Saph Pani

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

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Deliverable D2.4

Cross case analysis of three MAR case studies including recommendations for MAR applications in India

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1 Introduction

Managed Aquifer Recharge (MAR) are methods involving changes in the land surface or creation of facilities for deliberately increasing groundwater recharge. MAR will eventually expect to increase groundwater storage by increasing recharge through precipitation as well as treated waste water. MAR can be used to replenish the depleted aquifers and thereby control the seawater intrusion in coastal aquifers and improve the groundwater quality. MAR often provides the cheapest form of safe water supply for towns and small communities (Dillon, 2005). Different techniques of MAR, such as aquifer storage and recovery, aquifer storage transfer and recovery, bank filtration, dune filtration, infiltration ponds, percolation tanks, rain water harvesting, soil aquifer treatment, sand dams, underground dams are employed all over the world (Charlesworth et al., 2002, Marchant & Bristow 2007, Dillon et al., 2009). The efficiency and impact of MAR structures in India have been studied by many researchers (e.g. Dillon et al., 1983 and Gale et al., 2006, Saph Pani Deliverable 2.1). Parimalarenganayaki and Elango (2013b) carried out a review of research studies on MAR by check dams. According to the estimation made by Central Ground Water board of India, MAR can be successfully applied in India over an area of 448760 km^2 (CGWB 2005). A volume of 3643 million cubic meter will be then available for annual recharge. Even though this technique can enhance the volume of groundwater abstracted, MAR is not always a cure for overexploited aquifers.

As a part of Saph Pani, case studies on the effect of MAR were carried out at Raipur, Maheswaram and Chennai (Figure 1), as these regions are with contrasting geological and hydrogeological conditions and are from different parts of India. In the case of Raipur, the effect of surface reservoir (locally referred as ‘talabs’) in improving the groundwater storage was investigated. At Maheswaram, a percolation tank was investigated to assess the impact on aquifer replenishment in the hard rock aquifer. In the Chennai case study, the role of check dams in improving the groundwater recharge and the role of a pilot percolation pond in mitigating seawater intrusion at Periyapalayam and Andarmadam respectively were investigated. The salient outcomes of these case studies are described in the following sections.

1.1 Scope of the report

The major scope of this report is a deliverable related to tasks 2.1, 2.2, 2.3 and 2.4 listed in the Saph Pani project proposal which are given in Table 1.

Table 1 Description of the tasks 2.1, 2.2, 2.3 and 2.4

Task	Title	Involved partners
2.1	Potential of storm water infiltration from existing lakes and ponds into an extensively exploited urban aquifer and its effect on groundwater quality in Raipur	(Leader: KWB; Contributors: GTZ, RMC, NGRI, NIH, FHNW)
2.2	MAR for coping with sea-water intrusion and groundwater overexploitation in an aquifer used for drinking water production in Chennai	(Leader: ANNA; Contributors: KWB, FUB, SPT, GTZ)
2.3	Percolation tanks to enhance recharge and groundwater quality in over-exploited hard-rock aquifers in Maheshwaram	(Leader: NGRI; Contributors: BRGM, FHNW, IWMI, NIH)
2.4	General aspects of MAR in India	(Leader: FHNW; Contributors: KWB, FUB, NIH, NGRI)
2.4.1	India-wide review on MAR practice and experience	(Leader: FHNW; Contributors: ANNA, KWB, FUB, NGRI).
2.4.2	Cross-case analysis to develop guidelines and recommendations	(Leader: ANNA; Contributors: FHNW, FUB, NGRI, NIH)

The outcome of the tasks 2.1, 2.2 and 2.3 are the major input for the completion of task 2.4. This deliverable for task 2.4.2 describes the cross case analysis of the research studies carried out at different sites, as a part of this project, to suggest practicable recommendations for the potential end-users and authorities that foster the further implementation of these techniques in India and similar countries. One special element of this report is to present the impact of climate change on groundwater recharge and thus an analysis of the future potential for MAR in India and to focus on the technical aspects associated with MAR. The project was carried out to assess MAR and soil aquifer treatment at study regions in Chennai, Maheswaram and Raipur. The general outcome of the studies carried out at these three sites was described in Saph Pani D 2.3.

1.2 Objective of the MAR case studies

The MAR studies within Saph Pani focus on three case studies and the objectives of these studies are given in Table 2.

Table 2.Objectives of the case studies

Case study site	Objective
Raipur	To investigate the feasibility of MAR in an urban storm water management system.
Maheshwaram	To quantify the infiltration rates and aquifer recharge by storage tanks; To assess the evolution of water quality during this infiltration
Chennai	To investigate the effect of percolation ponds and Check dams in mitigating seawater intrusion To investigate the effect of check dam in improving groundwater recharge

2 General description of study sites

The locations of the investigated MAR sites in India are shown in Figure 1. Raipur is located in the Hirri sub-basin within the Chattisgarh state. The Maheshwaram watershed is located 30 km south of Hyderabad, the capital city of Telangana state. Chennai case study is located within the Arani – Korattalai river basin, north of Chennai, Tamil Nadu state. The Geology of Raipur area comprises limestone and shale, whereas the Maheswaram area comprises hard rocks of the basement. Chennai area is characterized by fluvial /marine unconsolidated sediments. Further information about the study sites are described in the following sections.

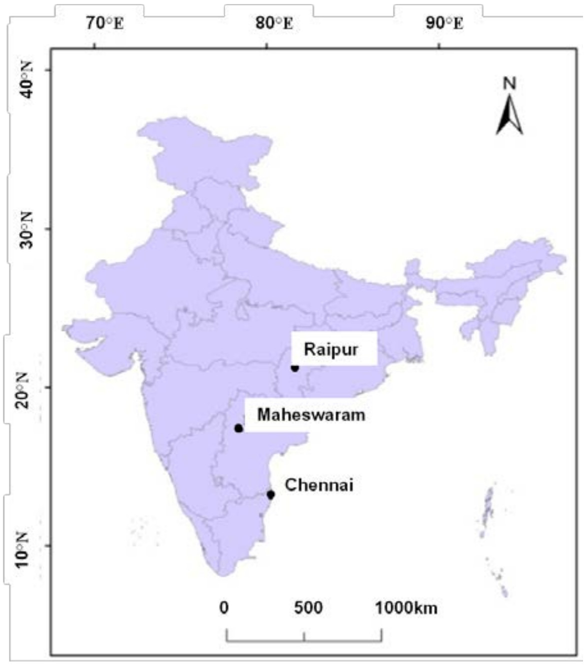

Figure 1.Location of MAR sites investigated in Saph Pani

2.1 Raipur

Geologically, the area is predominantly consisting of Raipur limestone and Deondogarh Shale, where the former is characterized by secondary porosity. The average annual rainfall in this area is 1300 mm, contributed by monsoons (Roy, et al., 2009; Mukherjee, et al., 2011). The depth to groundwater level in the area varies from 2 to 13 m during pre-monsoon and from 0.1 to 7 m during post monsoon period in the shallow aquifers (Saph Pani deliverables D 2.1). The bore wells in the limestone aquifer yields 18 l/s. The location of the Raipur study site is shown in Figure 2.

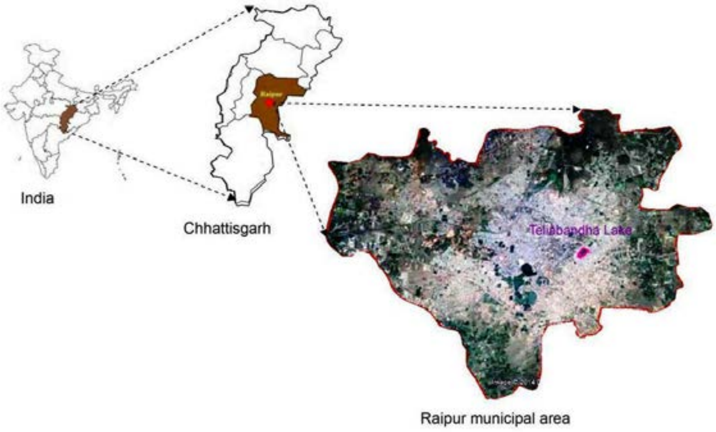

Figure 2.Location of Teliabandha lake at Raipur study site

2.2 Maheswaram

The Maheshwaram watershed (Figure 3) covers an area of 53 km^2 and comprises Archean granites. The elevation of the area ranges from 590 to 670 m msl. Rainfall occurs through short events during the monsoon from June to October with an average of 750 mm/year. No perennial surface water bodies exist in this watershed. The weathering profile is composed of saprolite, a sandy-clay material with high porosity and low permeability which constitute the main storage reservoir of the aquifer, followed by the fractured granite which ensure the transmissive capacity of the aquifer. Within the deeper non-weathered basement the hydraulic conductivity is significantly reduced (Dewandel et al., 2006, Maréchal et al., 2003; 2004, Boisson et al., submitted).The depth to groundwater table in the area ranges from 15 to 25 m.

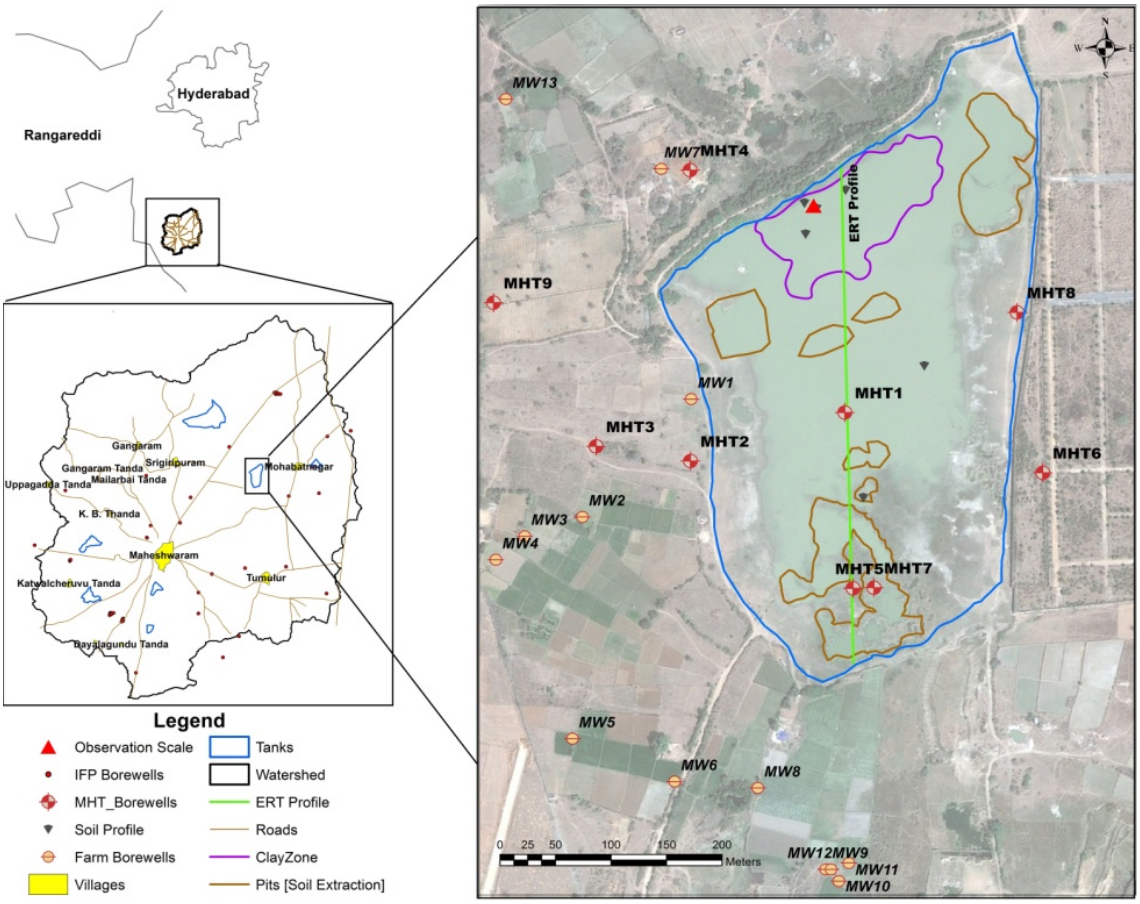

Figure 3. Location of the investigated tank in the Maheshwaram study site (Boisson et al., 2014, Saph Pani deliverable D2.3)

2.3 Chennai

The Chennai study sites are located in the Arani-Korattalai river basin north of the city (Figure 4). The Arani and Korattalai rivers flow seaward only during north east monsoon. During the dry periods, seawater enters into the river and encroach several kilometers landward. The geological, geomorphological and hydrogeological conditions of the area were investigated and presented in Saph Pani Deliverable, D 2.3. The basin consists mainly of sand intercalated with silt and clay. Several ferricrete surfaces exist in the basin, one of them outcropping in the southwest portion of the study area (Brueckner 2014). The formation of ferricretes is due to changes in groundwater level (Pappu 1999). Geomorphologically, the area is characterized by alluvial plains, flood plains, coastal plains, pediments, pediplains and water bodies. Quaternary alluvium is the main aquifer in the area. Agriculture is the main occupation in the area, with paddy as main product, and also roses, jasmine and vegetables.

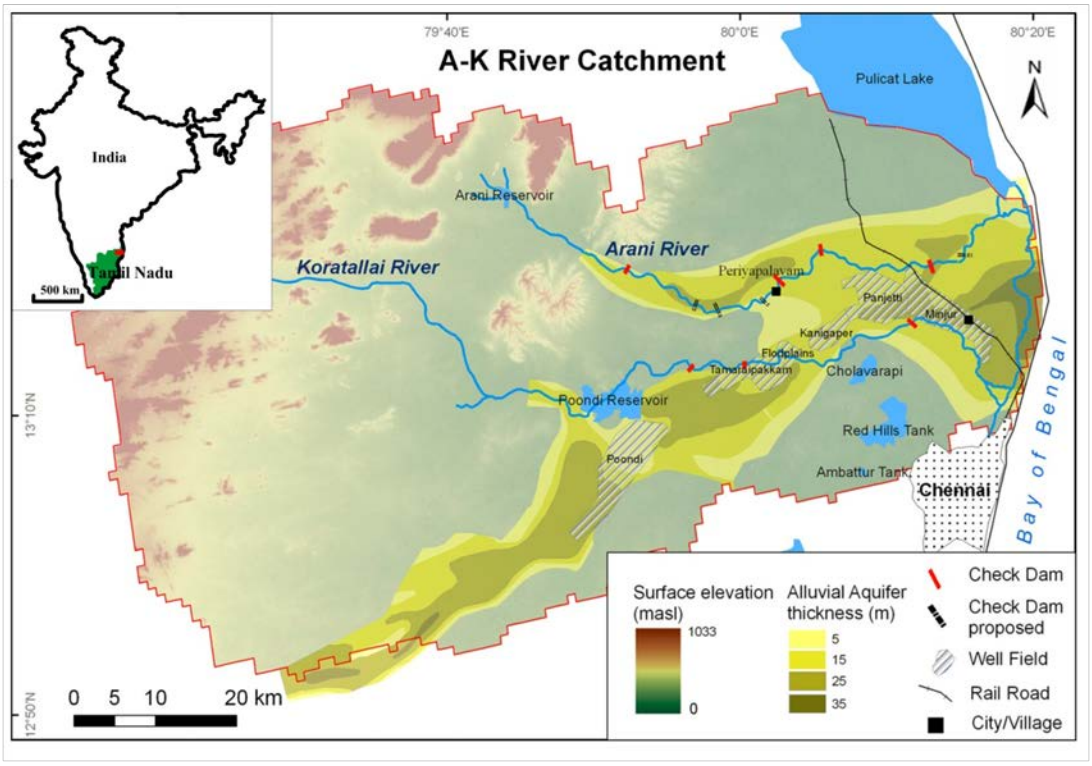

Figure 4. Topography and aquifer thickness of the Arani–Koratallai river catchment near Chennai. Extent and thickness of alluvial aquifer and well field location from Charalambous and Garratt (2009), digital surface model from SRTM data, A–K river catchment from Hydro1 K (USGS 2008) (Sprenger et al. 2014).

3 Methods of Investigation

The different methods adopted to carry out the investigation at the study sites are given in Table.3

Table.3 Methods of investigation at the case study sites

	Maheswaram	Chennai		Raipur
		Percolation pond	Check dam	
	Geological survey Electrical Resistivity Tomography and geomagnetic survey Borehole loggings (camera flow meters)	Maps from Geological survey of India	Maps from Geological survey of India	Maps from Central Groundwater Board (2007)
		GPR, VES, Bore hole logging	GPR, VES, Bore hole logging	VES, Bore hole logs
Geology		Lab method, textural analysis	Lab methods	
Hydraulic conductivity	Pumping tests	Pumping test	Data from CGWB, slug tests	Recovery test
Porosity	Probes either in bucket or flow-through cell multiparameter probe and borehole logging	Portable multiparameter probe	Portable multiparameter probe	Probes
Electrical conductivity	multiparameter probe	Portable multiparameter probe	Portable multiparameter probe	Probes
Major and minor ions	Not measured	Alkalinity kit	Alkalinity kit	Acid-base titration
Trace elements		Ion chromatography	Ion chromatography	Laboratory

	None	Trace metal analyzer	Trace metal analyzer	None

4 Overview of MAR structures

The Raipur case study investigates the effect of MAR on a sub-catchment basin, whereas the Maheswaram case study is based on the investigation of a local structure. In the case of Chennai, the effect of MAR structures such as percolation ponds and check dams are investigated. To study the effect of percolation pond, a pilot scale pond was constructed as a part of this project near Chennai, whereas the existing structures were investigated at other locations.

4.1 Raipur

The study was carried out in the Telibandha Lake (Figure 5) with a catchment area of 1.14 Km^2.

Figure 5.Photographs of the Telibandha Lake

The area receives monsoon rains and it leads to urban storm water floods. The lake water level with time is as shown in Figure 6.

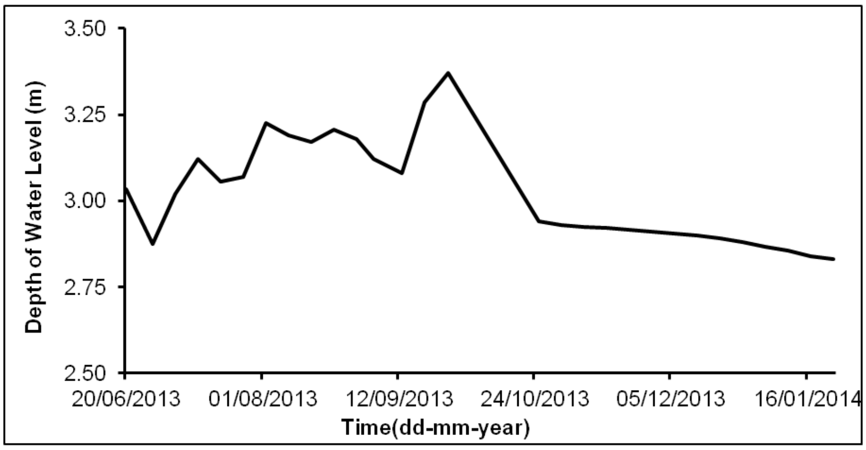

Figure 6. Temporal variation in the water level of the Telibandha Lake

Storm water runoff mixes with waste water which drain into surface water bodies locally called as talabs. The water thus stored in the talabs is of poor quality. The objective of the Raipur case study is to investigate the feasibility of MAR by a pilot study in Telibandha

Lake. The length, width and depth of the lake are 4744, 231 and 1.29 m respectively. Comprehensive hydrogeological and groundwater quality studies were carried out and the water balance of the lake was also calculated. The turbidity, COD and the concentration of fecal and total coliform exceded the BIS limits of drinking water standards.

4.2 Maheshwaram

The monitored tank is located in the downstream part of the watershed and has been used for more than 10 years for water storage (Figure 7). An earthen bund in northern part dams the natural stream outlet and consequently the runoff water is stored over an estimated area of 130'000 m^2 and a maximum water depth of 4 m.

Figure 7. Photographs of the tank: from the dam. a) 01/05/2012 and b) 28/08/2013

Before the first significant rainfall event, the soil is withered due to a dry period which creates important shrinkage cracks. The soil specificities of the tank are the clayey zone, mainly in the lower northern part of the tank. The rest of the tank area is mostly covered by silty loam soil on the surface underlain by sandy loam at a depth of 40–80 cm. Nine monitoring wells were implemented to measure piezometric levels and one staff gauge records the surface water level within the tank. Filling of the tank can be highly variable. The water stored in the tank is also used by the surrounding farmers by pumping the individual bore wells. Irrigation periods are controlled by the availability of electricity (7 h/ day). The percolation tank constitutes a drinking water supply source for livestock (goats and buffaloes in limited number) as well as for buffalo washing and hence may induce microbial contamination. The area is also known to be prone to geogenic fluoride contamination (Pettenati et al., 2013, 2014) with concentration up to 5 mg/L. Tank functioning has been described in detail in Boisson et al. (2014).

4.3 Chennai

Percolation pond

At the Chennai study site, a percolation pond with a recharge shaft was constructed and its impact on improving the groundwater quality and quantity was investigated. The design of this structure is described in detail in the Saph Pani deliverable 2.2 and 2.3. The study site is located in a paddy field and it comprises fine silt and silty sand. Investigations indicated that the rate of infiltration was high initially during the filling up of water in the pond and later on it gradually decreased due to the settlement of finer particles at the bottom of the pond. The pond begins to fill up during September after the rains and it becomes dry during May. In order to overcome the problem of reduction in infiltration due to settling of finer particles, a recharge shaft was constructed at the centre of the pond. Figure 8 shows the photographs of the pond taken in August and December 2012 and October 2013.

Figure 8 Photographs of pond in August 2012, December 2012 and October 2013 (Photo: Raicy M C).

Check dam

Two check dams, located across the Arani River, at Periyapalam and Ariapakkam were also taken up for the study. The Periyapalam check dam is constructed in 2010 by the Government of Tamil Nadu and the length and height of the dam are 260 m and 3.5 m respectively. The check dam usually gets filled during August – September and dries up during March – May depending upon the variability in climatic parameters. Figure 9 shows photographs of check dam with and without water.

Fig. 9. Photographs of Periyapalayam check dam with and without water (Photo: Kolja Bosch)

5 Results of scientific investigations

The salient features and data collected on hydrogeological, hydrogeochemical and microbiological aspects of the study sites during the scientific investigations are given in Table 4.

Table. 4 Salient features and results of water analysis of the study sites.

	Raipur	Maheswaram	Percolation pond - Chennai	Check dam - Chennai
GENERAL INFORMATION ABOUT THE AREA				
Population density	5816 people/km^2	NA	56/km^2	800/km^2
Temperature	summer:28-42°C Winter:11-27°C	average 26°C, min 7°C max 45°C	24.3 to 44ºC	24.3 to 44ºC
Annual average regional rainfall (mm)	1206	750	1104	1104
Annual average pan evaporation (mm)	1996	1800	2003	2003
Elevation (m msl)	270-304	590-670	0-7	28 - 19
Geomorphology	geomorphic dome	Flat	Alluvium – flood plains	Fluvial and erosional landforms

Top soil type	Vertisols and Ultisols	red soil (bimodal sandy clay soil)	Sandy, clayey to fine alluvial	alfisols, inceptisols, vetisols (USDA classification)
Major rock type	Shale & Stromatolitic limestone	Granite	Alluvium	Unconsolidated sediments
Depth to bed rock (m)	0-2	10-80	>50	50
Structural control in the area	No	No	No	No
Drainage pattern	Radial pattern		Dendritic	Dentritic
Depth to groundwater table (m)	Pre-monsoon, 2011: 2-13 post monsoon, 2011: 1-11	1-25	0-3	5 to 12
Aquifer type	Unconfined	Unconfined	Unconfined	Unconfined
Aquifer bottom	Massive rock	Massive rock	Clay	Clay
Nature of unsaturated zone	Weathered hard rock	Saprolite	Unconsolidated sediments	Unconsolidated sediments
Aquifer thickness (m)	Ranges up to 12 m around Telibandha Lake	10-70	35	45
Hydraulic conductivity (m/day)	27	1.7×10^{-5} to 2.4×10^{-5}	-	65
Porosity	Highly variable	1-10%	30 to 40 %	30-40%

RESULTS OF WATER ANALYSIS						
	Raipur	Maheswaram		Percolation pond		Check dam
	Existing tank	Before recharge	After recharge	Before MAR	After MAR	After MAR
Electrical conductivity (µS/cm)	563	720-3200	510-3200	68000-69000	2000-69000	700-1800
pH	8.38	6.9-7.7	6.9-8.15	6.5-8.4	6.5-7.6	6.5-7.5
BOD (mg/l)	1.5	NA	NA	NA	NA	< 2
COD (mg/l)	7	NA	NA	NA	NA	4-22
Alkalinity (mg/l)	134	350-500	200-550	230-450	33-41L	250
Turbidity	21 NTU	NA	NA	NA	NA	2
MICROBIOLOGICAL ANALYSIS						
Total bacterial count (µg/l)	240 MPN/100 ml					150 cfu/100
Faecal coliforms	21 MPN/100 ml	NA		NA		NA
E. coli. (cfu/100 µg/l)	NA					10
Enterococci (cfu/100 µg/l)	NA					6
MAJOR AND MINOR ION ANALYSIS						
Na^+ (mg/l)	78	80-200	50-210	13500-13600	50-110	45-554

K^+ (mg/l)	20	0.7-4	0.7-4	400-450	30-60	1-34
Ca^{2+} (mg/l)	22	25-300	30-200	500-600	40-60	17-134
Mg^{2+} (mg/l)	10	10- 80	12- 60	800-850	50-140	8 - 135
Li^+(µg/l)	NA	2 - 30	0.5 - 20	NA	NA	NA
NH_4^+ (mg/l)	NA	0 - 7	0 - 4	NA	NA	NA
Cl^-(mg/l)	89	10- 470	10- 350	23000-26000	300-600	NA
CO_3^{2-} (mg/l)	NA	NA	0- 16	NA	NA	NA
HCO_3^- (mg/l)	163	350-500	200-550	230-450	33-41	80-575
SO_4^{2-} (mg/l)	25	20 - 400	20 - 230	300-3500	70-170	10-300
NO_3^- (mg/l)	2.2	0-40	0-100	40-70	7-23	0.45 - 12.8
NO_2^- (mg/l)	0.5	0-0.06	0-0.3	NA	NA	0-0.36
PO_4^- (mg/l)	0.65	0 - 0.7	0 - 0.4	NA	NA	NA
Br (mg/l)		Below detectable limit	Below detectable limit	0.2-0.4	0.05-0.15	0-0.7

<table>
<tr><td>F (mg/l)</td><td>0.57</td><td>0.7 - 5</td><td>0.7 - 5</td><td>NA</td><td>NA</td><td>0-1.5</td></tr>
<tr><td colspan="7">TRACE ELEMENTS</td></tr>
<tr><td>B(µg/l)</td><td rowspan="5">NA</td><td>Below detectable limit</td><td>Below detectable limit</td><td colspan="2" rowspan="4">NA</td><td>NA</td></tr>
<tr><td>Cd (µg/l)</td><td>0 - 0.01</td><td>0 - 0.1</td><td>Below detectable limit</td></tr>
<tr><td>Cr (µg/l)</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Co (µg/l)</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Cu (µg/l)</td><td>0.3 - 3</td><td>0.7 - 7</td><td>Below detectable limit</td><td>NA</td><td>NA</td></tr>
<tr><td>Fe (mg/L)</td><td>0.07</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>0-0.64</td></tr>
<tr><td>Pb (µg/l)</td><td>NA</td><td>0.5 - 90</td><td>0.5 - 80</td><td>0.028</td><td>NA</td><td rowspan="3">Below detectable limit</td></tr>
<tr><td>Mn (µg/l)</td><td>0.1 mg/L</td><td>0.3 - 200</td><td>NA</td><td colspan="2" rowspan="5">NA</td></tr>
<tr><td>Mo (µg/l)</td><td>NA</td><td colspan="2">NA</td></tr>
<tr><td>Ni (µg/l)</td><td>NA</td><td>0.5 - 2</td><td>0.1 - 3</td><td>NA</td></tr>
<tr><td>Ba (µg/l)</td><td>NA</td><td>40 - 150</td><td>50 - 200</td><td>NA</td></tr>
<tr><td>Zn (µg/l)</td><td>NA</td><td>2 - 50</td><td>3 - 90</td><td>NA</td></tr>
</table>

The table shows that recharge from the percolation ponds and check dams has improved the groundwater quality in the nearby areas. However, the lithological characteristics, availability of rainfall and clogging of suspended particles at the recharge surface have affected the performance of the recharge structures. In case of Raipur, the geologic formation limits the natural purification of lake water during recharge, and hence the groundwater quality of the nearby area has not improved. In the case of Maheswaram, the effect of pond on the improvement of groundwater level and quality was not significant. Figure 10 shows improvement in groundwater quality after MAR structures at two study sites.

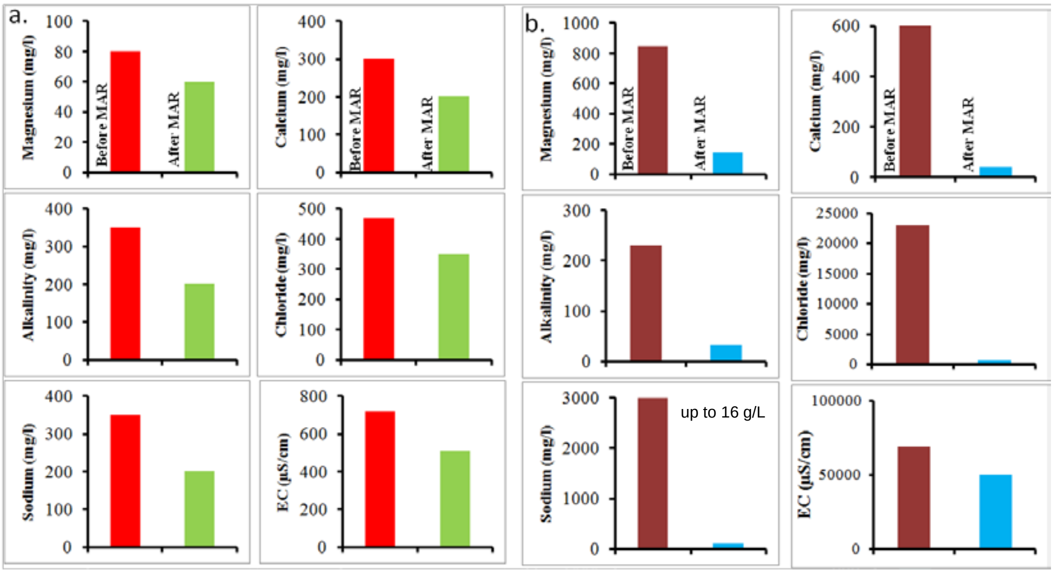

Figure 10 Improvement in groundwater quality a) Maheswaram (before and after rainfall) b) Chennai percolation pond (before and after MAR)

5.1 Raipur

The study revealed that “MAR - Aquifer Storage Transport and Recovery” by any engineered scheme is not viable in the area because of the geologic configuration in the area. The hydraulic conductivity of the area is modeled to be 0.00147 m/day, which is very low. This indicates that the seepage from the lake bed is between 3.75 and 4.82 mm/day/m^2. The overflow of large quantity of water without potential uses reduces the effectiveness of the lake. As the massive limestone in this area is highly porous, the self purification capacity is very low. The variation in water balance components of the Telibandha Lake is shown in Figure 11.

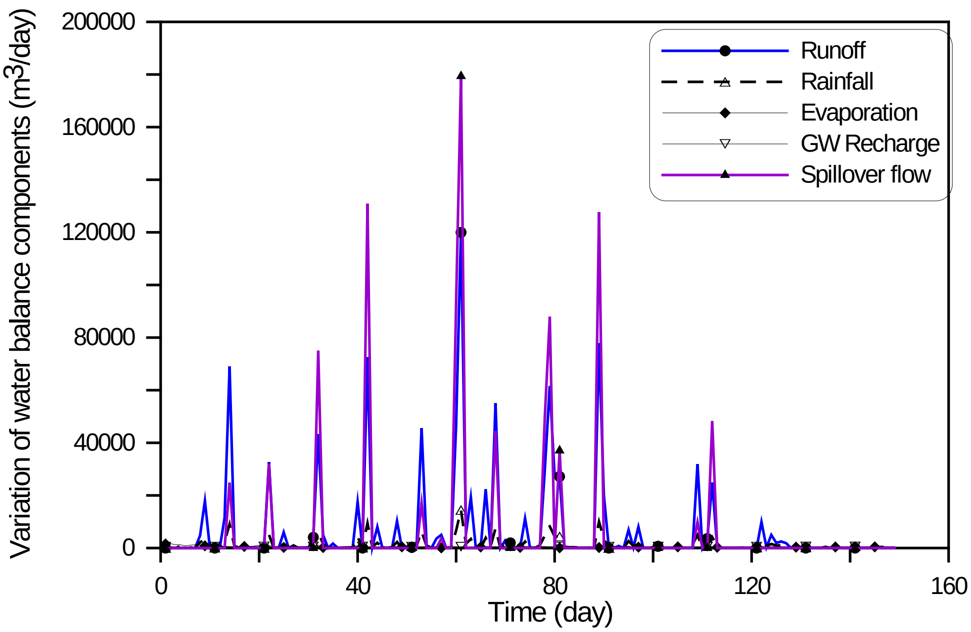

Figure 11. Variation in water balance components

5.2 Maheshwaram case Study

Water budgeting presented on Figure 12 shows the high variability of the efficiency with 11'730 m^3 of percolated water in 2012 and 229'155 m^3 in 2013. The ratio of evaporation over stored water is 38%.

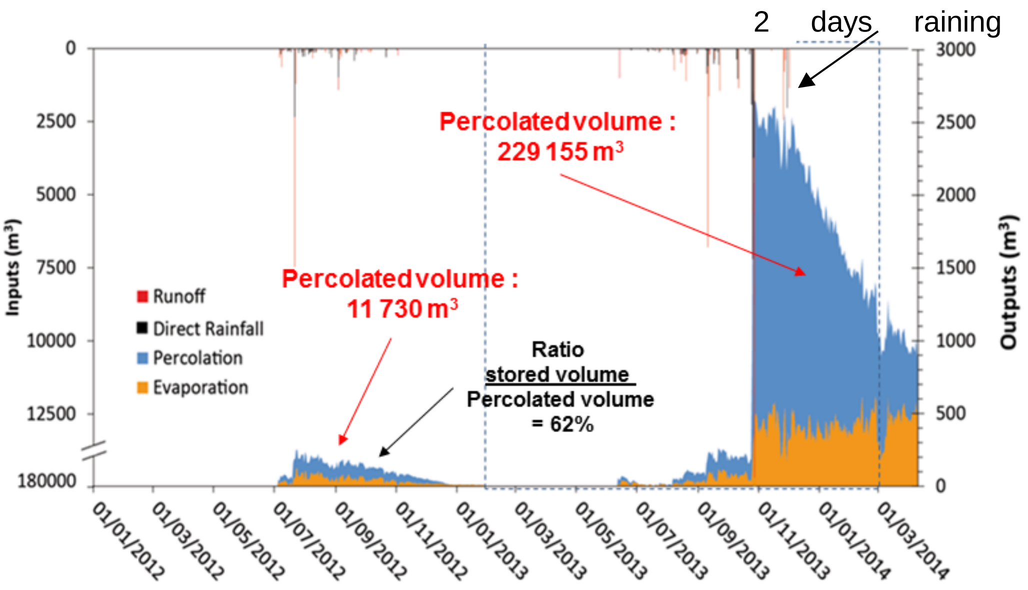

Figure 12. Water budget in the Tummulur tank over period of two years.

Chemical monitoring on the Maheshwaram study site highlighted the limited impact of the recharge structure on the water quality. The main threat on the area is related to geogenic source of fluoride in groundwater. Chemical evolution of groundwater in the boreholes located nearby the pond shows a limited impact on the water quality. As an example, in the case of fluoride (Figure.13) after recharge by the monsoon and from the pond, the fluoride concentration remain stable with only a limited decrease and even an increase is some of the wells. Most of the boreholes remain above the permissible limit of 1.2 mg/L (BIS 2012).

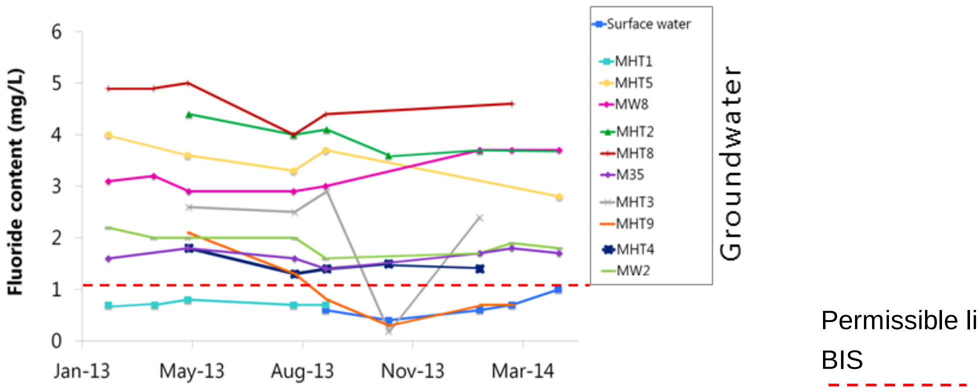

Figure 13. Evolution of fluoride concentration in the monitored boreholes surrounding the tank.

In these crystalline rock aquifers water chemistry is highly affected by local heterogeneities as demonstrated in Alazard et al. (submitted) showing that even at small scale complex flow paths do not allow dilution on a systematic way and may even enhance concentration of elements. Complexity of the flow through fractured media is illustrated in Figure 14 where a few fractures control the flow and the chemical mixing within the borehole.

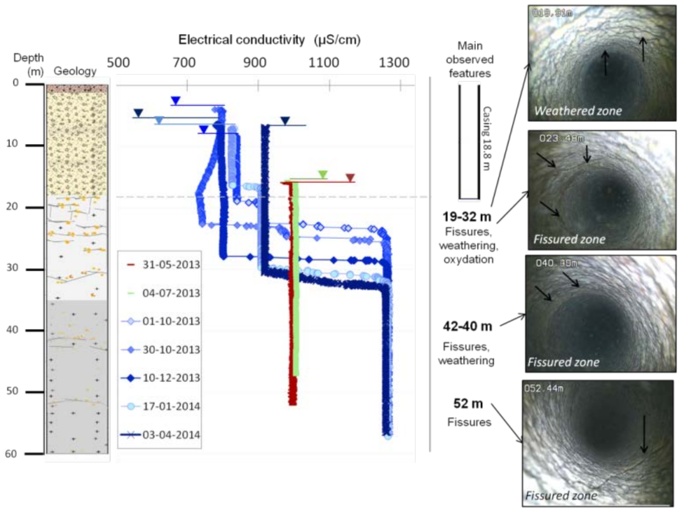

Figure 14. Geological log of MHT9 borehole; Electrical conductivity loggings evolution and fractures observed in borehole. Pre-monsoon campaign is shown in red, early stage of the monsoon (i.e. July 2013) is shown in green, and late stages of the monsoon and post-monsoon campaigns are shown in blue. Water level for each campaign is shown (triangles).

Processes controlling the fluoride release have been studied on this site and watershed through modeling using PHREEQC (Pettenati et al., 2013; 2014). From these studies it is shown that complex weathering kinetics, adsorption and cation exchange are impacted by local land use and that a single structure will hardly counteract the natural release of fluoride. Hence percolation tank in crystalline rock aquifers appear to have a limited impact on water quality.

5.3 Chennai

5.3.1 Percolation pond

The study indicated that about 250-300 m^3 of water is recharged per year from the pilot pond constructed. The recharge has raised the groundwater level by about 1.5 m in an area of about 30 m^2. The electrical conductivity of groundwater up to about 2 m from the water table was 3'000 µs/cm. The variation in electrical conductivity of water in the pond and the nearby piezometer of 4 m depth is shown in Figure 15. As the recharge amount is very low and the ambient groundwater is highly saline, the recharge has not improved the quality significantly beyond 2 m below the water table. However, construction of ponds at an interval of 100 m in this region will improve the groundwater quality regionally. The approximate costs of water recharged annually in the percolation pond as a part of the study was estimated as Rs. 0.15 - 0.3 per m^3 (Raicy and Elango, 2014b).

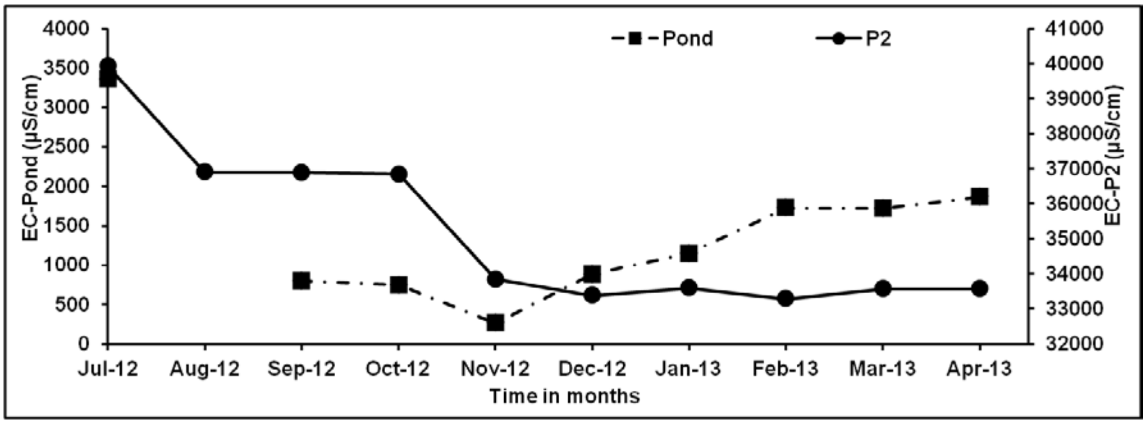

Figure 15. Temporal variation in electrical conductivity of water in the pond water and piezometer (Raicy and Elango, 2014b).

5.3.2. Check dam

The sampling campaign around the Periyapalam check dam indicated an improvement in groundwater quality in the nearby areas. The region of the Periyapalayam check dam, where the groundwater level has increased due to the recharge of water from the check dam was deciphered based on comparison of water level in the check dam and groundwater level in the nearby wells (Figure 16). Figure 16 shows that water level fluctuation in the wells nearby the Periyapalayam check dam is mainly due to the recharge from the check dam. The study indicated that about 1.14 Mm^3 water will be recharged if the check dam is filled within a year. The cost of water recharged works out to be about Rs. 1.2 per m^3 (Parimalarenganayaki and Elango, 2014).

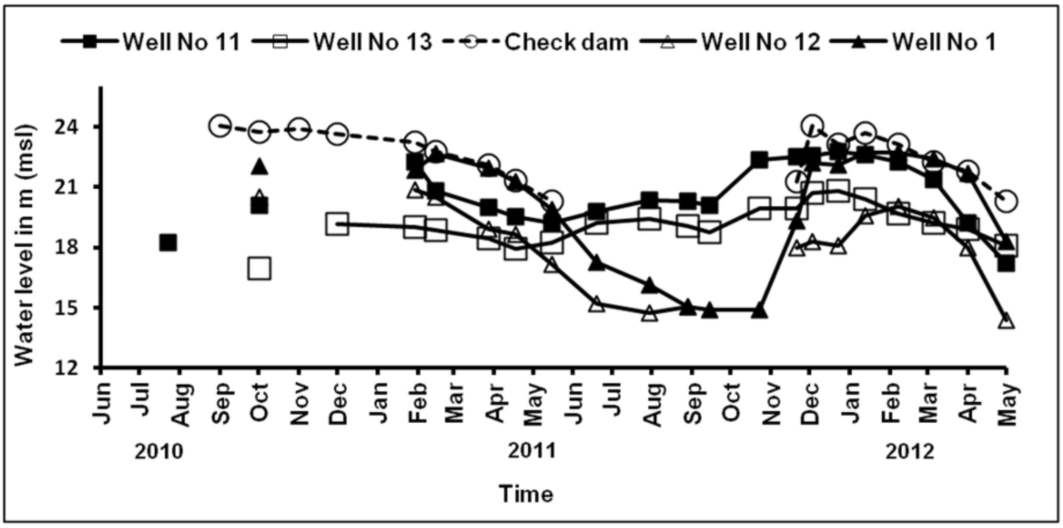

Figure 16. Temporal variation of water level in wells and the Periyapalayam check dam (Parimalarenganayaki and Elango, 2013a)

The groundwater quality in the region around Ariapakkam check dam, upstream of the Periyapalayam check dam was taken into consideration for hydrogeochemical modeling to investigate the evolution of groundwater chemistry from infiltration (recharge) to discharge to the sea as well as the effect of check dam in improving groundwater quality (Thomas et al. 2014). Wells in the southwest of the study area around Ariapakkam check dam have low ionic concentrations, indicating that precipitation is the most important factor, whereas wells in the north have higher concentrations. Infiltration of surface water, stored in the check dam, is indicated by similar groundwater chemistry (Brueckner 2014).

Hydrogeochemical modeling using the thermodynamic computer program PHREEQC, Version 3 (Parkhurst and Appelo 2013) indicates mineral dissolution within the aquifer. Hydrogeochemical modeling has shown that different mixing ratios of freshwater and seawater can explain the hydrochemical composition of groundwater, sampled in different wells in the coastal region (Table. 5).

Table.5. Mixing of freshwater and seawater in the coastal region (PHREEQC calculations) and comparison with groundwater sampled in wells using bromide as tracer ion, as well as analyzed chloride concentrations

Sample	Mixing ratio freshwater:seawater)	Seawater percent	Chloride [mg/l]	Water type (analysed samples)
Freshwater	1.0 : 0.0	0.0	52	Ca-Na-HCO_3-Cl
Well A	0.98 : 0.02	2.0	466	Na-Cl
Well B	0.97 : 0.03	3.0	620	Ca-Na-Mg-Cl-HCO_3

Well C	0.97 : 0.03	3.0	972	Na-Cl-SO_4
Well D	0.965 : 0.035	3.5	1,075	Na-Ca-Cl
Well E	0.74 : 0.26	26.0	4,800	Na-Cl
Seawater (Elliots Beach)	0.0 : 1:0	100.0	14,600	Na-Cl

6 Impact of climate change on recharge structure efficiency

Assessment of the impact of climate change on four key aspects agriculture, water, natural ecosystems & biodiversity and health until the year 2030 was carried out by the Ministry of Environment and Forests, Government of India (INCCA, 2010). This study predicted the variation in temperature, precipitation, number of rainy days and the possibility for extreme events in India until the year 2030. This forecast was used to understand the possible impact of climate change in the three study locations of the Saph Pani project. This study (INCCA, 2010) indicated an all-round warming, associated with increasing greenhouse gas concentrations over the Indian subcontinent. The rise in annual mean surface air temperature by the 2030s will range from 1.7°C to 2.0°C. The variability of seasonal mean temperature may be higher in the winter months (INCCA, 2010). The climate model indicates that a small increase in annual precipitation by the year 2030, with respect to the baseline, that is, 1961– 1990s (or 1970s). Krishna Kumar et al. (2008) reported that the rainfall variability over India will be increased to about 5% by 2100. The climate model (INCCA report, 2010) indicates that the rainfall in Chennai and in Maheshwaram is likely to increase by 6-8% by the year 2030.

Monitoring of the percolation tanks during Saph Pani project highlights gave some insight important aspects of recharge processes. First of all, the impact of the study tank is limited in term of quantity infiltrating the aquifer in the case of Maheshwaram. Over the 2 years of monitoring, the amount of stored water in the Maheswaram tank vary from 11,750 m^3 in 2012 to 229,155 m^3 in 2013 highlighting the high variability of the system. While the improvement in terms of quantity was important in 2013, it was almost negligible in 2012. On the same study period most of the water stored (90%) come from a single rainfall event of two days (Figure 12). More details are available in the Saph pani deliverable D2.3. The water stored and recharged at the Chennai percolation pond is very low, as its size is small as compared to that in Maheswaram. However, the recharge from the pond has locally improved the quality of groundwater. The efficiency of the MAR structures like ponds, check dam and lakes depend on the quantum and duration of rainfall. If the rainfall occurs for a longer period, the recharge structure will remain filled with water for longer time and thus its efficiency will be higher. Since climatic change investigations forecast a more erratic monsoon in the future, the variability of the efficiency of recharge structures may increase. Moreover, as the atmospheric temperature is expected to increase, evaporation will increase accordingly. As shown in Figure 12 in case of Maheshwaram, 38% of the water stored in the tank evaporates during the year 2012. Hence, from a quantitative point of view, climate change with an increasing variability of rainfall and an increasing temperature will increase the already important variability of the efficiency of the system and reduce its efficiency by increasing the evaporation. On the other hand, the climate change projections for the east coast of India estimated that the annual rainfall may increase in 2030's with respect to the 1970's from 2 to 54 mm, an increase of 0.2% to 4.4 % (INCCA 2010). It is also interesting to note that the maximum increase in rainfall is projected to happen in March, April and May in 2030's, with rainfall set to increase by 14 mm on an average with respect to the same period in 1970's (INCCA 2010). In the case of the Chennai case study, the present rainfall itself is sufficient to fill most of the check dams and ponds in a shorter period of time as the rainfall in Chennai is rapid and heavy. Hence, even with the projected rainfall increase, effectiveness of managed aquifer recharge structures will not be altered. However, if the number of rainy days increases, especially as projected in summer months of March, April and May, water will be stored in the recharge structures for a longer period. Thus, the efficiency of the MAR structures may slightly alter due to the increase in temperature, coupled with evaporation. However, this will be compensated by the projected increase in rainfall especially at the east coast of India.

7 Main findings and recommendations

In order to investigate the similarities and differences among the three case study sites, a comparison of the salient outcome based on the data gathered was carried out. Based on the case studies at three sites, it is evident that the MAR structures in general enhance the groundwater quality and groundwater quantity only around a limited area. The effect of recharge on improving the groundwater quality was evident at the Chennai site whereas it is not significant in Maheswaram. In limestone regions, MAR with treated waste water may lead to adverse impact on groundwater quality due to rapid recharge. Further, the effect of the MAR structure depends on source and quantity of input water which is quantitatively reduced in the case of Chennai and Maheswaram. In the case of Chennai the check dam did not get any water during the year 2012 due to low rainfall in the upper part of the catchment. MAR in regions prone for geogenic sources need to be very carefully planned. In the case of Maheswaram study the geogenic source of fluoride in the rocks leads to an increase in fluoride in groundwater near to the pond. The higher degree of evaporation and weathering of fluoride bearing matrix minerals within the critical zone during the tank water percolation reduces the effectiveness of MAR in Maheswaram (Pettenati et al., 2014). Similar findings have been also reported on different MAR sites from various parts of the world (Corre et al., 2012; Dillon et al., 2008: Dillon and Jimenez, 2008; Bouwer 1998; Franson, 1998). A Check dam, which is a cost intensive structure, could effectively enhance the groundwater quality in its vicinity. In case of percolation ponds, as the amount of water that can be recharged is very low, the effect of dilution or improvement in groundwater quality is also comparatively low. However, the cost of water recharged by small-size percolation ponds will be comparatively lower than the water costs recharged from check dams. MAR structures in unconsolidated formations (Chennai) have usually a higher performance than the ones in crystalline rocks (Maheswaram) and limestones (Raipur). The percolation pond in unconsolidated formations (Chennai) can improve groundwater quantity and quality, whereas in the case of Maheswaram, no improvement in groundwater quality could be detected. At Raipur, the recharge was very low due to the poor hydraulic conductivity of shales and limestone. The studies carried out at three different sites confirm the meaning of the regional geology in controlling the efficiency of the recharge structures. The Saph Pani project has shown, that check dams should be constructed with sluice gates. Sluice gates can be opened to release sufficient water to the downstream side improving the recharge. Further, the sluice gates can be opened when the dam is filled, so that the accumulated sediments at the bottom can be washed away. This practice will considerably prevent accumulation of sediments and physical clogging. In areas where the rainfall is heavy, check dams can be used to improve groundwater recharge and to mitigate the problem of depletion of resources. In case of percolation ponds, the lithology of the surrounding area from where the surface run off originates, plays an important role. If the area is characterized by fine-grained material, the suspended load in the pond water will be deposited reducing the infiltration rate. According to the sedimentation rate, this layer should be removed regularly. A Recharge shaft can be constructed in areas where the top layer is characterized by low hydraulic conductivity. The Chennai study indicated an increase in recharge by about 3 times after implementing a recharge shaft.

Overall the Saph Pani study carried out at three different lithological settings has shown the importance of the hydrogeological situation, the characteristics of rainfall and runoff in controlling the efficiency of managed aquifer recharge. Because of complex interactions between climatic parameters, the impact of climate change on groundwater recharge is still unknown.

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