# Saph Pani

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

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Deliverable D 2.1

# Report on existing MAR practice and experience in India, especially in Chennai, Maheshwaram, Raipur

SAPHPANI

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# 1 Introduction

## 1.1 Importance and Exploitation of Groundwater in India

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 1990) and shallow tube wells (from 3000 in 1951 to 8.5 million in 1990) (Muralidharan, 1998; 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, 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 total surface-water reservoirs.

One way to address the lack of groundwater is through the use of Managed Aquifer Recharge (MAR). It is estimated that about 14% of the total land area in India is suitable for MAR and that a volume of 36 $km^3$ is available for recharge annually. This is equivalent to an average of 80 mm over the entire area and the volume equates to about 18% of the 200 $km^3$ of groundwater that is currently utilised annually for irrigation (Central Ground Water Board, 2007).

One work package of the Saph Pani project is dedicated to MAR. The overall objectives of this work package are:

- To determine the quantitative and qualitative effects of monsoon water recharge of an overexploited urban aquifer through existing ponds and lakes.
- To assess the impact of existing measures for monsoon water infiltration on counteracting seawater intrusion into a coastal aquifer used for urban drinking water production and develop an alternative low-cost and low-tech measure
- To evaluate the impact of MAR through percolation tanks on groundwater recharge and quality in a peri-urban over-exploited hard-rock aquifer
- To derive general recommendations for the implementation of MAR under the specific conditions met in India.

Modelling of MAR data, evaluation of post-treatment options for MAR and also an integral assessment of the MAR sites including social, economic, health and organizational aspects are outputs of other work packages which are completing and supporting those activities.

## 1.2 Scope of the Report

This report is a deliverable related to task 2.4.1 in the description of work of the project (Table 1).

Table 1: Description of the related task 2.4.1

| | |
|---|---|
| Title | India-wide review on MAR practice and experience |
| Involved Partners | FHNW (lead), NIH, KWB, FUB, NGRI |
| Description | In the initial phase of the project an inventory of the MAR applications found in India will be collected and documented in a data-base. Available data from these applications will be analyzed with respect to hydrogeological context, source water, capacities, infiltration methods, pre- and post-treatment, abstraction methods etc. The resulting report shall give a comprehensive overview of the currently known potential and also limitations of MAR techniques for natural water treatment in India. |

The report follows the scope described in the task and focus on the technical aspects associated with MAR, discussing state of the art in India with respect to the techniques used and to the amount of water being artificially recharged. It does not consider, or only tangentially touches on the socio-economic impacts of MAR. These aspects will be treated in the integrated sustainability assessment in the work package 6 of Saph Pani.

Following an introduction the Indian Water cycle will be described (Chapter 2) and the potential for MAR in different Indian states will be summarized based on the regional water cycle and quality data (Chapter 3). Thereafter the chapter 4, “MAR experience in India” will present the activities of the Central Ground Water Board (CGWB) and other coordinated actions as well as knowledge gained from those activities. Finally the previous experience on the Saph Pani study sites will be presented (Chapter 5).and knowledge gaps that can be filled by Saph Pani will be identified (Chapter 6).

## 1.3 Definition of Managed Aquifer Recharge

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), Sharma and Amy (2011) included the techniques Soil Aquifer Treatment (SAT), Aquifer Storage and Recovery (ASR), Aquifer Storage Transfer and Recovery (ASTR), Subsurface groundwater treatment (SGT; (Sharma, et al., 2011)) and Bank filtration (BF) in the wider frame of MAR. The term Artificial Recharge (AR) commonly used in India denotes recharge of the aquifer for later use. Artificial Recharge is practiced in order to increase quantity and not to improve quality. It is similar to the term ARR used by Sharma and Amy (Sharma, et al., 2011) and encloses ASR and ASTR.

In the Saph Pani project MAR only 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 2). 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 have exclusively the intention of treatment and consequently do not fall under the definition of MAR in the Saph Pani project. BF is the subject of a separate work package in the Saph Pani project.

Table 2: Characterization of techniques for MAR with respect to the intention and the water flow

| Method | ASR | ASTR | SAT | SGT | BF |
|---|---|---|---|---|---|
| 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 |

## 1.4 Purpose of MAR

India faces major challenges due to water scarcity because of its growing demands. To meet these demands, groundwater is pumped beyond sustainable levels, which has led to rapid depletion of groundwater in some aquifers. In these situations, MAR can serve as an effective option to meet the growing groundwater demands. The large-scale promotion of MAR addresses the following challenges:

- securing and enhancing water supplies
- augmenting groundwater resources in depleted aquifers
- regaining previous groundwater levels
- improving groundwater quality
- maintaining base flow of rivers
- preventing salt water from intruding into coastal aquifers
- reducing evaporation of stored water
- maintaining environmental flows and groundwater-dependent ecosystems

Some of the important purposes of the MAR are discussed below.

### 1.4.1 Alleviation of Water Scarcity

An average rainfall of 1180 mm in India (Guhathakurta & Rajeevan, 2006) is relatively high by global standards. Water scarcity in India is not due to lack of rainfall, but due to its uneven spatial and temporal distribution (see chapter 2). Since the majority of rainfall is concentrated in the monsoon seasons it is lost as runoff to the sea. This runoff water could potentially be captured in MAR structures and thus improve the groundwater levels by increasing the recharge, thereby helping to ease water scarcity problems during the summer months. Also, by proper use of the MAR structures and better planning, groundwater problems can be sustainably managed. To summarize: an important purpose of MAR is to improve the groundwater availability and alleviate water scarcity.

### 1.4.2 Flood Mitigation

As most of the rainfall occurs in relatively short periods, surface run off may lead to flooding during heavy rains. So, harvesting the rainwater will not only solve the problem of water scarcity, but also reduce the floods. When the seasonal rivers are nearly full during the monsoons, they can be diverted through canals to MAR structures so that it will reduce the risk of flood along the direction of river flow. This will also lead to reduction in soil erosion.

### 1.4.3 Prevention of Salt Water Intrusion

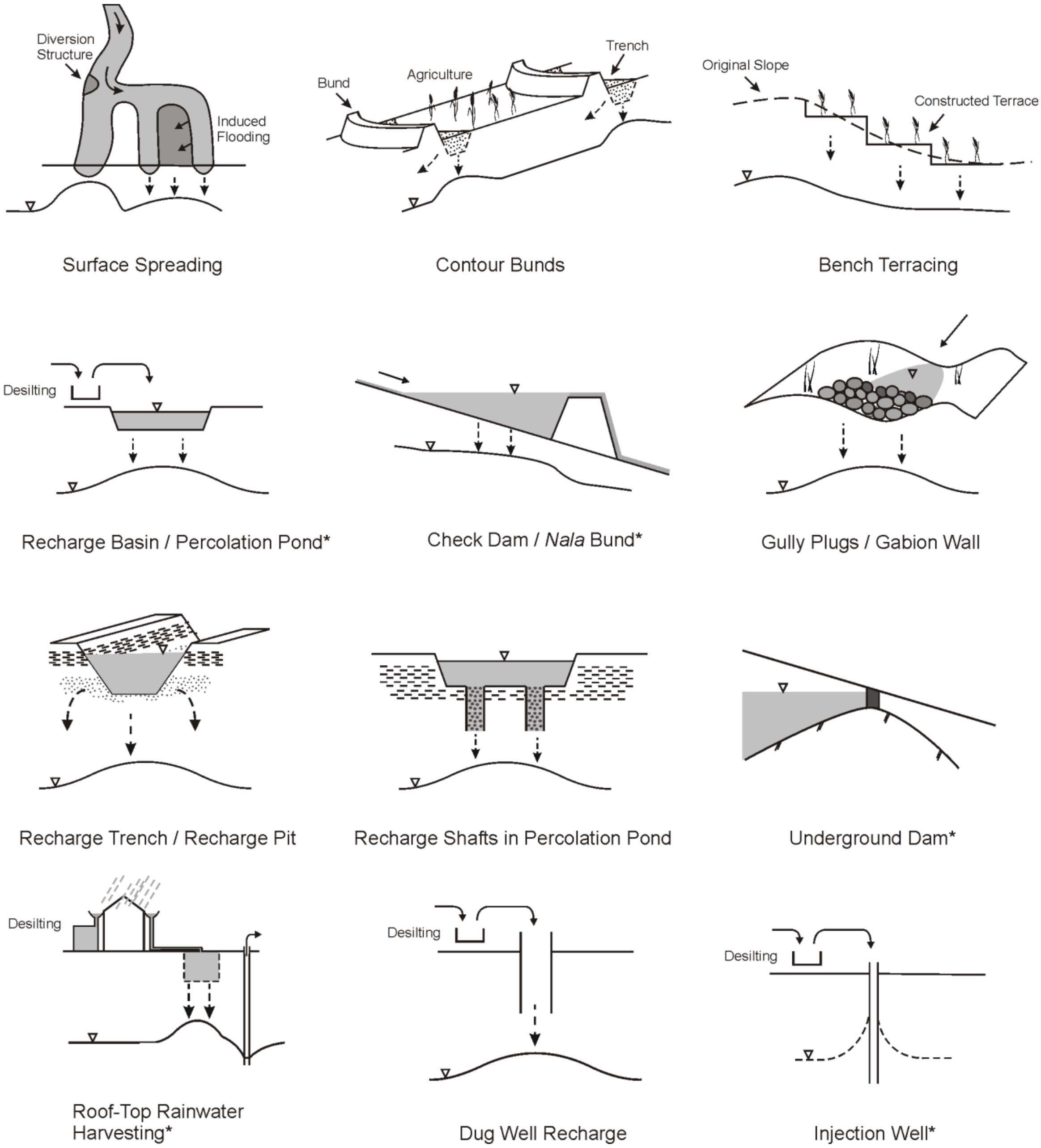
One of the most important causes of saline water intrusion is the reversal of groundwater gradient in coastal aquifers due to over-pumping. Reduction in pumping of existing freshwater wells and changing the locations of pumping wells to inland areas can mitigate the problem of seawater intrusion. Groundwater levels can be also be raised by MAR through recharge wells for confined aquifers and surface spreading for unconfined aquifers. Injection barriers can also be considered to prevent seawater intrusion into freshwater aquifers.

### 1.4.4 Improvement of Groundwater Quality

MAR also helps largely to improve groundwater quality. With proper knowledge on the sources of contamination and the geology and hydrogeology of an area, locations for MAR can be planned and implemented. This will help to dilute the groundwater and thereby reduce the impact of contamination in the groundwater. MAR can also help remove contaminants in the source water or the ground water (see chapter 4.2.1.3).

### 1.4.5 Structures for MAR

MAR can be broadly divided into three main groups (Central Ground Water Board, 2007): surface-spreading, run-off conservation and sub-surface structures. Also, existing structures can be used for MAR through rooftop rainwater harvesting and dug well recharge. Because of India’s long tradition of water harvesting and its many languages, there are many different names for very similar structures. The list of structures is thus not exhaustive, but covers the main types. More detailed information on these structures is given by Narain et al (2005) by CGWB (2007) and Dilllon et al (2009).



Surface Spreading
Contour Bunds
Bench Terracing
Recharge Basin / Percolation Pond*
Check Dam / *Nala* Bund*
Gully Plugs / Gabion Wall
Recharge Trench / Recharge Pit
Recharge Shafts in Percolation Pond
Underground Dam*
Roof-Top Rainwater Harvesting*
Dug Well Recharge
Injection Well*

Figure 1: Sketches of managed aquifer recharge structures commonly used in India (*modified from Gale (2005))

### 1.4.6 Surface Spreading

Surface spreading structures (Figure 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.

### 1.4.7 Contour Bund and Contour Trench

A bund is an embankment of earth. Contour bunds and trenches (Figure 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 fix nitrogen in to 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 thus also the washing out of nutrients.

### 1.4.8 Bench Terracing

Bench terracing (Figure 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.

### 1.4.9 Percolation or Infiltration Pond or Tank and Recharge Basin

Percolation tank or pond (Figure 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.

### 1.4.10 Check Dam, Nala Bund and Gully Plug

Check-dams (Figure 3) or Nala bunds (Figure 2) are barriers built across the direction of water flow of rivers. These dams retain part of the water flow during monsoon rains in the area upstream of the structure. The increased pressure in the reservoir area increases the infiltration rate.

### 1.4.11 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 1). In connection with water management gabions walls are used often for erosion control, bank stabilization, channel linings and weirs. Gabion walls reduce the speed of run-off water. They are also constructed to protect the bank of lakes and rivers against the 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 replenishes groundwater.

### 1.4.12 Recharge Pit

Recharge pits (Figure 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 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. Abandoned mine shafts and quarries are often converted to recharge pits if they are in contact with an underlying aquifer.

### 1.4.13 Recharge Shaft

Recharge shafts like recharge pits (Figure 1) are recharge structures which penetrate an upper layer with 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.

### 1.4.14 Injection Well or Recharge Well

Injection wells (Figure 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.

### 1.4.15 Underground Dam

Underground dams (Figure 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.

### 1.4.16 Rooftop Rainwater Harvesting Structure

Rooftop Rainwater harvesting (Figure 1) collects and infiltrates the roof runoff from buildings. Most commonly injection will take place through dug or bore wells, but recharge through percolation ponds is also possible.

### 1.4.17 Dug Well Recharge

Dug wells (Figure 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 common to desilt the water before infiltration to avoid clogging.

Figure 2: Nala Bund (Source: Elango Lakshmanan)

Figure 3: Check dam on Araniyar River in Tamil Nadu (Source: Christoph Sprenger)

Figure 4: Recharge pit at Raipur Municipal Corporation (RMC) headquarters (Source: RMC)

# 2 Indian Water Cycle

## 2.1 Current Global Situation

The main features of India's water cycle are shown in Figure 5 and given in Table 3 and Table 4. The availability and use of water and the interactions between surface and groundwater is shown, allowing an appraisal of the role of MAR in the Indian water supply.

Potential Evapotranspiration (PET) is the maximum amount of water evaporated and lost by transpiration from vegetation (Allen, 1998). India's potential evapotranspiration (5'200 km$^3$) is higher than its rainfall (4'000 km$^3$). 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 runoff 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.

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 6% and 8% are abstracted for irrigation and other uses, from groundwater and from surface water bodies respectively. Part of the water evaporates during use and part of it returns to the groundwater table and surface water bodies.

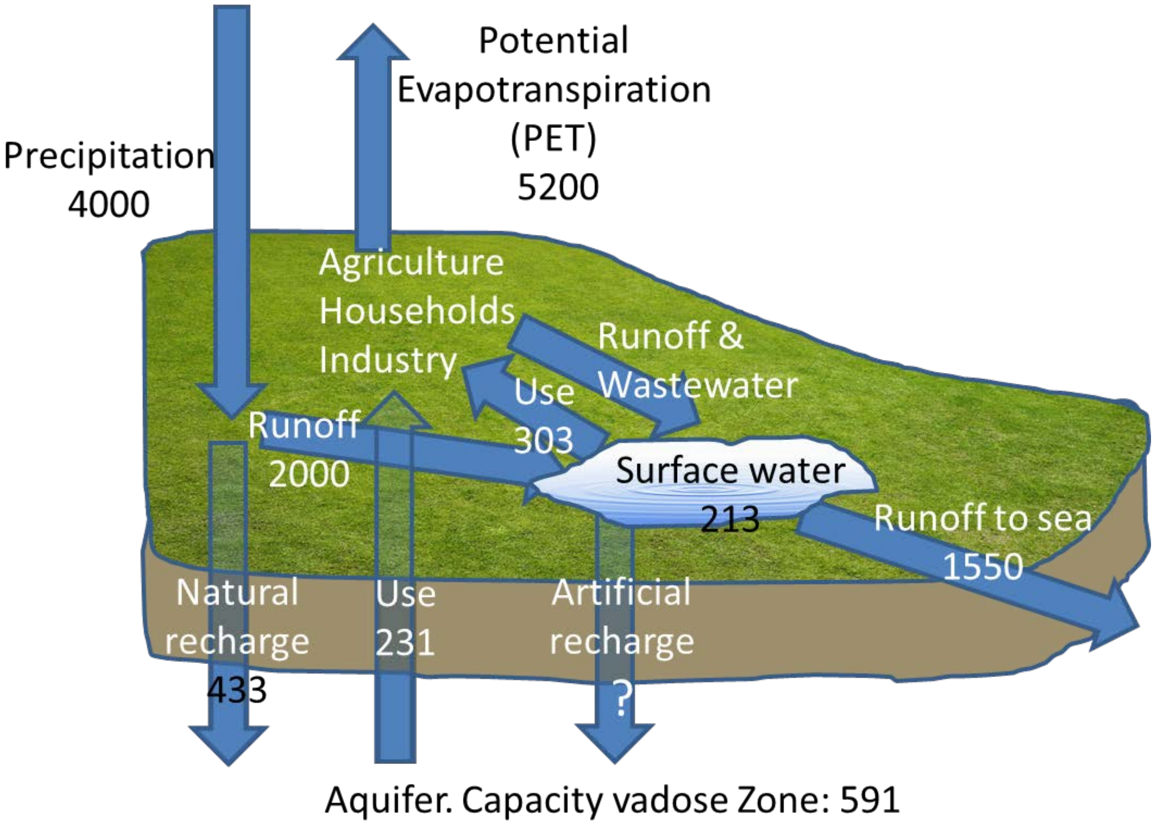


Figure 5: Water cycle of India with flows in km$^3$/year and capacities in km$^3$. Values and literature references in Table 3

There is no official figure for the total volume of MAR in India (see chapter 4.1.2). The surface water body statistical data also include the volumes of MAR structures. Often structures are used conjunctively for irrigation and infiltration. The extent of infiltration then depends on whether a passage to the vadose zone has been freed and whether silt has accumulated since then. The total volume (36 km$^3$) to be recharged in the structures suggested in the Master Plan of the CGWB (Central Ground Water Board, 2002) is 1% of the total rainfall. This gives an idea of the importance of MAR in India's water cycle. It is a small fraction of the total rainfall, but could make a contribution (27 km$^3$, 12%[1]) to the amount of groundwater used (231 km$^3$).

Table 3: Indian Overall Water Balance

| **Overall Water Balance** | | |
|---|---|---|
| | km$^3$ | mm [2] |
| Annual Precipitation | 4000[3] | 1200 |
| Annual Potential Evapotranspiration (PET) | 5200 | 1580[4] |
| Annual Runoff to surface water | 1890[5]-2440[6] | 570-740 |
| Annual Runoff to sea | 1548[7] | 470 |
| Annual Surface Water Use | Irrigation: 228[8]<br>Other: 75 | Irrigation: 69<br>Other: 23 |
| Surface storage | 213[9] | 65 |

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[1] The amount of infiltrated water is calculated from the amount of recharge water (36 km$^3$) and the efficiency of the structure (75% was assumed).

[2] In general the average number of mm was recalculated from the volume using the area of India (3'288'000 km$^2$).

[3] (Central Water Commission, 2005)

[4] (India Meteorological Department, 1971)

[5] (Chaturvedi, 1976)

[6] (Zade, et al., 2005)

[7] (Parikh, et al., 2007)

[8] (Central Water Commission, 2005), Data for year 2000, (Central Ground Water Board, 2006), difference between total and groundwater use

[9] (Central Water Commission, 2005), Data for 2002

Table 4: Indian Groundwater Balance

| **Groundwater Balance** | | |
|---|---|---|
| | km$^3$ | mm $^2$ |
| Annual Natural Recharge | 433[10] | 132 |
| Annual Groundwater Use | Irrigation: 213[10]<br>Other: 18 | Irrigation: 65<br>Other: 6 |
| Annual Natural Discharge Non-Monsoon | 34[10] | 10 |
| Annual Balance | 168[10] | 51 |
| Unsaturated Aquifer deeper than 3 m below Ground | 591[11] | 180 |

## 2.2 Spatial Variation

The parameters of the Indian water cycle (Figure 5, Table 3 and Table 4) are average values. India has high spatial variability of rainfall across the country, ranging from 150 mm at the west to 11690 mm at the northeast (Figure 6). Thus the water availability and the possibilities for MAR are very different in different parts of the country. The water cycle and groundwater quality in the different states will be outlined in Chapter 3.

## 2.3 Seasonal Variation

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 Indian rain period, the monsoon, comes either from the southwest or the northeast. All states are subject to the southwest monsoon that accounts about 74 %of the annual rainfall (Guhathakurta & Rajeevan, 2006), while Tamil Nadu and some stretches in the peninsular India are also subject to the north-east monsoon which accounts for about 11% of the annual rainfall.

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/day. The duration of the 90% wet period varies from 112 days in the central part of the country to 186 days in the north of the country (Deshpande & Singh, 2010).

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[10] (Central Ground Water Board, 2006)

[11] (Central Ground Water Board, 1996)

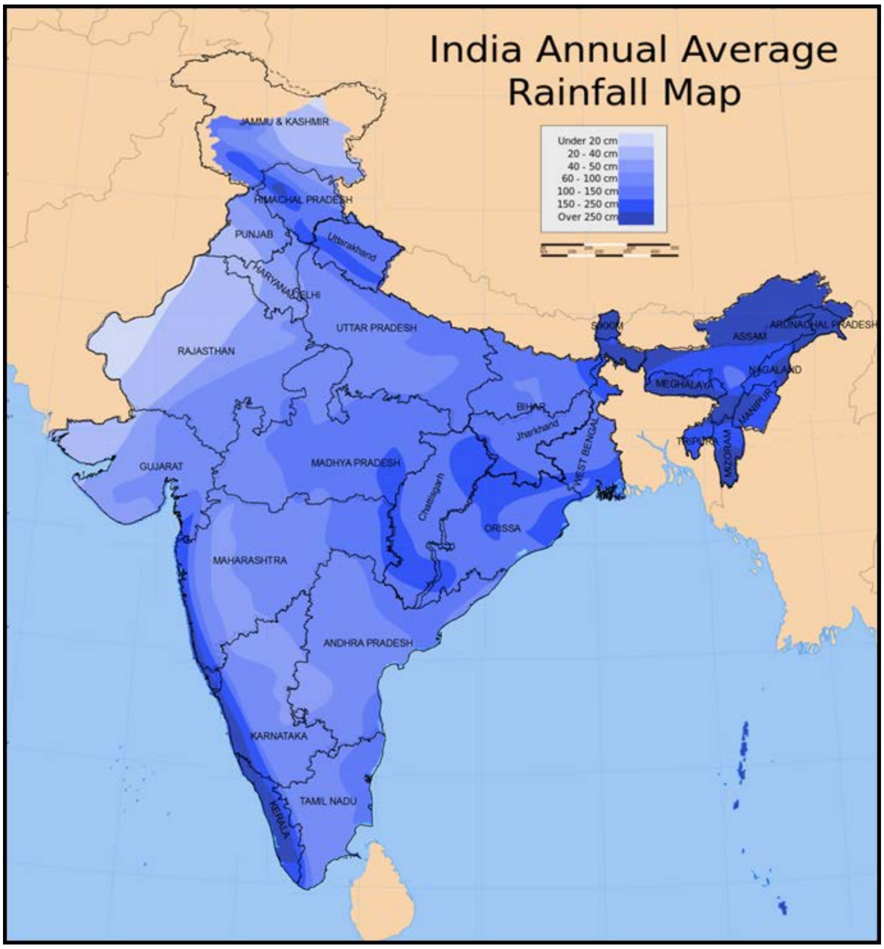


Figure 6: Indian average rainfall map of Indian Meteorological Department (Indian Meterological Department, 2004), modified

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.

## 2.4 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). 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 and India Infrastructure Research is above 600 km$^3$/year in 2010, which is somewhat higher than the values given by CGWB and CWC (total of 534 km$^3$ in 2005 Table 3). 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: Expected increase in total water consumption (Kumar, et al., 2005)

| | 1997/1998 | 2010 | 2025 | 2050 |
|---|---|---|---|---|
| Total consumption $km^3$ | 629 | 694-710 | 784-843 | 973-1180 |
| Increase (%) | | 12 | 29 | 71 |

# 3 Potential and Challenges of MAR in different States

## 3.1 Introduction and Data Sources

The challenges that can be addressed by MAR will be outlined below based on available water balance and groundwater quality data. In India, water resources development and management fall under state jurisdiction. Therefore the analysis is made state-wise.

Water quantity and quality data have been selected and complemented by calculations. They are presented in pictorial form for each state. The data used is briefly explained below. The water data (Annex 1) contain the following components: (i) PET (ii) Rainfall (iii) Surface Runoff Potential (iv) Surface Runoff Committed for Surface Storage, (v) Balance Surface Runoff, (v) Groundwater Potential, (vi) Groundwater Draft + Natural Discharge, (vii) Balance Groundwater (viii) Aquifer Storage Capacity, and (ix) Master Plan for Aquifer Recharge by CGWB. The water quality data (Annex 2) include salinity, fluoride, chloride, iron, nitrate, and arsenic.

### 3.1.1 Overall Balance

Precipitation, input of water, runoff, availability of surface water and PET are the primary driving variables of a hydrologic system.

India receives annual precipitation of about 4’000 km$^3$, including snowfall. The average annual **Rainfall** of the whole country is about 1’180 mm (Guhathakurta & Rajeevan, 2006). An isohyetal map (Indian Meterological Department, 2004), was used to calculate the average annual precipitation value of each state.

Zade et al, (Zade, et al., 2005) used remote sensing data, curve number approach and considered annual rainfall data of 376 stations, to develop a spatial variability map of one square kilometer units for **Surface Runoff** in the whole country. The sum of runoff estimated by Zade et al. is 2’439 km$^3$ which thus comprises both inter- and intra-basin runoff (i.e. runoff flowing within basins and runoff crossing basin borders). The Central Water Commission (CWC) estimated the inter-basin runoff to a total of 1’870 km$^3$ (Central Water Commission, 2005). In order to calculate the inter-state runoff the surface runoff of Zade et al. (2005) was scaled so that its total corresponds to 1870 km$^3$. The thus obtained state values are probably a bit low; the total of inter-state runoff is expected to be higher than the total of inter-basin runoff since states are smaller units. The **Surface Runoff Potential** in terms of depth (mm) for each state is given in Annex 1. By subtracting the runoff committed for **Surface Water Storage** (Central Water Commission, 2005) for each state from the **Surface Runoff Potential** of the respective state, the **Balance Surface Runoff** (mm)**,** which cannot be captured at the moment, is calculated.

### 3.1.2 Groundwater Balance

The **Net Recharge Volume** was calculated by the CGWB (Central Ground Water Board, 2006) from the rise in groundwater level, the land area and the aquifer porosity under consideration of the abstraction. The results were compared with an alternative calculation based on infiltration ratios, rainfall and surface water area. The **Draft** was given by the CGWB (2006) in the categories domestic, industry and irrigation, most likely based on a combination of statistical surveys and calculations. Also the **Natural Discharge during Non-Monsoon Season** was estimated by the CGWB. **Balance Groundwater** was calculated by subtracting draft and natural discharge during non-monsoon season from the net recharge. Normally a negative balance should reflect a sinking groundwater level. The state-wise **Aquifer Storage Capacity** was estimated by The CGWB (2002), considering the post monsoon thickness of the available unsaturated zone (deeper than 3 m below ground to avoid water logging) as the volume of unsaturated strata multiplied by their porosity. In the **Master Plan for Artificial Recharge** (2002) the CGWB suggested volumes for development of MAR in each state based on the availability of source water and capability of subsurface formations to accommodate it.

### 3.1.3 Groundwater Quality

Based on CGWB data for each state (Central Ground Water Board, 2012) the fraction of the districts was calculated where the concentration of the salinity, fluoride, chloride, iron, nitrate, and arsenic exceeded the Indian quality limits (Equation 1).

$$Fraction\ with\ exceeded\ quality\ limits\ = \frac{Number\ of\ districts\ with\ exceeded\ limits}{Total\ number\ of\ districts\ in\ the\ state} \text{(Equation 1)}$$

As shown in Table 7 for arsenic in Bihar the apparent fraction of a state affected by a certain kind of pollution varies greatly with resolution. 42% of the greater units (districts) have an arsenic problem, whereas only 11% of the smaller units (blocks) have one. It is to be expected that the fraction affected decreases with resolution if the number of observations is unchanged. This should be kept in mind and before concluding that one state has a widespread contamination problem more documents with higher resolution need to be evaluated. When choosing the resolution scale several factors have to be taken into account, like amount of available data, contaminant characteristics and possible origin, aquifer distribution and ground water flow.

Table 6: Water Quality Standards of India used by the CGWB. In general the “Acceptable Limits” are used, but for nitrate the lower “desirable limit” is used. (Government-of-India, 2009)

| Salinity | Fluoride | Chloride | Iron | Nitrate | Arsenic |
|---|---|---|---|---|---|
| 3000 µS/cm$^2$ | 1.5 mg/l | 1000 mg/l | 1.0 mg/l | 45 mg/l | 0.05 mg/l |

Table 7: Effect of resolution on fraction of affected regions shown with arsenic in Bihar (Ministry of Water Resources, 2012)

| Resolution | District | Block |
|---|---|---|
| Number affected by arsenic | 15/36 | 57/515 |
| Percentage affected by arsenic | 42% | 11% |

## 3.2 State descriptions

To help decide the prospect of MAR for each state, a pictorial representation of the state water data (Annex 1) and existing groundwater quality scenario (Annex 2) are presented for each state. The components of surface water and groundwater are presented separately to help identify the scope of surface runoffs availability for MAR practices and its implementation feasibility within the aquifer conditions of the state. The abbreviations used in the legend of the graphs are listed in Table 8.

Table 8: Abbreviations used for representing the components of water data

| | Abbreviation |
|---|---|
| Potential Evapotranspiration | PET |
| Rainfall | RAI |
| Surface Runoff Potential | RUP |
| Surface Water Storage | SWS |
| Balance Runoff | BRU |
| Ground Water Potential | GWP |
| Groundwater Draft and Natural Discharge | GWD |
| Groundwater Balance | GWB |
| Aquifer Storage Capacity | ASC |
| Master Plan for Aquifer Recharge by CGWB | MPR |

### 3.2.1 Andhra Pradesh

Located on the east coast of the southern peninsula, the average annual rainfall of the state is 912 mm per annum (variation from 500 mm to 1100 mm). The average annual PET of about 1731 mm is nearly double the rainfall. The state constitutes three major rivers, viz. Godavari, Krishna and Pennar, ten medium and a large number of minor rivers, which carry about 45% (415 mm) of the rainfall as surface runoff (Figure 7 and Annex 1). 31% (130 mm) of the surface runoff potential is committed for surface storage, and the balance 69% (285 mm) flows out of the state to the Bay of Bengal as the non-committed runoff.

The average level of groundwater development (or draft) of the state is about 50% (67 mm) of the groundwater potential of 133 mm. However, substantial areas in the state experience development beyond the safe level viz., 18% of total 1231 tehsils (tehsil is an administrative unit) in the state have reported over-exploited (groundwater draft higher than potential) (Central Ground Water Board, 2009). The aquifer storage capacity of those depleted groundwater areas estimated to be 1.1 $km^3$ (equivalent to 4 mm, when divided by the area of the whole state) is much smaller than the balance surface runoff available (285 mm). The contribution of MAR can thus be important in areas where groundwater levels are declining, but in the overall groundwater balance it will play a relatively minor role. The state is underlain by consolidated formations (85%), and remaining 15% is underlain by soft rocks including Gondwanas, Rajamundhri Sandstone and alluvium formations. The water quality scenario of Andhra Pradesh (Figure 7 and Annex 1) indicated that the state has problems with contamination of groundwater in all districts. The contaminants nitrate (100% of districts), fluoride (83%) and salinity (70%) were particularly prominent. Groundwater abstraction for drinking purposes would generally have to be coupled with post-treatment.

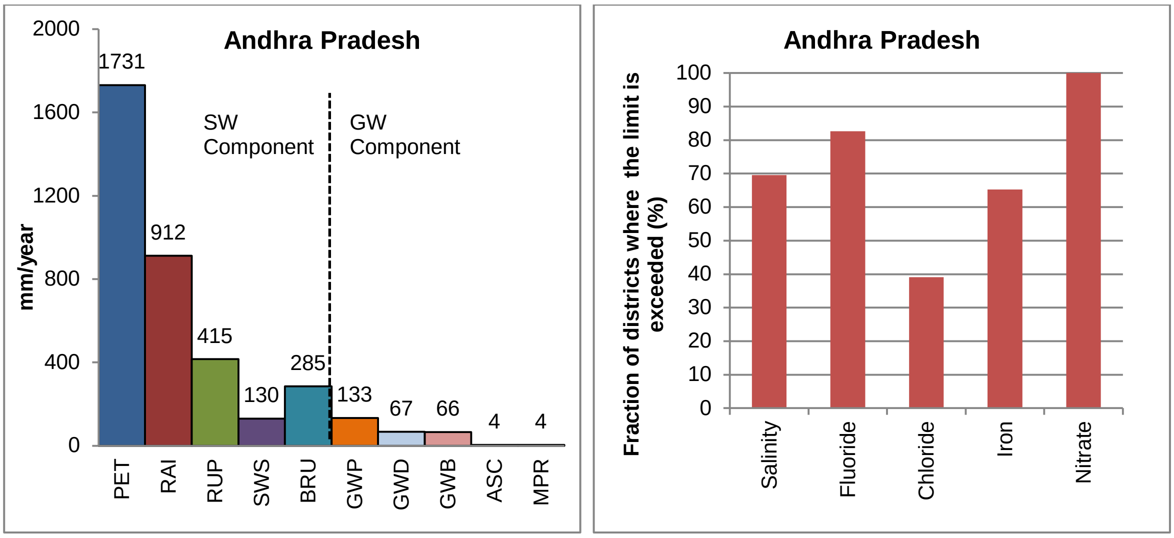
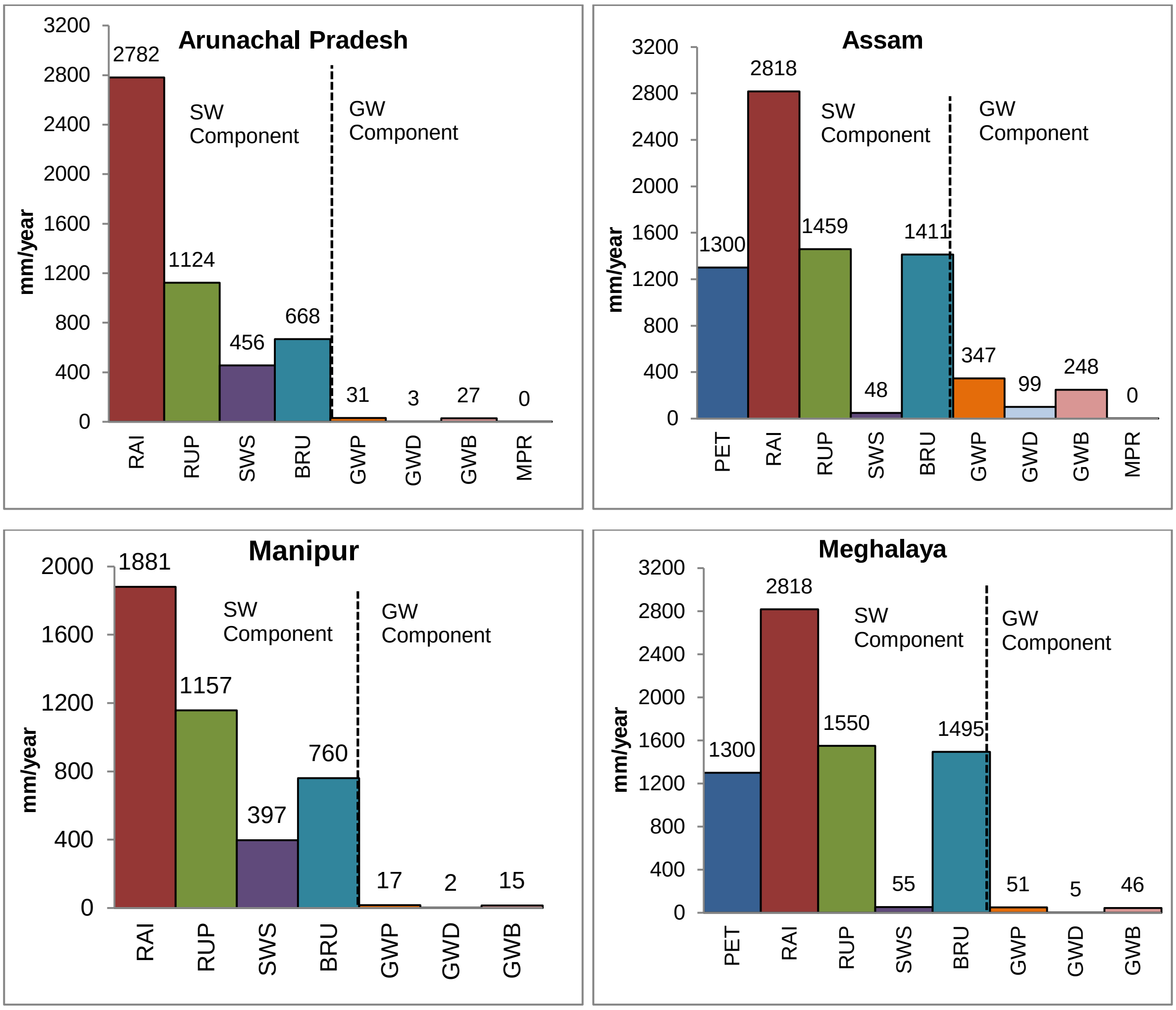


Figure 7: Water and groundwater quality scenario of Andhra Pradesh

### 3.2.2 North-Eastern States – Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura

The North-eastern states, known as eight sisters of India are part of the Brahmaputra-Barak basins except the Sikkim, which is a part of the Teesta River. The average annual rainfall of these states ranges from 1881 mm to 2818 mm. These states have large surface water runoff which ranges from 43% to 55% of the rainfall. Drinking water scarcity is a common problem in almost every state because of high topographic variations. All these states in the northeast, except Assam, have very low groundwater uses, the stage of development (or use) ranges between 0.04 % and 17% of groundwater potential. Assam is an exception with 28% groundwater development (Figure 8 and Annex 1).



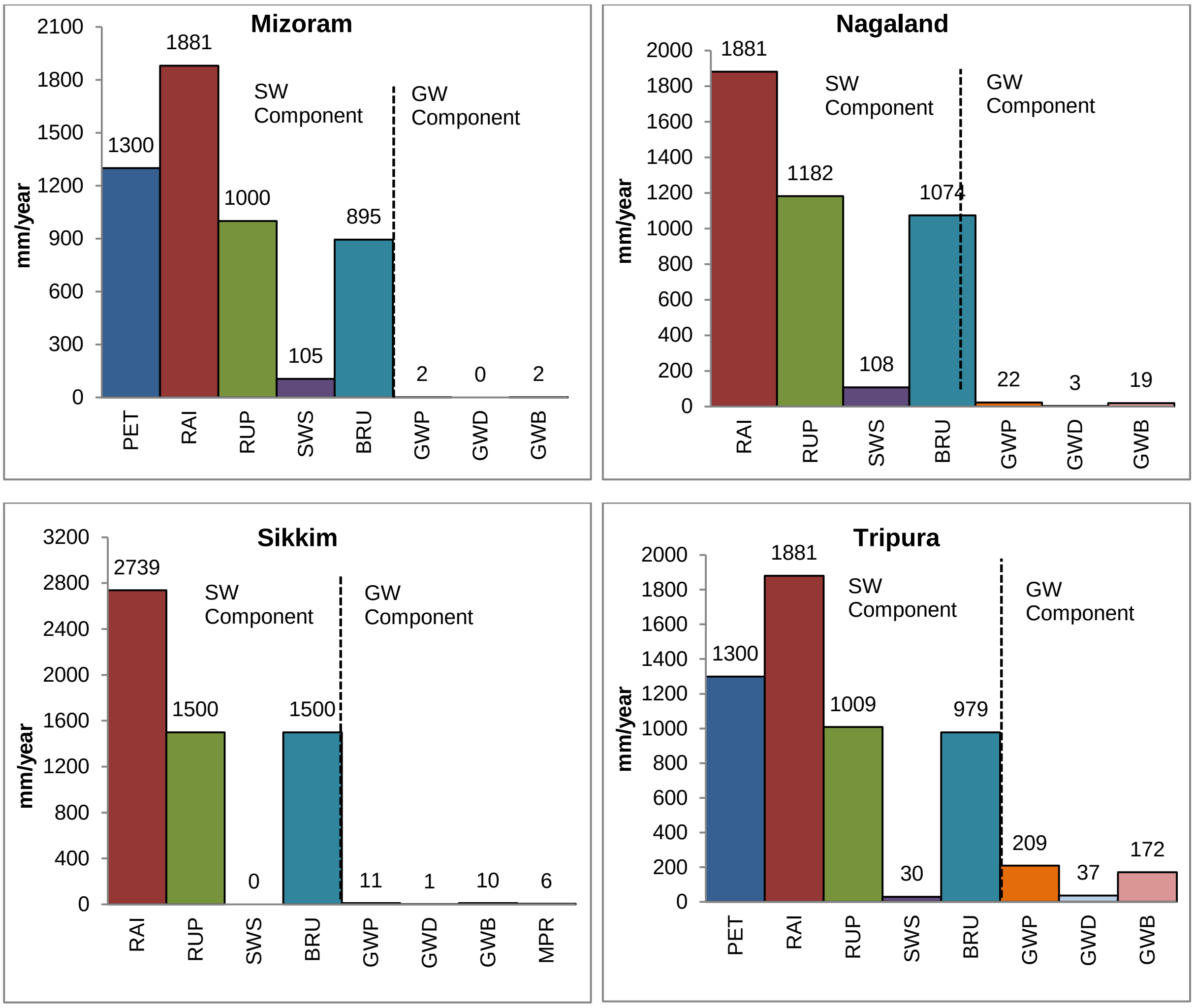
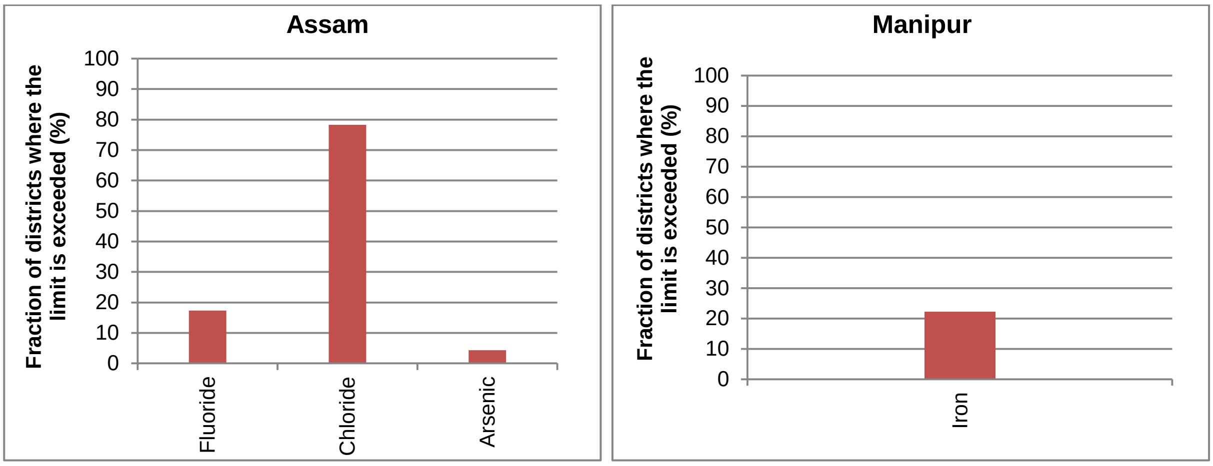


Figure 8: Groundwater scenarios for North-Eastern States

Compared to other states, the fraction of districts where groundwater of insufficient quality occurs is low in the Northeast. Assam has problems with fluoride (17% of districts), iron (78%), and arsenic (4%); Manipur (20%), Meghalaya (42%), and Tripura (100%) have problems with iron (Figure 9 and Annex 1).



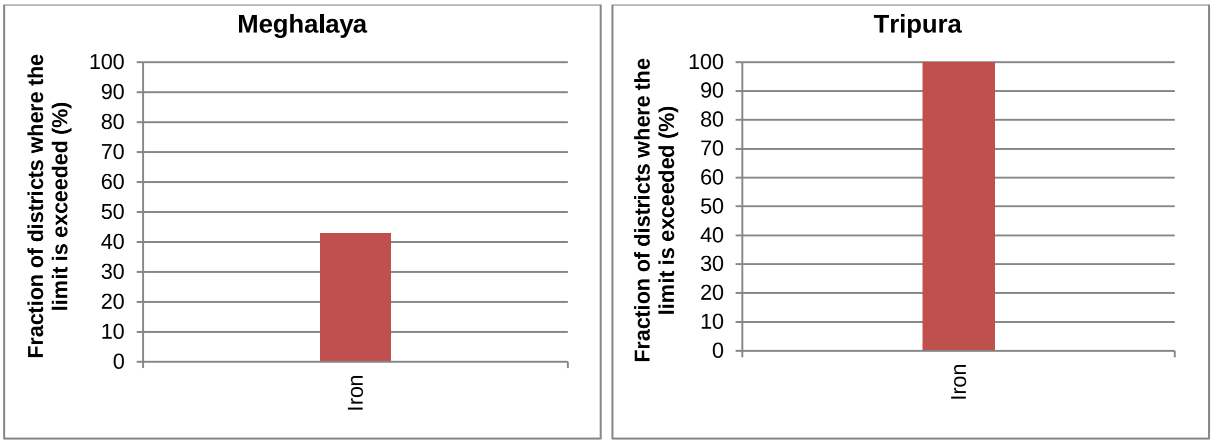


Figure 9: Groundwater quality in North-Eastern states.

### 3.2.3 Bihar

Bihar is a part of the Gangetic plains, and it has a network of 21 rivers including the Ganga. The average annual rainfall of the state is 1256 mm, and the PET is about 1401 mm (Figure 6 and Annex 1). The surface runoff potential (529 mm) is approximately 42% of the annual rainfall. 17% (89 mm) of the surface runoff potential is committed for surface storage. The remaining 83% (440 mm), mostly monsoon runoff, flows out unutilized from the state to the downstream state. In Bihar groundwater is predominantly used for irrigation and drinking water in rural areas.

The average level of groundwater development is about 43% of the groundwater potential of 310 mm. No areas had been categorized as unsafe in the context of groundwater development. However, as per the CGWB’s estimates, scope exist in some areas for aquifer storage. The aquifer storage capacity estimated to be 0.43 km$^3$ (equivalent to 5 mm, when divided by the area of the whole state) is much less than the balance surface runoff available (440 mm). The aquifer formations are mostly Indo-Gangetic alluvium except some areas in the southern part of the state where it is consolidated formations. Thus, hydrogeologically the state has a good potential for MAR practices.

The groundwater quality scenarios of the state indicate (Figure 7 and Annex 2) high levels of arsenic (41% of districts), iron (54%), fluoride (24%), and nitrate (24%). The contribution of MAR in places where groundwater quality is deteriorated can help dilution of concentration of contaminants in the groundwater.

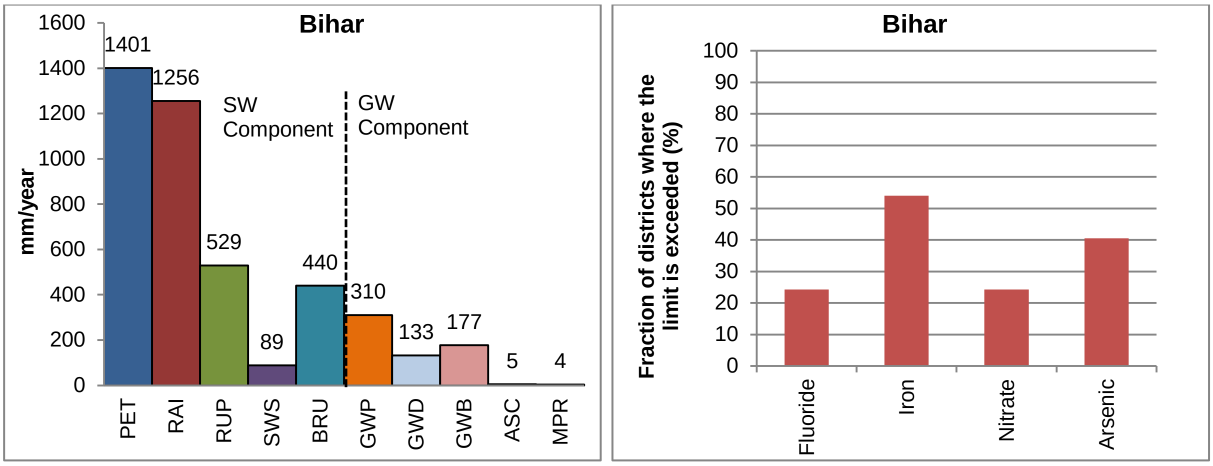


Figure 10: Water and groundwater quality scenarios of Bihar.

### 3.2.4 Chhattisgarh

The state comprises catchment area of Mahanadi, and Godavari basins and some parts of Ganga, Narmada and Subarnarekha basins. The average annual rainfall is 1292 mm, and the PET is 1482 mm (Figure 7 and Annex 1). The surface runoff potential (750 mm) is about 58% of the rainfall. 8% (57 mm) of the surface runoff potential is committed for the surface storage, and remaining 92% (693 mm) is the non-committed surface runoff.

The level of groundwater development of 30 mm is about 27% of the groundwater potential of 110 mm (Figure 7). No Tehsil in the state has been categorized as critical in the context of groundwater development. The state has a good potential of aquifer storage. The estimate of aquifer storage capacity by the CGWB of 3.26 $km^3$ (equivalent to 24 mm) is much less than the balance surface runoff (693 mm).

The groundwater quality of the state indicated high levels of fluoride (75% of districts), nitrate (75%), iron (25%) and arsenic (6%) (Figure 11 and Annex 2). The aquifer formations of the state are characterized by diverse rock types of different geological ages from Pre-Cambrian to Recent. As scope exists for aquifer storage and there is a large quantity of non-committed surface runoffs, MAR can contribute to the augmentation of aquifer storage and dilution of contaminants' concentration in groundwater where level of water quality is deteriorated.

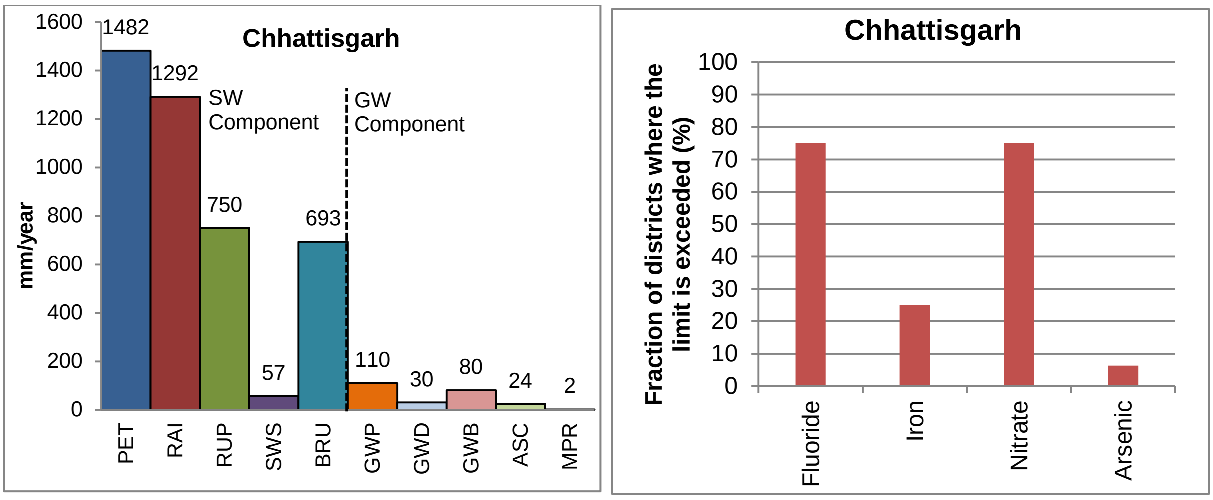


Figure 11: Water and groundwater quality scenario of Chhattisgarh.

### 3.2.5 Delhi

Delhi region is a part of the Indo-Gangetic plains. The average annual rainfall is 620 mm, of which 87% occurs during monsoon, and PET is 1700 mm. The surface runoff potential (347 mm) is about 56% of the rainfall (Figure 8 and Annex 1). There is no committed surface water storage in the Delhi region. Therefore, the entire quantity of surface runoff flows out from the region unutilized. MAR can thus contribute to retaining unutilized surface runoff for its subsequent beneficial uses. The level of groundwater development is 167% (337 mm) against the annual groundwater potential of 202 mm. The Delhi region thus has negative groundwater balance and a sinking groundwater level. The estimate of aquifer storage capacity of 0.44 km$^3$ (299 mm) is less close to the surface runoff potential of 347 mm. The groundwater quality measurements of the state indicate (Figure 8 and Annex 2) high levels of salinity (33% of districts), fluoride (56%), chloride (33%), and nitrate (78%). The state has good potential of MAR practices which will not only help augmentation of groundwater level but also dilution of concentration of contaminants in groundwater. Geologically, the Delhi is occupied by of the Quartzite of Delhi system and alluvial deposit classified into older and newer alluvium. Rooftop rainwater harvesting, percolation tanks, recharge wells, and uses of existing dug wells are MAR structures recommended by the CGWB.

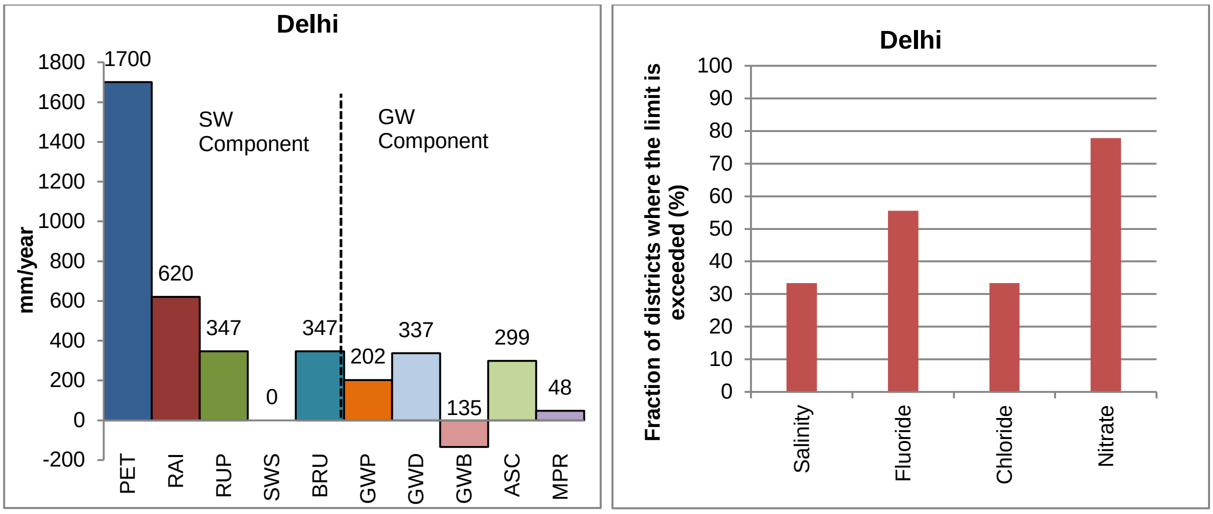


Figure 12: Water and groundwater quality scenarios of Delhi

### 3.2.6 Goa

Goa state located along the west coast is endowed with rich water resources with average annual rainfall of 3005 mm and the PET of 1659 mm is lower than the rainfall. The state has about 53% of the rainfall as surface runoff potential (1610 mm). 4.5%(73 mm) of the surface runoff is committed for surface storage leaving balance of 95.5% (1537 mm) that goes unused to the sea.

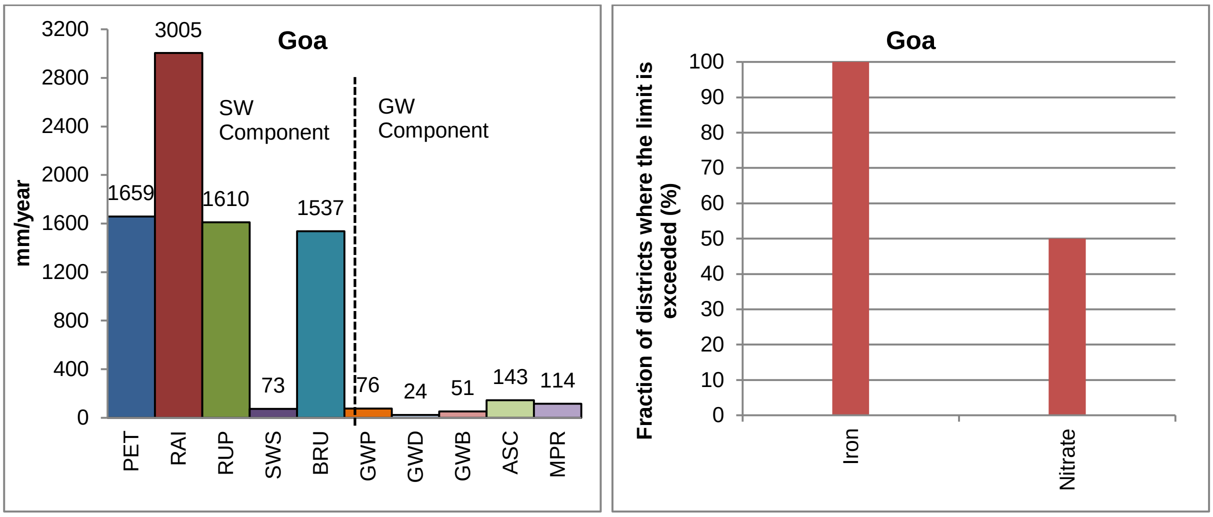


Figure 13: Water and groundwater quality scenarios of Goa State.

The level of groundwater development (24 mm) is about 31% of the groundwater potential of 76 mm, and the state has been categorized as safe in respect of groundwater development. The estimate of aquifer storage capacity showed scope of storing 0.5 km$^3$ (143 mm) in the aquifer Thus only a fraction of the balance surface runoff of 1537 mm can be captured with MAR. Groundwater quality measurements (Figure 13 and Annex 2) indicate that the water has high levels of iron (100% of districts), and nitrate (50%). The major part of the state is underlain by consolidated formation of Dharwar super group. Groundwater occurs under unconfined to semi-confined conditions in beach sands, laterites and weathered and fractured crystalline rocks. Check dams, and rooftop rainwater harvesting particularly in urban areas are MAR structures recommended by the CGWB.

### 3.2.7 Gujarat

The state has the average annual rainfall of 798 mm with variation from about 2000 mm in the extreme south to 300 mm in Kachchh district located in the north-west, while the PET is about 1768 mm (Figure 14 and Annex 1). The average surface runoff potential of 320 mm is 40% of the annual rainfall. 43% (140 mm) of the surface runoff potential is committed for surface storage and remaining 57% (180 mm) seems to be non-committed surface runoff; fraction of which can contribute to MAR.

The level of groundwater development (63mm) is about 78% of the groundwater potential of 81 mm. This indicates that largely the state is under the category of semi-critical condition of groundwater uses. 14% Tehsils out of 223 have a draft exceeding the available groundwater potential (Central Ground Water Board, 2009). Augmentation of groundwater storage is, therefore, essentially required to counter declining groundwater levels in the overexploited areas. The estimated aquifer storage capacity of 61 km$^3$ (equivalent to 313 mm (Central Ground Water Board, 2002)) is much higher than the balance surface runoff available of 180 mm (Figure 10). Part of the aquifer storage space can be fed from the excess surface runoff in feasible locations. Groundwater quality data (Figure 14 and Annex 2) showed problems with salinity (80% of districts), fluoride (72%), chloride (68%), iron (20%) and nitrate (88%). Geologically, the major part of the state is hardrocks comprise of gneisses, schists, rhyolites, sandstones and basalts. Remaining area in the north and central Gujarat is occupied by soft rocks including coastal alluvium. Percolation tanks, check dams and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

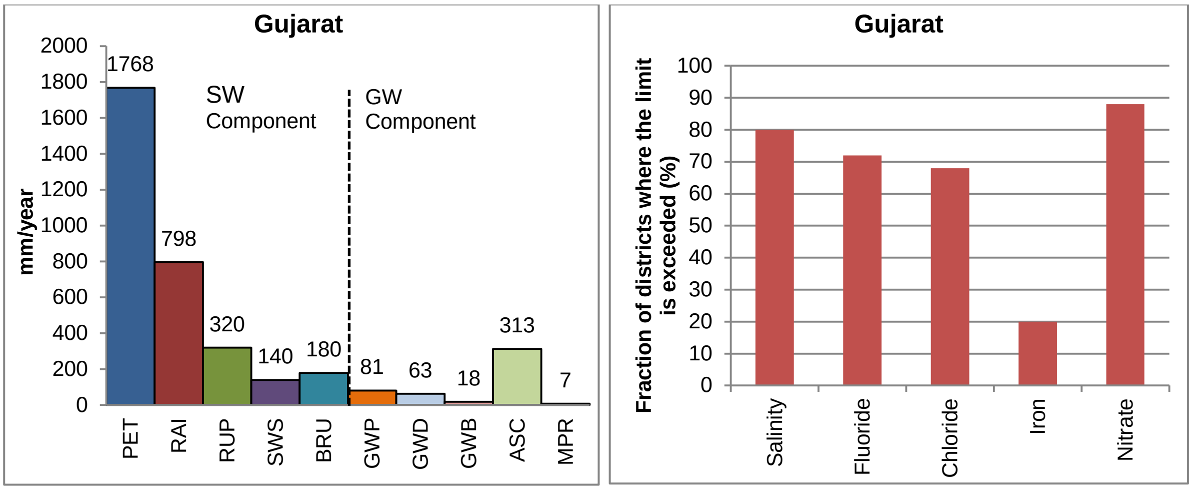


Figure 14: Water and groundwater quality scenarios of Gujarat state.

### 3.2.8 Haryana

The state constitutes part of the Ganga and Indus basin. Approximately, 97% of the state is situated in the Indo-Gangetic plain. The average annual rainfall of the state is about 617 mm, and the PET (1620 mm) is about 2.6 times higher. The surface runoff potential (281 mm) is about 45% of the rainfall (Figure 15 and Annex 1). 2% (6 mm) of the surface runoff potential is committed surface storage; remaining 98% (275 mm) is non-committed surface runoff, part of which in feasible locations could be used for MAR.

Drought is a common phenomenon in the south-western part of the state. Geologically, the major part is occupied by the alluvium formations. The southern part is occupied by consolidated formation of Delhi system, and in the northern part, Siwaliks are present. Haryana is one of the largest groundwater users for its dominant agricultural productivity, and rural drinking water supply. Excessive use of groundwater has led to a negative groundwater balance; the level of groundwater development (229 mm) is 109% of the annual groundwater resources potential of 211 mm. 41% of Tehsils have a groundwater draft exceeding the potential. The state has a good potential of aquifer storage (369 mm), higher than the balance surface runoff available (275 mm). Surface runoff harvest and its uses as MAR could significantly contribute in augmenting declining groundwater levels and in maintaining sustainability in groundwater uses.

Groundwater quality measurements in the state Figure 15 and Annex 2) show contamination with salinity (55% of districts), fluoride (70%), chloride (10%), iron (85%), and nitrate (95%). Recharge Pits and Recharge Shafts, and rooftop rainwater harvesting particularly in urban areas are MAR structures recommended by the CGWB.

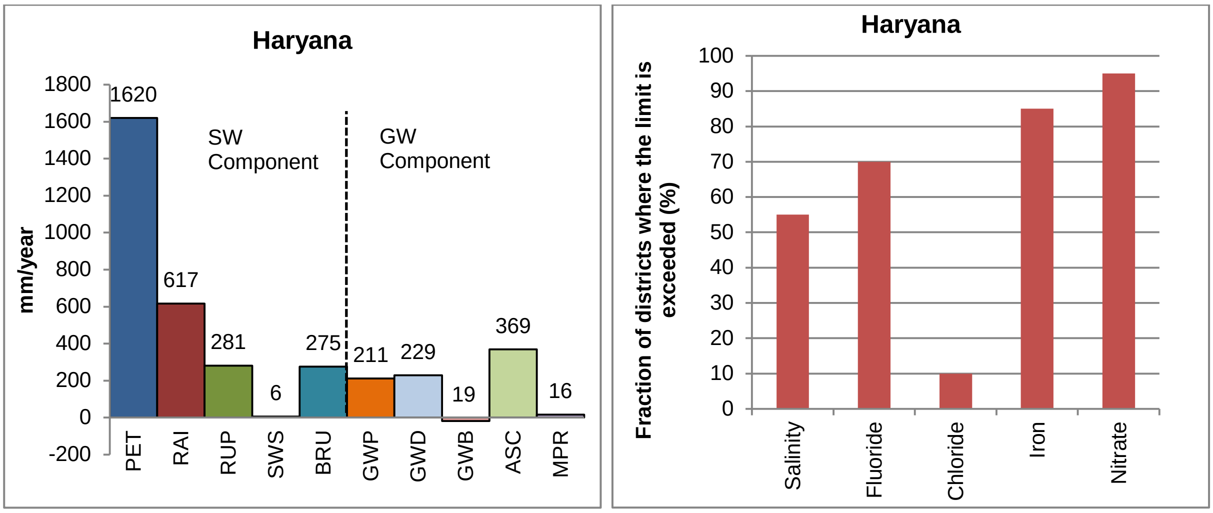


Figure 15: Water and groundwater quality scenarios of Haryana state.

### 3.2.9 Himachal Pradesh

Himachal Pradesh is one of the northernmost states and it has a good network of major river systems. The catchment of the river systems are also fed by snow and glacier melt water. The annual rainfall in the state varies from 900 mm to 2000 mm that gives an average annual rainfall of 1251 mm. The PET of 1300 mm is nearly equal to the average rainfall (Figure 16 and Annex 1). The surface runoff potential of 655 mm is about 52% of the rainfall and 43% (279 mm) are committed surface storage. The remaining 57% (376 mm) are non-committed surface runoff, a fraction of which can be used for MAR in feasible locations. The state topography essentially represents hilly terrain, comprising of fissured formations with a few inter-montage valleys occupied by Quaternary alluvium. Kandi belt and adjoining hill slopes are underlain by boulders, gravels and clays. As a result, the groundwater exploitation is limited to valleys and hill slopes areas.

The annual groundwater potential in the state is estimated to be 0.43 km$^3$. 30% thereof (0.12 km$^3$) has so far been brought to use mainly for drinking water supply and in some areas for agricultural uses. 8 mm and 3 mm are the potential groundwater resource and groundwater draft respectively in the context of the whole state (Figure 16). No specific estimate on aquifer storage capacity is available. However, (Central Ground Water Board, 2002) has given an estimate of potential groundwater recharge of 0.15 km$^3$ (equivalent to 10 mm) using structures like subsurface dykes, check dams, by rival of ponds and springs, and rooftop rainwater harvesting particularly in urban areas. No groundwater quality problem has been reported in the state.

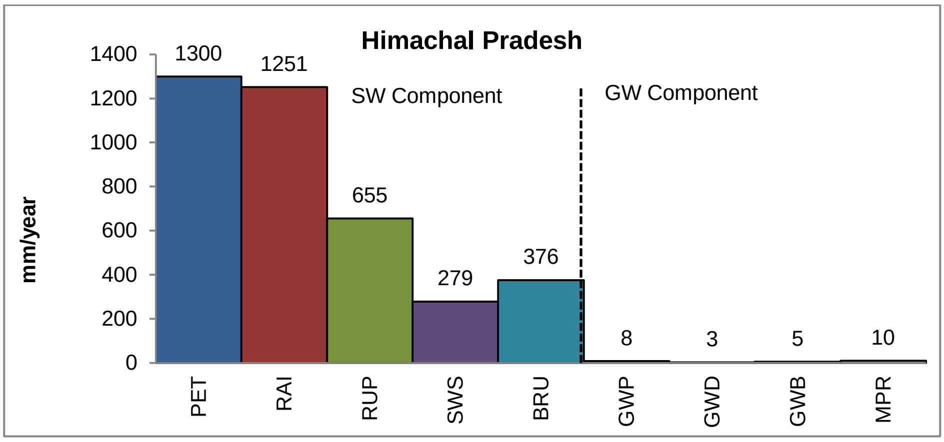


Figure 16: Water scenario of Himachal Pradesh.

### 3.2.10 Jammu and Kashmir

The Indus River system covers almost the entire state. The average annual rainfall of 1011 mm is slightly less than the PET of 1300 mm (Figure 17 and Annex 1). The runoff potential is 40% the rainfall (408 mm). About 2% (9 mm) of the surface runoff potential is the committed surface storage; remaining 98% (399 mm) is non-committed surface runoff, which may significantly change the groundwater balance if used for MAR in feasible locations. For example, the Kandi area in the state has acute water shortage problem. The major part of the state is occupied by high hills. The level of groundwater development of 0.33 km$^3$ (equivalent to 3 mm) is 29% of the groundwater potential of 2.7 km$^3$ (equivalent to 12 mm). Groundwater quality of the state (Figure 17 and Annex 2) showed high concentration of fluoride (14% of districts), iron (43%) and nitrate (14%). Sub-surface dykes, revival of Khandi ponds and rooftop rainwater harvesting in urban areas are MAR structures recommended by the CGWB.

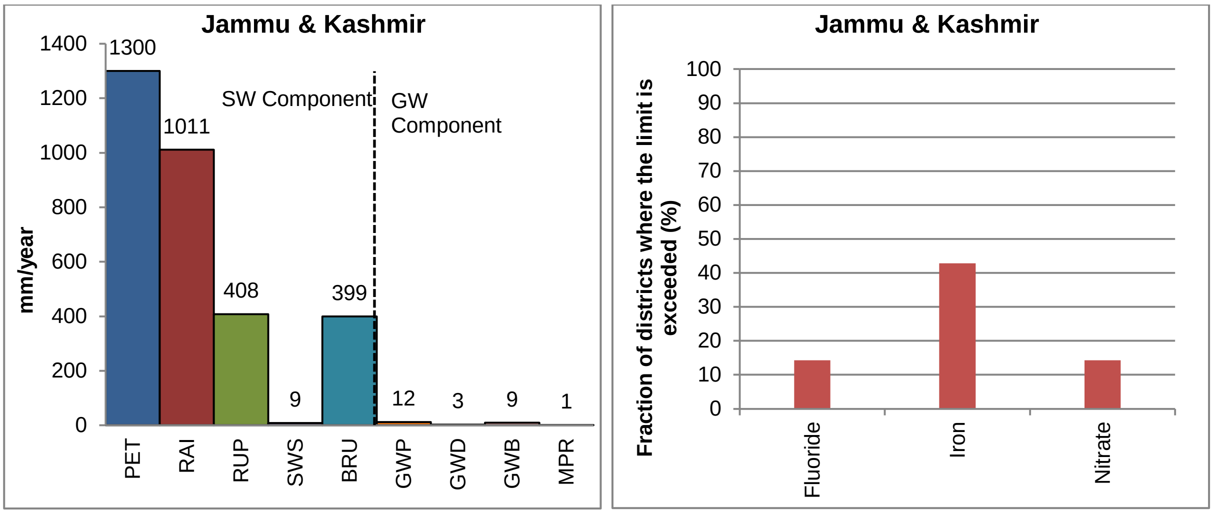


Figure 17: Water and groundwater quality scenarios of Jammu and Kashmir state.

### 3.2.11 Jharkhand

Figure 18 and Annex 1 give the state water scenarios. The river Ganga is the one of most important rivers of Jharkhand: the other rivers flow as tributaries to the river Ganga. Another river that flows in the state is Damodar. The average annual rainfall of the state is 1320 mm, and the PET is 1492 mm. The surface runoff potential (625mm) is about 47% of the rainfall. 20% (124 mm) of the surface runoff potential are committed to surface storage; the remaining 80% (501 mm) can contribute to MAR in feasible locations. The level of groundwater development is 26% (18 mm) of the groundwater potential (70 mm) and shows more scope of groundwater uses. The CGWB indicated potential aquifer storage of 0.69 km$^3$ (equivalent to 9 mm) which is much less than balance surface runoff of 501 mm. Maybe one reason is that 85% of Jharkhand are underlain by hard rocks consisting of granite, granite-gneisses and other formations.

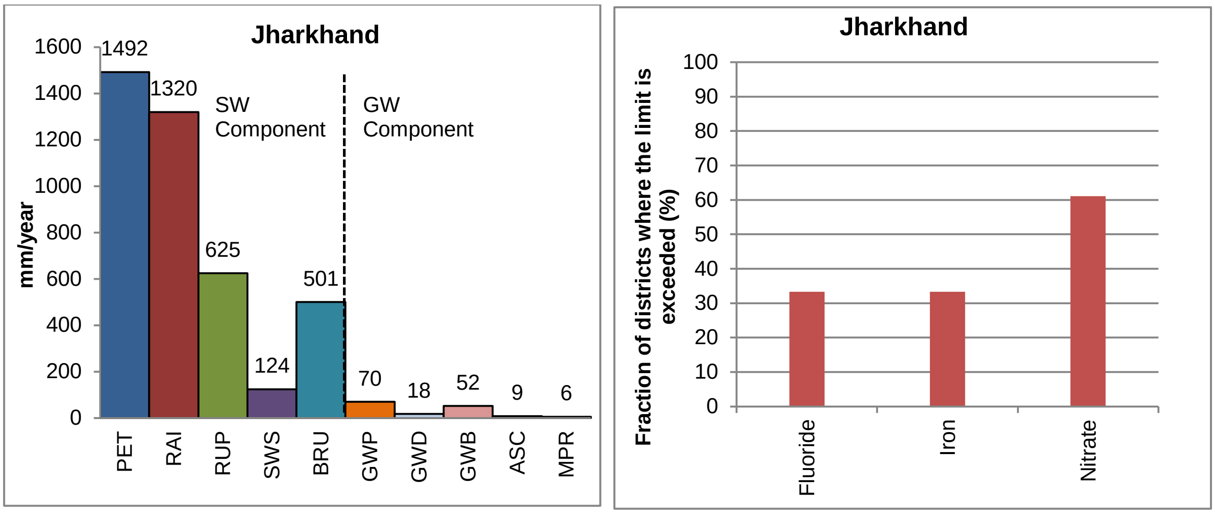


Figure 18: Water and groundwater quality scenarios of Jharkhand state.

Groundwater water quality measurements showed (Figure 18 and Annex 2) that the state has high levels of fluoride (33% of districts), iron (33%) and nitrate (61%). Percolation tanks, Contour trenches and Recharge shafts are MAR structures recommended by the CGWB.

### 3.2.12 Karnataka

The state has a network of six major river basins, viz. Godavari, Krishna, Cauvery, Palar, Ponnaiyar, and Pennar. The average annual rainfall of 1771 mm is higher than the PET of 1677 mm. The surface runoff potential (732 mm) is about 41% of the rainfall. 26% (188 mm) of the surface runoff potential is the committed surface storage. The remaining 74% (544 mm) is the non-committed surface runoff (Figure 19 and Annex 1). The level of groundwater development (59 mm) is nearly 71% of the groundwater potential of 80 mm. 37% of Tehsils have a groundwater draft exceeding the potential. MAR can help in increasing groundwater level using fraction of non-committed surface runoff. The CGWB identified scope for aquifer storage of 3.7 km$^3$ (equivalent to 19 mm) which is much less than the balance surface runoff of 544 mm. The state has diversified hydrogeological conditions occupied mainly by peninsular gneisses, granites, schists, basalts along with sedimentaries. The recent alluvium is restricted to coastal area. Groundwater quality measurements (Figure 19 and Annex 2) showed high salinity (26% of districts), fluoride (74%), chloride (15%), iron (81%), and nitrate (85%). Percolation tanks, sub-surface dams, check dams, and rooftop rainwater harvesting particularly in urban areas are MAR structures recommended by the CGWB.

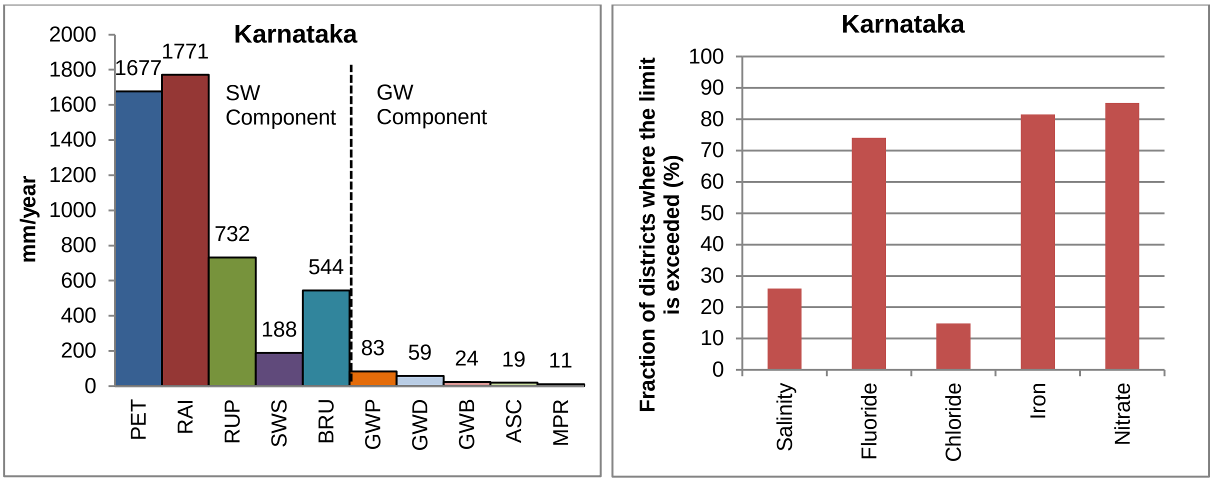


Figure 19: Water and groundwater quality scenarios of Karnataka state.

### 3.2.13 Kerala

The state has a network of 41 west flowing and 3 east flowing rivers. The average annual rainfall of the state (3055 mm) is much higher than the PET (1700 mm). The surface runoff potential corresponding to the rainfall is expected to be about 36% (1115 mm) (Figure 20 and Annex 1). 20% (221 mm) of the potential surface runoff is committed surface storage; the remaining 80% (895 mm) flows out to the sea unutilized. The level of groundwater development (91 mm) is about 47% of the groundwater potential of 176 mm. 3% of Tehsils are overexploited (draft>groundwater potential). The aquifer storage capacity of 1.5 $km^3$ (equivalent to 39 mm) is small, limiting the potential for MAR in the state. The major part of the state is underlain by crystalline rocks. At places, sedimentary formations overlie the crystalline rocks mainly in the western part of the state. The coastal belt is occupied by alluvial deposits of recent origin. The groundwater quality measurements (Figure 20 and Annex 2) show mainly contamination with iron (100%) and nitrate (79%). Check dams, sub-surface dykes, gully plugs, contour trenches, and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

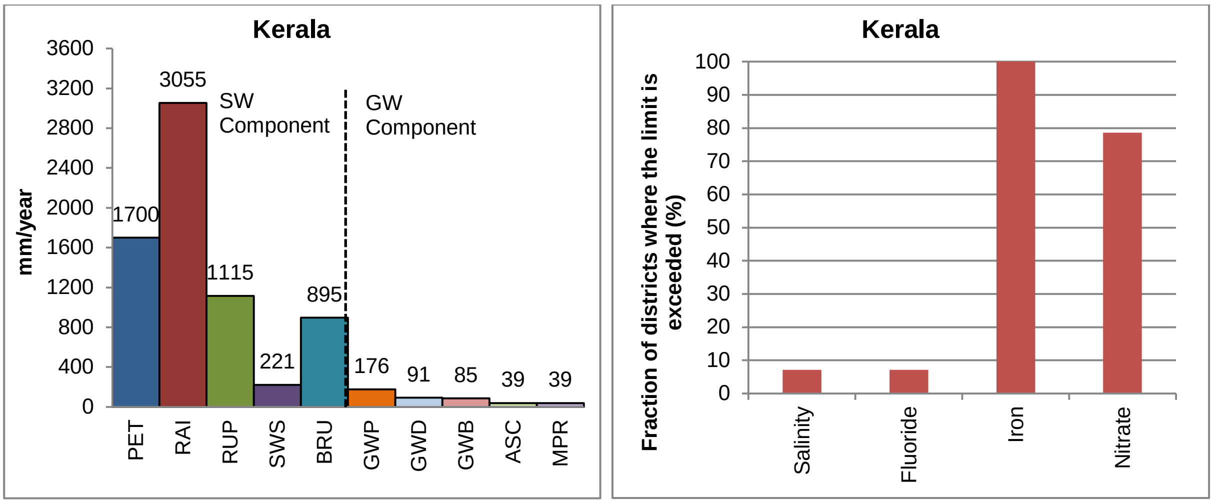


Figure 20: Water and groundwater quality of Kerala state.

### 3.2.14 Madhya Pradesh

The state has a network of five major river basins, namely; Ganga, Narmada, Cauveri, Tapi, and Mahi. The average annual rainfall of the state is 1178 mm, and the PET is 1573 mm (Figure 21 and Annex 1). The surface runoff potential (577mm) is 49% of the average annual rainfall. The fraction of committed surface runoff for surface storage is 24% (136 mm) and the balance surface runoff is 76% (442 mm). The level of groundwater development (62 mm) is 51% of the groundwater potential of 121 mm. Although the overall groundwater use is low 8% of Tehsils are overexploited. The estimated aquifer storage capacity of 2.84 km$^3$ (equivalent to 9 mm) is much less than the balance surface runoff available (442 mm). The sub-surface of the state by and large consists of hardrock formations. Groundwater measurements indicates that the main contaminants are fluoride (40% of districts), iron (52%), and nitrate (96%) (Figure 21 and Annex 2). Percolation tanks, Check dams, Recharge shafts, Gully Plugs, and Gabion structures are MAR structures recommended by the CGWB.

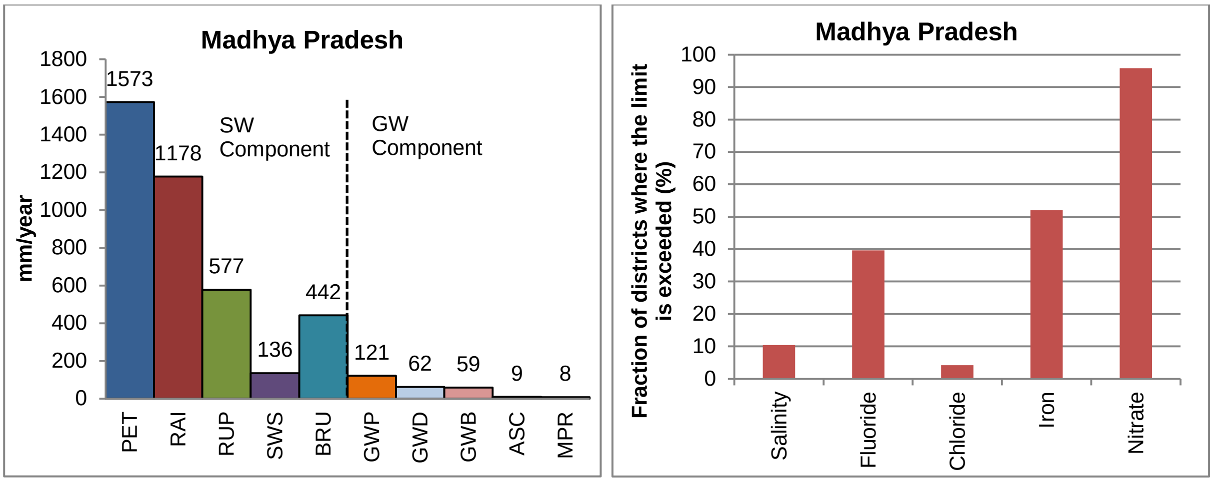


Figure 21: Water and groundwater quality scenarios of Madhya Pradesh state.

### 3.2.15 Maharastra

The state occupies catchments of four river basins, namely; Godavari, Krishna, and Tapi-Purna. The average annual rainfall (1456 mm) is 87% of the PET (1682 mm) (Figure 22 and Annex 1). The surface runoff potential is about 35% of the rainfall. 25% (131 mm) of the surface runoff potential is the committed surface water storage; remaining 75% (379 mm) is the non-committed surface runoff, fraction of can be used for groundwater recharge. The level of groundwater development (55 mm) is about 51% of the groundwater potential (107mm). 2% out of 318 Tehsils have a groundwater draft exceeding the potential. The aquifer storage capacity of 11.2 km$^3$ (equivalent to 37 mm) is much less than the balance surface runoff (379 mm). About 85% of the state is covered by Deccan basalts and rest is occupied by Gondwanas, Vindhyans, Archaeans and Quaternary alluvium.

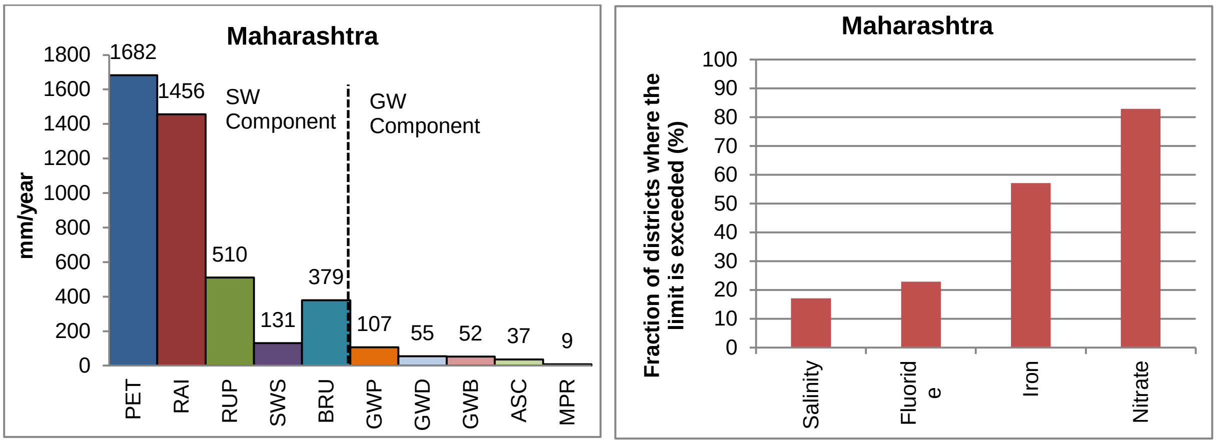


Figure 22: Water and groundwater quality scenarios in Maharastra state.

Groundwater quality measurements (Figure 22 and Annex 2) show contamination with salinity (17% of districts), fluoride (23%), iron (57%) and nitrate (83%). Percolation tanks, Cement Plugs, Recharge shafts, Rooftop rainwater harvesting are MAR structures recommended by the CGWB.

### 3.2.1 Orissa

The state comprises areas of 8 major river basins, in which Mahanadi is the largest. The average annual rainfall (1489 mm) is nearly same of the PET (1500 mm). The surface runoff potential (650 mm) is about 44% of the rainfall. The committed surface storage (262 mm) is 40% of the surface runoff potential (Figure 23 and Annex 1). The balance surface runoff of 388 mm flows to the Bay of Bengal unutilized. The level of groundwater development is about 27% of the groundwater potential (148 mm). Very limited scope for aquifer storage was identified (2 mm) (Central Ground Water Board, 2002) compared to the available runoff balance (388 mm). The state is underlain by diverse rock types, consolidated rock formations which include, hard, crystalline and compact sedimentaries. The semi-consolidated formations include Gondwanas. The unconsolidated formations consist of laterites and alluvium. The state has some groundwater quality problems (Figure 23 and Annex 2) with fluoride (37% of districts), iron (67%), and nitrate (93%). Percolation tanks, Sub-surface dykes, Contour bunds, Check dams, Water spreading, Induced recharge and Recharge shafts are MAR structures recommended by the CGWB.

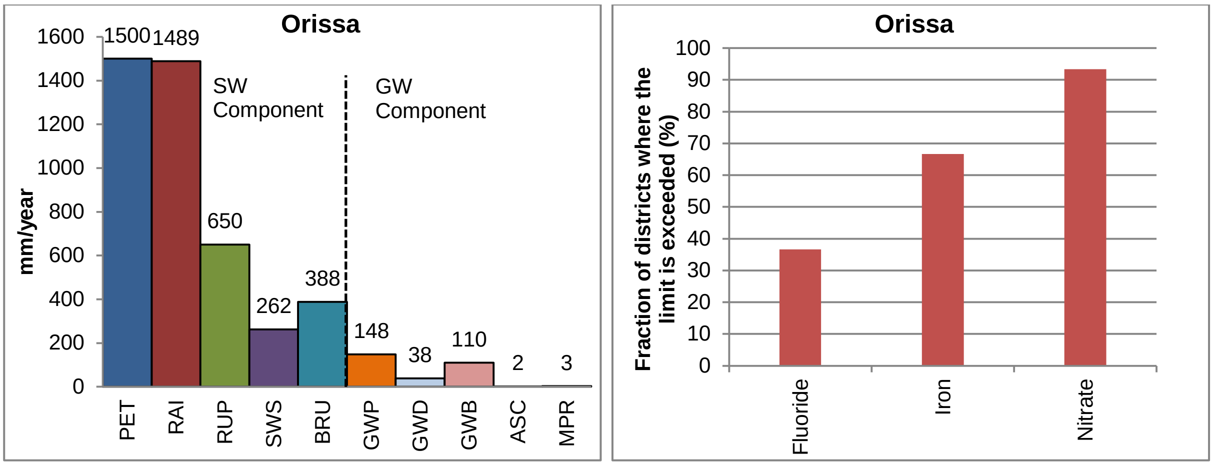


Figure 23: Water and groundwater quality scenarios of Orissa state.

### 3.2.2 Punjab

Punjab encompasses part of the Indus river systems. It has average annual rainfall of 649 mm. The PET (1490 mm) is double the rainfall. The surface runoff potential (310 mm) is 48% of the rainfall. 15% (48 mm) of the surface runoff potential is the committed surface storage. A part of the remaining 85% (262 mm) of the surface runoff potential could contribute to MAR. The level of groundwater development was 141% (665 mm) of the annual replenishable groundwater resources of 472 mm (Figure 24 and Annex 1). The state's aquifers have considerable potential of sub-surface storages. The estimated aquifer storage capacity of 375 mm is more than the balance surface runoff (262 mm). The scope for MAR identified by the CGWB is a modest 24 mm. Possibly treated wastewater could add to MAR potential. The state is mainly underlain by Quaternary alluvium of considerable thickness, which abuts against the semi-consolidated formation of Siwalik system towards northeast. Groundwater quality measurements (Figure 24 and Annex 2) indicate problems with salinity (35% of districts), fluoride (65%), chloride (12%), iron (53%), and nitrate (94%). Recharge shafts, Recharge Trenches, and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

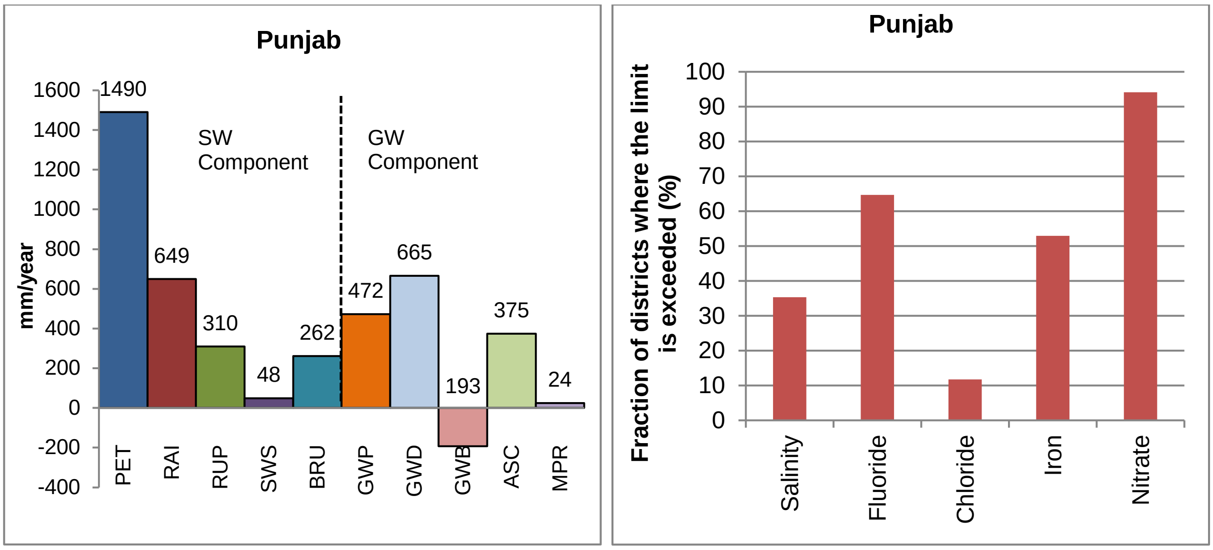


Figure 24: Water and groundwater quality scenarios of Punjab State.

### 3.2.3 Rajasthan

Rajasthan is the driest and most water deficient state of India. The state has a network of 14 river basins, which are seasonal in nature. The average annual rainfall of 494 mm is 28% of the PET (1735 mm) (Figure 25 and Annex 1). The surface runoff potential (237 mm) is 48% of the annual rainfall. 14% (34 mm) is the committed surface storage; a fraction of the remaining 86% (203 mm) can contribute to MAR. The state mainly relies on groundwater for its agricultural and drinking water. The level of groundwater development (41 mm) is 121% of the groundwater potential (34 mm). The aquifer storage capacity is a considerable 96 mm, but the CGWB has only identified limited scope for MAR (3 mm). (202 mm). Unconsolidated and semi-consolidated formations occupy major part of the state. Groundwater quality measurements show (Figure 25 and Annex 2) widespread contamination with Salinity (81% of districts), fluoride (94%), chloride (47%), iron (88%), and nitrate (100%). Percolation tanks, Anicuts, Recharge Shafts and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

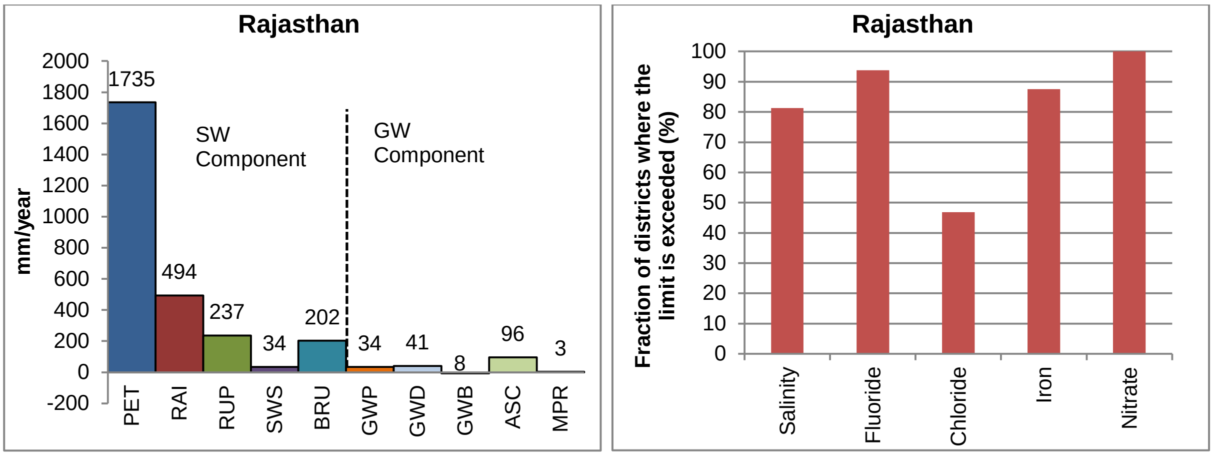


Figure 25: Water and groundwater quality scenarios of Rajasthan state.

### 3.2.4 Tamil Nadu

The state being located along the Bay of Bengal has many rivers flowing within its geographical boundary. Except for the Thamarabharani River, all rivers are ephemeral and flow only for a short time in the year. The state receives rainfall from south-west (52%) as well as north-east (28%) monsoons, and the average annual rainfall is about 998 mm, while the PET is expected to be 1726 mm (Figure 26 and Annex 1). The surface runoff potential (421mm) is approximately 42% of the rainfall. 12% (52 mm) of the surface runoff potential is the committed surface storage; remaining 88% (369 mm) is the excess runoff that flows out from the state non-committed. The level of groundwater development (152 mm) is 86% of the groundwater potential (177 mm). 39% of Tehsils have declining groundwater levels. The estimate of aquifer storage capacity of 21 mm is much less than the balance surface runoff of 369 mm. Thus the potential quantity of MAR is limited by storage capacity. Geologically, 73% of the state is characterized by hard rocks, semi-consolidated and consolidated formations. Groundwater quality measurements show (Figure 26 and Annex 2) problems with salinity (47% of districts), fluoride (57%), chloride (27%), iron (7%) and nitrate (90%). Percolation tanks, check dams and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

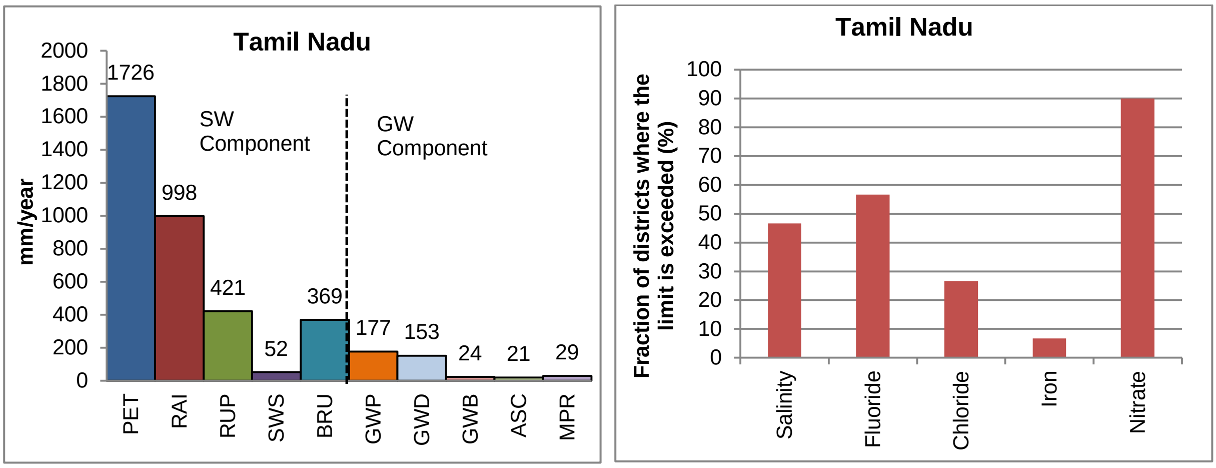


Figure 26: Water and groundwater quality scenarios of Tamil Nadu state.

### 3.2.5 Uttar Pradesh

The state is a part of the Ganga, Yamuna, Ramganga, Gomti, Ghagra and Son sub-basins. The PET (1476 mm) is about 25% higher than the average annual rainfall (1196 mm). The surface runoff potential (515 mm) is approximately 43% of the rainfall (Figure 27 and Annex 1). The committed surface storage (153 mm) is about 30% of the surface runoff potential and surplus runoff is 70% (362 mm), a fraction of which can be trapped for augmentation of groundwater resources in feasible locations. The state is one of Indias largest users of groundwater. The level of groundwater development (228 mm) is about 72% of the groundwater potential (317 mm). The aquifer storage capacity of 93 mm showed it has good potential of sub-surface storage and the CGWB identified considerable scope for MAR (63 mm). The state has three distinct hydrogeological units- Bhabar, Terai, and Central Ganga plains. Bhabar is the recharge zone having deeper water levels. The alluvial plains and southern rocky terrain are mainly the water bearing formations. Groundwater quality measurements (Figure 27 and Annex 2) show high levels of salinity (4% of districts), fluoride (14%), chloride (3%), iron (21%), nitrate (60%), and arsenic (13%). Percolation tanks, Cement Plugs, Recharge Shafts, and rooftop rainwater are MAR structures recommended by the CGWB.

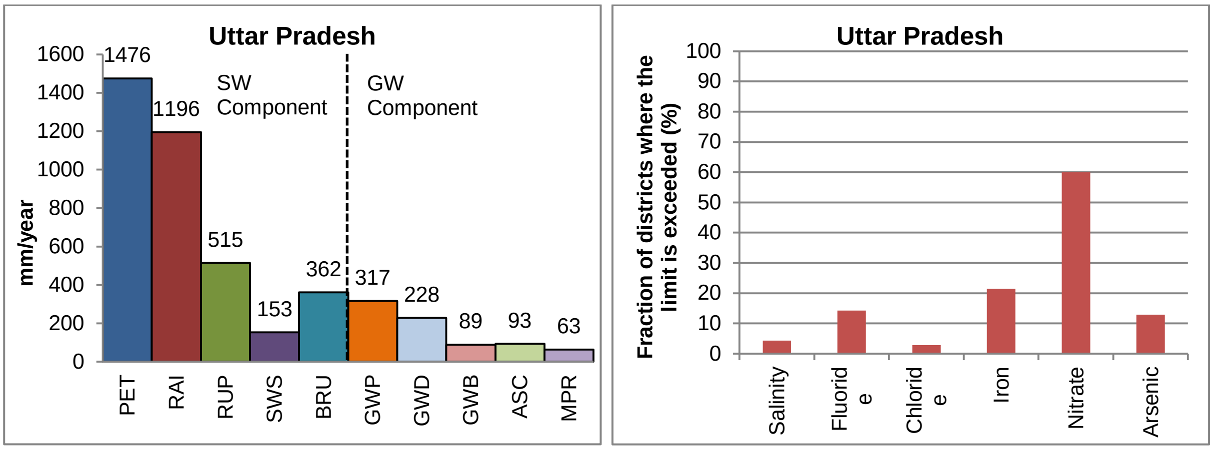


Figure 27: Water and groundwater quality scenarios in Uttar Pradesh state.

### 3.2.6 Uttarakhand

Uttarakhand is a part of the Himalayan and sub-Himalayan zone. Alaknanda, Bhaghirathi, Ghori Ganga, Kali, Pindar, Ramganga, Sarayu, the Ganges, and Yumana are the main river systems of the state. The state receives average annual rainfall of about 1583 mm. The PET (1300 mm) is less than the rainfall. The surface runoff potential (731 mm) is about 46% of the rainfall 22% of which (162 mm) is committed for surface storage (Figure 28 and Annex 1). Remaining 78% (569 mm) is flows out from the state non-committed. Fraction of the excess surface runoff can be used for MAR in locations where groundwater levels are shrinking. The level of groundwater development is about 69% of the groundwater potential (42 mm). The Uttarakhand has varied hydrogeological setups consisting of gangetic alluvial plains and Himalayan mountain belt. Compared to other states, it has no major groundwater quality data problems, only contamination with nitrate in 20% of districts (Figure 28 and Annex 2). MAR structures similar to those of Uttar Pradesh are recommended by the CGWB.

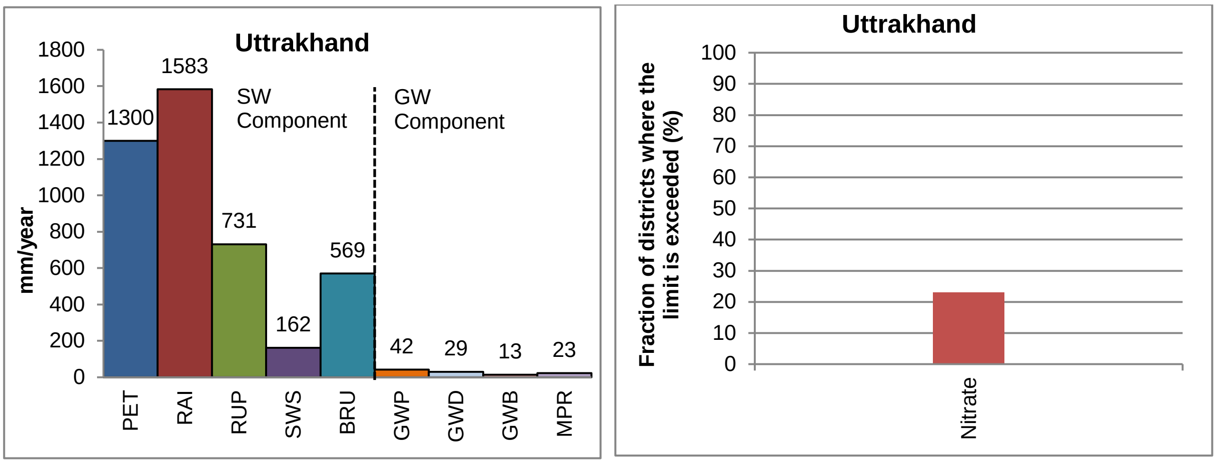


Figure 28: Water and groundwater quality scenarios of Uttarakhand state.

### 3.2.7 West Bengal

The state has three major river systems, namely the Ganga, Bhrahmaputra, and Subernarekha. The average annual rainfall (2089 mm) is much higher than the PET (1443 mm). The surface runoff potential (872 mm) has been estimated to be about 42% of the rainfall (Figure 29 and Annex 1). 2% (19 mm) thereof are committed to surface storage and the remaining 98% (853 mm) flows out from the state. The level of groundwater development of 164 mm is 57% of the groundwater potential of 342 mm. As can be expected for a coastal humid stated, the identified aquifer storage capacity (23 mm) is much lower than the balance surface runoff (852 mm). The MAR scope is similar to the aquifer storage capacity (23 mm) Geologically, two-third of the area of the state is occupied by unconsolidated sediments and remaining part has hard rock formations. The state has some groundwater quality problems (Figure 29 and Annex 2) with salinity (17% of districts), fluoride (44%), chloride (11%), iron (83%), nitrate (11%) and arsenic (44%). Arsenic contamination has been reported to be one of the biggest natural calamities in the state. Percolation tanks with shafts, Gabian structures, Cement Plugs, Re-excavation of village ponds, Sub-surface dykes, and rooftop rainwater harvesting are MAR structures recommended by the CGWB.

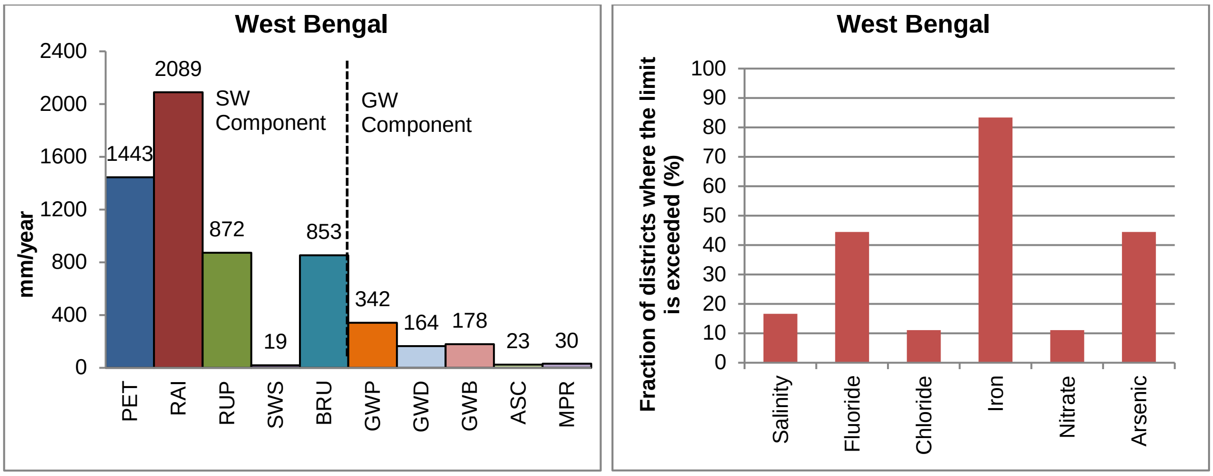


Figure 29: Water and groundwater quality scenarios of West Bengal state.

# 4 MAR Experience in India

## 4.1 Coordinated Actions for Promoting Artificial Recharge and Rainwater Harvesting

### 4.1.1 Pilot Schemes of the Central Ground Water Board (CGWB)

The Central Ground Water Board (CGWB), a subordinate office of the Ministry of Water Resources, Government of India, is entrusted with the responsibilities of providing scientific inputs for management, exploration, monitoring, assessment, augmentation and regulation of groundwater resources of the country. (Central Ground Water Board, 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 groundwater depletion, sea water ingress, groundwater contamination, conjunctive use of surface and groundwater, water balance are also part of the CGWB activities. The CGWB also organises internal and external capacity building activities as well as mass awareness campaigns on the importance of water conservation and judicious groundwater management (Central Ground Water Board, 2012).

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 9). 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 were to be constructed 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 (Table 9) 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” (Central Ground Water Board, 2012).

Table 9: Artificial Recharge Studies undertaken by the CGWB during different five year plans (Chadha, 2012; Central Ground Water Board, 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<br>(Total States – 4)<br>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)<br>Pilot projects 82; 1475 structures | 1000 |

The CGWB Perspective Plan for Artificial Recharge (1996) was prepared to use surplus non-committed runoff. A first estimation of the non-committed surplus monsoon run off available for recharge in India was made 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 for each basin the lowest of those two values the “feasible groundwater storage” can be 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.

As a sequel to the Perspective Plan, the Master Plan for Artificial Recharge to Groundwater (Central Ground Water Board, 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 above.

Table 10: List of Structures proposed under the Master Plan (Central Ground Water Board, 2002)

| | |
|---|---|
| Area Identified for Artificial Recharge | 448’760 $km^2$ |
| Volume of water to be recharged | 36.5 $km^3$ |
| | |
| Number of structures in rural areas | 225’000 |
| Number of structures in urban areas (rooftop rainwater harvesting) | 3’700’000 |
| Total number of structures proposed | 3’925’000 |
| Total cost of structures proposed | 245’000 MINR |
| Check Dams/Cement Plug/Anicuts | 110’000 |
| Recharge Shafts and Dug wells | 48’000 |
| Gully Plugs /Gabion Structures | 26’000 |
| Development of Springs | 2’700 |
| Revival of Ponds/Tanks | 1’000 |

A revised Master Plan will be published in 2012 including those experiences and taking additional identified non committed runoff (about 85 $km^3$) for utilization for water conservation /MAR projects.

### 4.1.2 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 (over 0.5 Million according to Saktivadivel (2007), there among 0.25 Million in hardrock areas and 80.000 only in Gujarat (Chadha, 2012). Several agencies in India provide financial support for constructions which will 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 11).

The Department of Land Resources have integrated and consolidated three programmes namely, Drought Prone Areas Programme (DPAP), Desert Development Programme (DDP) 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, checkdams 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 107’000 km$^2$ have been sanctioned. A total number of 770 projects covering an area of 49’000 km$^2$ were completed until 2011. Other projects are at various stages of implementation in different States. Central funds to the tune of INR 43'616 million have been released up to December 31, 2012 (Ministry of Rural Development, 2012)

The Ministry of Water Resources writes (2007) “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 scheme was introduced in 2005 in order to restore these bodies, one of the ten goals being 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 3000 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 restoration 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 Repair, Renovation and Restoration 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$^2$ of additional irrigated land, at least 28’000 km$^2$ should be irrigated with groundwater and 10’000 km$^2$ as a consequence of the RRR scheme (Ministry of Water Resources, 2012). The additional water demand will be drawn partly from existing groundwater potential, but likely also additional potential will 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 (Ministry of Rural Development, 2010). The National Rural Drinking Water Programme was performed with the objective to move away from over dependence on 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, Government of India. 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, including subsidy component of INR 14'993 million. This project was implemented in seven states to recharge the existing dug wells, 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).

Table 11: Main features of some important programs of the Government of India involving MAR

| Year | Name of the Program | Financing Organization | Budget | Additional Info |
|---|---|---|---|---|
| 1995- | Integrated Watershed Management Program (IWMP) | Ministry of Rural Development, Government of India | INR 43'616 million released until 2012.<br>(EUR 633 million) | 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; EUR 871 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, Government of India | INR 223'992 million (EUR 3’249 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 261 million) | Seven states are involved. 4.5 million dug-wells proposed. |

Rainwater harvesting has been made mandatory in several cities and some states of India with an aim to meet the increasing groundwater needs. In Tamil Nadu only 36% of the habitations (28'623 of 80’421) are fully covered with rural water supply. The drinking water crisis is acute due to negative groundwater balance in many areas. The National Bank for Agriculture and Rural Development (NABARD) project is aiming at water resource conservation and management by rooftop rainwater harvesting (National Bank fo Agriculture and Rural Development, 2012).

## 4.2 State-of-the-Art of MAR Implementation in India

Broadly MAR activities can be divided in:

- Planning and construction
- Operation and Maintenance

This review covers knowledge and experience of MAR in India, focusing on the technical aspects. There is also a larger context which is excluded in this review, mainly social and economic aspects. These also need to be considered along with the technical aspects to evaluate whether additional MAR structures are desirable, how to best organize the construction and maintenance and how to make the most of the recharged water.

### 4.2.1 Planning and construction

After the need for 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 (Kumar, et al., 2008) and the CGWB (Central Ground Water Board, 2000, p. 52):

- Rainfall over time (incl. 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 can be quantified as given by CGWB (Central Ground Water Board, 2000, p. 100).

#### *4.2.1.1 Rainfall over time / source water availability*

The CGWB recommends using rainwater, runoff or treated waste water for recharge (Central Ground Water Board, 2007, p. 15). For determining the availability of rainwater Kumar et al (2008) shows the importance determining of 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 then be only partly utilized most years and consequently have low percolation efficiency (volume of infiltrated volume in relation to volume of the structure).

As mentioned in Chapter 3.1.1 the runoff can be 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 none, 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 period pre-/ and post- MAR intervention. According to this calculation the rainfall amount which is needed to fill the reservoir increased from 320 mm/a to 800 mm/a. 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 decentralised groundwater recharge gives an additional value to the local communities. The unused balance runoff per state is presented in chapter 3.2 of this report. Runoff in urban areas, sometimes referred to as storm water, is increasingly captured by rooftop rainwater harvesting schemes as mentioned in chapter 4.1.2 (Central Ground Water Board, 2011; Central Ground Water Board, 2002).

According to DK Chadha, former president 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. Soil aquifer treatment (SAT) is evaluated in India (Nema, et al., 2001) and practiced 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 it to the more neutral 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.

#### *4.2.1.2 Hydrogeological data*

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 (Central Ground Water Board, 2006): unconsolidated porous, semi-consolidated porous and consolidated fissured formations. Unconsolidated formations have the highest transmissivity, hydraulic conductivity and storativity (Table 12). 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 12: Properties of aquifers in different groups of rock (Groundwater Estimation Committee, 2009).

| Formation | Area Fraction (%) | Transmissivity ($m^2$/day) | Hydraulic Conductivity (m/day) | Storativity |
|---|---|---|---|---|
| Unconsolidated | 30 | 250- 4000 | 10 to 800 | $10^{-4}$ to$10^{-3}$ |
| Semi-consolidated | 7 | 100- 2300 | 0.5- 70 | $10^{-3}$- $10^{-2}$ |
| Consolidated | 63 | 10- 500 | 0.05- 15 | $10^{-2}$- $10^{-1}$ |

#### *4.2.1.3 Surface and groundwater quality over time*

The CGWB recommends using rainwater and runoff or treated wastewater for recharge. As mentioned above recharge of wastewater is not practiced and it is commonly assumed that the source water is pure. This assumption is not always valid since the runoff may flush out accumulated contaminants on the way to the recharging point. For example, Meera and Ahammed (2006) and Ashworth (2005) found that the quality of harvested water from roof catchments often exceeds drinking water standards. It is stated that pathogenic organisms, heavy metals and organic trace compounds are the contaminants of concern (Meera & Ahammed, 2006). On the other hand the recharged 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, the underground passage is an effective medium for microbiological removal (Sharma, et al., 2011). In case of sufficient flow path distance and residence time during underground 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 tenth of meter travel distance for viruses (Tufenkji, et al., 2002; Schijven, 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 (PhACs) 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 characterised 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 database on organic micropollutants in the environment is 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.

### Mineral contamination

As seen in chapter 3.2, 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 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 mobilise 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.

### 4.2.2 Operation and Maintenance

#### *4.2.2.1 Prevention of Clogging and Countermeasures*

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 may be managed by treatment of the recharge water by simple sedimentation and filtration to remove suspended solids as described in subchapter 4.3.2. 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 redevelopment 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 influenced source water is used. Chlorine disinfection or other disinfectants with residual effects reduces biological activity at the infiltration interface. Finally the general clogging rate also depends on the infiltration rate, because with high infiltration rates higher amounts of nutrients and suspended solids arrive at the infiltration surface.

#### *4.2.2.2 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 runoff 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.

## 4.3 Experience from Case Studies on MAR in India

For an overview of the state-of-the-art of MAR in other regions in India a literature review of published case studies on aquifer recharge in scientific journals was compiled and evaluated. Although MAR has been implemented in numerous cases in India (Chapter 4.5), published scientific investigations on the performance in terms of quantity (infiltration rates) and quality are scarce. In total, 27 publications were found, dealing with MAR and documenting case studies with quantitative data on different scales:

- 13 publications reported individual case 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 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
- For 3 publications the number of structures was not given

The structures investigated can be categorized as given in Figure 30. 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 are also studied in the small scale investigations to a considerable extent.

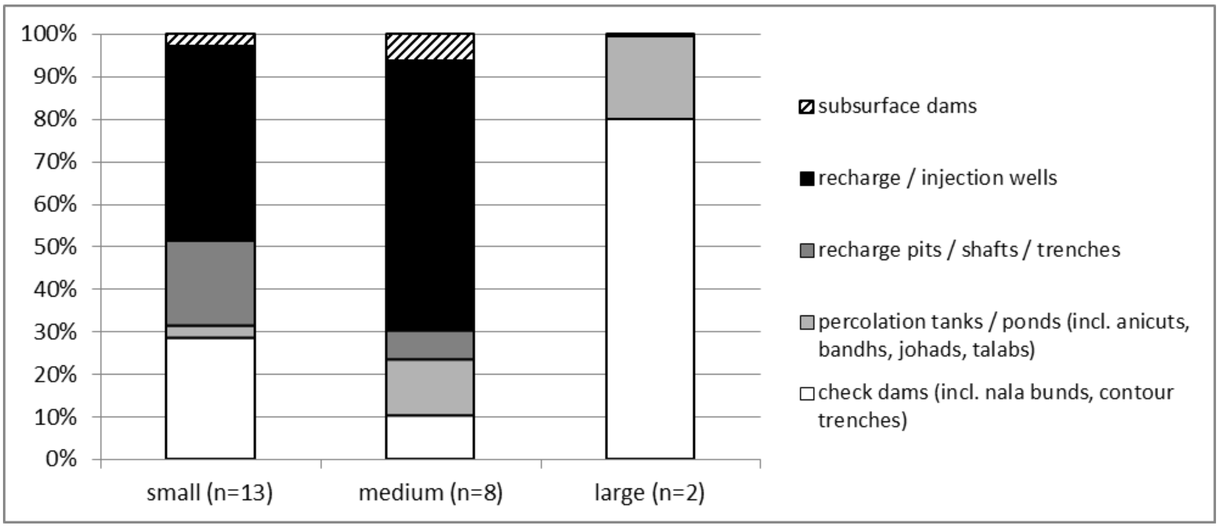


Figure 30: Aquifer recharge structures in considered case study publications on small (< 5 structures), medium (5 to < 100 structures) and large scale (> 100 structures).

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 cases 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.

### 4.3.1 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

(Central Ground Water Board, 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 (three, six and four case studies report information on these parameters, respectively). 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 highest values in alluvial aquifers (Bhadrak, Orissa (Central Ground Water Board, 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, but as data on draw-down and well design is lacking quantitative information on specific capacities or transmissivities cannot be derived.

### 4.3.2 Infiltration Rates and Related Issues

The quantification of the recharged water is in the focus of most considered publications. This is either done by small scale observations (measuring water table fluctuations) or on catchment / subcatchment 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) report a relevant amount (90 % and more) of the rainfall to 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 m³/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 (Central Ground Water Board, 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. (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.

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. 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 coconut fiber mats and achieved concentrations around 180 mg/L. An overview of pre- and post-treatment currently applied in India for MAR is being prepared as part of the SAPH-PANI project (D 4.1b: Review report on status quo of pre- and post-treatment for MAR in India).

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).

The CGWB (2011) reports on 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). Although this report gives a large amount on information on MAR systems in the different Indian states, it is difficult to derive general trends and transferable recommendations due to the above mentioned variability and lack of detailed, scientific data. As suggested by Glendenning et al. (2012) increased field data collection 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.

### 4.3.3 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 as an issue in nearly all of the studies (for infiltration efficiency, see above), with exception of mountainous streams in the Tapi alluvial Belt, Maharashtra (Central Ground Water Board, 2011), where direct infiltration without pre-treatment is possible.

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 EC from 9000 to 1500 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 (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.

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 (Central Ground Water Board, 2011).

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.

## 4.4 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 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 m3/day SAT system using primary settled domestic water was proposed for the city (Central Ground Water Board, 2011).

## 4.5 General Evaluation of MAR Implementation in India

The CGWB evaluated the performance of different MAR structures in different hydrogeological and meteorological contexts based on data from numerous pilot studies (Chapter 4.1). The results were thoroughly documented (Chadha, 2012). Benchmark performances (e.g. 75% percolation efficiency (Central Ground Water Board, 2002)) and suitability of structures for different contexts (Central Ground Water Board, 2000, p. 100) were published. However, unfortunately most results remain inaccessible to the research community. Consequently there is little published data describing the characteristics of the recharge structures of India.

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). As an indication the major MAR implementation schemes were outlined in Chapter Implementation Schemes 4.1.2. From the review of the case studies in chapter 0 it can be seen that the scientific evidence for both positive and negative effects of MAR interventions is scarce, an observation confirmed by Glendenning et al (2012). 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 can aquifer recharge be managed, and only then correctly be designated as MAR.

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).

# 5 Review of Saph Pani Study Site Experience

The investigations on MAR within the Saph Pani projects will focus on three case studies, located in different parts of India, with different foci:

- Chennai: MAR for countering saline intrusion along India’s southeast coast,
- Maheshwaram: MAR in a peri-urban area, focusing on hydraulics and hydrochemistry in a typical hard-rock environment
- Raipur: feasibility of MAR within an urban storm water management system.

All three case studies will deal with quantifying the amount of infiltrated water, i.e. the efficiency of the systems in terms of quantity – although at different scales: While in Chennai, both a basin-wide approach and a local structure will be investigated, the work in Maheshwaram will focus on one structure only and Raipur will cover the city (sub-catchment). Regarding the hydrogeological context Chennai deals mainly with unconsolidated aquifers, while in Maheshwaram and Raipur hard-rock aquifers prevail, with groundwater flow within the weathered or fractured zones. Thus the two main settings occurring in the Indian subcontinent are covered. Quite detailed previous investigations exist in the region of Chennai and Maheshwaram, although not dealing with the structures under investigation, whereas for Raipur the information on infiltration through MAR structures is limited. The level of detail of information gained from the three case studies will therefore vary considerably: while Chennai and Mahesharam can benefit from previous experience and set new results into relation to published data the conclusions for Raipur will be more general and give indications for further work.

Existing knowledge on the three case studies will be described in detail in the following chapters.

## 5.1 MAR in Chennai

Seawater intrusion is a major problem in India due to its long coastline comprising of unconsolidated formations and due to over exploitation of groundwater to meet the needs of huge population living on the coast. Chennai, the fourth largest city in India located on the east coast, also faces the problem of seawater intrusion due to over pumping of groundwater since the 1970s to meet the drinking water supply of the well fields located in alluvial formations (CGWB-Chennai, 2007). The saline water intrusion forced the shifting of well fields progressively towards the west. Furthermore, the well fields which were located closer to the coast were made redundant due to seawater intrusion. Hence, there is a need to mitigate the seawater intrusion by MAR. For example MAR by the construction of check dams across the rivers to store the excess runoff and percolation ponds will result in increased groundwater recharge thereby preventing seawater intrusion (Figure 31).

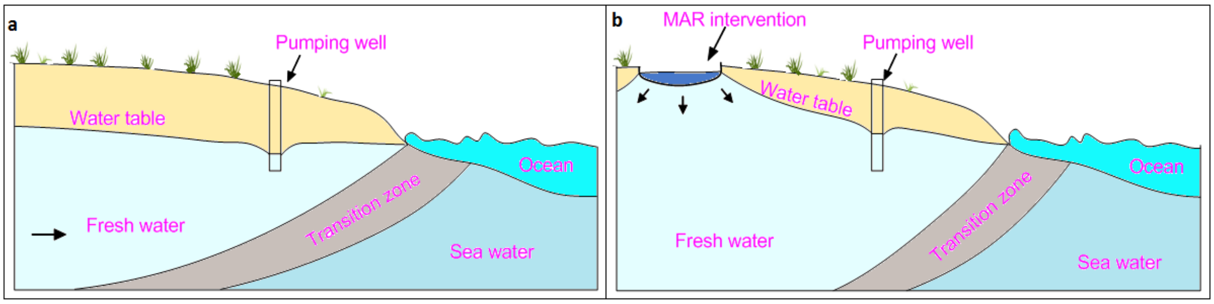


Figure 31: MAR as a technique to mitigate seawater intrusion

UNDP (1987) ascertained that the Arani-Korttalaiyar groundwater basin in north Chennai where well fields are located could be artificially recharged through infiltration ponds. Seawater intrusion in north Chennai was monitored by Elango and Manickam (1986; 1987). Later, Elango (1992) identified that sodium chloride dominant groundwater was present in most parts of Arani-Korttalai river basin, indicating that the scenario has not changed since 1986. The geochemical processes that controlled the groundwater chemistry were dissolution and deposition of minerals, ion exchange, changes in carbonate chemistry and sulphate reduction. A mass balance discrete model was set up and was run for hundred years to understand the behavior of the aquifer system in various conditions. Seawater intrusion was identified using vertical electrical sounding in the coastal aquifer located south of Chennai (Gnanasundar and Elango, 2000). Numerical modelling of groundwater flow was performed in the south Chennai coastal aquifer by Gnanasundar and Elango (Gnanasundar and Elango, 2000) and Sivakumar et al. (2006) to simulate the effect of pumping and the changes in rainfall pattern. Balakrishnan (2008) investigated the hydrogeology and hydrochemistry of the Chennai region and identified salinity ingress as one of the main groundwater problem. Ganesan and Thayumanavan (2009) developed a groundwater flow and transport model for the coastal aquifer north of Chennai. The feasibility of controlling the overland flow to augment the groundwater resources in the Arani-Korttalaiyar river basin was studied by numerical modelling (Anuthaman, 2009).

Modelling of the impact of a subsurface barrier on groundwater flow in the lower Palar River basin, 70 km south of Chennai was carried out to understand the increase in groundwater heads and to minimize the subsurface discharge of groundwater into the sea (Senthilkumar & Elango, 2011). Solute transport modelling was performed by Sivakumar and Elango (2010) which helped to understand the salinization process of groundwater by the 2004 tsunami. This study indicated that the natural rainfall recharge will reduce the groundwater salinity to the pre tsunami level within four years. Three dimensional electrical resistivity tomography was used to identify the seawater intrusion in southern part of Chennai (Sathish, et al., 2011).

## 5.2 MAR in Maheshwaram and other Hardrock Aquifers

The Maheshwaram watershed is located 30 km south of Hyderabad, the capital city of Andhra Pradesh. For more than 10 years it has been subject to research activities by the

Saph Pani project partners under various national and international programs of which the main results are summarized below.

### 5.2.1 Location and Hydrogeology

The Indian sub-continent is underlain by Archean basement i.e. hard rock formations that are devoid of primary porosity and occupy more than 2/3 of the landmass. (Gustafson & Krasny, 1994) proposed that the term "hard rock" might, from a groundwater exploration point of view, include all rocks without sufficient primary porosity and conductivity for feasible groundwater extraction. As a common feature, these rocks tend to become weathered at shallow levels, semi-weathered and fissured at intermediate levels and fractured at deeper depths under the influence of pressure, temperature and rock-aquifer interactions. Thus these hard rocks in general consist of two zones viz., the weathered and the fractured that may be separated through a semi fractured layer. The fractured zone ends up in massive hard rock at deeper levels of about 40 to 50 m. The adaptation of latest drilling technology in India during the last few decades has led to groundwater exploitation on a large scale. This has resulted in declining water levels in the wells of the Maheshwaram area. Presently the situation is very alarming, since the weathered zone of 12 to18 meters has become mostly dry.

The Maheshwaram catchment is a closed watershed of 55 km$^2$ in the south of Hyderabad, India which has been selected considering a number of scientific and logistic parameters as a pilot area for research (Figure 32). The area has been thoroughly investigated with respect to inventory of wells, extent of geological outcrops, the depth and yield of wells, measurement of structural orientations, lithology and geo-electrical studies.

### 5.2.2 Results of Previous Hydrogeological and Geophysical Investigations in Maheshwaram

#### *5.2.2.1 Geophysical Investigations*

A combination of geophysical methods viz., electrical imaging, mise-a-la-masse[12] resistivity profiling as well as sounding and magnetic have been used to measure the geometry of the aquifer, thickness of the fractured zones and also the extent of the fractures (Chandra, et al., 2010). The Self Potential[13] method together with measurement of the potential distribution under Mise-a-la-masse technique could indicate the direction and extent of the fractures that have been encountered in the bore well (Kumar, et al., 2003). A number of dolerite dykes present in the area were characterized by the magnetic survey and geophysical profiling with different electrode separation.

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[12] Mise a' la masse is a three point pole-dipole electrical geophysical method that uses an applied voltage to determine the dimensions of a mineralized ore body.

[13] Self Potential (SP) geophysical surveys measure the difference in potential between two points on the ground produced by small, naturally produced currents to determine the dimensions of a mineralized ore body.

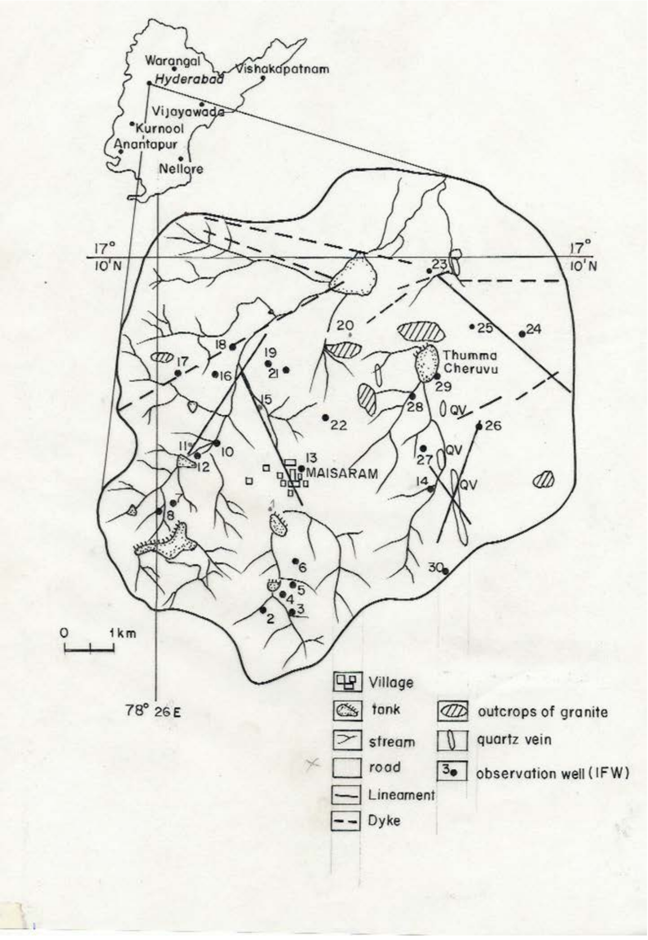

Figure 32: Location of the Maheshwaram study area with drainage and structural features as well as with monitoring wells.

#### 5.2.2.2 Hydraulic tests

The characterization of the hydraulic properties of the weathered-fractured layer has been performed using hydraulic tests at different scales: slug tests, flow measurements during injection and pumping tests. The latter are interpreted using specific methods to fractured media - anisotropic, double porosity, single fracture and fractional dimension flow models - leading to characterization of the geometry and hydraulic properties of fracture networks and blocks. Two secondary networks of fractures have been identified (Maréchal, et al., 2004; Dewandel, et al., 2006):

- A main network of horizontal fractures is responsible for the horizontal conductivity of the weathered-fractured layer.
- A second network of less permeable vertical fractures insures the connectivity of the aquifer at the borehole scale.

The vertical anisotropy ratio is close to 10 (Maréchal, et al., 2003). A primary network of fractures contributes to increase the permeability and storage of the matrix in the blocks. Results are compiled in a hydrodynamic model.

The pumping test analyses show a wide disparity in results with a transmissivity variation of 30 to 240 m2/day and low storage coefficient.

Finally, it was shown that the weathering process is at the origin of fracturing and hydraulic properties of the aquifer.

#### *5.2.2.3 Geostatistical Analyses*

The aquifer parameters including water levels and water quality were analyzed geostatistically through variographic analyses. It has also been possible to evolve common variogram(s) for different time periods that help estimating the water level without involving the cumbersome process of variographic analyses each time. Geostatistical methods of estimation variance reduction could prepare the optimal water level monitoring network and it was shown that out of 57 wells only 40 could be sufficient to obtain the same regional picture of the water levels (Faisal, et al., 2007; Ahmed, 2002). This exercise has helped in avoiding some of the wells to be monitored continuously.

#### *5.2.2.4 Groundwater budget and Aquifer Modelling*

A two layered numerical model, first layer representing the weathered aquifer and the 2nd for the fractured-fissured aquifer has been prepared using integrated finite difference approximation with the code MARTHE developed at the BRGM, France (Thiery, 1993; Ahmed, et al., 2006). Initially the model has no flow from the boundaries following the surface topography with small outflow at the northern tip. The up-scaled hydraulic parameters have been assigned to each mesh after estimation. Various intrusive structures (quartz reef; (Dewandel, et al., 2011) are to be considered carefully e.g.; as conduits in the weathered layer but as barriers in the fractured layers as well as strong heterogeneity due to weathering lead to compartmentalization (Perrin, et al., 2011b) of the aquifer. The semi-arid condition with over exploitation has resulted in a rapid water level decline. In such a condition, estimation of recharge is important as the rainfall recharge through unsaturated zones including weathered zones are negligible compared to the preferred path recharge (Ahmed, et al., 2008). The water-balance and simulation of flow shows a constant water level decline in the area in the future (Dewandel, et al., 2007; 2010) leading to an important decrease of the bore wells yields and an increase of energy costs. Moreover this understanding of hydrodynamic evolution is of importance as a decreasing water table due to over-exploitation and important return flow (Dewandel, et al., 2008) has led to a salinization of the aquifer (Perrin, et al., 2011a).

### 5.2.3 Ongoing MAR Activities in Maheshwaram and Related Research

A dug well having large catchment area has been selected and equipped with a pit to remove the silt and then the water is transferred to the dug well. The dug well bottom infiltration rates were 129 mm/hr (Sreedevi, et al., Submitted, 2012). Continuous recording of water levels in a nearby bore-well (Figure 33) adjacent to the dug-well shows clear effect of artificial recharge and rise in water level in spite of groundwater withdrawal in the well. The rise continued until the rainy season and then gradual decline has been observed after the rainy season was over. The bore well is located at a distance of about 15 m. from the dug well. The water levels in the bore rose about 5.0 m whereas the level in other bore wells in the watershed under natural recharge conditions rose of about 1.0 m for the same amount of rainfall.

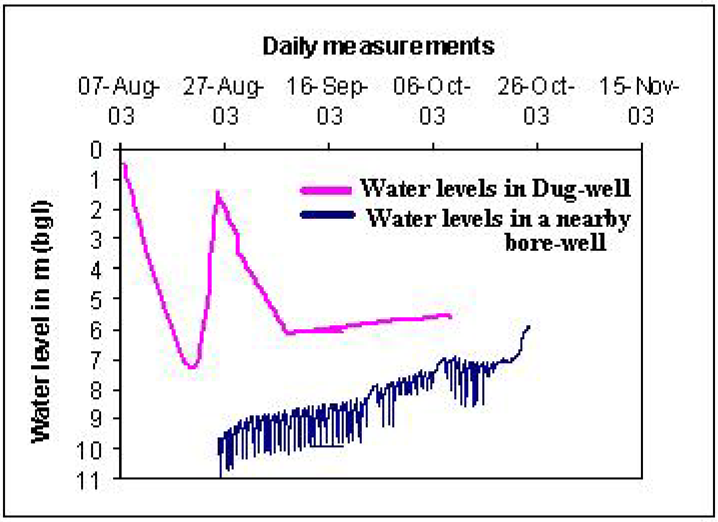

Figure 33: Water level in a recharged dugwell and water level rise in a nearby bore-well during artificial recharge in one rainy season (Sreedevi, et al., Submitted, 2012)

Thus the recharge has been quantified and the advantages include the reduced evaporation losses and higher infiltration, compared to the surface tanks. Infiltration apparently also takes place through the walls of the well that often have horizontal fractures. However, the following questions still need to be addressed:

- Quality of water: Arrangements have been made to let suspended solids in runoff water settle in a pit before the water flows into the dug well. However some fine silt may still enter the dug well.
- Water availability: the climate change and erratic behaviour of the monsoon etc. (Negrel, et al., 2011) provide a lot of uncertainty and availability of water at the right time is also necessary for the success of the experiment.
- Maintenance: in order to avoid that the recharged dug-well becomes clogged like the tanks in the area, it is necessary to clean the bottom and the walls regularly.

## 5.3 Possibility of MAR in Raipur

### 5.3.1 Location and Hydrogeology

Raipur is located in the Chandi formation of the Raipur Group within the Chhattisgarh basin. The Chandi formation can be divided into the Raipur Limestone and the Deondongarh Shale. Stratigraphically the region is made up of Raipur limestones and Deondongarh Shale. Raipur Limestone is characterized by grey, fine grained, horizontally bedded, stromatolitic, massive limestone. It has high secondary porosity due to joints and karstification with negligible primary porosity (Mukherjee, et al., 2011; Bodhankar & Chatterjee, 1994). The Deondonghar Shale consists of laminated purple shale layers interspaced with ferruginous, thinly to thickly bedded sandstone (Mukherjee, et al., 2011) with thicknesses of up to 4 m (Roy, et al., 2009); by (Bornemann & Gröschke, 2012). The average annual rainfall is 1300 mm principally contributed by the monsoons from mid- June to early October (Roy, et al., 2009; Mukherjee, et al., 2011). The depth of water level varies from 2 to 13 mbgl during pre- monsoon and from 0.1 to 7 mbgl during post monsoon period in the shallow aquifers. Water level measurements indicate that about 18% of the wells in pre-monsoon and 3% of the wells in the post monsoon period show a significant (20 cm/year) falling trend. The exploration by Central Ground Water Board indicated the presence of potential fractures up to 130 mbgl. The optimum depth of bore wells in the district is found to be between 50 to 80 mbgl. The yield of borewells in the limestone aquifer reaches more than 18 l/s.

### 5.3.2 Ongoing MAR Activities in Raipur and Related Research

Ongoing artificial recharge activities in Raipur could be broadly divided into three categories on the basis of agencies involved compiled by Dar et al (2012).

#### *5.3.2.1 Activities of the Raipur Municipal Corporation*

Raipur Municipal Corporation has taken made it compulsory for every new construction to build a recharge structure for groundwater recharge. In order to implement the rain water harvesting culture the Municipal Corporation has:

- Issued various guidelines and specifications to build the re-charging structure.
- Authorized various private agencies for providing the consultancy on building of recharging structures at appropriate places at the new construction sites on a right proportional scale.
- Made it mandatory for the new constructions to deposit a prefixed security amount.
- Undertaken projects for cleaning of the percolation tanks located on Chandi Limestone, in order to enhance the groundwater quality.

Figure 34. Ongoing construction of recharge structures at a construction site in Raipur.

#### 5.3.2.2 Activities of the Central Ground Water Board (Raipur)

The Central government agency, CGWB, Raipur has shown a keen interest in the R&D and development of technological knowhow for building the recharging structures at an appropriate place and to develop the structure of appropriate sizes. The CGWB has:

- Undertaken extensive geophysical surveys in order to know the structures and the broad lithology of the area.
- Undertaken an extensive geological fieldwork in order to know the general geology of the area and also correlate the geophysical data.
- Provided training and consultation to various private parties on the aquifer recharging methods.
- Initiated various pilot projects in order to monitor and understand the groundwater recharging methods.

#### 5.3.2.3 Activities of Private Agencies

Various Non-Governmental Organizations and private agencies are involved in educating the general public and raising awareness of the benefits of groundwater recharge.

#### 5.3.2.4 Related research

A study was performed in Raipur city prior to project start by (Bornemann & Gröschke, 2012) around the Narayia Talab, the Budha Talab and the Maharajbandh Talab to assess the hydrogeological and hydrochemical characteristics. In the frame of this study 21 observation wells, dug wells and hand pumps were sampled and analyzed for main cations and anions, nutrients, inorganic trace elements and stable isotopes. Although, all groundwater samples show anthropogenic influence this is probably not due to MAR activities as only little infiltration was observed from the talabs into the aquifers. The analyses of the water budgets of the talabs, indicated that untreated or poorly treated sewage might contribute relevantly to the water volume in the talabs. An infiltration into the main aquifer at this stage is therefore not recommended and further investigations are proposed with respect to microbiological quality of the source water and transferability of the results to talabs with different hydrogeological context.

# 6 Conclusion

## 6.1 Main findings

In most parts of India, the monsoon lasts some four months, followed by a dry period of some eight months. This rainfall pattern imposes huge seasonal variation in water availability. Aquifer recharge has been practiced to a large extent and since a long time to recharge the groundwater and assure access to water all year. Experience with structures and groundwater management has been developed in and adapted to the various climatic and hydrogeological situations, 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% India’s water demand. As shown in Chapter 3 (See also Annex 1), demand exceeds the supply in four states. This leads to sinking ground water tables in those states and also in parts of other states. As shown in Chapter 2 (Figure 5), MAR is only one factor influencing the water balance and for example water use for irrigation and consequently the type and the number of crops and the irrigation methods have an even larger influence. Additional recharge through MAR can only make a minor contribution to the overall water balance. However it might be a substantial contribution compared to the drinking water consumption and relieve the situation in regions with particular water deficits.

MAR requires an aquifer with storage capacity and surplus water for recharge. Available data for these two factors are shown in Chapter 3 for each state. The first factor is limiting for example in the states in the Brahmaputra basin that usually have large amounts of runoff to the sea during monsoon season, but no unsaturated aquifer to store it. The second factor is not visibly limiting: the review of water balances of the states do not show any states having no unused water. However, as discussed in Chapter 4.2.11, the large amount of water used and the seasonal variations make it difficult to unambiguously identify non-committed water. When new MAR structures are constructed, additional water recharged upstream might be lacking and lead to longer dry periods downstream.

Water quality is an area attracting growing attention in India. Up to now little attention was paid to the quality of recharge water, most of the screened Indian case studies of MAR do not measure quality of source water or effluent (Chapter 4.3.3). It was generally assumed that the used sources, rainfall and runoff were safe to use (Chapter 4.2.1.3). However, a review of the situation in the Indian states (Chapter 3) shows a problem with ground water quality. Almost all districts have areas with nitrate contamination, and also excessive concentration of other pollutants like arsenic, salt, fluoride and iron is widespread.

The Central Ground Water Board of the Ministry of Water Resources of India has financed pilot structures to assess and demonstrate the performance of different MAR structures in various climatic and hydrogeological conditions. Based on those experiences, CGWB has made recommendations for the amount and type of structures to be built in different states. Planning, construction and also renovation of MAR structures is financed by the Ministry of Water resources and the Ministry of Rural development under different schemes.

## 6.2 Knowledge gaps

This review covers knowledge and experience in India. It is 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 the most of the recharged water. Based on the review, knowledge gaps were identified:

- The planning and construction of structures requires knowledge of the properties of the location which are available and can be complemented during the planning phase. Saph Pani can contribute to an improved knowledge of the characteristics of different structures on the study sites and their performance.
- Some accounts of experience from operation and maintenance of recharge structures were found. Saph Pani can contribute a systematic evaluation of operation and maintenance techniques and guidelines for recharge scheme operation.
- Despite a vast experience with countless recharge structures over centuries the impact of MAR in India is poorly known. A census of structures coupled with their performance would make it possible to estimate the global and regional impact of MAR. Saph Pani will provide a good understanding of three areas based on modelling of the study site experiences in Maheshwaram, Chennai and Hyderabad.
- Data on water quantity available at a certain time in a certain location is known to some extent. However, it is difficult to obtain spatial and temporal data on stream flow from governmental agencies since the data is often kept confidential.
- Data on water quality are scarce. In Saph Pani numerous water quality analyses will be performed on the study sites giving a good view of the quality of source water and groundwater. Pre- and post-treatment options for different end-uses will be proposed.

Table 13: Knowledge gaps and the contribution of Saph Pani

| | **Still needed** | **Available** | **Saph Pani does** |
|---|---|---|---|
| Site location and characterization | | Hydrogeology, land-use, aquifer properties | Suggestions for distance between sites. |
| Planning construction of structures | Structure characteristics and performance. | Rainfall<br>Topography<br>Soil properties<br>Runoff<br>Hydrogeology<br>(to complement with detailed data necessary for projects) | Structure characteristics and performance in Maheshwaram and Chennai. |

| | Still needed | Available | Saph Pani does |
|---|---|---|---|
| Operation of structures | Techniques for coping with clogging and other technical problems.<br>Maintenance and operation guidelines. | | Evaluation of pre-treatment techniques.<br>Recommendations for operation and maintenance at case study sites. |
| Impact of structures on water balance. | Census of structures<br>Methodology for evaluating the performance.<br>Performance of structures over time, sustainability.<br>Impact of structures. | Percolation efficiency of many structures (CGWB 2011), total infiltration including natural recharge volume per state. | Recommendations for evaluating performance over time (sustainability).<br>Data on performance of structures in Maheshwaram and Chennai.<br>Modelling of infiltration impact in Maheshwaram, Chennai and Hyderabad. |
| Water Quantity | Which runoff/ surface water quality available in which quantity as a function of location and season? | Water quantity without quality knowledge per location and season. | Quantity-quality data couples over time from Maheshwaram and Chennai |
| Water Quality | Quality of affected ground water per location and season<br>Process understanding of arsenic, fluoride, nitrate and heavy metal mobility in groundwater affected by MAR.<br>Suitable strategies/techniques for:<br>• solving quality problems<br>• coping with existing quality problems<br>• avoiding additional quality problems | | Quality data as a function of location and season from Maheshwaram and Chennai.<br>Pre and post treatment options for Maheshwaram and Chennai. |

# 7 List of abbreviations

| | |
|---|---|
| ARR | Artificial Recharge and Recovery |
| ASR | Artificial Storage and Recovery |
| ASTR | Artificial Storage Transfer and Recovery |
| BF | Bank Filtration |
| CGWB | Central Ground Water Board |
| mbgl | meters below ground level |
| MAR | Managed Aquifer Recharge |
| MGNREGA | Mahatma Gandhi National Rural Employment Guarantee Act |
| SAT | Soil Aquifer Treatment |
| SGT | Subsurface Groundwater Treatment |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |

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# Annex 1 Water Data for States and Union Territories

| No. | State | Area | PET | Rainfall | Surface Runoff Potential | Surface Water Storage | Balance Runoff | Ground Water Potential | GW Draft+ Natural Discharge | Ground Water Balance | Aquifer Storage Capacity | Master Plan Re-charge, CGWB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (km$^2$) | (mm) | | | | | | | | | |
| 1 | Andhra Pradesh | 275069 | 1731 | 912 | 415 | 130 | 285 | 133 | 67 | 66 | 4 | 4 |
| 2 | Arunachal Pradesh | 83743 | - | 2782 | 1124 | 456 | 668 | 31 | 3 | 28 | - | 0 |
| 3 | Assam | 78438 | 1300 | 2818 | 1459 | 48 | 1411 | 347 | 99 | 248 | - | 0 |
| 4 | Bihar | 94163 | 1401 | 1256 | 529 | 89 | 440 | 310 | 133 | 177 | 5 | 4 |
| 5 | Chhattisgarh | 136034 | 1482 | 1292 | 750 | 57 | 693 | 110 | 30 | 80 | 24 | 2 |
| 6 | Delhi | 1483 | 1700 | 620 | 347 | 0 | 347 | 202 | 337 | -135 | 299 | 48 |
| 7 | Goa | 3702 | 1659 | 3005 | 1610 | 73 | 1537 | 76 | 24 | 51 | 143 | 114 |
| 8 | Gujarat | 196024 | 1768 | 798 | 320 | 140 | 180 | 81 | 63 | 18 | 313 | 7 |
| 9 | Haryana | 44212 | 1620 | 617 | 281 | 6 | 275 | 211 | 229 | -19 | 369 | 16 |
| 10 | Himachal Pradesh | 55673 | 1300 | 1251 | 655 | 279 | 376 | 8 | 3 | 5 | - | 10 |
| 11 | Jammu & Kashmir | 222236 | 1300 | 1011 | 408 | 9 | 399 | 12 | 3 | 9 | - | 1 |
| 12 | Jharkhand | 79714 | 1492 | 1320 | 625 | 124 | 501 | 70 | 18 | 52 | 9 | 6 |
| 13 | Karnataka | 191791 | 1677 | 1771 | 732 | 188 | 544 | 83 | 59 | 24 | 19 | 11 |

| No. | State | Area | PET | Rainfall | Surface Runoff Potential | Surface Water Storage | Balance Runoff | Ground Water Potential | GW Draft+ Natural Discharge | Ground Water Balance | Aquifer Storage Capacity | Master Plan Re-charge, CGWB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | Kerala | 38863 | 1700 | 3055 | 1115 | 221 | 895 | 176 | 91 | 85 | 39 | 39 |
| 15 | Madhya Pradesh | 308000 | 1573 | 1178 | 577 | 136 | 442 | 121 | 62 | 59 | 9 | 8 |
| 16 | Maharashtra | 307713 | 1682 | 1456 | 510 | 131 | 379 | 107 | 55 | 52 | 37 | 9 |
| 17 | Manipur | 22327 | - | 1881 | 1157 | 397 | 760 | 17 | 2 | 15 | - | - |
| 18 | Meghalaya | 22429 | 1300 | 2818 | 1550 | 55 | 1495 | 51 | 5 | 46 | - | - |
| 19 | Mizoram | 21081 | 1300 | 1881 | 1000 | 105 | 895 | 2 | 0 | 2 | - | - |
| 20 | Nagaland | 16579 | - | 1881 | 1182 | 108 | 1074 | 22 | 3 | 19 | - | - |
| 21 | Orissa | 155707 | 1500 | 1489 | 650 | 262 | 388 | 148 | 38 | 110 | 2 | 3 |
| 22 | Punjab | 50362 | 1490 | 649 | 310 | 48 | 262 | 472 | 665 | -193 | 375 | 24 |
| 23 | Rajasthan | 342239 | 1735 | 494 | 237 | 34 | 202 | 34 | 41 | -8 | 96 | 3 |
| 24 | Sikkim | 7096 | - | 2739 | 1500 | 0 | 1500 | 11 | 1 | 10 | - | 6 |
| 25 | Tamil Nadu | 130058 | 1726 | 998 | 421 | 52 | 369 | 177 | 153 | 24 | 21 | 29 |
| 26 | Tripura | 10492 | 1300 | 1881 | 1009 | 30 | 979 | 209 | 37 | 172 | - | - |
| 27 | Uttar Pradesh | 240928 | 1476 | 1196 | 515 | 153 | 362 | 317 | 228 | 89 | 93 | 63 |
| 28 | Uttrakhand | 53484 | 1300 | 1583 | 731 | 162 | 569 | 42 | 29 | 13 | - | 23 |
| 29 | West Bengal | 88752 | 1443 | 2089 | 872 | 19 | 853 | 342 | 164 | 178 | 23 | 30 |

| No. | Union Territories | Area | PET | Rainfall | Surface Runoff Potential | Surface Water Storage | Balance Runoff | Ground Water Potential | GW Draft+ Natural Discharge | Ground Water Balance | Aquifer Storage Capacity | Master Plan Re-charge, CGWB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (km$^2$) | (mm) | | | | | | | | | |
| 1 | Andaman & Nicobar Islands | 8249 | - | 2967 | - | - | - | 40 | 2 | 38 | | |
| 2 | Chandigarh | 114 | 1300 | 617 | 350 | - | - | 202 | 18 | 184 | | |
| 3 | Dadara & Nagar Haveli | 491 | 1700 | 979 | 701 | - | - | 128 | 24 | 104 | | |
| 4 | Daman & Diu | 112 | 1700 | 798 | 353 | - | - | 80 | 84 | -4 | | |
| 5 | Lakshadweep | 32 | - | 1515 | - | - | - | 375 | 344 | 31 | | |
| 6 | Pondicherry | 479 | 1700 | 998 | 782 | 22 | 752 | 334 | 349 | -15 | | |

# Annex 2 State Groundwater Quality Data

| No. | State | Salinity | Fluoride | Chloride | Iron | Nitrate | Arsenic |
|---|---|---|---|---|---|---|---|
| | | (% of districts where quality limits are exceeded) | | | | | |
| 1 | Andhra Pradesh | 70 | 83 | 39 | 65 | 100 | - |
| 2 | Arunachal Pradesh | - | - | - | - | - | - |
| 3 | Assam | - | 17 | 78 | - | - | 4 |
| 4 | Bihar | - | 24 | - | 54 | 24 | 41 |
| 5 | Chhattisgarh | - | 75 | - | 25 | 75 | 6 |
| 6 | Delhi | 33 | 56 | 33 | - | 78 | - |
| 7 | Goa | - | - | - | 100 | 50 | - |
| 8 | Gujarat | 80 | 72 | 68 | 20 | 88 | - |
| 9 | Haryana | 55 | 70 | 10 | 85 | 95 | - |
| 10 | Himachal Pradesh | - | - | - | - | - | - |
| 11 | Jammu & Kashmir | - | 14 | - | 43 | 14 | - |
| 12 | Jharkhand | - | 33 | - | 33 | 61 | - |
| 13 | Karnataka | 26 | 74 | 15 | 81 | 85 | - |
| 14 | Kerala | 7 | 7 | - | 100 | 79 | - |
| 15 | Madhya Pradesh | 10 | 40 | 4 | 52 | 96 | - |
| 16 | Maharashtra | 17 | 23 | - | 57 | 83 | - |
| 17 | Manipur | - | - | - | 22 | - | - |
| 18 | Meghalaya | - | - | - | 43 | - | - |
| 19 | Mizoram | - | - | - | - | - | - |
| 20 | Nagaland | - | - | - | - | - | - |
| 21 | Orissa | - | 37 | | 67 | 93 | - |
| 22 | Punjab | 35 | 65 | 12 | 53 | 94 | - |
| 23 | Rajasthan | 81 | 94 | 47 | 88 | 100 | - |
| 24 | Sikkim | - | - | - | - | - | - |
| 25 | Tamil Nadu | 47 | 57 | 27 | 7 | 90 | - |

| No. | State | Salinity | Fluoride | Chloride | Iron | Nitrate | Arsenic |
|---|---|---|---|---|---|---|---|
| 26 | Tripura | - | - | - | 100 | - | - |
| 27 | Uttar Pradesh | 4 | 14 | 3 | 21 | 60 | 13 |
| 28 | Uttrakhand | - | - | - | - | 23 | - |
| 29 | West Bengal | 17 | 44 | 11 | 83 | 11 | 44 |