Rural Development fund groundwater recharge related projects (Table 5.7).

Table 5.7 Main features of some important programs of the Government of India (GoI) involving MAR.

Year	Name of the Program	Financing Organization	Budget*	Additional Info
1995–	Integrated Watershed Management Program (IWMP)	Ministry of Rural Development, GoI	INR 43,616 million released until 2012 (EUR 536.4 million)	All states. 1,900 projects covering 107,000 km^2 were financed until 2012.
2007–2012	Repair, Renovation and Restoration (RRR) scheme	Ministry of Water Resources, GoI	INR 60,000 million (partly local government; EUR 738 Million)	Planned were 23,000 water bodies for irrigation of 17,000 km^2. One of ten goals was MAR.
2005–2009	Bharat Nirman	Ministry of Rural Development, GoI	INR 223,992 million (EUR 2,755.1 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 (EUR 221.2 million)	Seven states are involved. 4.5 million dug-wells proposed.

*(Average exchange rate of year 2014: INR EUR = 0.0123; Online Currency Converter, 2015).

The Department of Land Resources have integrated and consolidated three programmes namely, Drought Prone Areas Programme, Desert Development Programme and Integrated Wastelands Development Programme (IWDP) into a single modified programme called Integrated Watershed Management Programme (IWMP). The major activities of this project include rainwater harvesting activities like farm ponds, percolation tanks, check dams etc. The projects under the programme are being implemented in 470 districts in all 28 states of the country. From 1995 to 2007, 1,877 IWDP projects covering an area of 107,000km^2 have been sanctioned. A total number of 770 projects covering an area of 49,000 km^2 were completed by 2011. Other projects are at various stages of implementation in different States. Central funds to the tune of INR 43,616 million (EUR 536.4 million[2]) have been released by December 31, 2012 (Ministry of Rural Development, 2012).

The Ministry of Water Resources (2009) writes "In India, tanks/ponds and lakes have traditionally played an important role in irrigation, drinking water supply, hydropower, ecology, tourism/culture and domestic use. Relative importance of some of these water bodies has waned due to a number of reasons such as shifting away from community based tank system to individual beneficiary oriented ground water dependent system, encroachments, silting, population pressure, multiplicity of agencies responsible for their upkeep, etc."

The Repair, Renovation and Restoration (RRR) scheme was introduced in 2005 in order to restore these bodies, and one of the ten goals is groundwater recharge. The scheme is financed partly by the central government (in most states 25%; in some states 90%) and partly by the state governments. A pilot phase (INR 3,000 million from the central government) was followed by a regular phase (Total project cost projected INR 60,000 million from the central and local government) for the period 2007–2012. The scheme pertains to the restoration of 23,000 water bodies in almost all states with a target to create 17,000 km^2 of additional irrigation potential (Ministry of Water Resources, 2009).

The RRR scheme is part of the Bharat Nirman program. Bharat Nirman is covering improvement of rural infrastructure and two out of six parts are related to MAR, namely additional irrigation for 100,000 km^2 and drinking water supply for 55,000 habitations. Out of the 100,000 km^2 additional irrigated land, at least 28,000 km^2 should be irrigated with groundwater and 10,000 km^2 with water from the RRR scheme (Ministry of Water Resources, 2012). The additional water demand will be drawn partly from existing groundwater potential, but likely additional potential will also be created (MAR). Bharat Nirman was launched by the Ministry of Rural Development in 2005/2006. Under Bharat Nirman Phase I (2005 to 2009), funds utilized were INR 223,992 million (EUR 2,755 million) (Ministry of Rural Development, 2010). The National Rural Drinking Water Programme was performed with the objective to move away from over-dependence on a single drinking water source to multiple sources through conjunctive use of surface water, groundwater and rainwater harvesting; ensure sustainability in drinking water schemes.

The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) is supported under the Ministry of Rural Development, GoI. The activities that are supported under this act include water conservation, water harvesting and renovation of traditional water bodies among other things. Under the MGNREGA, a scheme on 'Artificial Recharge of Groundwater through dugwells' was launched in the year 2008 with a total outlay of INR 17,987 million (EUR 221.2 million), including subsidy component of INR 14,993 million (EUR 184.4 million). This project was implemented in seven states to recharge the existing dugwells, improve groundwater storage, increase the sustainability of groundwater during lean periods and improve the overall agricultural productivity. The total number of irrigation dug wells proposed for recharge is 4.45 million (Ministry of Water Resources, 2010).

The cost of the revised Master plan of the CGWB can be compared to the existing programs. CGWB proposes an implementation of the master plan (INR 792,000 million; EUR 9,741.6 million) over 10 years with joint financing in similar shares by the Ministry of Water resources, MGNREGA, stakeholder industries and state governments. The annual expenditure for such a plan would far exceed the sum of the water-related parts of the programs in Table 5.5. The implementation would thus require a complete change in Indian water policy.

Rainwater harvesting has been made mandatory in several cities and in some states of India with the aim to meet the increasing groundwater needs. A National Bank for Agriculture and Rural Development (NABARD) project is aiming at water resource conservation and management by rooftop rainwater harvesting (NABARD, 2012).

5.4 STATE-OF-THE-ART OF MAR IMPLEMENTATION IN INDIA

Although MAR has been implemented in millions of places in India, published results on the performance in terms of quantity (infiltration rates) and quality are scarce. In total, 27 publications as of March 2012 were found dealing with MAR and documenting field studies with quantitative data on different scales:

- 13 publications reported on field studies with less than 5 recharge structures,
- 8 publications gave examples of groups of structures with more than 5 and less than 100 recharge structures,

[2]Average currency exchange rate of year 2014: INR EUR = 0.0123 (Online Currency Converter, 2015). All amounts indicated in EUR were calculated with the same currency exchange rate.

- 2 publications gave overviews of recharge structures on a regional level with more than 100 structures,
- One publication took a theoretical approach only (groundwater modelling), and
- In 3 publications, the number of structures was not given.

The structures investigated can be categorized as given in Figure 5.6. In the small and medium scale investigations, recharge or injection wells represent the majority of investigated structures, whereas for large scale investigations most reported structures are check dams (incl. nala bunds and contour trenches) that were also studied in the small scale investigations to a considerable extent.

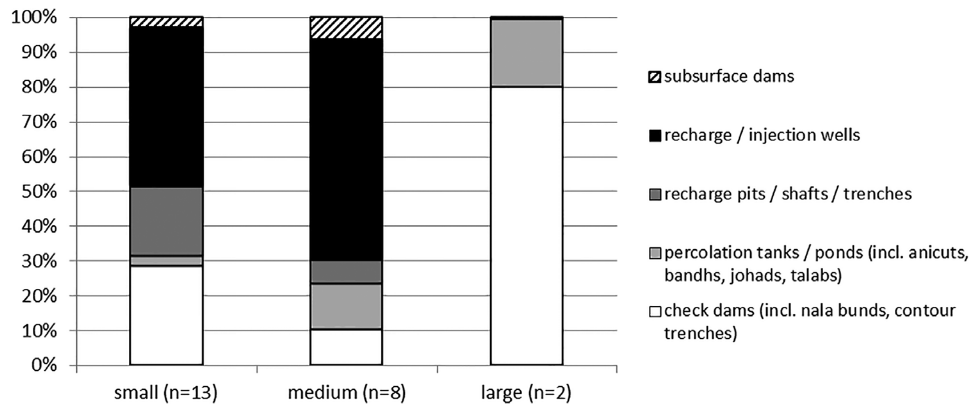

Figure 5.6 Aquifer recharge structures in publications as on March, 2012 on field studies with quantitative results. The field studies are divided in small (<5 structures), medium (5 to <100 structures) and large scale (>100 structures).

The abstraction is mainly carried out by bore-wells or dug wells, either with hand pumps or electrically equipped. The recharged water is usually used for irrigation, but in 10 of the 27 field studies with quantitative results domestic or drinking water use is also mentioned. Three urban case studies deal with water recharged for drinking water purposes only (Hyderabad, Bangalore and Chennai all mentioned in (UNESCO, 2006)). These are, however all direct rainwater harvesting structures from rooftops.

In the following sections the findings from field studies and related literature are reported in relation to the different activities related to MAR. Broadly MAR activities can be divided in:

- Planning and construction
- Operation and maintenance

After the need for modified or additional MAR structures has been quantified, the planning and construction of a structure can be addressed. The knowledge necessary for planning of a structure can be summarized as follows based on listings from Kumar *et al.* (2008) and the CGWB (2000: p. 52):

- Source water availability (see below)
- Topography
- Properties of soil
- Hydrogeological data (see below)
- Surface and groundwater quality over time (see below)

These factors are generally measured more precisely in the planning phase. Once these factors are known, the suitable structures for different topography, hydrogeology and rainfall and their percolation efficiency are quantified as given by CGWB (2000: p. 100).

5.4.1 Source water availability

The CGWB recommends using rainwater, run-off or treated waste water for recharge (CGWB, 2007: p. 15). For determining the availability of rainwater Kumar *et al.* (2008) show the importance of determining the rainfall distribution over the years, especially in arid regions. High rainfall in some rarely occurring years in these regions can only be captured with over-dimensioned structures. These will therefore only be partly utilized in most years and consequently have low percolation efficiency (volume of infiltrated water in relation to volume of the structure).

The run-off is calculated based on average rainfall, soil infiltration properties and topography (Zade *et al.* 2005). However, MAR activities may capture water that is planned to be utilized downstream, resulting in reallocation of water between users with little or no additional benefit (Kumar *et al.* 2008). Kumar *et al.* (2008) reported reduced inflow into the Ghelo-Somnath reservoir (Gujarat) because of intensive water harvesting in the upstream catchment of the reservoir. The authors calculated rainfall – run-off regression lines for the pre-/ and post- MAR intervention period. According to this calculation the rainfall amount which is needed to fill the reservoir increased from 320 mm/year to 800 mm/year. Rama *et al.* (2003) studied the redistribution of surface run-off in small catchments in Andhra Pradesh and Karnataka before, during and after groundwater recharge initiatives. The authors found strong evidence that extensive MAR interventions resulted in decreased run-off generation and, thus, reduced flow captured in the traditional water tanks situated downstream. This effect could be attributed to MAR interventions, and other factors such as deforestation or reduced rainfall could be ruled out (Rama *et al.* 2003). Once the run-off is captured in MAR structures, this water either evaporates or recharges the aquifer and is then pumped for irrigation. It is not clear if this reallocation of water, from traditional tank supply to decentralized groundwater recharge gives an additional value to the local communities. Run-off in urban areas, often referred to as storm water, is increasingly captured by rooftop rainwater harvesting schemes as mentioned in section 5.3.2 (CGWB, 2011a).

According to DK Chadha, former Chairman of the CGWB (Chadha, 2012), treated wastewater was not used up to now, partly because no quality guidelines for source water exist. However, in order to increase the available amounts of water, treated wastewater could also be considered for recharge. Treatment could take place in conventional wastewater treatment plants, constructed wetlands or soil aquifer treatment (SAT) type systems and need to be coupled with quality control to avoid contamination of aquifers. SAT is evaluated in India (Nema *et al.* 2001) and practiced in other countries, i.e. Israel, Australia and USA, with promising results (O'Connor *et al.* 2008). Negative social and religious views on applying treated wastewater for irrigation or drinking water purposes is often stronger than rational arguments based on water quality and risks. Using it for MAR transforms the water to more neutrally perceived groundwater and thus might be a way to overcome these reservations.

Finally, water from other catchments can be transported by canals over long distances. Some major projects have been implemented and others are planned (Central Water Commission, 2009). This is a costly option and might be considered in basins where no other sources are available.

5.4.2 Hydrogeological data

The 27 field studies with quantitative results cover a wide variety of natural settings: the average annual precipitation varied between 612 mm (Moga, Punjab: Bassian Drain, Block Nihalsisngh Wala (CGWB, 2011b)) and 1,788 mm (Balasore district + Field Site, Orissa (Hollaender *et al.* 2009)), with high inter-annual variations (long-term average minima: 331 mm; maxima: 1,424 mm reported for Delhi (UNESCO, 2006)). For those case studies for which hydrogeological information were 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 (three, six and four case studies respectively report information on these parameters). Well yield is, however, a parameter that is frequently given in the publications. In sedimentary formations well yields vary between 1 and 115 m^3/h with the highest values in alluvial aquifers (Bhadrak, Orissa (CGWB, 2011b)) and the Tapi alluvial Belt Maharashtra (Jain, 2006). Maximum well yield in hard-rock environments, on the other hand, is always below 14 m^3/h (Deccan traps, Maharashtra (Jain, 2006)) and usually lie between 0.8 and 4 m^3/h. These figures give an idea of the hydraulic permeability encountered, but as data on draw-down and well design is lacking, quantitative information on specific capacities or transmissivities cannot be derived.

Aquifer properties as part of the hydrogeological data define the amount of water which can be infiltrated and stored in the aquifer. India's aquifers are broadly comprised of three groups of rock formations of different hydraulic properties (CGWB, 2006): unconsolidated porous, semi-consolidated porous and consolidated fissured formations. Unconsolidated formations have high transmissivity, hydraulic conductivity (Table 5.8) and also high storativity. They can thus rapidly absorb and store large amounts of water per unit volume, which make them well suited for MAR. The high transmissivity leads to high groundwater flow, redistributing water within the aquifer away from the infiltration point and along topographical gradients, which is not always desirable.

Table 5.8 Properties of aquifers in different groups of rock (Groundwater Estimation Committee, 2009).

Formation	Area Fraction [%]	Transmissivity [m^2/d]	Hydraulic Conductivity [m/d]
Unconsolidated	30	250–4,000	10 to 800
Semi-consolidated	7	100–2,300	0.5–70
Consolidated	63	10–500	0.05–15

5.4.3 Surface and groundwater quality over time

The CGWB recommends use of rainwater and run-off or treated wastewater for recharge. As mentioned above recharge of wastewater is not practiced and it is commonly assumed that the source water is impure. This assumption is not always valid since the run-off may flush out accumulated contaminants on the way to the recharging point. Once recharged, the water will undergo changes in quality during the underground passage. Quality parameters of source water and known positive and negative effects from India and elsewhere are reviewed below.

Pathogens

Generally, subsurface passage is an effective medium for microbiological removal (Sharma *et al.* 2011). In case of sufficient flow path length and residence time during the subsurface passage, microbial contamination will be attenuated by physical straining and inactivation (or die-off) to levels below drinking water standards. Pathogens are critical for bank filtration systems because of the often short residence times. Bank filtration can achieve, under optimal conditions, several log removal over distances of few tens of meter travel distance for viruses (Tufenkji *et al.* 2002). Higher removal can be expected for larger particles i.e. protozoa and bacteria. For example the natural capacity for attenuation in bank filtration and lake filtration in Delhi and Naini Tal in India was shown to be effective and no breakthrough of bacteria was measured (Sprenger *et al.* 2008; Dash *et al.* 2008). Some countries have established a minimum subsurface travel time for recharge water (i.e. Germany 50 days) to ensure a certain removal. Thus it is important that sufficient travel times of contaminated surface water to wells and consequently a sufficient distance (e.g. >20 m, depending on geology, temperatures and water) to a recharge site are assured to avoid a pathogen breakthrough. In the Indian context a study of soil aquifer treatment of Nema *et al.* (2001) evaluates attenuation potential in relation to aquifer recharge.

Organic chemicals

Different schemes of MAR were found to remove organic trace contaminants, including pesticides, personal-care products, endocrine-disrupting compounds, and pharmaceutical active compounds to varying extents (Sharma *et al.* 2011; Maeng *et al.* 2010). Many of these substances are toxic, carcinogenic or suspected to be endocrine disruptors and therefore considered not only hazardous to the ecosystem but also to human health. The removal of these micro pollutants during subsurface passage depends on several factors such as: concentration level of the contaminant, redox conditions (Massmann *et al.* 2006; Patterson *et al.* 2002; Pavelic *et al.* 2005), residence time and the occurrence of organic matter in the aquifer (availability of electron donors) rather than the travel time (Schmidt & Lange, 2006). Removal capacity is very site-specific and general predictions are difficult to give. Anyhow, minimum travel time for a 30% removal of pharmaceutically active compounds is estimated to be at least 75 days (Maeng *et al.* 2010). Many MAR sites are characterized by the occurrence of a more or less developed redox sequence, providing oxic and anoxic conditions which in turn leads to the removal of many redox sensitive micro pollutants.

In India the data on organic micropollutants in the environment are limited. Warren *et al.* (2002) described the fate of organic contaminants (Lindane, benzo(a)pyrene) at the Rihand reservoir (Uttar Pradesh) and developed a mass balance model. Shukla *et al.* (2005) analysed the organochlorine pesticide contamination in groundwater in Hyderabad and detected several pesticides exceeding drinking water standards set by European countries.

Sampling in six bore wells in Chennai show fairly high quality compared to the WHO guidelines in terms of physical/chemical parameters (WHO, 2008). Out of eight chlorinated pesticides analyzed only Atrazine was detected in low concentrations (ng/L). On the other hand, various types of water borne pathogens were detected in all samples except those from a sealed well (Saph Pani Deliverable 4.3, 2014).

Samples from the Yamuna river in Delhi show presence of 12 respectively 18 of 39 selected micropollutants including pharmaceuticals and artificial sweeteners (Table 5.9). Further samples from bank filtration wells nearby show attenuation during the soil passage (Saph Pani Deliverable 4.4, 2014).

Table 5.9 Attenuation of 39 selected micropollutants in the Yamuna river and in nearby wells. Travel speed has been estimated to 0.9 m/d (Sprenger, 2011).

	Surface Water	Groundwater 200 m Distance	Groundwater 500 m Distance
Sum of concentrations July 2013 [ng/L]	11,133	2,393	1,123
Number of detected compounds July 2013	18	7	11
Sum of concentrations December 2013 [ng/L]	728	262	97
Number of detected compounds December 2013	12	4	3

Ionic contamination

As reported by CGWB (2012) the groundwater in numerous areas is unsuitable for drinking because of mineral contaminants such as fluoride, nitrate, arsenic or mineral salts. Indian researchers have identified mechanisms and sources for fluorine contamination (Rao, 2009; Reddy *et al.* 2010) and a recent review identifies filtration with magnesia as a suitable post-treatment in rural areas (Ibrahim, 2011). Reddy *et al.* (2011) showed how animal and human excrements can lead to rapid nitrate contamination under undiluted circumstances. Arsenic was shown to accumulate in shallow aquifers after desorption from sediments in Bengal rice cultivation (Farooq *et al.* 2010) and lakes (Acharyya & Shah, 2007). Pawar *et al.* (1998) showed the importance of protecting the aquifer from industrial effluents by analyzing the polluting effects of saline effluents of a sugar mill, whereas Garduno *et al.* (2011) listed contamination coming from industrial point sources, as well as geogenic contamination and agriculture all over India.

Mineral contaminants are in many cases present in the aquifer. Possible goals of MAR can be not to mobilize them or even to stabilize them by acting on the ion content and the redox potential of the infiltrated water. MAR can also help dilute mineral contaminants or provide pockets of water suitable for drinking in otherwise contaminated aquifers. And obviously a primordial goal would be to infiltrate water that does not add to the contamination.

In 11 of the 27 field studies with quantitative results, water quality information is given and mineral contamination is always a concern. 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.

Salinity has been reported to be a problem in the state of Haryana (Malik *et al.* 2006) 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 electrical conductivity from 9,000 to 1,500 μS/cm).

In other cases it is clearly stated that the implementation of MAR has led 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 the 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 (2011b). A connection to MAR is not clear and Gale *et al.* (2006) postulated agricultural influence.

To our knowledge, investigations on arsenic concentrations in artificially recharged groundwater are lacking, though implementation of MAR has been suggested to be a possible countermeasure in case of elevated concentrations in the groundwater (CGWB, 2011b).

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 Riverbed in Ahmedabad (Nema *et al.* 2001). The authors found that 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 55,000 m^3/d SAT system using primary settled domestic wastewater was proposed for the city (CGWB, 2011b).

5.4.4 Infiltration rate and prevention of clogging

The CGWB (2011b) classifies 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 ranges from 2 m^3 per m trench (Bhubaneswar, Raj Bhawan premises) to 24,000 m^3 per well (Bhadrak, Orissa) but are difficult to compare due to diverse hydrogeology, varying precipitation rates and a multitude of studied structures. Reported increase in groundwater level range from 0.2 to 1 m, but in some cases the number of abstraction wells has also increased considerably (18 additional wells resulting from the installation of 2 trenches and 3 recharge wells in Moga, Punjab Bassian Drain). The CGWB evaluated the performance of different MAR structures in different hydrogeological and meteorological contexts based on data from numerous pilot studies (section 5.3). The results were thoroughly documented (Chadha, 2012). Benchmark performances (e.g. 75% percolation efficiency (CGWB, 2013) and the suitability of structures for different contexts (CGWB, 2000: p. 100) were published. However, most results unfortunately remain inaccessible to the research community. Although a large amount of information on MAR systems in the different Indian states was found, it is difficult to derive general trends and transferable recommendations due to the above mentioned variability and lack of detailed scientific data.

The quantification of the recharged water is in the focus of the 27 field studies with quantitative results. This is 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 73% 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 90% and more of the rainfall was 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 the 73% found by Perrin *et al.* (2010), 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) reported a 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, 2011b; 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) desilting improved the percolation efficiency from 83% to 87% in check-dams in Coimbatore and Hollaender *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.

MAR measures often result in the development of a clogging layer at the area of recharge. The clogging layer has a lower hydraulic conductivity than the surrounding aquifer material and decreases infiltration rates. Clogging can be of physical (air entrapment in the aquifer, deposition of suspended solids), chemical (mineral precipitation, e.g. iron oxides) or biological nature (accumulation of organic matter). Physical clogging, e.g. silting, may be managed by treatment of the recharge water by simple sedimentation and filtration to remove suspended solids as described below. Chemical clogging of wells may be managed by frequent mechanical or chemical cleaning such as brushing or application of mild acids, respectively (McLaughlan, 1996). Periodic cleaning and re-development only delay the ageing process of the well. Biological clogging in ponds is often a result of algae die-off and can be managed by frequent removal and washing of the uppermost infiltration layer (Greskowiak *et al.* 2006). Algae growth and other biological clogging are reduced by minimizing nutrients (nitrogen and phosphorous) and organic carbon in the source water. This is in particular true where sewage is part of source water. Chlorine disinfection or other disinfectants with residual effects reduces biological activity at the infiltration interface. Finally, the clogging rates also depend on the infiltration rate, because with high infiltration rates higher amounts of nutrients and suspended solids arrive at the infiltration surface.

Generally silting is 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. Pre-treatment is widely used, either through sedimentation tanks (UNESCO, 2006), sand filters (Kaledhonkar *et al.* 2003; Sivakumar *et al.* 2006; Tuinhof and 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 a total removal rate of 70–90%, but TSS was still around 800 mg/L (See also chapter 12: Pre- and Post-treatment of BF and MAR in India: Present and Future). Panda (2002) tested gravel filters and embedded coconut fiber mats 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 (northern India) 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).

5.4.5 Maintenance of the structure and the surrounding area

Land-use activities in the vicinity of MAR structures need to be part of routine maintenance. For example a check dam constructed in 1975 collapsed in 1994 due to uncontrolled sand mining in the riverbed and the adjacent areas (Charalambous & Garratt, 2009).

MAR interventions reduce erosion, which is in general considered positive. However, prevention for movement of sediments with run-off and with river water may lead to reduced sediment influx into the sea, which may alter the erosional and depositional dynamics of the coast. To the best of our knowledge, studies on the impacts of MAR interventions such as check dams on changes in river sediment load and coastal stability in the Indian context are lacking.

5.5 CONCLUSION

In most parts of India, the monsoon lasts for about four months, followed by a dry period of about eight months. This rainfall pattern imposes huge seasonal variation in water availability. Aquifer recharge has been practiced to a large extent and for a long time to recharge the groundwater and ensure access to water all year. Experience with structures and groundwater management has developed in and been adapted to the various climatic and hydrogeological situations of India which is reflected by their variety and their presence at many historic sites.

India's use of groundwater has increased rapidly over the last fifty years. Today, groundwater covers about 43% of India's water demand. The demand exceeds the supply in many areas which leads to sinking groundwater tables. MAR is only one factor influencing the water balance. For example, water use for irrigation is of greater importance and consequently the type and the number of crops and the irrigation methods have a greater impact than MAR. Additional recharge through MAR could only make a minor contribution to the overall water balance (2%) according to rough estimations in the recent Master plan by CGWB (2013). However, it might contribute substantially (27%) to the groundwater consumption and relieve the situation in regions where water deficits exist. The Master plan of the CGWB (2013) proposes an additional 2.3 Million structures in rural areas to be constructed in the coming 10 years. There is no systematic inventory of existing structures today and numbers mentioned in literature range from 0.5 Million (Sakthivadivel, 2007) to 1.5 Million (Pandey *et al.* 2003).

The impact of aquifer recharge in the area on a watershed level and in India as a whole depends on the number of structures and also on their performance. But, from the review of field studies in literature, the quantitative scientific evidence for both positive and negative performance of MAR interventions is found scarce, an observation confirmed by Glendenning *et al.* (2012). As suggested by Glendenning *et al.* (2012), collection of quantifiable field data in combination with the development of new modelling tools is necessary in order to examine the wide range of potential positive and negative impacts of MAR measures on a watershed scale. In particular, as indicated by CGWB (2013: p. vii), data on the number, the performance and the effect of the existing structures would be necessary for future watershed management. This is especially important as the large amount of water used and the seasonal variations make it difficult to unambiguously identify non-committed water in a watershed. In several case studies new MAR structures recharge additional water upstream which is lacking downstream and lead to longer dry periods there.

Evaluation of the quantitative effect of recharge structures can show changes in performance over time. Monitoring of performance 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 (UN Department of Technical Cooperation for Development, 1987; Palanisami *et al.* 2006; Gale *et al.* 2006; Glendenning *et al.* 2012; CGWB, 2013). This is in general more cost effective than construction of new structures and should thus be prioritized (CGWB, 2013: p. 195).

Up to now little attention was paid to the quality of recharge water; most of the Indian field studies do not measure quality of source water at all (section 5.4.3) and none of them measures pathogens. Up to now it was generally assumed that the used sources, rainfall and run-off, were safe to use (section 5.4.1). The potential positive and negative effects of MAR interventions on water quality are attracting increased interest. This is important, since almost all Indian districts have areas with nitrate contamination in the groundwater, and excessive concentration of other pollutants like arsenic, salt and fluoride is also widespread.

Generally, information on mixing ratios between naturally and artificially recharged water as well as travel times or redox conditions were found missing. In the case of critical parameters such as 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.

This review covers knowledge and experience in India. It is mainly focused on how to plan, construct and operate MAR structures. There is also a larger context which is not treated, mainly social and economic factors. These need also 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 best use of the recharged water.

5.6 REFERENCES

Acharyya S. and Shah B. (2007). Arsenic-contaminated groundwater from parts of Damodar fan-delta and west of Bhagirathi River, West Bengal, India: Influence of fluvial geomorphology and Quaternary morphostratigraphy. *Environmental Geology*, **52**, 489–501.

Allen R. G. (1998). Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. http://www.fao.org/docrep/X0490E/X0490E00.htm (accessed 26 June 06 2012).

CGWB (1996). National Perspective Plan for Utilization of Surplus Runoff for Augmentation of Groundwater Resources in India. Report Central Groundwater Board, New Delhi, India.

CGWB (2000). Guide on Artificial Recharge to Ground Water. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2002). Master Plan for Artificial Recharge to Ground Water. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2006). Dynamic Ground Water Resources of India. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2007). Manual on Artificial Recharge to Groundwater. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2011a). Groundwater Scenario in Major Cities of India. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2011b). Selected Case Studies, Rainwater Harvesting and Artificial Recharge. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

CGWB (2012). Central Ground Water Board. http://cgwb.gov.in/aboutcgwb.html (accessed 25 June 2012).

CGWB (2013). Master Plan for Artificial Recharge to Groundwater. Report Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

Central Water Commission (2005). Water Resources Information System Data Book-2005. Report Central Water Commission, Ministry of Water Resources, Government of India, New Delhi, India.

Central Water Commission (2009). Water resources map of India.

Chadha D. K. (2012). Personal communication 15 August 2012.

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

Charalambous A. and Garratt P. (2009). Recharge abstraction relationships and sustainable yield in the Araniar Kortalaiyar groundwater basin, India. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 39–50.

Chaturvedi M. C. (1976). Water-Second India Studies. Macmillan Company of India Ltd, New Delhi.

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

Deshpande N. and Singh N. (2010). Spatial and temporal variations in the occurrences of wet periods over major river basins in India. *J. Earth Syst. Sci.*, **119**, 561–578.

Dillon P., Gale I., Contreras S., Pavelic P., Evans R. and Ward J. (2009). Managing Aquifer Recharge and Discharge to Sustain Irrigation Livelihoods under Water Scarcity and Climate Change. IAHS Publications 330, Hyderabad, India.

European Environment Agency (2012). Average Annual Precipitation. http://www.eea.europa.eu/data-and-maps/figures/average-annual-precipitation (accessed 10 April 2012).

Farooq S., Chandrasekharam D., Berner Z., Norra S. and Stüben D. (2010). Influence of traditional agricultural practices on mobilization of arsenic from sediments to groundwater in Bengal delta. *Water Research*, **44**(19), 5575–5588.

Gale I. (2005). Strategies for Managed Aquifer Recharge (MAR) in Semi-Arid Areas. International Hydrological Programme, UNESCO, Paris.

Gale I. N., Macdonald D. M. J., Calow R. C., Neumann I., Moench M., Kulkarni H., Mudrakartha S. and Palanisami K. (2006). Managed aquifer recharge: An assessment of its role and effectiveness in watershed management. British Geological Survey Commissioned Report, CR/06/107N.

Garduńo H., Romani S., Sengupta B., Tuinhof A. and Davis R. (2011). India, Groundwater Governance – A Case study. Report World Bank, New Delhi, India.

Glendenning C. J. and Vervoort R. W. (2010). Hydrological impacts of rainwater harvesting (RWH) in a case study catchment: The Arvari River, Rajasthan, India. Part 1: Field-scale impacts. *Agricultural Water Management*, **98**(2), 331–342.

Glendenning C. J., van Ogtrop F. F., Mishra A. K. and Vervoort R. W. (2012). Balancing watershed and local scale impacts of rain water harvesting in India – A review. *Agricultural Water Management*, **107**, 1–13. doi: 10.1016/j.agwat.2012.01.011.

Greskowiak J., Prommer H., Massmann G. and Nuetzmann G. (2006). Modeling seasonal redox dynamics and the corresponding fate of the pharmaceutical residue phenazone during artificial recharge of groundwater. *Environmental Science & Technology*, **40**(21), 6615–6621.

Groundwater Estimation Committee (2009). Report of the Groundwater Resources Estimation Committee, Ministry of Water Resources. Government of India, New Delhi, India.

Guhathakurta P. and Rajeevan M. (2006). Trends in the rainfall pattern over India. Report no. 2/200, National Climate Centre, India Meteorological Department, Pune, India.

Hollaender H., Mull R. and Panda S. (2009). A concept for managed aquifer recharge using ASR-wells for sustainable use of groundwater resources in an alluvial coastal aquifer in Eastern India. *Physics and Chemistry of the Earth, Parts A/B/C*, **34**(4–5), 270–278.

Ibrahim M. A. (2011). Effects of fluoride contents in ground water: A review. *International Journal of Pharmaceutical Applications*, **2**, 128–134.

India Infrastructure Research (2012). Water and Wastewater in India 2012. Report India Infrastructure Publishing Pvt. Ltd., New Delhi, India.

India Meteorological Department (1971). Scientific Report No. 136., India Meteorological Department, Government of India, New Delhi, India.

Indian Meterological Department (2004). Normal Annual Rainfall. http://www.imd.gov.in/section/climate/annual-rainfall.htm (accessed 26 June 2012).

Jain S. K. (2006). Artificial recharge to groundwater in an overdeveloped watershed – A case study of semi –arid region of Maharashtra, India. In: Final Report UNESCO G-WADI Meeting on Water Harvesting, Edmunds W. M. and Cardona C. (eds), UNESCO, United States, pp. 111–118.

Kaledhonkar M. J., Singh O. P., Ambast S. K., Tyagi N. K. and Tyagi K. C. (2003). Artificial groundwater recharge through recharge tube wells: A case study. *International Journal of Agricultural Research*, **84**, 28–32.

Kanhe N. M. and Bhole A. (2006). Study of Experiments on Roof Top Rainwater Harvesting and Surface Rainwater Harvesting for Recharging of Wells.

Kumar M., Patel A., Ravindranath R. and Singh O. (2008). Chasing a mirage: Water harvesting and artificial recharge in naturally water-scarce regions. *Economic and Political Weekly*, **43**(35), 61–71.

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

Maeng S., Ameda E., Sharma S., Gruetzmacher G. and Amy G. (2010). Organic micropollutant removal from wastewater effluent-impacted drinking water sources during bank filtration and artificial recharge. *Water Research*, **44**(14), 4003–4014.

Malik R., Yadav D., Jhorar B., Jhorar B. and Streck T. (2006). Physical and chemical interactions in an ASR cavity well in a brackish aquifer. In: Recharge Systems for Protecting and Enhancing Groundwater Resources, IHP/2006/GW-13, UNESCO, United States, pp. 121–126.

Massmann G., Greskowiak J., Dünnbier U., Zuehlke S., Knappe A. and Pekdeger A. (2006). The impact of variable temperatures on the redox conditions and the behaviour of pharmaceutical residues during artificial recharge. *Journal of Hydrology*, **328**, 141–156.

McLaughlan R. G. (1996). Water well deterioration, diagnosis and control. 2nd edn, National Centre for Groundwater Management, University of Technology, Sydney.

Ministry of Rural Development (2012). Annual Report 2011–2012. Ministry of Rural Development, Government of India, New Delhi, India.

Ministry of Water Resources (2009). Guidelines for Repair, Renovation and Restoration of Water Bodies with Domestic Support. Ministry of Water Resources, Government of India, New Delhi, India.

Ministry of Water Resources (2010). Press Information Bureau, GoI. http://pib.nic.in/newsite/erelease.aspx?relid=57646 (accessed 10 August 2012).

Ministry of Water Resources (2012). Ministry of Water Resources. http://mowr.gov.in/writereaddata/linkimages/arsenic14193577002.pdf (accessed 9 August 2012).

NABARD (2012). Model and Innovative Projects. http://www.nabard.org/ridf/model_rainwater.asp (accessed 15 September 2012).

Nema P., Ojha C., Kumar A. and Khanna P. (2001). Techno-economic evaluation of soil-aquifer treatment using primary effluent at Ahmedabad, India. *Water Research*, **35**(9), 2179–2190.

O'Connor G. A., Elliot H. and Bstian R. (2008). Degraded water reuse: An overview. *Journal of Environmental Quality*, **37**, 157–168.

Online Currency Converter (2015). http://www.freecurrencyrates.com/exchange-rate-history/EUR-INR/2014 (accessed 28 April 2015).

Palanisami K., Raviraj A., Thirumurthi S. and Sellamuthu K. (2006). Augmenting Ground Water Resources by Artificial Recharge AGRAR. Inception Report for the research site at Kodangipalayam village, Coimbatore District, Tamil Nadu, Water Technology Centre, Tamil Nadu, India.

Panda S. (2002). Rainwater Harvesting-cum-artificial Groundwater Recharge for Sustainable Water Resources Management. Report Submitted to Ministry of Human Resource Development, Department of Agricultural and Food Engineering, I.I.T Kharagpur, Kharagpur, West Bengal, India.

Pandey D. N., Gupta A. K. and Anderson D. M. (2003). Rainwater harvesting as an adaptation to climate change. *Current Science*, **85**(1), 46–59.

Parikh S., Shah T., Chadha D., Dubash N., Mohanty N., Jagawat H., Reddy P., Jha B., Moni M., Dhumal V., Mathew K., Palaniappan N., Takshi K. and Mishra A. (2007). Groundwater Management and Ownership – Report of the Expert Group. Planning Comission, Government of India, New Delhi, India.

Patterson B., Franzmann P., Davis G., Elbers J. and Zappia L. (2002). Using polymer mats to biodegrade atrazine in groundwater: Laboratory column experiments. *Journal of Contaminant Hydrology*, **54**, 195–213.

Pavelic P., Nicholson B. C., Dillon P. J. and Barry K. E. (2005). Fate of disinfection by-products in groundwater during aquifer storage and recovery with reclaimed water. *Journal of Contaminant Hydrology*, **77**(12), 119–141.

Pawar N. J., Pondhe G. M. and Patil S. F. (1998). Groundwater pollution due to sugar-mill effluent, at Sonai, Maharashtra, India. *Environmental Geology*, **34**, 151–158.

Perrin J., Massuel S. and Ahmed S. (2010). Contribution of percolation tanks to total aquifer recharge: The example of Gajwel watershed, southern India. Ismar Abu Dhabi. In: Achieving Groundwater Supply Sustainability and Reliability through Managed Aquifer Recharge, Proceedings of the Symposium ISMAR 7, California, United States, pp. 251–258.

Qader M. M. (2005). The ganges water diversion: Environmental effects and implications – An introduction. In: The Ganges Water Diversion: Environmental Effects and Implications, Qader M. M. and Singh V. (eds), Springer, The Netherlands, Vol. 49, pp. 1–12.

Rama M. S., Batchelor C. H., James A. J., Nagaraja R., Seeley J. and Butterworth J. A. (2003). Andhra Pradesh Rural Livelihoods Programme APRLP Water Audit Report, APRLP, Hyderabad, India.

Rao N. (2009). Fluoride in groundwater, Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India. *Environmental Monitoring and Assessment*, **152**, 47–60.

Reddy D., Nagabhushanam P. and Peters E. (2011). Village environs as source of nitrate contamination in groundwater: A case study in basaltic geo-environment in central India. *Environmental Monitoring and Assessment*, **174**, 481–492.

Reddy D., Nagabhushanam P., Sukhija B., Reddy A. and Smedley P. (2010). Fluoride dynamics in the granitic aquifer of the Wailapally watershed, Nalgonda District, India. *Chemical Geology*, **269**(3–4), 278–289.

Rodell, M., Velicogna I. and Famiglietti J. (2009). Satellite-based estimates of groundwater depletion in India, *Nature* **460**, 999–1002.

Sakthivadivel R. (2007). The groundwater recharge movement in India. In: The Agricultural Groundwater Revolution: Opportunities and Threats to Development, Giordano M. and Villhot K. G. (eds), CAB International, Wallingford, United Kingdom, pp. 191–210.

Saph Pani D4.3 (2014). Post-treatment requirements of different natural treatment systems. *Saph Pani Project Deliverable*. http://www.saphpani.eu/downloads (accessed 19 August 2014).

Saph Pani D4.4 (2012). Recommended post-treatment options for water utilities employing natural treatment systems. *Saph Pani Project Deliverable*. http://www.saphpani.eu/downloads (accessed 19 August 2014).

Sayana V., Arunbabu E., Kumar L., Ravichandran S. and Karunakaran K. (2010). Groundwater responses to artificial recharge of rainwater in Chennai, India: A case study in an educational institution campus. *Indian Journal of Science and Technology*, **3**(2), 124–130.

Schmidt C. and Lange F. (2006). Ermittlung der Potenziellen Reinigungsleistung der Uferfiltration/Untergrundpassage Hinsichtlich der Eliminierung Organischer Schadstoffe unter Standortspezifischen Randbedingungen (Calculation of potential cleaning performance of bank filtration/subsoil with regard to the elimination of organic pollutants under site-specific conditions), Report BMBF-Project 02WT0280, BMBF-Projektverbund: Export-oriented research and development in the field of water supply and sanitation, Federal Ministry of Education and Research, Berlin, Germany.

Sharma S., Hussen M. and Amy G. (2011). Soil aquifer treatment using advanced primary effluent. *Water Science and Technology*, **64**(3), 640–646.

Shukla G., Kumar A., Bhanti M., Joseph P. and Taneja, A. (2005). Organochlorine pesticide contamination of ground water in the city of Hyderabad. *Environment International*, **32**, 244–247.

Singh D. and Singh A. (2002). Groundwater situation in India: Problems and perspectives. *Water Resources Development*, **18**, 563–580.

Sivakumar C., Elango L. and Gnanasundar D. (2006). Numerical modelling of groundwater flow in south Chennai coastal aquifer. In: MODFLOW and More 2006: Managing Ground-Water Systems, Poeter E., Hill M. and Zhen C. (eds), Colorado School of Mines, Colorado, USA, pp. 506–510.

Sprenger C., Lorenzen G. and Pekdeger A. (2008). Occurrence and Fate of Microbial Pathogens and Organic Trace Compounds at Riverbank Filtration Sites in Delhi, India. Techneau Integrated Project, D5.2.6, European Comission.

Sprenger C. (2011). Surface-/groundwater interactions associated with river bank filtration in Delhi (India) – Investigation and Modelling of Hydraulic and Hydrochemical Processes. PhD thesis, Department of Geosciences, Freie Universität Berlin, Berlin, Germany.

Tufenkji N., Ryan J. and Elimelech M. (2002). The promise of bank filtration. *Environmental Science & Technology*, **36**, 422A–428A.

Tuinhof A. and Heederik J. (2003). Management of aquifer recharge and subsurface storage. *Netherlands National Committee—International Association of Hydrogeology*, **4**(4), 1–94.

UN Department of Technical Cooperation for Development (1987). Hydrogeological and artificial recharge studies, Madras. Technical Report, UN Department of Technical Co-operation for Development, New York, United States.

UNESCO (2006). National Seminar on Rainwater Harvesting and Water Management. United Nations Educational, Scientific and Cultural Organization (UNESCO), Nagpur, India.

Warren C. S., Mackay D., Bahadur N. P. and Boocock D. G. (2002). A suite of multi-segment fugacity models describing the fate of organic contaminants in aquatic systems: Application to the Rihand Reservoir, India. *Water Research*, **36**(17), 4341–4355.

WHO (2008). Guidelines for Drinking-water Quality. Third Edition Incorporating the First and Second Addenda – Volume 1 Recommendations, World Health Organization, Geneva, Switzerland.

Zade M., Ray S., Dutta S. and Panigrahy S. (2005). Analysis of runoff pattern for all major basins of India derived using remote sensing data. *Current Science*, **88**(8), 1301–1305.