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

Editors

Elango Lakshmanan
Vikas C. Goyal
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SAPHPANI

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Preface

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

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

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

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

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

5th December 2012

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

Gesche Gruetzmacher and P.J. Sajil Kumar

Kompetenzzentrum Wasser Berlin, Cicerostr. 24, 10709 Berlin, Germany

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

Introduction

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

Objectives

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

Water quantity objectives

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

Water quality objectives

- Improve water quality in degraded aquifers (e.g. nutrient reduction from agricultural run-off).

- To reduce effort for water treatment (e.g. disinfection byproducts (DBPs) reduction prior to drinking water supply).

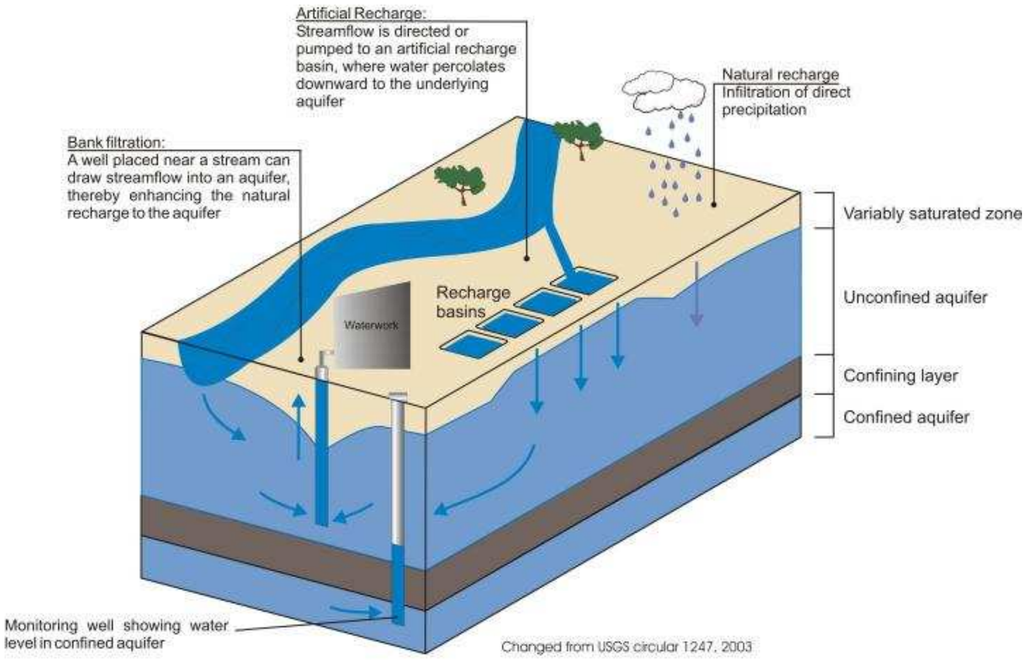

Fig.1. Components of natural and artificial recharge and Bank Filtration techniques (changed from USGS circular 1247, 2003).

Environmental management objectives

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

Managed Aquifer Recharge (MAR) Structures

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

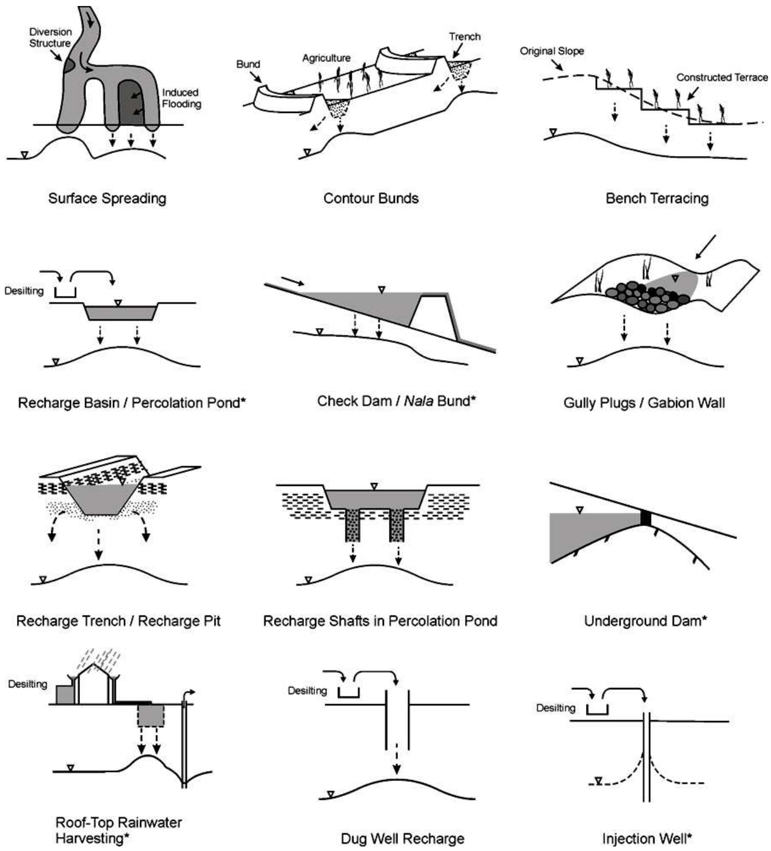

Fig.2. Managed aquifer recharge structures commonly used in India (SAPH-PANI D2.1 (2012), modified from Gale (2005)).

Criteria for initiating MAR projects

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

- Ground water levels are declining on regular basis.
- The availability of ground water is inadequate in lean months.
- A substantial amount of aquifer has already been desaturated.
- The site is adjacent to a leaky fault or a semi-confining layer containing poor quality water.
- The aquifer contains poor quality water and is highly heterogeneous or has a high lateral flow rate.
- Aquifers show saline intrusion.

Constraints & disadvantages

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

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

Factors influencing feasibility and performance of MAR

Hydrogeology

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

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

- Geological and hydraulic boundaries: data on this parameters are normally available in the regional geology/hydrologelogy maps of the study area
- Inflow and outflow of waters: data regarding these parameters can either be collected from environmental / water authorities or must be measured in the field
- Storage capacity, porosity, hydraulic conductivity, transmissivity: these aquifer parameters must be obtained through pump tests and hydraulic flow models. An overview of hydraulic conductivity values measured in at BF and AR sites for drinking water production is shown in Fig.3.

- Natural discharge and recharge: recharge estimation may be calculated using the water table fluctuation method or the hydrologic budget method.. Remote sensing-GIS methods can also give valuable information on natural groundwater recharge.

- Water availability for recharge and water balance: source water availability may be calculated from the annual rainfall data, river flow estimation, surface runoff estimation etc.

- Lithology, depth of the aquifer and tectonic boundaries: these datacan be obtained from bore holes, aerial photographs etc.

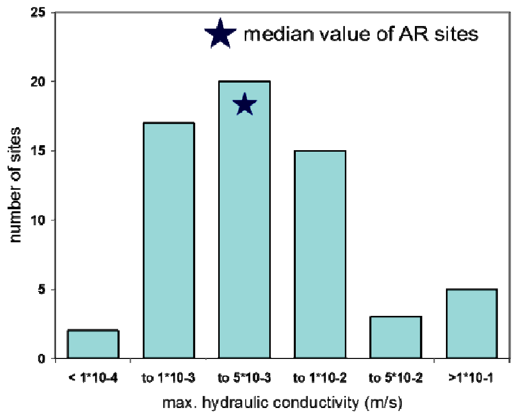

Fig.3. Hydraulic conductivity values observed in the BF and AR sites for drinking water production world wide (n=62).

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

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

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

Consolidated sandstones are one of the favorite geological formations for groundwater storage because of their good storage capacity and transmissive properties. However, if the aquifer permeability is too high, the recharged water may dissipate quickly and is thus lost to the base flow in rivers. A thorough knowledge in aquifer hydraulics is necessary for the successful implementation of MAR in this kind of aquifers. In certain locations, annual overdraft was adopted as a measure to create storage during wet season.Carbonate rocks are highly dynamic formation in terms of hydrogeochemistry. Due to this high reactivity, groundwaters in these formations often exhibit high hardness. Carbonate aquifers can show high dissipation of recharged water and fast pathways for pollutants. Despite of this behaviour, carbonate aquifers are considered as good water bearing formations all over the world. A considerable modification in the flow patterns can be expected in carbonate aquifers with in a short period. MAR in these formations demands a good understanding of aquifer hydrogeology.

Influence of climate and hydrology on MAR systems

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

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

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

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

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

Source water and its requirements

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

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

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

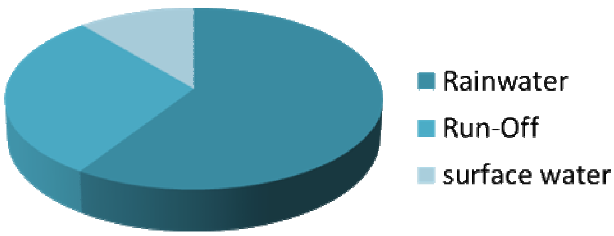

Fig.4. Source water for MAR in India (based on 22 case studies; SAPH-PANI D2.1 (2012).

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

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

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

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

Design and operation

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

Clogging

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

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

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

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

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

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

Pre- treatment

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

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

Examples for Successfull MAR World-Wide

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

	Berlin (DE) Greskowiak et al.(2005)	**Orange County (US) Hammer & Elser (1980)**	**Salisbury (AUS) Page et al. (2009)**
Study area and History	RBF had been practiced in Berlin since 1850 for drinking water supply. Since 1960 three infiltration ponds have commenced operation near Lake Tegel to cope with increasing water demand.	Orange County district, CA, USA. Excessive pumping and subsequent seawater intrusion deteriorated the water quality. By 1969, the recharge schemes were proved to be successful in rejuvenating the groundwater basin.	In operation since in 2006
Objectives	Enhancement of groundwater resources for drinking water supply.	To prevent seawater intrusion by creating a hydraulic barrier by injecting the fresh water	To store and treat wetland-treated stormwater for non-potable supply and municipal irrigation
Hydrogeological setting	Quaternary sediments of fluvial and glacio-fluvial, medium-sized sand deposits, average range of hydraulic conductivities: 10 to 100 m/d	A deep structural alluvial basin containing a thick accumulation of inter-bedded sand, silt and clay. The overall hydraulic conductivity of the aquifers is 100 m/d	A confined low to moderate porous limestone, approximately 60 m thick. Brackish groundwater.
Source water characteristics	Surface water from lake Tagel is the source for MAR. The quality of the water is within the permissible guideline values for drinking water.	*Rainwater* was used for the infiltration basin. Salinity up to 430 mg/L. *aimed waste water* (treated using lime clarification,	Urban stormwater derived from Parafield Stormwater Harvesting Scheme. Majority of the

	Clogging is encountered in the system due to physical processes and microbial activities. A microstainer is used as pre-treatment	ammonia stripping, mixed media filtration, activated carbon sorption and chlorination) is later mixed with fresh *deep groundwater* to achieve permissible Cl level (120 mg/L) before recharging through injection wells.	parameters are blow the Australian drinking water guidelines. Exceptions: turbidity and *e.coli*.
Design and Operation	Structure: 3 infiltration ponds (area: 8700 m^2; depth: 3 m) Infiltration rate: At the beginning operational cycle about 3 m/d ; after clogging: 0.3 m/d. Water quality monitoring: Wells: once per year Purified water (after post treatment): daily Abstraction: >40 production wells	The river water is desilted and recharged through percolation tank. Additional extraction wells (*7*), 3 km away from the coast, are pumping the brackish water and return to it to the ocean. 23 recharge wells, located further inland, used for injecting the freshwater. 25 monitoring wells are available for water quality monitoring.	Total catchment area: 1,600 ha. Water harvesting scheme area: 11.2 ha Well system: 4 recharge- ; 2 recovery wells; Wells penetrate the aquifer to a depth of 165 to 182 m with 50 m spacing in a quadrilateral configuration. This allows for pathogen attenuation in the aquifer. Monitoring: 3 piezometers

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The progression of artificial recharge to ground water in India

R. Sakthivadivel

Centre for Water Resources, Anna University, Chennai- 600 025, India.

Introduction

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

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

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

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

The rainfall occurrence in the country is monsoon dependant and in large part of the country, rainfall is limited to about three months period ranging from 20 to 30 days. The natural recharge to ground water reservoirs is restricted to this period only. The artificial recharge techniques aim at increasing the recharge period in the post-monsoon season for about 3 months providing additional recharge. This results in providing sustainability to ground water development during lean season.

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

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

Traditional practices of artificial recharging

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

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

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

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

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

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

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

Western Rajasthan, Kutch region of Gujarat,Bhatinda and Ferozpur districts of Punjab and most of Hissar and parts of Mahindergarh district of Haryana fall under Thar desert. Many traditional artificial recharge structures such as Khunds,Kuis, Bers, Jharmas,Nadi,Tobas, Tankas, Khadins, Bavadis, Virdas etc., have been practiced. Khund looks like an upturned cup nestling in a saucer.Khund, essentially a circular underground well, has a saucer- shaped catchment area that gently slopes towards the centre where the well is situated. Kuis are 10-12 m deep pit dug near tanks to collect the seepage water. The mouth of the pit is usually made narrow to prevent evaporation from the collected water. Bers are mostly community wells that are used for drinking purposes. Jhalars were human made tanks, often rectangular in design having steps on three or four sides. The Jhalars collect underground seepage of a Talab or a lake located upstream and used for community bathing and religious rites. Nadis are village ponds, used for collecting and storing water from adjoining natural catchment during rainy season. It is planned and constructed by villagers themselves for their use.

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

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

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

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

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

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

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

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

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

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

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

Efforts and promotion of artificial recharging in India

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

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

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

- The quantum of harvested rain water and recharge to ground water for improving the effects of ground water abstraction.
- Adoption of water conservation measures like technologies used for ensuring water conservation, water audits for ensuring minimal use of water in various sectors.
- Recycling and reuse of effluents conforming to standard norms prescribed by Government of India.

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

- Spreading Methods

  -Infiltration ponds and basins

  -Controlled flooding

  -Incidental recharge from irrigation
- In-channel modifications

  -percolation ponds behind check dams

  -earthen storage dams

  -sub surface dam

  -leaky dams and recharge releases
- Well, shaft and borehole recharge

  -open wells and shafts
- Induced Bank infiltration

  - Riverine and canal bank infiltration

  - Inter-dune filtration
- Rain Water Harvesting

  -Field bunds

  -roof-top rain water harvesting

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

Institutional aspects of artificial recharging in India

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

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

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

Concluding remarks

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

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

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

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

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

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Managed Aquifer Recharge Practices in India

N. C. Ghosh

National Institute of Hydrology, Roorkee, India, Email : ncg@nih.ernet.in

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

Managed Aquifer Recharge – definition and use

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

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

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

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

Why is MAR necessary in India?

- India is now the biggest groundwater user for agriculture in the World (Shah, 2009).

- Groundwater has been the most preferred source for drinking water in India, particularly in rural and peri-urban areas.

- Statistics revealed that over the last 50 years, number of groundwater structures have increased manifolds from 3.9 million in the year 1951 to 18.5 million in the year 2001 out of which about 50% accounts tube wells (Fig.2) [Minor Irrigation Census, 2001]. The number of groundwater structures is now expected to be around 27 million (Shah, 2009).

- The poor public irrigation and drinking water delivery, new pump technologies, flexibility and timeliness of groundwater supply, government subsidy on electricity in the rural areas, and lack of groundwater regulation legislation, have given rise to preferential growth of groundwater uses in India.

- The growth in the groundwater structures had also increased the groundwater based irrigation potential, and at the same time, diminished the share of surface water uses for irrigation from 60% in the 1950s to 30% in the first decade of the 21st century (Fig. 3).

- Natural recharge measurements carried out in about 20 river basins suggested that only about 5 to 10 percent of the seasonal rainfall is contributed as annual recharge in the peninsular hard rock regions, and is about 15 to 20 percent of the rainfall in the alluvial areas (Athavale et al 1992). Rapid urbanization and land use changes have reduced drastically the infiltration rate into the soil and are diminishing the natural recharging of aquifers by rainfall. This has created lowering of water table, drying of wells and deterioration in quality.

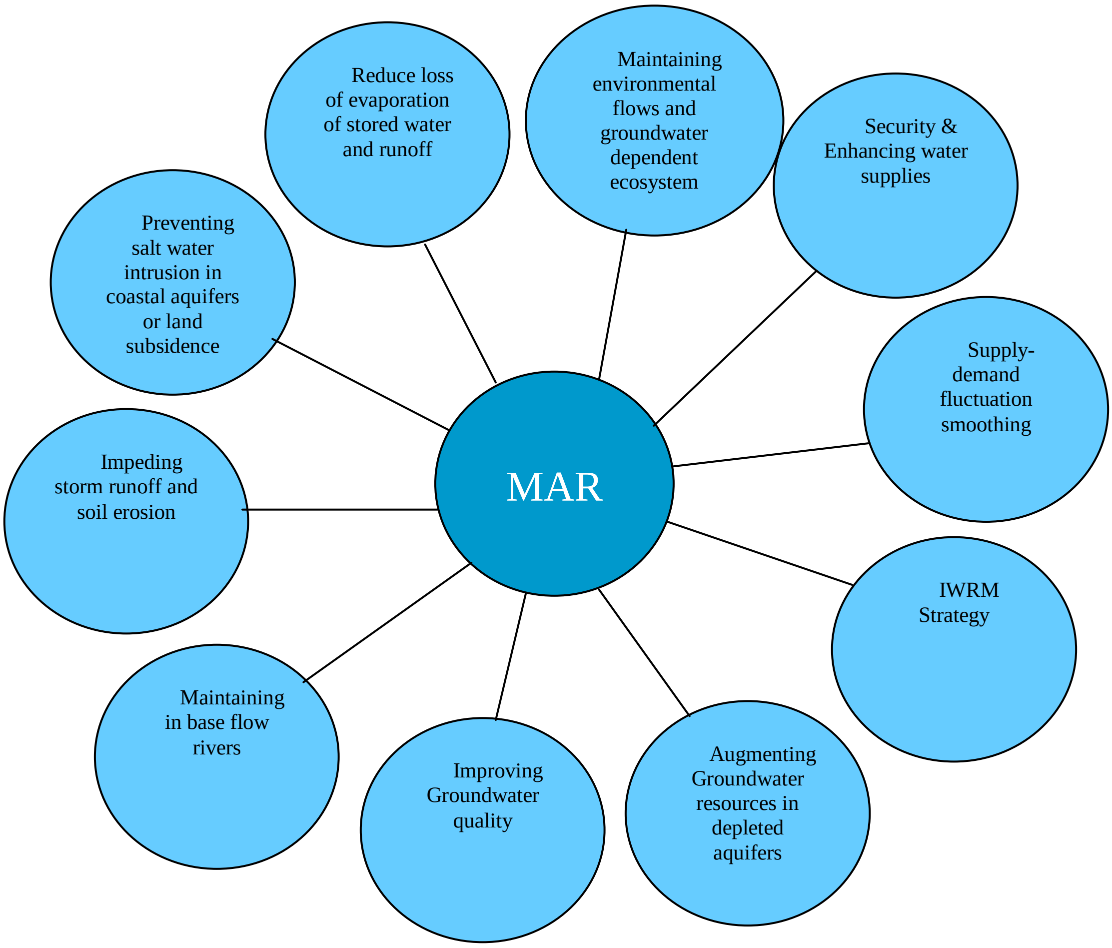

Fig.1. Some important groundwater conservation and management issues, which can be addressed by MAR

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

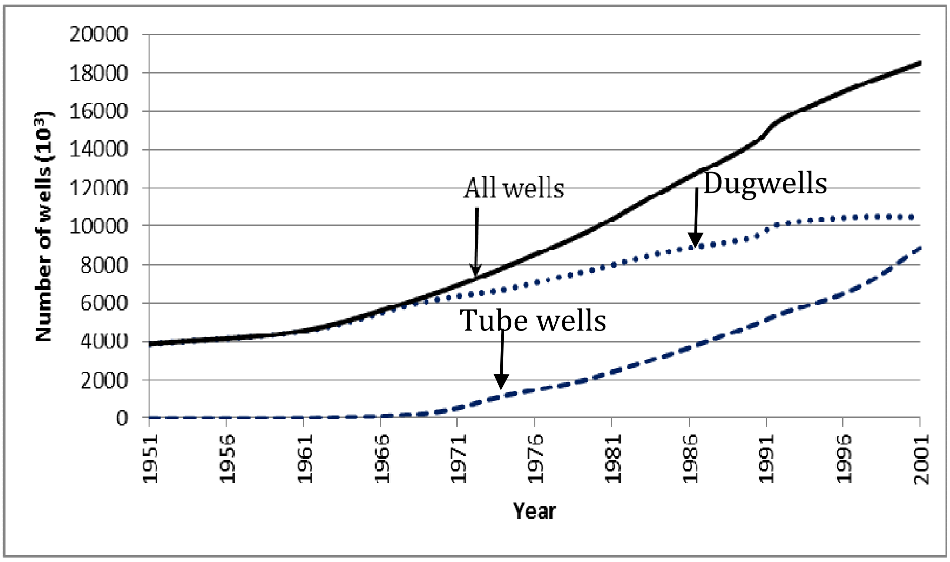

Fig. 2. Growth of groundwater structures in India (1951-2001)

[Source : Graph prepared using data of Minor Irrigation Census, 2001 & data compiled by Singh & Singh, 2002] .

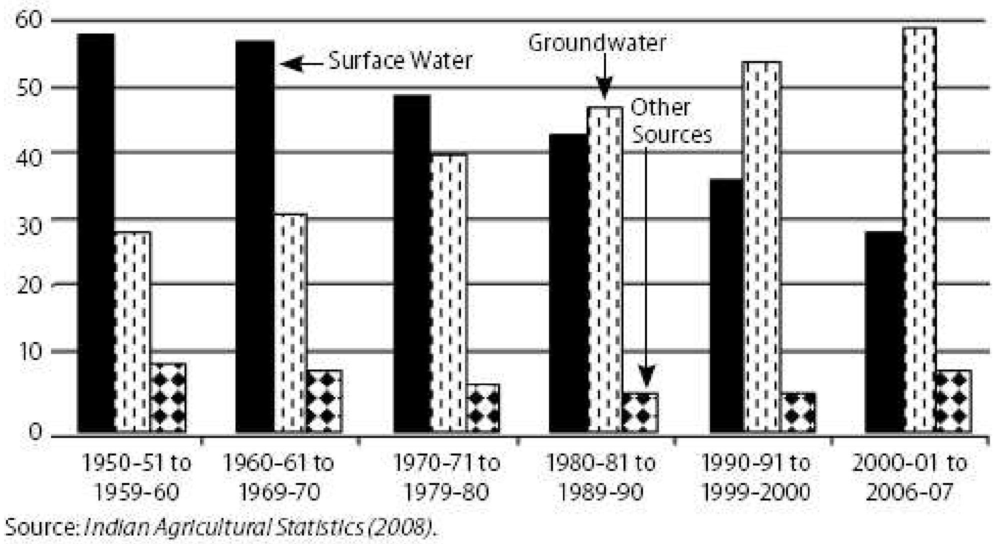

Fig 3. Decade-wise share of surface water and groundwater in net irrigated area in % (adopted from Vijay Sankar et al., 2011) .

- Indiscriminate extraction and development had led substantial ground water table depletion in many parts of India both in the hard rocks and alluvial areas. Long-term decline of ground water table had been reported mostly from the states of Rajasthan, Gujarat, Tamil Nadu, Punjab, Delhi and Haryana.

- For example, out of 5723 assessment units (Blocks/Mandals/Talukas) in different states by CGWB(2007), 839 units (15%) had been categorised as ‘overexploited’ with ground water extraction more than the net annual recharge, and about 4% has been categorized as ‘critical’, extraction between 90% and 100 % of the net annual recharge. And 30 blocks had been categorized as the saline ground water (CGWB, 2007).

- Groundwater contamination from the sources of geogenic (Arsenic, Fluoride, and Salinity) and anthropogenic origin is another threat to the availability of safe groundwater resources.

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

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

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

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

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

MAR Practices in India

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

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

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

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

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

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

The First Phase - Period before 1960

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

The Second Phase – Period between 1960 and 1990

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

The Third Phase – Period from 1990 to date

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

Common Techniques Employed for Artificial Recharge in India

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

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

Lithology	Topography	Type of structure
0Alluvial or hard rock	Plain area or gently undulating area	Spreading pond, subsurface dike, minor irrigation tank, check dam, percolation tank or unlined canal system
Hard rock down to 40 m depth	Valley slopes	Contour bunding or trenching
Hard Rock	Plateau regions	Recharge ponds
Alluvial or hard rock with confined aquifer to 40 m depth.	Plain or gently sloping of flood plains	Injection well or connector well
Hard rock	Foot hill zones	Farm ponds or recharge trenches
Hard rock or alluvium	Forested areas	Subsurface dikes

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

Pilot Projects on Artificial Recharge by CGWB

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

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

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

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

Period and Plan	Status	Cost (in million INR)
1972-1984	Haryana, Kerala, Gujarat	NA
1984-1992	No rainwater harvesting or groundwater development programs	0
1992-1997, VIII	Maharashtra, Karnataka, Andhra Pradesh, Delhi, Kerala, Madhya Pradesh, Tamil Nadu, West Bengal & Chandigarh (Total States/UT –9)	32.3
1997-2002, IX	Andhra Pradesh, Arunachal Pradesh, Assam, Bihar, Chandigarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkand, Kerala, Lakshdweep, Madhya Pradesh, Maharashtra, Meghalaya, Mizoram, Nagaland, NCT Delhi, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal (Total States/UT – 25)	331
2002-2007, X	Andhra Pradesh, Karnataka, Madhya Pradesh and Tamil Nadu (Total States – 4) Pilot projects 18 ; 197 structures	56
2007-2012, XI	Arunachal Pradesh, Punjab, Tamil Nadu, Kerala, Karnataka, West Bengal, Andhra Pradesh, Uttar Pradesh, Madhya Pradesh, Delhi, Chandigarh, Gujarat, Maharashtra, Jharkhand, Himachal Pradesh, Jammu & Kashmir, Orissa, Rajasthan and Bihar (Total States/UT – 19) Pilot projects 82; 1475 structures	1000

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

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

[Source : Saph Pani, 2012]

Area Identified for Artificial Recharge	**448760 km^2**
Volume of water to be recharged	36.5 km^3
In rural areas	225000
In urban areas (rooftop rainwater harvesting)	3700000
Total number of structures proposed	3,925,000
Total cost of structures proposed	245000 MINR
Check Dams/Cement Plug/Anicuts	110000
Recharge Shafts and Dug wells	48000
Gully Plugs /Gabion Structures	26000
Development of Springs	2700
Revival of Ponds/Tanks	1000

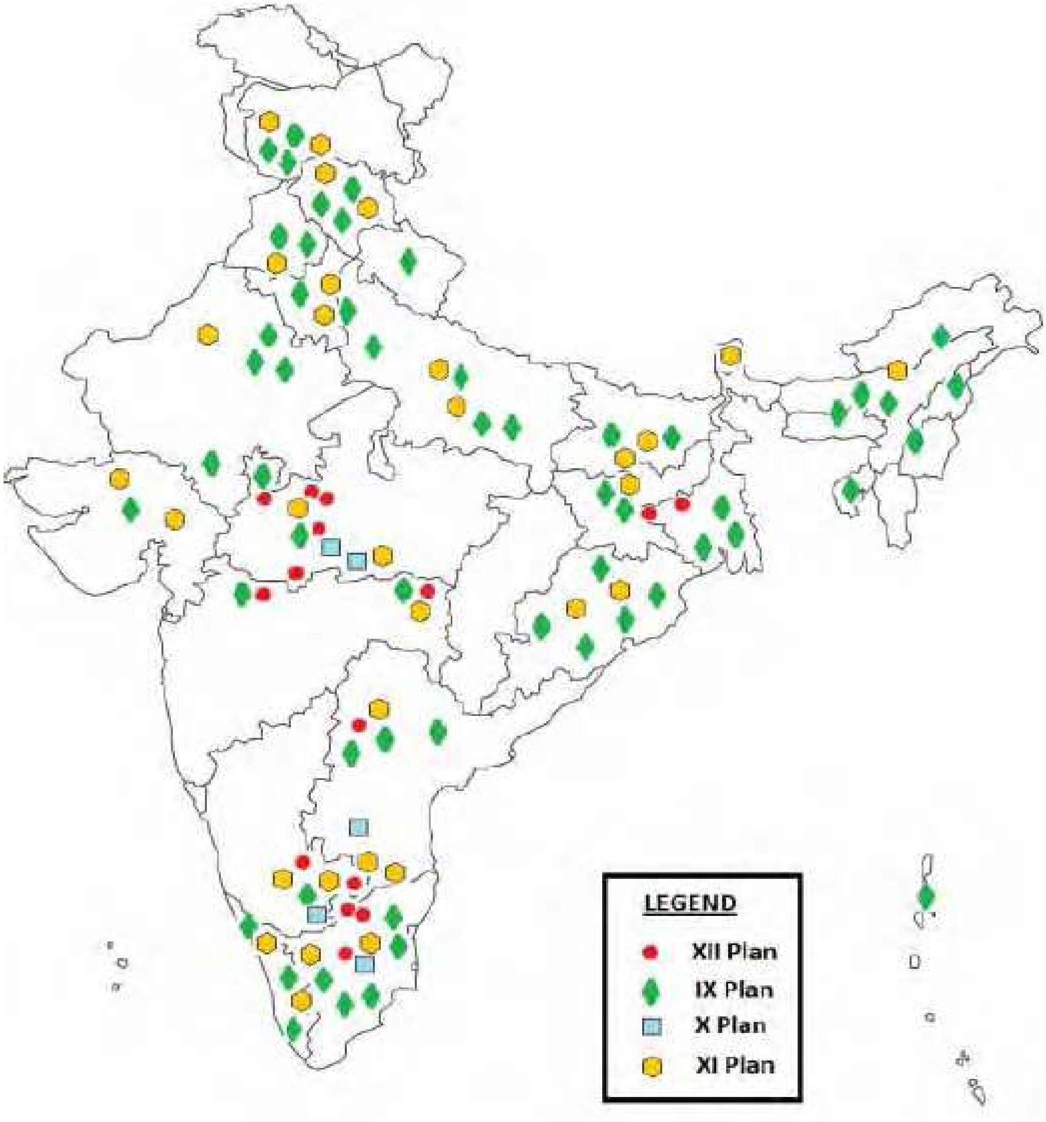

Fig. 4. Artificial recharge schemes developed by CGWB in different states of India under various five year plan (Source : CGWB, 2011)

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

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

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

Experience from Case Studies on MAR in India

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

Hydrological and hydrogeological situations

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

Infiltration Rates and Related Issues

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

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

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

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

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

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

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

Water Quality Issues

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

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

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

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

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

Experience from Case Studies on SAT in India

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

General Evaluation of MAR Implementation in India

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

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

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

Conclusions

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

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

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

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

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ANNEXURE - I

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

Name of structures	Place and State in which practices	Region	Features
Zing	Ladhak district in Jammu & Kashmir	Trans-Himalayan Region. Cold deserts.	Traditional water harvesting structure is comprised of a small tank which collect melted glacier water through network of guiding channels.
Kul	Valleys of Himachal Pradesh, and Jammu & Kashmir	Western Himalayan Region. Precipitous mountains.	Traditional rainwater harvesting structure is comprised of water channels which collect precipitated water from glaciers to village valleys.
Naula	Uttarakhand	Western Himalayan Region.	Traditional surface water harvesting structure is comprised of small well or pond in which water is collected by making stone wall across a stream.
Khatri	Hamirpur, Kangra, and Mandi districts in Himachal Pradesh	Western Himalayan Region.	Traditional water harvesting structure of about 12 ft.x 10ft x 6 ft in size carve in hard rock mountain, in which rainwater is collected from roof through pipes or through seepage from through rocks.
Kuhl	Himachal Pradesh	Western Himalayan Region	Traditional irrigation system consists of headwall constructed across ravine for storage and diversion of flow through a canal to irrigation fields.
Apatani	Arunachal Pradesh, Sikkim & Darjeeling district in West Bengal.	Eastern Himalayan Region.	Traditional rainwater harvesting system for surface water conservation. In Apatani system, valleys are traced into plots separated by about 0.6 m high earthen dams. These plots are connected to one another by inlet and outlet arrangement located on opposite sides. The inlet of low lying plot acts as the outlet of the adjoining plot. Deeper channels connect the inlet point to the outlet point. Traced plot can be flooded or drained off by opening and blocking the inlets and outlets. Stream water tapped near forest hill slopes is conveyed to the agricultural fields through a channel network.
Zabo (Ruza system)	Nagaland	Northeaster Hill range	Traditional rainwater harvesting structure like pond in which runoff passes through terraces are collected in it for forestry, agriculture and animal care.
Bamboo Drip Irrigation	Meghalaya	Northeaster Hill range	About 200 years old traditional system. Bamboo pipes are used to divert perennial streams and springs at the hilltops to lower reaches by gravity for irrigation of plantations. The channel sections, which are made of bamboo, divert and convey to the plot site from where it is again distributed to branches.
Dongs	Assam	Brahmaputra Valley	Traditional artificial groundwater recharge system is comprised of ponds, normally constructed for irrigation. These ponds receive water from surrounding hills.
Dungs and Jampois	Jalpaiguri in West Bengal	Brahmaputra Valley	Small irrigation channels which link rice fields to streams
Dighi	West Bengal	Indo-Gengatic plains	A square or circular reservoir with steps to enter. Each Dighi has its own catchment area and a sluice

			gate. People are not allowed to bathe and washed clothes on the steps of Dighi, however allowed to take water for personal use. Most of the houses had either their own wells or smaller dighis on their premises.
Kunds/Kundis	Western Rajasthan & Some areas in Gujarat	Thar Desert	Rainwater harvesting structures look like an unturned cup nestling in a saucer. Essentially a circular underground well in which rainwater is collected for drinking. The sides of the well pits are covered with lime and ash. Most of the pits have dome shaped cover or at least a lid to protect water. The depth and diameter of the kund depend on the requirement of water.
Kuis and Beris	Western Rajasthan	Thar Desert	Seepage collecting structures of 10-12 m deep pits dug near tanks. Kuis are also used to harvesting rainwater in areas of meagre rainfall. The mouth of a pit is usually made very narrow to prevent evaporation. Pit gets wider as it burrows under the ground to enable it seep into large surface area.
Baoris/Bers	Rajasthan	Thar Derest	Community wells collect rainwater for use to meet drinking water needs. Baoris can hold water for long time because of almost negligible evaporation.
Jhalaras	Rajasthan & Gujarat	Thar Desert	Man-made community tanks uses for religious rites. Often rectangular in shape and have steps from three or four sides. Jhalaras are groundwater bodies which collect subterranean seepage water of talab or lake located upstream and are built to ensure easy and regular supply of water for bathing and religious rites.
Nadis	Jodhpur, Rajasthan	Thar Desert	Village ponds used for storing water from adjoining natural catchment during rainy season. Sites for nadis are selected by villagers based on natural catchments and their yields.
Tobas	Rajasthan	Thar Desert	Natural ground depression in a catchment having low porosity uses for storing of surface water from rainy season.
Tankas	Bikaner in Rajasthan & Dwarka in Gujarat	Thar Desert	Small underground tanks generally circular in shape & lined with fine polish lime, built in the main house or courtyard to collect rainwater. These tanks' water are used for drinking
Khadin	Jaisalmer in Rajasthan	Thar Desert	A rainwater harvesting system on farmland designed storing surface runoff for agriculture. Its main feature is a long earthen embankment (100-300 m) across lower hill slopes.
Vay/Vavdi/ Baoli/ Bavadi	Gujarat & Rajasthan	Thar Desert	These are step wells known by Vay or Vavdi in Gujarat and Baoli or Bavadi in Rajasthan. Practices of these types of step wells are found non-existence nowadays.
Virdas	Rann area of Kutch in Gujarat	Thar Desert	Shallow wells dug in low depression called Jheels (Tanks).. These structures harvest rainwater. The sites selection of these structures are made such a way that they separate freshwater from unpotable saltwater.
Talabs/Bhandis	Eastern Rajasthan & Bundelkhand in Madhya Pradesh	Central Highlands	Natural or man-made reservoirs. A reservoir area less than five bighas is called talai; a medium sized lake is called talab; bigger lakes are called sagar or samand. These reservoirs serve irrigation and drinking water requirements. When the water in the reservoir dries up just a few days after the monsoon, the reservoir beds are used for rice cultivation.
Saza Kuva	Aravalli hills in Marwar in	Central Highlands	An open well with multiple owners used for irrigation. It is constructed by digging soil and

	Eastern Rajasthan		generally circular in shape.
Johads	Alwar district in Rajasthan	Central Highlands	Small earthen check dams that capture and conserve rainwater, improve percolation and groundwater recharge. It has successfully been used since 1984.
Rapat	Eastern Rajasthan	Central Highlands	Percolation tank with a bund by either masonry wall or earthen, to impound runoff from watershed. It is mainly used for groundwater recharge.
Katas/Mundas/ Bandhas	Orissa & Madhya Pradesh	Eastern Highlands	These were ancient structures used for irrigation purposes. A kata is constructed north to south or east to west of a village by a strong earthen embankment curved at either end and is built on a drainage line to guide drainage water from upland to the irrigation field.
Cheruvu	Chitoor and Cuddapah districts in Andhra Pradesh	Deccan Plateau	Traditional water harvesting reservoirs to store runoff.
Kohlis	Bhandara district in Maharastra	Deccan Plateau	Traditional water tanks which hold rainwater for irrigation of sugarcane and paddy cultivation.
Bandharas	Maharastra	Deccan Plateau	Traditional stream/river water harvesting structures consist of check dams or diversion weirs constructed across streams/rivers to raise water level in the streams/rivers for diversion of water to irrigation fields. Most of the Bandharas are defunct today.
Kere	Central Karnataka	Deccan Plateau	Tanks traditionally used for supply of irrigation water. These tanks are fed either by channels branching off from anicuts (check dams) built across streams or by streams in valleys.
Ramtek model	Maharastra	Deccan Plateau	Surface water runoff harvesting tanks connected in series to catch rainwater from watersheds and supported by high yielding wells and structures like baories, kunds.. The tank located at the upper reaches close to hills are filled up, water flows to downstream to successive tanks through interconnecting channels. This sequential arrangement generally ends to a small watershed to store the remaining water.
Surangam	Karnataka	Western Ghats	Surangam (means tunnel) is a horizontal well mostly excavated in hard laterite rock formations. The excavation is done to a depth till a good amount of water is struck. Underground water seeps out of the hard rock and flows out of the tunnel. This water is collected in an open pit constructed outside a surangam.
Korambu	Kasargod and Thrissur districts in Kerala	Eastern Ghats	Korambu is a temporary dam constructed across mouth of channels by brushwood, mud and grass. It is used to raise water level in the canal and to divert the water into field channels. It is designed in such a way that required quantity can flow to the diversion channel and excess water can overflow through it. Water is allowed to flow from one field to another until all fields are irrigated.
Eris	Tamilnadu	Eastern Coastal Plains	Eris (tanks) are very common in irrigated area of Tamilnadu. They play several important roles: maintaining ecological harmony, preventing soil erosion and wastage of surface runoff, and recharging groundwater in the surrounding areas.

Looking for Suitable Sites for MAR Projects

V. C. Goyal

National Institute of Hydrology, Roorkee-247667, India

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

Artificial Recharge (MAR) Projects

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

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

The two basic requirements in any artificial recharge projects are:

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

Design of an Aquifer Recharge System

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

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

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

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

Factors considered useful in selecting the sites are:

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

Field Investigations

Hydrological Studies

Useful in assessment of availability of source water:

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

Also useful in deriving the following information:

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

Soil Infiltration Studies

Useful in

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

Hydro-geological Studies

Useful in

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

Geo-morphological Studies

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

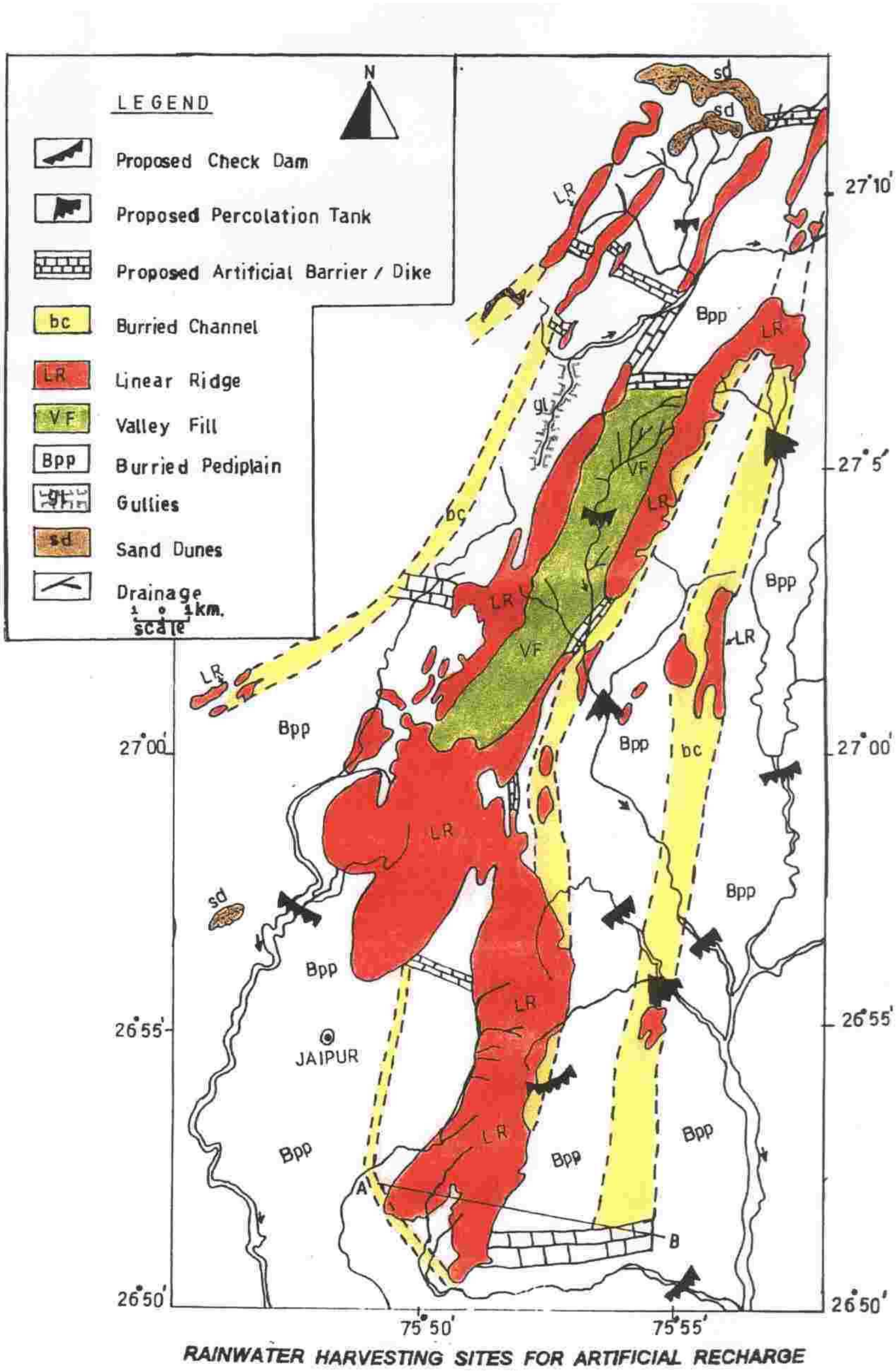


Fig. 1 Dhund river basin, Rajasthan

Table-1. Recharge site identification based on hydro-geomorphic analysis

(Source: A. K. Sinha; S. P. Yadav and Shyamanuj Dubey, Dept. of Geology, University of Rajasthan, Jaipur)

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

Geophysical Studies

Useful in

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

Use of Ground Water Prospects Maps prepared by NRSC

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

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

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

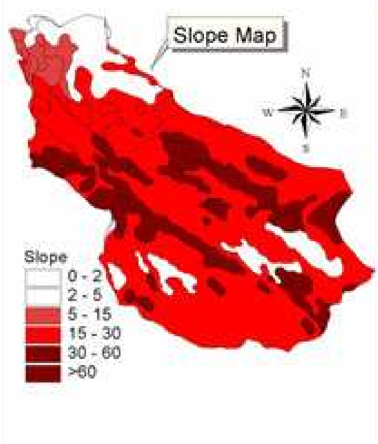
S N	Type	Represented as
1	Hydro-geomorphic units where ground water recharge is required with high priority	High priority
2	Hydro-geomorphic units where ground water recharge is required with medium priority	Medium priority
3	Hydro-geomorphic units where ground water recharge is required with low priority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

Remote Sensing & GIS-based Technique

Useful in delineation of various thematic layers such as

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

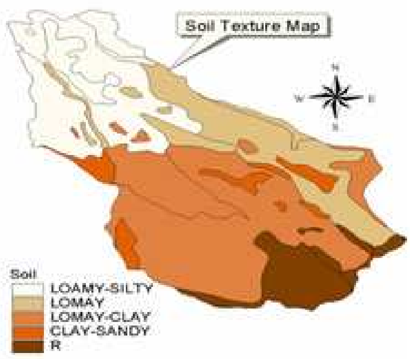
Modelling approaches, such as Weighted Linear Combination (WLC) model, are used to derive a suitability index map, which shows probable ground water recharge zones in the area. The figure below shows an example from Isfahan (central part of Iran).



2. Slope Map

1. Land Use Map

4. Stream Map



3. Soil Texture Map

5. Artificial Recharge Map

Sources of Information

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Hydraulics of infiltration ponds and determination of relevant parameters

Michael Schneider

Freie Universität Berlin, Institute of Geological Sciences, Hydrogeology Group, Malteserstr. 74-100, 12249 Berlin, Germany

m.schneider@fu-berlin.de

1 Artificial recharge – General remarks

Purpose of artificial recharge:

- replenishment of groundwater resources
- water purification through underground passage
- infiltration of cooling and process water
- infiltration of rainwater

Types of recharge facilities

- facilities at/on the surface (e.g. infiltration ponds, artificial/natural lakes, open ditches, flooding of plains)
- subsurface installations (e.g. infiltration wells, percolation pipes, slotted percolation ditches)

<u>Subsurface installations: slotted percolation ditch</u>

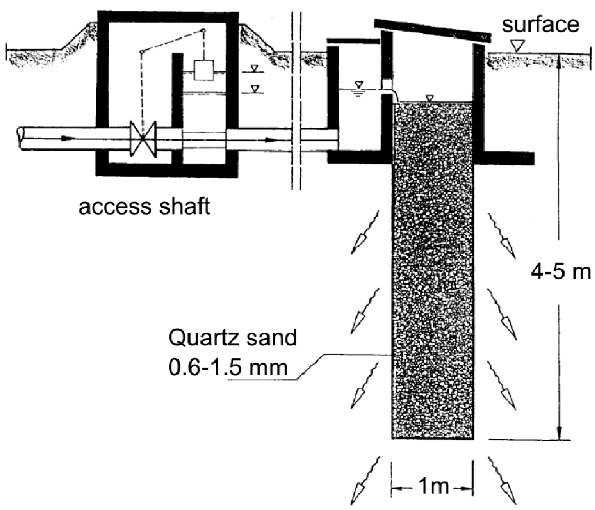

Fig1. Typical design of a slotted percolation ditch (DVGW 1996)

Surface installations: infiltration ponds

Unsaturated case: Unsaturated water flow from the bottom of infiltration pond to the water table

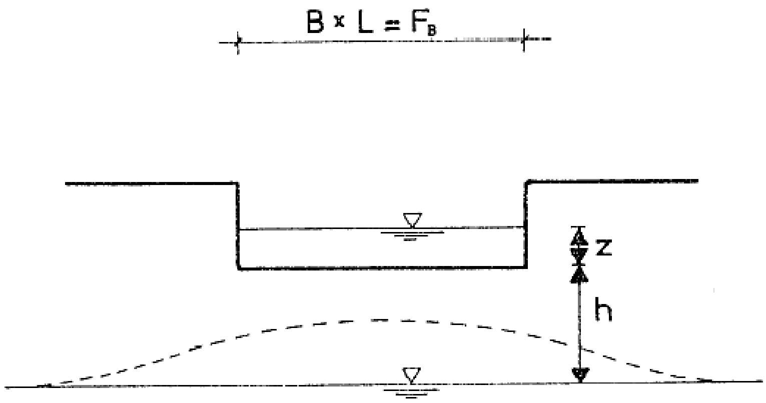

Fig. 2: Infiltration pond with a large distance (several meters) between pond bottom and groundwater surface

with

$$Q = \frac{F_B * (h + Z) * k_{fl}}{h}$$

and

$$k_{fl} = \frac{k_f}{2}$$

Q = Infiltration rate [m^3/sec]

F_B = Area of infiltration pond [m^2]

Z = Depth of water table in the infiltration pond [m]

h = Depth to groundwater table from the bottom of the pond [m]

k_f = Hydraulic conductivity [m/sec]

k_{fl} = Unsaturated hydraulic conductivity [m/sec]

Saturated case: Saturated water flow from the bottom of infiltration pond to the water table

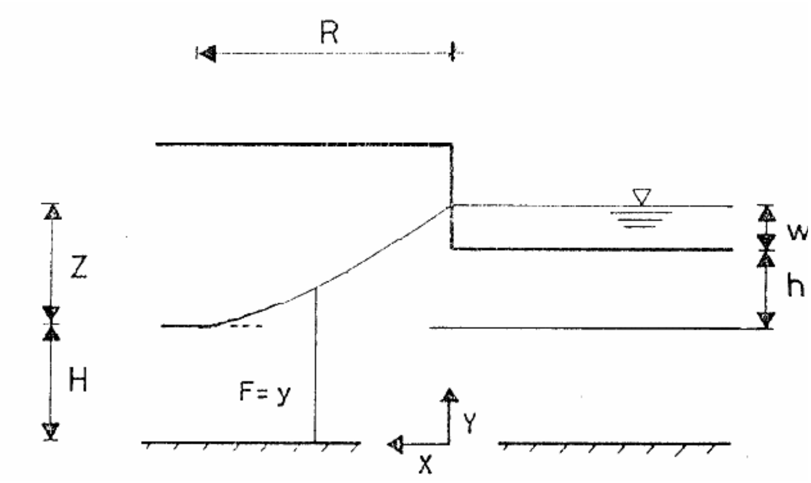

Fig. 3: Infiltration pond with a short distance between pond bottom and groundwater surface

with

$$Q = \frac{k_f * (2 * HZ + Z^2)}{2 * R}$$

and

$$W = \sqrt{\frac{2 * Q}{k_f} * R + H^2} - h - H$$

2 Unsaturated flow – Theoretical background

Saturated porous medium:

All voids are completely filled with water. The saturated zone comprises the zone below the groundwater table and the closed capillary zone. The saturated zone is a two-phase-system (rock matrix and soil water).

Unsaturated porous medium:

Voids are partially filled with water. The unsaturated zone comprises the percolation zone and the open capillary zone. The unsaturated zone is a three-phase-system (rock matrix, soil air and soil water).

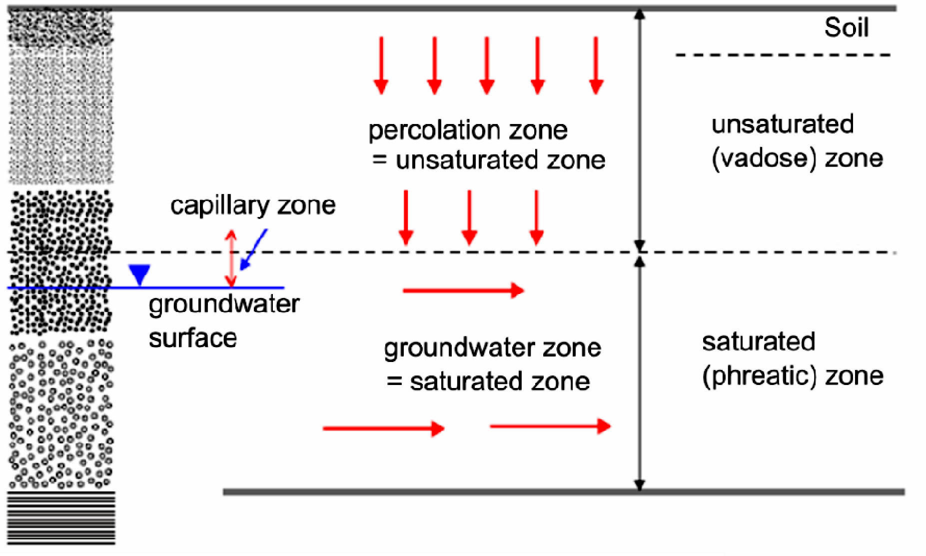

Fig. 4: Occurrence of water in the unsaturated and saturated zones

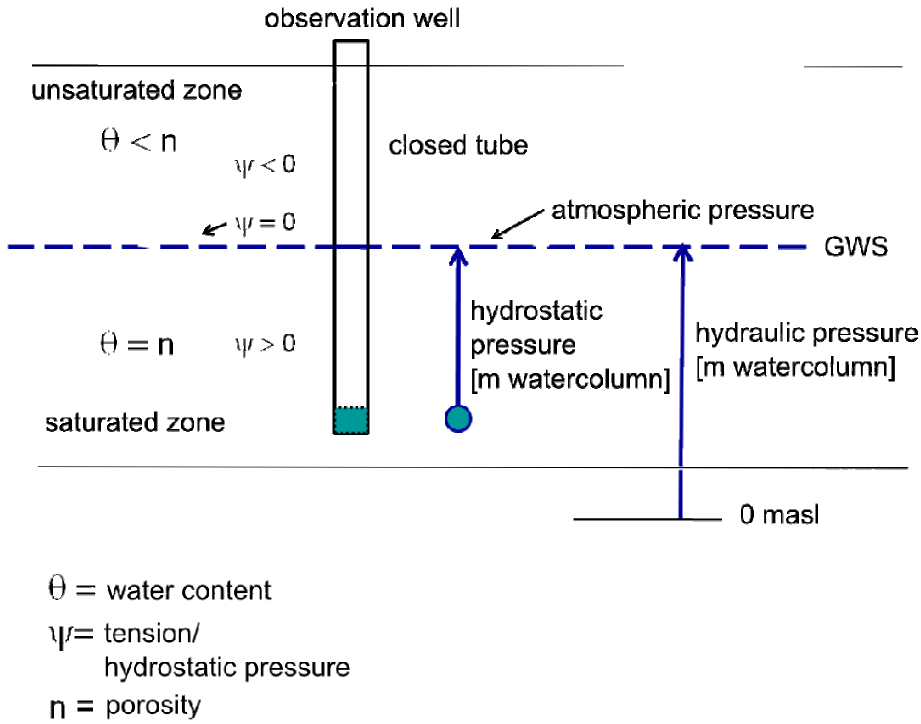

Fig. 5: Pressure conditions in the saturated and unsaturated zone

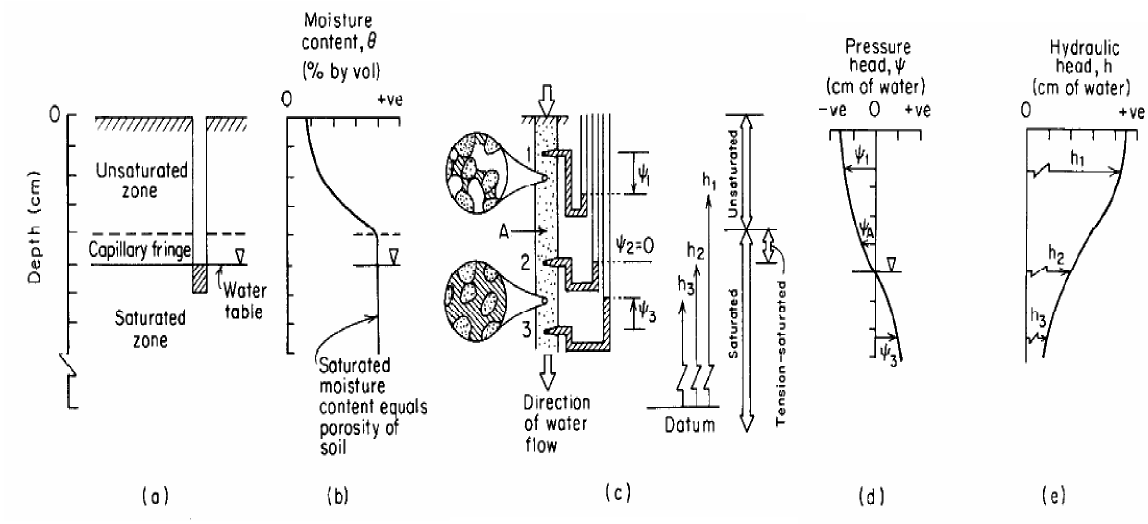

Fig. 6: Groundwater conditions near ground surface. (a) Saturated and unsaturated zones; (b) profile of moisture content versus depth; (c) pressure-head and hydraulic-head relationships; insets: water retention under pressure heads less than (top) and greater than (bottom) atmospheric; (d) profile of pressure head versus depth; (e) profile of hydraulic head versus depth (Freeze & Cherry 1979).

3 Determination of hydraulic conductivity and infiltration capacity

The hydraulic conductivity can be determined by applying the following methods:

Saturated case (k_f):

- Grain size analysis
- Darcy-test

Unsaturated case (k_{fl}):

- Double-ring infiltrometer test

<u>Grain size analysis (by Hazen & Bayer)</u>

The k_f-value is depending on grain size and distribution in the sediment. It is assumed, that in heterogeneous sediments, grains of small diameter are more controlling the hydraulic conductivity than grains of large diameter. For calculating the k_f-value, the grain diameter (in mm) is used at 10 cumulative percent in the grain-size distribution plot. This method is only applicable, if the unconformity index d_{60}/d_{10} is smaller than 5.

The hydraulic conductivity can be determined with the following empirical equation:

$$k_f = C * (d_{10})^2$$

using

C = empirical factor = (0.7 + 0.03 * t) / 86.4 =0.0116 at 10°C

t = water temperature [°C]

d_{10} = grain size at the intersection point of the 10 cumulative percent with sieving curve of the sediment [mm]

Table 1: empirical factor C depending on unconformity index

unconformity index U	C (limits)	C (average)
1,0 ... 1,9	(120 ... 105) · 10^{-4}	110 · 10^{-4}
2,0 ... 2,9	(105 ... 95) · 10^{-4}	100 · 10^{-4}
3,0 ... 4,9	(95 ... 85) · 10^{-4}	90 · 10^{-4}
5,0 ... 9,9	(85 ... 75) · 10^{-4}	80 · 10^{-4}
10,0 ... 19,9	(75 ... 65) · 10^{-4}	70 · 10^{-4}
> 20,0	< 65 · 10^{-4}	60 · 10^{-4}

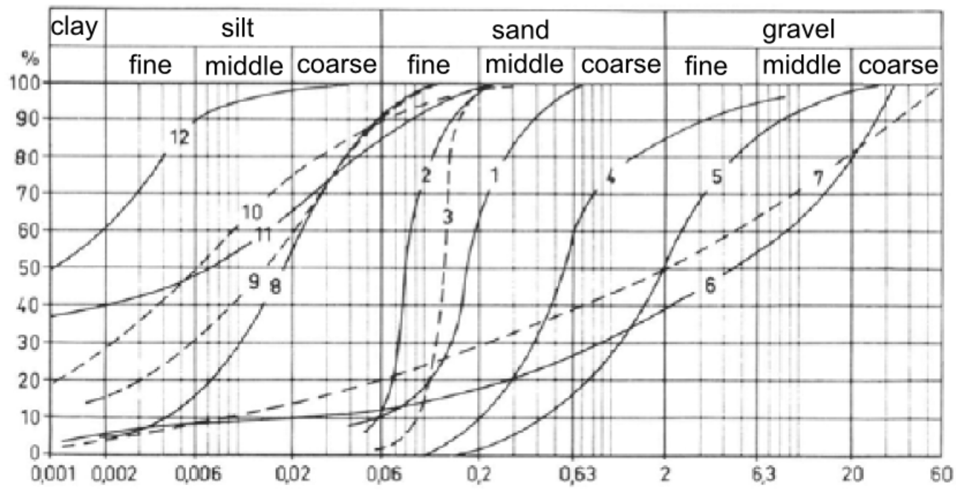

Fig. 7: Example of a grain-size distribution plot

Permeameter test (Darcy-Test)

With a constant-head permeameter, the hydraulic conductivity of a soil sample of length l and cross-sectional area F can be measured (saturated condition)

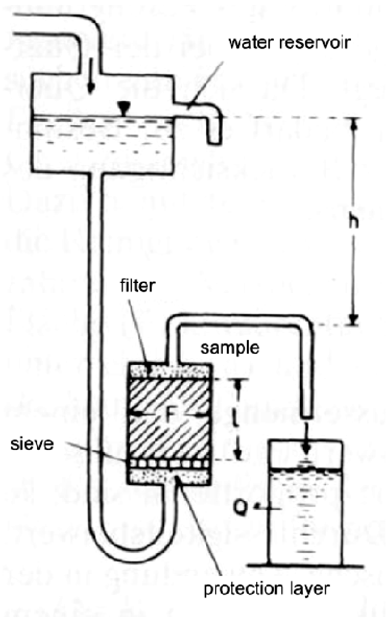

Fig. 8: Schematic setup of a Darcy-test

The k_f-value can be calculated with the following equations (Darcy's law):

$$kf = \frac{Q * l}{F * h}$$

k_f = hydraulic conductivity of low mineralized water at 10 °C [m/s]

Q = water flux [m^3/s]

l = length of sample [m]

h = constant-head differential [m]

F = cross-sectional area of cylinder [m^2]

Double-ring infiltrometer test

This test is used to calculate hydraulic conductivities in the unsaturated zone during water seepage with constant rate. The device is consisting of two metal rings of different diameters, which are inserted of about 10 cm into the soil.

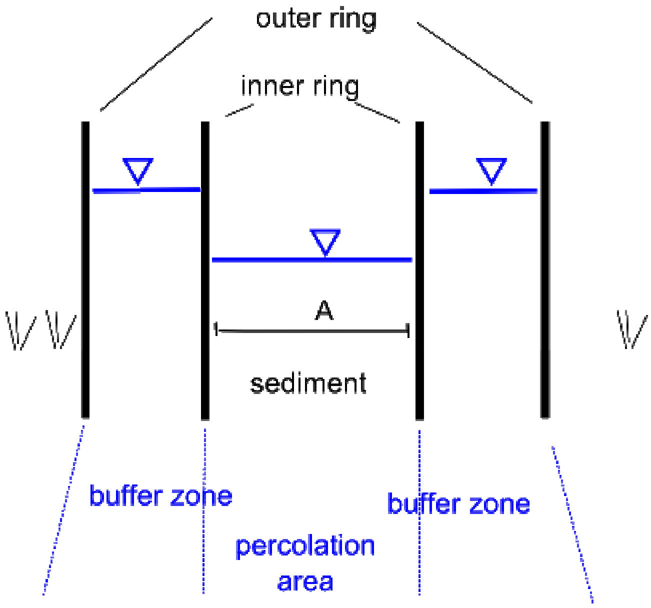

Fig. 9: Schematic set-up of a double-ring infiltrometer test

The external ring is filled with water to establish defined boundary conditions in the surrounding of the permeameter and to minimize the lateral flux from the water reservoir in the internal ring.

The internal ring ring is filled up to 10 cm. The water level must be kept constant by addition of water. The infiltration rate, respectively the hydraulic conductivity under the given partial saturation can be calculated:

$$I = \frac{V}{A * t}$$

with

I = Infiltration rate / hydraulic conductivity [m/s]

V = infiltrating volume of water (over a time period t) [m^3]

A = cross-sectional area of the interanl ring [m^2]

t =time [s]

Fig. 10: Installation of a double-ring infiltrometer

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Potential of water harvesting structures for groundwater recharge in India

M. Starkl and L. Essl

Centre for Environmental Management and Decision Support, Gregor-Mendel Strasse 33, Vienna, Austria

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

Introduction

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

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

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

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

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

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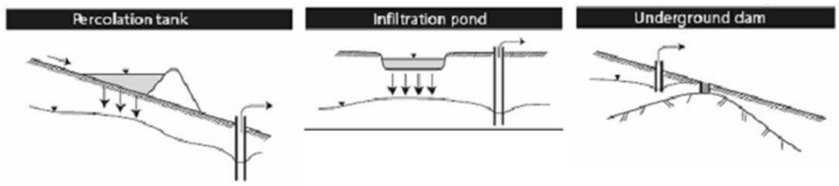

Fig.1. Modern technologies for managed aquifer recharge in India: percolation tank, infiltration pond and underground dam (from left to right) (Source: NRMMC et al. 2009)

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

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

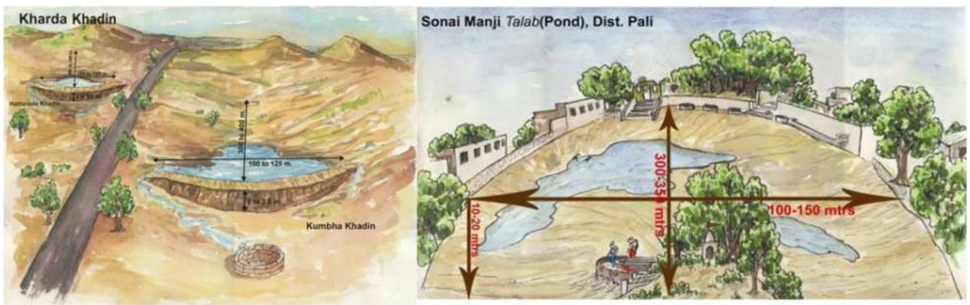

Fig.2. Traditional technologies for managed aquifer recharge in India: *Khadin* (left) and *Talab* (right) (Source: Bishnoi and Gupta 2011)

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

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

Experiences in India

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

Environmental and human health impact

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

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

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

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

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

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

Social impact

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

Institutional impact

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

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

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

Economic impact:

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

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

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

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

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

Potential for India

To assess the potential of water harvesting structures for groundwater recharge in India, a SWOT-analysis was conducted. SWOT analysis was initially developed for business management, but has also been used in natural resource management (e.g. Srivastava 2005, Terrados 2007, Mainali 2011). The SWOT analysis provides a framework for analyzing a situation by identifying strengths and weaknesses, but also recognises challenges and developes strategies for the future

(Srivastava 2005). Thereby, strengths are advantages that support the decision to implement MAR systems; weaknesses show what can be improved or what needs to be investigated before implementing MAR systems. Opportunities refer to possible chances and positive improvements of MAR systems, whereas threats show risks and obstacles for the future. The following text discussed the SWOTs of MAR structures building up on the previous section.

Strengths

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

Weaknesses

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

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

Opportunities

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

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

Threats

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

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

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

STRENGTHS	WEAKNESSES
• benefits for local communities (social and economic) • high acceptance • high recharge possible (10% of rainwater)	• uneven distribution of benefits • contaminated water in (traditional) structures
OPPORTUNITIES	**THREATS**
• revival of traditional structures and combination with modern components • (sub-) catchment based approach can ensure equality	• over-estimation of recharged water • change to unsustainable cropping pattern • lack of participation can endanger ownership of structure and willingness for O&M • adverse impact on downstream users

Fig.3. SWOT analysis based on existing evaluation results

Conclusions

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

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

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

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

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

Acknowledgements

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Mitigation of seawater intrusion by Managed Aquifer Recharge

Raicy, M. C., Parimala Renganayaki, S., Brindha, K. and Elango, L.

Department of Geology, Anna University, Chennai 600025, India

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

Introduction

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

Causes of seawater intrusion

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

One of the most important causes of seawater intrusion is the reversal of groundwater gradients in coastal aquifers, where over pumping of wells disturbs the hydrodynamic balance. Over pumping of fresh water aquifers results in the development of a cone of depression and the reversal of groundwater gradient. This causes the entry of saltwater to the original fresh water zones.

Seawater intrusion also results from the destruction of natural barriers that separate freshwater and salinewaters. Saltwater may infiltrate into freshwater zones where coastal water way dredging causes the exposure of low permeable materials and transverse fault zones. Salinewater intrusion results from the subsurface disposal of waste salinewater such as into disposal wells, landfills or other waste repositories. In some areas, the structural reliability of the zone of dispersion is inadequate due to natural fracturing, thus permitting vertical intrusion.

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

Identification of seawater intrusion

Groundwater level measurements

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

Geoelectrical studies

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

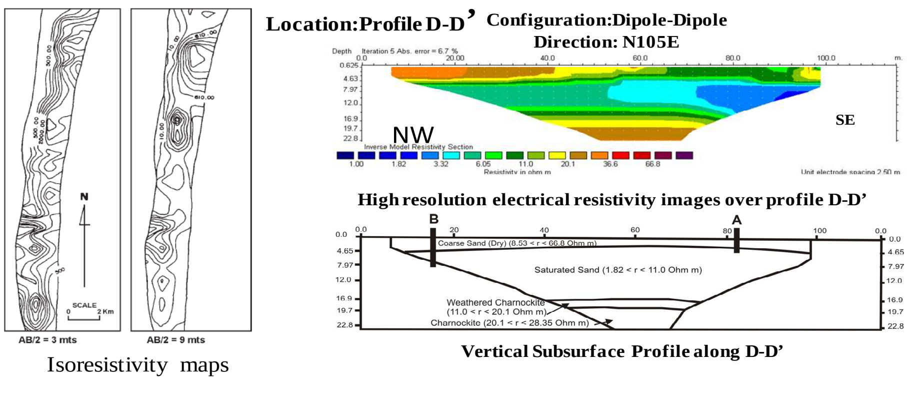


Fig.1 Vertical subsurface profile along the Chennai coastal aquifer

Geochemical studies

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

Isotope studies

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

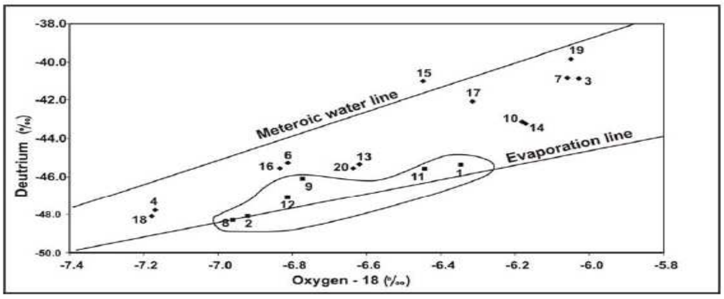
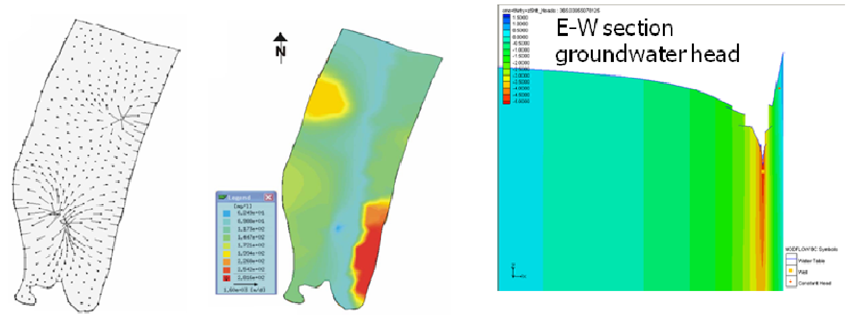


Fig.2 Correlation of groundwater Oxygen-18 & Deuterium

Groundwater modeling

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



Regional groundwater flow vector

Simulated chloride ion concentration of groundwater in January 2007

Fig.3 Groundwater model or the coastal regions of Chennai

Mitigation measures of salt water intrusion

Considerable attention has been focused on alternative methods to mitigate salinewater intrusion. Reduction in pumping of existing wells and changing the locations of pumping wells to inland areas can reestablish stronger seaward hydraulic gradient and can slow down the inflow of salinewater towards the fresh water aquifer. Another way of mitigation of salt water intrusion is the construction of an impermeable subsurface barrier composing of sheet piling parallel to the coast. The injection of emulsified asphalt, plastics and other materials can also reduce the permeability which can retard seawater intrusion. Fresh water ridges, artificially constructed near the sea can also control seawater intrusion. This method requires a continuous maintenance of a fresh water ridge in the principle water bearing deposits along the coasts through the application of artificial recharge techniques. By applying an injection barrier, the pressure ridge along the coast will be maintained by means of line of recharge wells; an extraction barrier maintains a continuous trough with a line of wells adjacent to the sea.

Artificial groundwater recharge is a process by which the augmentation of groundwater reservoir takes place at a higher rate than that under natural conditions of replenishment or it refers to the intentional replenishment of groundwater bodies. Managed Aquifer Recharge is the most environment friendly and cost effective method of mitigation of seawater intrusion. Several studies have shown that MAR can be very effective in raising groundwater levels (CGWB 2000; Muralidharan et al. 2007; Shivanna et al. 2004). Effective improvement in groundwater head by the construction of subsurface barriers was also studied by Elango and Senthilkumar (2006) in Tamil Nadu, India. These studies demonstrated that MAR is a very effective solution to overcome water scarcity.

Managed aquifer recharge (MAR)

Managed Aquifer Recharge (MAR) is the process of adding water source to aquifers under controlled conditions for withdrawal at a later date, or used as a barrier to prevent saltwater or other contaminants from entering the aquifer. The sources of groundwater recharge may be natural or artificial. Preliminary investigations such as water quality issues of the area, transmissivity of soil and other soil tests are to be carried out before the commencement of the method. Pretreatment of water is carried out to manage clogging layers.

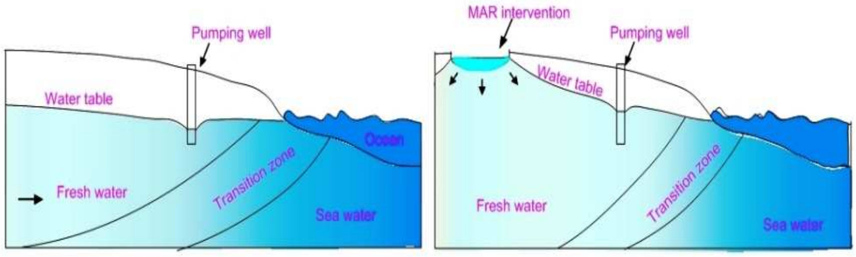


Fig. 4 Conceptual cross section showing (a) seawater intrusion due to overpumping and (b) MAR intervention for mitigation

MAR structures can improve the quality of coastal water and groundwater, enhance the water supply, mitigate floods, facilitate urban landscape improvement and assist in harvesting abundant water in urban areas. MAR structures, reduce the evaporation of stored water and maintain the environmental flows and groundwater dependant ecosystems. MAR increases water storage in the aquifer which can make more water available for irrigation and other uses and also to preserve water levels in wetlands that are maintained by groundwater. Methods of MAR, used to mitigate seawater intrusion involve percolation tanks or spreading basins, check dams, Gabion structure, village tanks, injection wells, induced recharge and rain water harvesting.

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

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

The Chennai case study

Chennai, in the southeastern part of India, is one among the vulnerable areas of salt water intrusion. The rate of hydrological pollution along the coastal zones of Chennai has been increasing day to day by the uncontrolled disposal of wastewater and pollutants due to human activities. Several studies have been carried out on the extent of seawater intrusion along the coastal aquifers of Chennai (Gnanasundar and Elango 1998, 1999; Sathish et al. 2011a, b). Seawater intrusion was identified earlier in the Panjetti- Ponneri- Minjur areas of Chennai in 1986 (Elango and Manickam 1986, 1987). Later, Elango (1992) identified that groundwater in most parts of Arani- Korattalaiyar river basin is enriched with sodium chloride. The trace/toxic metal concentrations are found to be significantly higher than the permissible limit of international standards at several locations (Shanmugam et al. 2006; Das 2011). Anuthaman (2009) proved practicability of controlling the excess run off in enhancing the augmentation of the groundwater resources in the Arani-Korattalaiyar basin. Studies made by UNDP (1987) concludes that the Chennai water supply system can meet the city water needs by diverting the water in Arani River to the Korattalaiyar River through a canal and by recharging the Arani- Korattalaiyar groundwater basin artificially through infiltration ponds.

The study area forms a part of Arani- Korattalaiyar river basin located north of Chennai, Tamil Nadu, India. The Arani and Korattalaiyar Rivers which run through the northern and southern parts of the study area are non perennial and normally flow only for a few days during north east monsoon from October to December. Near the eastern boundary, the Buckingham Canal runs parallel to the coast and this carries salinewater. After monsoon, the river usually becomes dry and the salinewater from the sea enters the river. Salinity in the Arani River has been mainly attributed to the entry of seawater from the Bay of Bengal through the Pulicat Lake towards the land. Seasonally the concentration of Na-Cl ions in groundwater varies according to the water level fluctuations. The groundwater is not suitable for irrigation at few places due to salt water intrusion, salt pan activities and backwaters. Both salinewater and seawater is pumped for salt pan activity towards the eastern part of the area near to the coast.

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

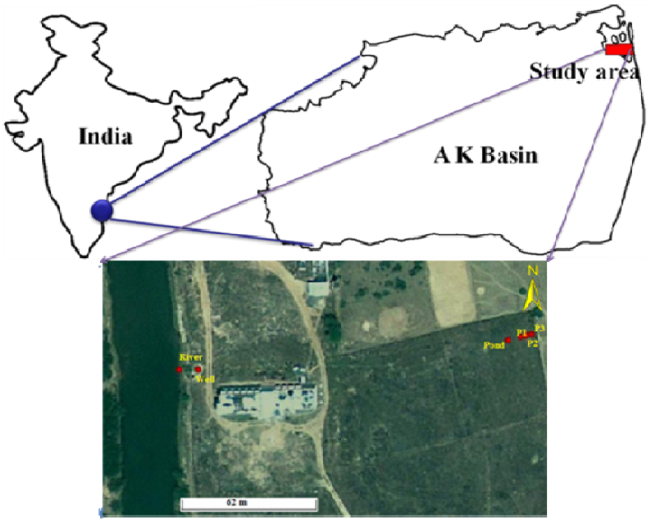


Fig. 5 Location of the pilot pond

For the detailed lithological investigations of the study site, bore holes were drilled at four corners of the school ground with the aid of hand auger and soil samples were collected at every one feet depth. From the textural analysis of soil samples, sand and silt are dominating in the area and is shown in the fence diagram (Fig. 6). Ground penetrating radar (GPR) with 50 MHz antenna was used to capture the subsurface geophysical signatures of the area and the processed data were compared with the existing litho log data of the area.

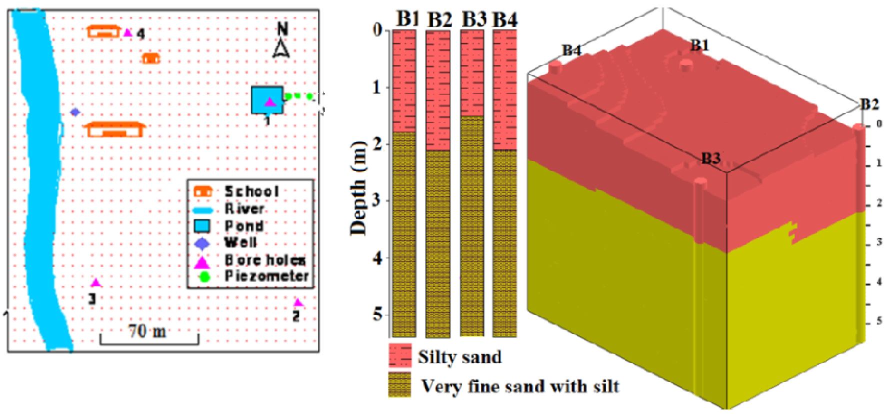


Fig. 6 Lithologic fence model of the study area

Three observation wells (fig. 3) at different depths were constructed to measure the groundwater levels (marked as ‘P1’, ‘P2’ and ‘P3’). These piezometers (fig. 7.1) are constructed in such a way that the bottom of the pipe is netted for 0.5 to 1 m depth for water filtration and are properly sealed. Water level indicators are installed inside the piezometers and in the pond in order to allow continuous monitoring of groundwater level fluctuations once in 3 minutes. Rainfall, wind speed, wind direction, outdoor temperature, pressure and humidity will be automatically measured and stored by the automatic weather station, installed in the study area. Field parameters such as pH, EC, salinity, TDS, temperature and DO are being measured once every month. The groundwater quality of Arani River, school well, pond, and the piezometers for the last four months were compared and it was found that the effect of pond in diluting the salinity in the piezometers is negligible. This is mainly due to the clogging of fine suspended particles and also due to the low hydraulic conductivity of soil of the area.

Electrical conductivity of ground water samples collected from different piezometers shows no much connection even after heavy rain fall and a revised design was proposed for the Pond and piezometers (fig. 7.2). A vertical shaft of diameter 8 inches and depth 10 m (from pond bottom level) is planned to be drilled at the centre of the pond. The exposed portion of the shaft should be slotted except for the bottom part (nearly 10 cm). The shaft should be perfectly closed with a lid. An impervious layer with natural material should be kept around the shaft at the pond bottom. A slotted drum which is covered by a cloth or sack bag will be placed over the shaft and the purpose of the cloth is to prevent the entry o contaminants. The drum should be fixed in such a way that it could be easily remove and clean. The contaminants and other fine grained particles in water will be deposited and clogged on the pond bottom and are to be removed after drying up the pond and can be used for farming. The shaft below surface will be slotted except for 1 m below the pond bottom level. Water in the pond will enter the shaft through the drum after infiltration and will low laterally to the aquifer. Piezometers are to be drilled with depths 10m and 8 m and water level indicators are to be installed. Shrubs such as Tulsi, ixora and lemon plants should be planted around the pond to prevent soil erosion and to avaoid collapse of side of the pond. Also water stagnation in the pond is expected only for 45-60 days. If stagnation is expected to be for more days, care to be taken to prevent bacterial contamination of water in the pond. If bacteria or other contaminants start in the pond, cloth or sack bag screen can be replaced by plastic sheets to prevent infiltration.

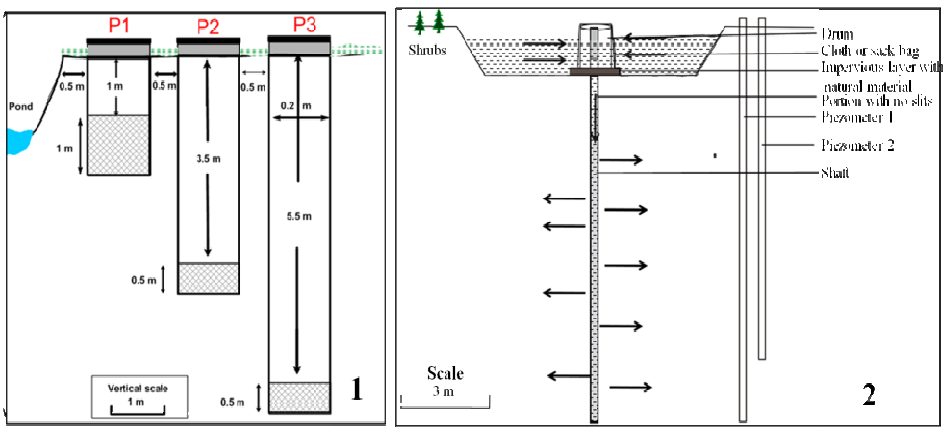


Fig. 7. Schematic design of existing (1)and proposed piezometers (2)

Check dams

In order to improve the groundwater potential and to mitigate the seawater intrusion in the Chennai's coastal aquifer, certain long-term water management measures such as construction of check dam across A-K rivers have been proposed by the Government to augment the groundwater resources is shown in Fig.8. This study shows the improvement on groundwater potential obtained through the check dam constructed across Arani River.

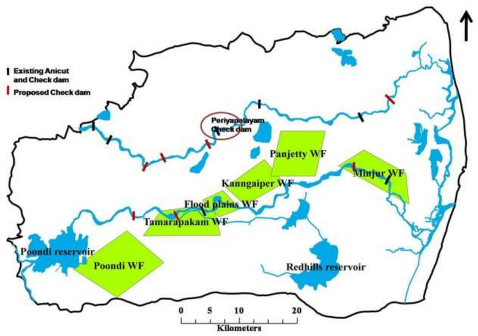


Fig. 8 Check dams across Arani and Karattlaiyar rivers

The electrical conductivity against chloride plot is shown in fig. 9 indicates that the water in the check dam is having the lowest electrical conductivity value of 551 µS/cm and lowest chloride value of 128 mg/l. Further this plot divides the wells into two groups based on the groundwater quality. The group 1 wells are having low electrical conductivity values varied from 746 µS/cm to 987 µS/cm and low chloride concentration varied from 135 mg/l to 156 mg/l is due to the most frequent recharge by the water in the check dam. Whereas group two wells are having high electrical conductivity values varied from 800 µS/cm to 2100 µS/cm and high chloride concentration varied from 180 mg/l to 380 mg/l which indicates that these wells are more frequently recharges by the rainfall or rarely receive recharge from the water in the check dam. This study indicates that series of check dam constructed across this A-K river will improve the groundwater quality by the recharge from this structure.

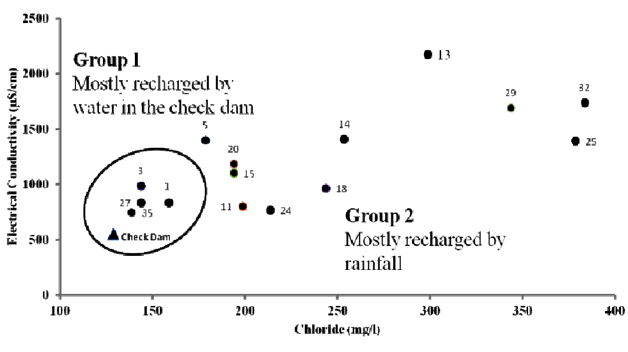


Fig.9. Plot on electrical conductivity and Chloride concentration for water in the check dam and groundwater

Limitations

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

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

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

Conclusion

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

Acknowledgements

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Role of temple tanks in MAR

Thirunavukkarasu Munuswamy

SPT Consultancy Services, Chennai

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

Temple tanks

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

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

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

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

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

Managed Aquifer Recharge

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

Water harvesting and recharge

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

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

Temple tanks in Chennai

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

1) Adipuriswarar- Adikesava Perumal Temple Tank (Chindadripet).

2) Kurungaleeswarar-Vaikundavasa Perumal Temple Tank (Koyambedu).

3) Agatheeswarar-Prasanna Venkatesa Perumal Temple Tank (Nungambakkam).

4) Suriamman Temple Tank (Pammal, Pallavaram).

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

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

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

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

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

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

Fig.2 Locations of the Tanks in Chennai

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

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

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

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

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

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

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

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