DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2026/7**

Review on Managed Aquifer Recharge in India

Bjørn Kaare Jensen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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Bjørn K. Jensen
Geological Survey of Denmark and Greenland (GEUS)

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2. Introduction

The Danish Strategic Sector Cooperation (SSC) Programme with India on water was launched in 2020. The overall responsibility of the SSC programme was delegated to the Danish Environmental Agency (DEPA), and it is facilitated by the Royal Danish Embassy in India.

The overall objective of the cooperation phase I is to contribute to achieving the Government of India's objective that by 2024 all rural households will receive drinking water supply in adequate quantity and of prescribed quality on regular and long-term basis at affordable service delivery charges, leading to improvement in living standards of rural communities. The so-called Jal Jeevan Mission.

A number of groundwater activities is carried out on the Danish side by the Geological Survey of Denmark and Greenland (GEUS) in cooperation with the Geoscience group on Aarhus University (AU) on geophysical methods for groundwater mapping, and on the Indian side, the Water Ressources Department in Tamil Nadu (WRDTN) was given the task to work together with the Danish partners on the different components of the sub-programme. The focus of Phase 1 has been on source sustainability, and a sketch of the holistic approach of this first phase is shown in Figure 1 below.

The project focused on the early stages of the holistic groundwater management cycle to secure safe drinking based on groundwater extraction. In that respect the project was based on the management approach, which is applied in Denmark for decades, and for which solutions and technology has been developed accordingly.

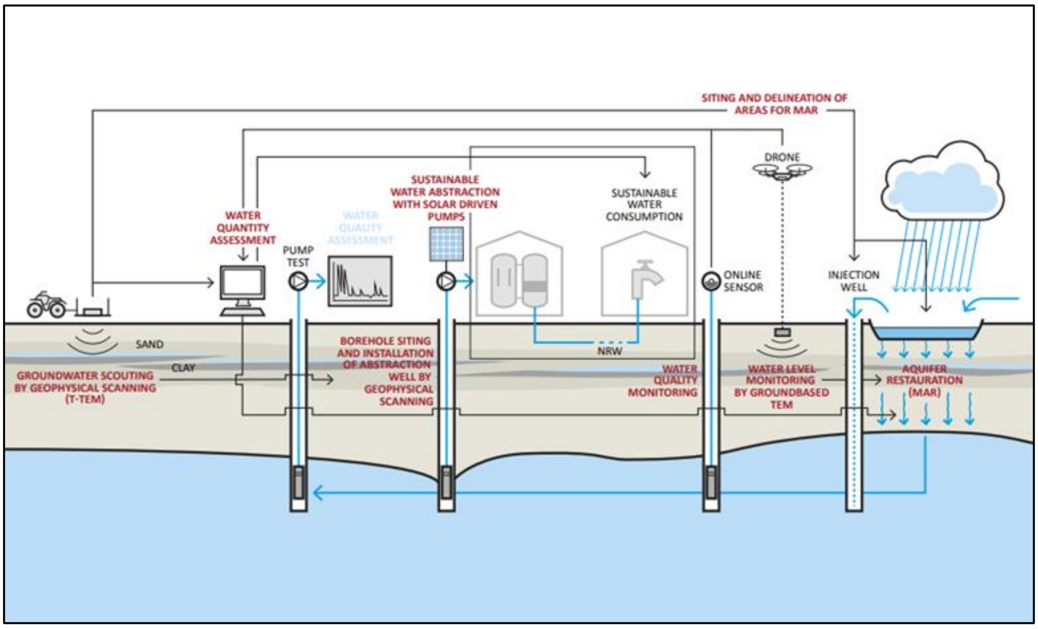

Figure 1. Conceptual sketch of holistic approach to groundwater-based water supply

Based on the lessons learned from activities carried out within Phase 1 of the SSC-GRW, a Phase 2 is now under development, and one of the activities which will be carried out during this phase is a field scale demonstration project on MAR for prevention of saltwater intrusion in coastal areas.

2.1 Scientific survey of Indian experience on MAR

As a consequence of this revised focus during Phase 2, it was decided to carry out a survey on Indian experience on MAR. Acknowledging that MAR has been – and still is – very high on the agenda in the groundwater management in India for different purposes (provision of more groundwater for rural water supply for agricultural and domestic use, prevention of saltwater intrusion, for mitigation of flooding, etc.), it was concluded that it will be beneficial for the outcome of the MAR activities to extract the experience already gained on MAR in India in a scientific survey.

This survey could then be the basis for inviting some key MAR experts from leading professional institutions, which have been involved in projects on MAR, to attend a knowledge sharing workshop in June 2025 on the outset to Phase 2 to discuss different options and technologies to be considered for a demonstration project in the MINJUR area.

MAR activities in Phase 2 are based on a concept to achieve long-term sustainability of MAR installations. Following this concept, some necessary pre-investigations prior to installing a MAR site should be carried out to achieve sustainability. These pre-investigations comprise 1) identification of a suitable location for the installation and delineation of the site prior to the installing the MAR scheme, 2) establish a reliable geological, conceptual model for the site, 3) quantity assessment of the source by hydrological modelling of the water cycle at and around the site, 4) quality risk assessment of the source water to ensure that the groundwater will not be adversely affected by the addition of the source water in question, 5) and test of potential other adverse effects, i.e. clogging, by mixing the source water and the groundwater. After installing the MAR scheme, water quality and quantity (water level) monitoring of the groundwater downstream and around the installation must take place, to ensure that the water quality and quantity is maintained or improved during the operation, and also that the performance of the MAR operation remains intact with time.

These steps are reflected in the view of Raj et al. 2024, that a MAR installation at a specific site consists of four stages: (i) assessing site suitability for artificial recharge, (ii) addressing water quality concerns for artificial recharge, (iii) identifying operational problems and challenges, and (iv) impact assessment of recharge structures.

The following survey, which is mainly based on the available scientific literature, will first give a short review of the use of groundwater for water supply in India and a short history of MAR globally, and based on this go through the literature on MAR experience in India. The aim is to evaluate Indian experience on the above mentioned steps to ensure MAR sustainability (Chapter 5.1), and also to review the experience on purposes (Chapter 5.2), sources (Chapter 5.3), and technologies (Chapter 5.4) applied in an Indian context.

3. Use of groundwater for water supply in India

India relies very much on groundwater for ensuring food and potable water security. According to estimations by CGWB, India extracted 241 km^3 of water from its aquifers in 2023, which has not changed significantly since 2004, see Table 1 (CGWB, 2024). This quantity is the world's highest, exceeding in 2017 the collective extraction of the United States and China (Saha et al., 2018) and accounts for app. 25% of the groundwater extracted on a global scale.

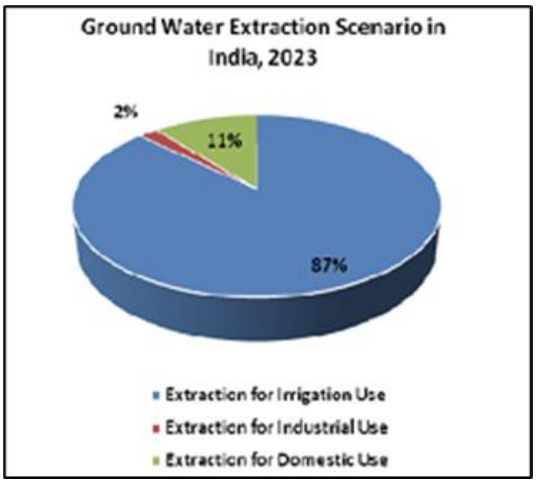

Figure 2. Use of groundwater for water supply in India

The vast majority of the extracted groundwater, 87 % in 2023, see Figure 2, is used for agricultural purposes, mainly irrigation, and only 13 % is used for domestic water supply and for industrial purposes. The same distribution is more or less the case for use of surface water in the water supply. This distribution with such a high percentage used for agricultural purposes is quite unique on a global scale, although agriculture in most countries is also the primary user of groundwater.

Groundwater accounts for app. 85% of the rural demand and app. 50% of urban requirements, the rest being surface water sources.

Table 1. Groundwater Resources assessment 2004 to 2023 (CGWB, 2024)

S. No.	Ground Water Resources Assessment	2004	2009	2011	2013	2017	2020	2022	2023
1	Annual Ground Water Recharge (bcm)	433	431	433	447	432	436	438	449
2	Annual Extractable Ground Water Resource (bcm)	399	396	398	411	393	398	398	407
3	Annual Ground Water Extractionfor Irrigation, Domestic & Industrial uses(bcm)	231	243	245	253	249	245	239	241
4	Stage of Ground Water Extraction (%)	58 %	61 %	62 %	62 %	63 %	62 %	60%	59%

The extensive exploitation of groundwater has significantly reduced water levels and exhausted groundwater reserves in some regions in India (Saha et al., 2018) although the percentage of overexploitation on a national scale has not increased very much since 2004, see Table 1 (CGWB, 2024).

The pressure on groundwater is also threatened by other factors, such as saltwater intrusion and contamination from various geogenic sources (fluoride, arsenic, and some trace elements as chromium) and anthropogenic sources, in particular nutrients and pesticides from agriculture, and heavy metals of industrial origin (Ravindiran et al, 2023). As can be seen from Figure 3, the percentage of saline groundwater has increased from 0,5 % in 2004 to about 2 % in 2023.

The main source of replenishable ground water resources is recharge from rainfall, some 60% of the total annual ground water recharge. India receives in average 119 cm of rain annually, with high spatial variation. A major part of the country receives rainfall mainly during the SW Monsoon season, from June to September, except in Tamil Nadu, where the major contribution is from the NE monsoon from October to December.

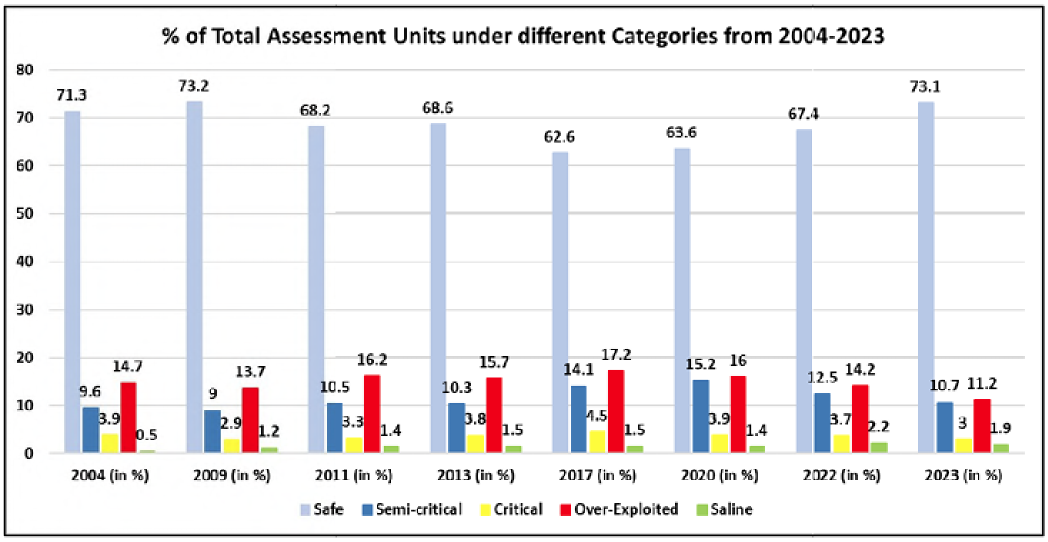

Figure 3. Different assessment categories 2004 to 2023 (CGWB, 2024)

4. MAR – from Artificial Recharge to Managed Aquifer Recharge

MAR is defined as the purposeful recharge of water to threatened aquifers used for water supply or serving other purposes for subsequent recovery and use or for environmental benefit (Dillon et. al 2009). In Figure 4, a conceptual model of MAR is shown.

Sustainable use of groundwater for water supply requires a sustainable balance between availability/extraction and demand. There are only two means to stabilize the groundwater level: reducing demand (through increased water use efficiency/savings and/or replace use of groundwater with other water sources) or increasing replenishment by MAR (Dillon et al. 2012).

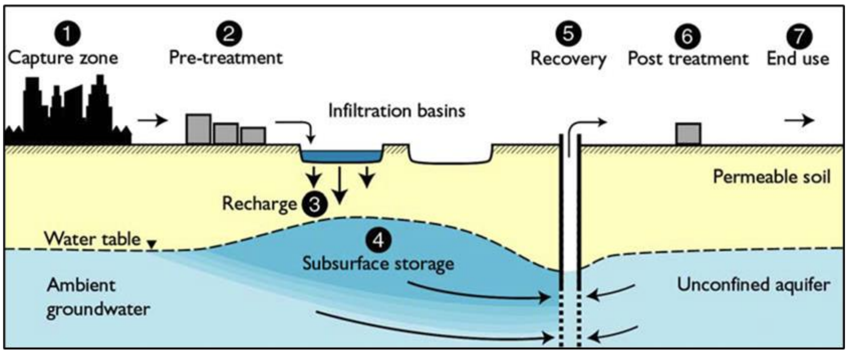

Figure 4. A conceptual model of MAR

The replenishment of groundwater by increasing the groundwater recharge beyond what it taking place without human manipulation has developed over the last 100 years. Different measures and technologies have been applied, and consequently these measures and interventions have been called by different names.

<u>Unintentional recharge enhancement</u> is the event taking place where the recharge is enhanced due to human activity but not for that purpose, se Table 3.

<u>Unmanaged recharge</u> describes the intervention where there is human intent to discharge waters into soil or aquifers but without consideration of the resource value of the disposed water, and often with no thought of the impacts on groundwater quality.

Whereas formerly, the term <u>artificial recharge</u>, has been used when the focus had been on augmenting the quantity of recharge, but with much less attention given to managing water quality, <u>Managed Aquifer Recharge (MAR)</u> means that both quantity and quality are managed effectively. Figure 4 shows a conceptual sketch of MAR.

Table 2. Different types of replenishment of aquifers. (Dillon et al. 2019)

Unintentional recharge enhancement	Unmanaged recharge (for disposal)	MAR (for recovery and/or environmental benefit)
• Clearing of deep rooted vegetation, or soil tillage	• Stormwater drainage wells and sumps	• Streambed channel modifications
• Spate irrigation	• Septic tank leach fields	• Bank filtration
• Irrigation deep seepage	• Mining and industrial water disposal to sumps	• Water spreading
• Leakage from water pipes and sewers	• Drainage water from construction pits	• Recharge wells and shafts
		• Reservoir releases

On a global scale the use of MAR – or artificial recharge as it was called earlier – has escalated during the last 50 years from an average annual MAR volume in 1965 of app. 1 km^3/year to almost 10 km^3/year in 2015.

There are clear differences in terms of volumes and applications used in different countries and regions of the world. In Europe, the approach of Bank Filtration has been applied in many countries such as Germany and the Netherlands (Dillon et al. 2018), while in USA and Australia, where there in general is more space for MAR, surface spreading techniques have been more widely applied.

In India, the development for the same period of 50 years has increased from 0.15 km^3/year to 3 km^3/year for 5 selected states (Andhra Pradesh, Gujarat, Jharkhand, Karnataka and Uttarakhand), which is by far the largest increase. The total recharge for India could potentially be between 2 and 5 times the five-state estimated amount in 2015, which was estimated to account for 31 % of the reported global MAR capacity. USA (26%), Germany (9%), Spain, Australia and Italy are coming next on the list (Dillon et al. 2019). Thus, the use of MAR has been high in some European countries, but here the increase has not been so significant, since they have been in the forefront from the beginning.

Even though the advantages of using MAR to counteract water scarcity and climate change effects on the water cycle is well acknowledged, the introduction of MAR has in some countries been limited due to a number of factors, including the risk of polluting the groundwater with the source water, long-term availability of source water and thus the long-term sustainability of an installed MAR scheme, and possible clogging effects from the mixing of groundwater with source water. In addition, there has also been some negative public perception against the use of groundwater and especially groundwater enhanced by MAR.

4.1 MAR technologies and water sources

Since the beginning, a number of different MAR techniques and applications have been developed and tested, including the following types of MAR:.

- Aquifer storage and recovery (ASR)
- Aquifer storage, transfer and recovery (ASTR)
- Surface water spreading
- Field infiltration
- Infiltration ponds or ditches
- Infiltration galleries

- Soil aquifer treatment (SAT)
- Percolation tanks
- Tunnel-wells
- Bank/dune filtration
- Well injection
- Recharge shafts
- Check dams/sand dams
- In-channel MAR
- Subsoil infiltration gallery
- Rainwater harvesting

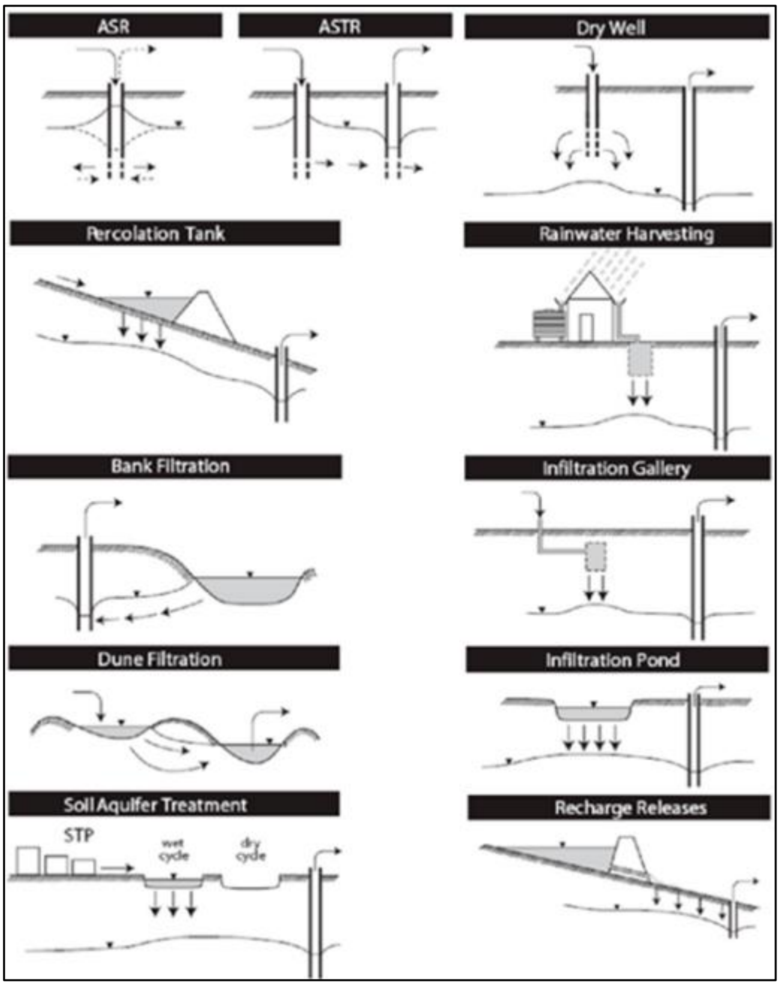

Figure 5. Examples of MAR technologies.

For a more detailed description of some of the technologies applied in an Indian context, see Chapter 5.4. The different applications have used many different sources of water ranging from river water and other types of surface freshwater, harvested rainwater and stormwater, and reclaimed wastewater (Dillon et al. 2018).

5. MAR in India

As mentioned above, MAR is one of the most effective instruments for restoration of over-exploited aquifers. It is mostly applied to counteract overexploitation where the demand for water exceeds the availability of useable sources for water supply. It can also be used to address a wide range of other challenges, i.e. storage of water in aquifers for use during droughts instead of open reservoirs and pits to minimize evaporation, thus balancing out supply and demand fluctuations. It has been used for counteracting decreasing groundwater levels causing soil subsidence – although this purpose is more often used in other countries than India, i.e. in the North China Plain -, to protect surface water ecosystems from drying out during droughts, to mitigate flooding, to prevent saltwater intrusion, etc.

As in many countries, the focus in India, at least until recently, has been on water quantity with less focus on water quality. In fact, despite the numerous MAR structures in India, by far exceeding the number of sites in the rest of the world, relatively few projects have evaluated the performance of the MAR operation at the sites, and in rather few MAR structures recharge has been monitored and documented (Dashora et al. 2018).

The reason for that is probably that the vast majority of the Indian MAR installations have been small scale decentralized schemes often established at community level by farmers and NGOs. Many of these schemes have been running for many years and have probably not faced major problems, but in any case it is not fully known to which extent these installations have been successfull in terms of long-term sustainability, i.e. whether there have been major quality issues, clogging phenomena, etc., since relatively few evaluation of the installed MAR schemes have been carried out.

This may seem a bit concerning since the Master Plan for Artificial recharge, launched by CGWB back in 2013 as a revision of the first plan in 2005, envisaged the implementation of some 11 million artificial recharge structures, and for this huge venture it is still necessary to be able to learn from potential past failures and drawbacks. However, during recent years more focus on quality issues have been experienced, and some studies evaluating the performance of MAR have now been reported in the scientific literature, see Chapter 5.1.5.

The use of MAR in India can be divided up into four distinct phases (Saha et al. 2022). Phase I is the period preceding the mid-1960s, when groundwater use was restricted, and local communities applied conventional water-harvesting. Phase II, from the mid-1960s to around 1990, was characterised by a significant rise in use of groundwater for various purposes, which caused over-exploitation in many regions. This again promoted a growing understanding of the potential importance of a more strategic effort to replenish aquifers. The period from 1990 to 2010, commonly referred to as Phase III, was characterised by a significant rise in groundwater extraction, and several MAR sites at different scales were established and documented across India. Phase-IV is the post-2012 period. During this time, a change in perception, policy, and actions to combat overexploitation is seen in the sense that the government now to a certain degree gives equal importance to both supply-side and demand-side interventions. In 2000, a Guide to Artificial Recharge to promote wider use of MAR was published by Central Groundwater Board (CGWB, 2000) and in 2007 a Manual on Artificial Recharge (CGWB, 2007).

In recent years, a renewed interest in the potentials of MAR in over-exploited areas has appeared, and investments in percolation tanks and other types of installations to infiltrate harvested or detained monsoon runoff in areas with droughts have been massive. A clear indication of the enhanced public interest in MAR is the increase in the number of scientific publications on MAR in India issued during the last 15 years from approximately 20 publications a year in 2008 to 100 publications a year in 2022, see Figure 6.

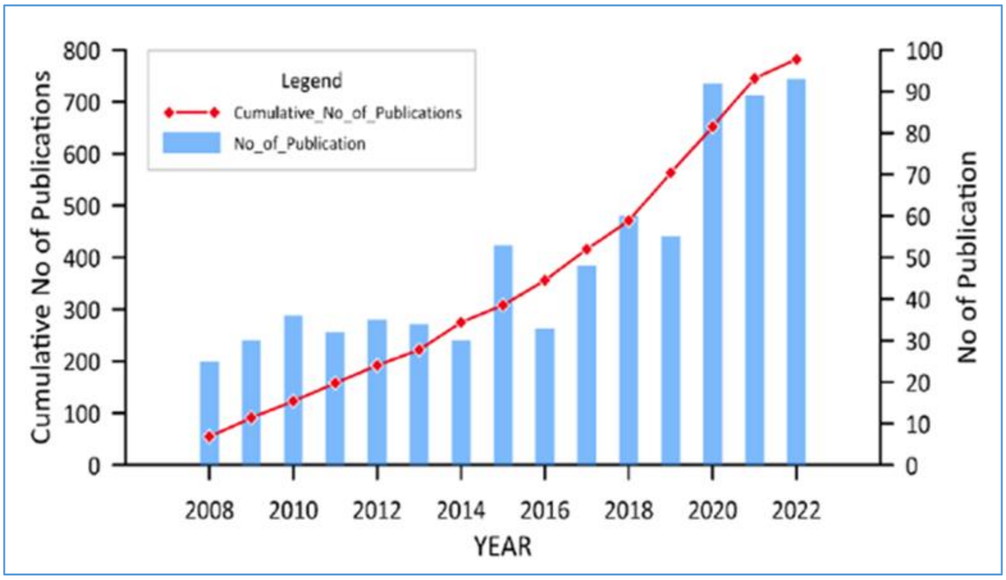

Figure 6. Number of scientific publications on MAR per year 2008 – 2022. From Raj et al. 2024)

A Master Plan for Artificial Recharge was launched in 2020 (CGWB, 2020), and according to this master plan, huge investments are projected to expand the use of MAR further by some 11 million structures in urban and rural areas at an estimated cost of US$10 billion (CGWB 2005, 2013). Thus, many new developments in terms of technology and use of MAR in a groundwater management context have been published, many of those inspired by a similar international increased interest in using groundwater for water supply and the use of MAR for various purposes (Ganguly & Ganguly, 2021; Raj et al. 2024).

5.1 Pre-investigations for MAR sustainability

As mentioned in the introduction, more attention has lately been on sustainability of MAR, which means that prior to installation of a MAR scheme, some pre-investigations to ensure the long-term efficiency of the MAR operations have to be applied.

Alam et al. (2021) described some sustainability MAR selection guidelines, combining such pre-investigations with other types of criteria to achieve sustainability. Pre-investigations include measures to ensure that the right location is identified, that there will be source water of a quality fit for the purpose for long-term operation, and no adverse effects, i.e. clogging of the site or contamination of the groundwater, will occur during the operation..

5.1.1 Site identification and delineation

As a first step, before a MAR scheme can be installed, a suitable site has to be identified based on some basic criteria in terms of space, geology (infiltration capacity), aquifer storage capacity, a proper and available water source, etc. Based on the geophysical measurements, a geological, conceptual model for the identified site can then be developed (Dar et al. 2017).

A recent campaign carried out in 2024 by Central Groundwater Board and the National Geophysical Research Institute using heliborne TEM (SkyTEM) has identified 1029 sites for MAR (CGWB, 2024b). But until now, very few concrete studies have been published using geophysical methodologies for site delineation (Andrade & Guru, 2020), and no studies on the use of ground-based TEM technologies.

MAR site delineation have mostly been carried out by applying remote sensing and GIS and a Analytic Hierarchy Process (AHP) used for ranking the different layers (Aju et al. 2021; Arshad et al. (2022); Arya et al. 2020; Baghel et al. 2023; Das, 2002; Raviraj et al. 2017; Chowdhury et al. 2010). As an example, Arshad et al. (2022) applied a GIS-based methodology with seven thematic layers to identify the aquifer recharge potential zones according to their suitability for groundwater recharge in the area. By this method they delineated 41 potential recharge sites, which were then reduced to 13 because of groundwater fluoride level fluctuation with recharge in the area.

5.1.2 Quantity assessment

Based on the delineation of the site and development of geological model, the next step to ensure long-term sustainability of MAR at a specific site is to carry out groundwater quantity assessment to estimate the long-term availability of water in the area, either natural water sources (rivers, lakes) or alternative sources such as harvested rain water and reclaimed wastewater. It should also be assessed how much aquifer store capacity is available for replenishing the aquifer.

To predict the impact of the MAR operation on the long-term availability of water, water balance modelling has to be carried out at the site. This exercise has been carried out in a few cases, and one approach is described by Rath & Hinge (2024) in a recent study. They integrated watershed modelling using the Soil and Water Assessment Tool (SWAT), which evaluate the availability of water for MAR followed by an multi-criteria decision analysis (MCDA-AHP) method to identify optimal sites for MAR based on ten spatial parameters.

5.1.3 Quality risk assessment

The quality risk assessment includes assessment of the water source (harvested rainwater or stormwater, freshwater, reclaimed wastewater, to be used for the MAR scheme to reveal any compounds which might cause problems in terms of contamination of the groundwater or cause problems when the source water is mixed with groundwater, i.e. giving rise to geochemical reactions resulting in chemical clogging.

Test of possible groundwater contamination or possible treatability options for the MAR installation can be tested in the laboratory test columns simulating the field conditions of the selected MAR site (Modrzyński et al. 2021, Raji & Packialakshmi, 2022). Such column studies are becoming standard prior to installing a MAR scheme of a certain size, and could be combined by reactive transport models coupling groundwater flow and solute transport with chemical reactions for predicting the fate and transport of any potential or occurring contaminants in the source water and thus the removal effect of certain MAR schemes (Waterhouse et al. 2021; . There are very few studies from India, where a quality risk assessment has been carried out before a MAR scheme is installed, and most studies have evaluated the effect of MAR on the groundwater quality after having installed the MAR scheme i.e. Pettenati et al. (2014) and Renganayaki & Elango (2014).

5.1.4 Test for other potential adverse effects

As mentioned above, clogging (physical, chemical or microbiological) is one of the major issues to be adressed in establishing MAR schemes. According to Lippera et al. (2023), clogging is often assessed based on field investigations and very few studies have carried out predictions based on geochemical modelling or lab scale feasibility studies. This is also the case in India. It is, however, becoming more common to do that in Europe, Australia and elsewhere. Predictive models have a drawback since they have difficulties addressing inhomogeneities which are often occurring at field scale. Therefore there is a need to carry out lab scale investigations for assessment of the feasibility of MAR at a specific site. A good example how this can be carried out is shown by Lippera et al. (2023), see Figure 7.

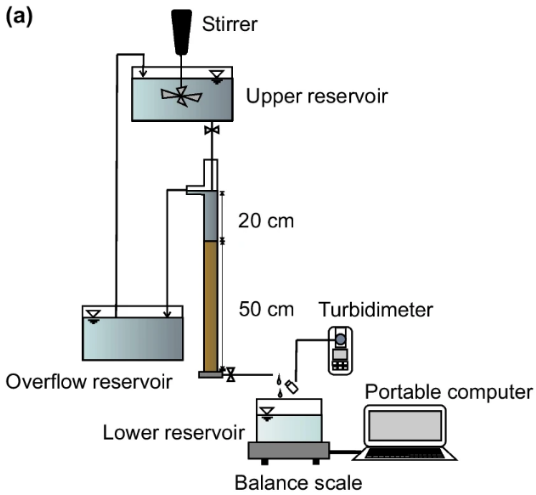

Figure 7. Laboratory set-up to test the potential clogging of MAR

5.1.5 Monitoring of potential effects and system performance

Prathapar et al. (2015) offers an approach to evaluate the performance and impact of MAR interventions, and the last 10-15 years more and more MAR installations have been monitored to test the efficiency and performance of various applications of MAR after having been put into operation, using different types of source water. The monitoring include both the effect on water quantity and on water quality of the receiving groundwater aquifers, and water levels and different quality parameters such as different types of compounds and microbial reagents. (Alam et al. 2020; Kumar et al. 2009; Mozzi et al. 2021; Saharawat et al. 2011; Stiefel et al. 2009). Sometimes also clogging is checked through monitoring of MAR structures (Renganayaki & Elango, 2018).

Most studies have focused on the effect on the water quantity and the groundwater level as a result of MAR operations but in later years also water quality changes have been included in the studies.. Stiefel et al. (2009) evaluated in an early study the effects on both water levels and water quality in wells at a site in Rajasthan. They proved that wells receiving artificial recharge had improved groundwater quality, and also a positive effect on the groundwater quantity in the wells. Abraham & Mohan (2015) confirmed this showing a significant increase of the groundwater table (2 – 5 meters) in the surrounding area of established check dams and percolation tanks in a watershed in Tamil Nadu after 2 years of artificial recharge. Other examples include Alam et al. (2021) who monitored the daily water balance of a check dam with analytical infiltration equations to assess check dam performance measured as temporal dynamics of storage, infiltration, and evaporation and Glorian et al. (2018) carried out campaigns to test the performance of riverbank filtration in terms of treatment efficiency towards a number of organic micropollutants, such as including pesticides and pharmaceutical compounds. Soni et al. (2020) monitored 11 wells in the Dharta watershed, Udaipur district, Rajasthan, measuring depth to water level and taking water samples for water quality analysis (pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, fluoride, and Escherichia coli) before and during the monsoon period. On the basis of results from this monitoring study, they recommended that rural runoff should not be added to injection wells that are used for, or close to, wells used for drinking water supplies.

In conclusion, the majority of monitoring studies carried out in India shows a beneficial effect of MAR operations on both water quantity and water quality. However, in terms of water quality the effect is governed by the quality of the source water and the complex interactions of mixing source water and groundwater, and to ensure sustainability it is recommended to carry out pre-investigations to get a better basis for choice of technology and potential pretreatment.

5.2 Main purposes of MAR in India

In India, MAR has been deployed for all purposes like in the rest of the world. As mentioned in chapter 4, the purpose in the beginning was mostly for providing more water for domestic and especially agricultural use, but later it was acknowledged that MAR is an efficient technology for preventing saltwater intrusion in coastal areas and also to counteract different phenomena caused by climate change, such as flooding and drought (Alam et al. 2020; Chinasamy et al. 2028). A more recent approach is to combine different purposes with the installation of MAR schemes (Gangopadhyay et al. 2018). In other parts of the world, MAR is also used to preserve ecosystems and for counteracting soil subsidence, but that does not seem to be a high priority in the development of MAR in India, although it has been on the table lately in some cases (Shaikh & Birajdar, 2024).

5.2.1 MAR for domestic water supply

MAR is often used for providing more drinking water for households, although it in rural areas is mostly used for keeping up with the high demands for water for irrigation. With the announcement of the Government of India in August 2019 to commit to provide piped water supply to every household in the rural areas by 2024 with a new national flagship programme – the Jal Jeevan (Water for life) Mission -, the ambitions of providing more drinking water to households accelerated the need for more water, including groundwater, for drinking water supply.

When applying MAR for replenishing groundwater aquifers to be used for domestic drinking water in the households, a more stringent focus on the quality of the resulting groundwater resource is needed. This again has importance on the choice of source water for MAR as well as the techniques to be applied.

5.2.2 MAR for replenishing groundwater for agricultural use (irrigation)

As mentioned, agriculture accounts for the majority of the groundwater produced by MAR, and a number of studies have been published concerning MAR for irrigation in India, many of them at local farm level. Just to mention a few, one study investigated the recharge of MAR by well injection of harvested rain through open dug wells, which led to some measures to protect the wells against contamination (Soni et al. 2020). Another study described a simple method to evaluate the performance of check dams also at farm level (Dashora et al. 2018), and a third study evaluated the performance of 7 MAR structures at farm level across India (Prathapar et al. 2015 The article pointed at the need to distinguish between performance and impact, and none of them could explicitly demonstrate that reported impacts were uniquely linked to MAR interventions.

5.2.3 MAR for prevention of saltwater intrusion

Coastal aquifers are often affected by saltwater intrusion due to various factors, including sea-level rise, shoreline erosion, coastal flooding, and various human activities (Prusty & Farooq, 2020), see Figure 8. Over-exploitation is the major human activity leading to saltwater intrusion in India (Kanagaraj et al. 2018).

The excessive groundwater withdrawal near the city of Chennai has led to seawater intrusion into coastal aquifers. Nair et al. (2013) investigated the subsurface water of the coastline aquifer in Chennai's northern area, and they showed saltwater intrusion up to 10 km inland.

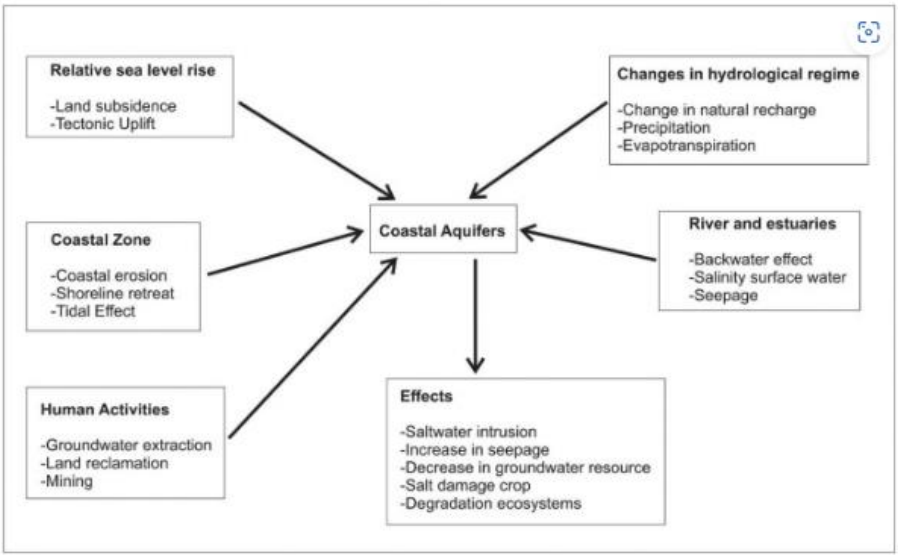

Figure 8. Factors affection coastal aquifers (Kumar 2006).

Buried paleochannels filled with high permeable sediments, often provide preferred pathways for the movement of groundwater and seawater in coastal regions. Thus, these paleochannels may support seawater intrusion with the increase in the groundwater abstraction on land, and they are also a suggested for establishing MAR schemes (Samadder et al. 2011).

It is complicated to define the best methodology for prevention or mitigation saltwater intrusion in coastal areas since it requires a very good geological model for the area, which again rely on good and dense geological, lithological and geochemical data. A number of approaches have been suggested and applied in India, including change of pumping strategies (Manivannan & Elango, 2018) often combined with demand management methodologies (water savings), use of other water sources, installation of sub-surface barriers and especially different managed aquifer recharge (MAR) techniques (Prusty & Farooq, 2020).

Kumar Maity et al. 2018 suggested 6 techniques, indicating pro, cons and price of the selected technique, including:

a) Keeping basin water level high. Groundwater levels in the overdrawn aquifers can be raised and maintained above sea level through artificial recharge utilizing surface spreading, percolation ponds/injection wells.
b) Creating a fresh water ridge near sea. The method would require the continuous maintenance of a fresh water ridge in the principal water bearing deposits along the coast through the application of water by surface spreading or injection wells.
c) Creating a pumping trough or extraction barrier trough. Development of an extraction barrier would require retaining a continuous pumping trough near ocean. Pumping troughs can be created and developed by means of a row of pumping wells, properly located along the seacoast.
d) Developing artificial subsurface barriers, This method involves the establishment of a subsurface (physical) barrier to reduce the permeability of water bearing deposits sufficiently to prevent the seawater inflow into fresh water strata.
e) Adopting rainwater harvesting technology and artificial recharging structures.

5.3 Water sources for MAR used in India

Various sources for MAR have been used in India, including surface water sources (river water, lake water, canal water), harvested rain water and stormwater, treated wastewater and groundwater. The most frequently used water sources are rain water and river water in different types of MAR applications (Duraiswami et al., 2016). From very early on, check dams and percolation tanks have been installed in huge numbers of cases all over India. Especially techniques for rain water harvesting have been installed across India for many years and are a very widely used applications (Stiefel et al. 2009; Raicy & Elango, 2017). In recent years stormwater has been introduced as a water source for MAR, thus combining mitigation of flooding and provision of additional drinking water for various purposes (Alem et al. 2020).

A third category of source water, which has attracted very much attention globally in recent years, is reclaimed wastewater. There have been health and environmental concerns using this water source, such as the risk of contaminating the receiving groundwater resources (Nijhawan et al. 2013). However, in this study 64.4% respondents in a survey were in favour of using treated municipal wastewater for artificial recharge of groundwater, 28.4% opposed and 7.2% remained indifferent. The main concern of those against the use of this source was the effectiveness of wastewater treatment in India, and not the recharge technique itself. On the other hand, if pretreated and monitored carefully, this source constitutes a very stable water source for MAR thus making it more sustainable, and it has also attracted attention in India (Raji & Packialakshmi, 2022).

5.4 MAR technologies applied

The different MAR techniques have been categorised in a number of studies. In Ganguly & Ganguly (2021) a very comprehensive review of MAR technologies applied in an Indian context is presented dividing the technologies up in infiltration methods, direct injection methods, filtration methods and rainwater harvesting. These authors point at percolation tanks, check dams, recharge shafts and rainwater harvesting techniques being very relevant in an Indian context because of their efficiency and easy application, and many other studies and reports confirm these techniques to be the most commonly used in India.

In the master plan published by CGWB (2020) are listed the different technologies to be applied, see Figure 8. The MAR structures are proposed based on various criteria and preconditions, i.e. terrain conditions and source water availability. As can be seen from the figure, a majority of the structures proposed are based on Rainwater Harvesting, which again covers different types of recharging.

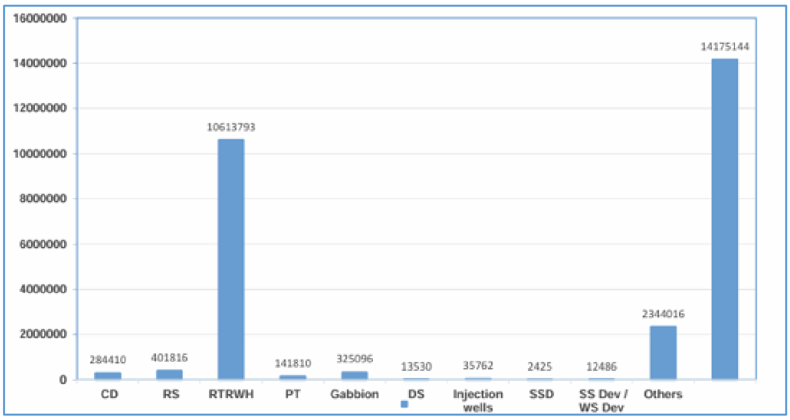

Figure 9. Different MAR technologies to be applied in India
CD-Check dam, RS-Recharge Shaft, RTRWH-Roof Top Rainwater Harvesting, PT=Percolation Tank, DS-Desilting, SSD- Sub-Surface Dyke, SS Dev/WS Dev-Springshed Development/Watershed development activities, Others - Other Structures

5.4.1 Rainwater harvesting

Rainwater harvesting is traditionally the most commonly applied techniques for use in MAR in India, which is also indicated in Figure 10. However, this technology is not in itself a MAR technology since it only refers to the approach of using collected rainwater. In many cases the rainwater is not use for replenishing the aquifer, but is stored in a water storage tank above ground and the water subsequently used directly for drinking water or irrigation. When combined with MAR, it often takes place by different applications of well injection.

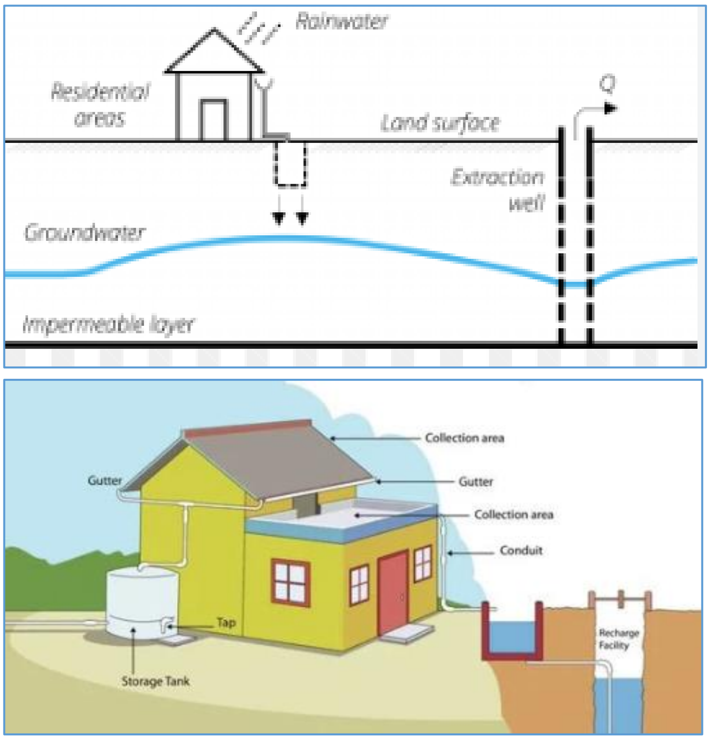

Figure 10. Concept of rainwater harvesting (after INOWAS)

5.4.2 *Infiltration methods*

In the above mentioned listing of technologies by Ganguly & Ganguly (2021), infiltration methods include surface spreading and percolation tanks, recharge pits and recharge shafts, and drainage trenches. Surface spreading is a technique with spreading water over an area for a certain period of time such that the entire water infiltrates and is also treated by the soil layers removing potential contaminants in the infiltrating water. It is suitable for unconfined aquifers where there are no impermeable layers and the topsoil is permeable.

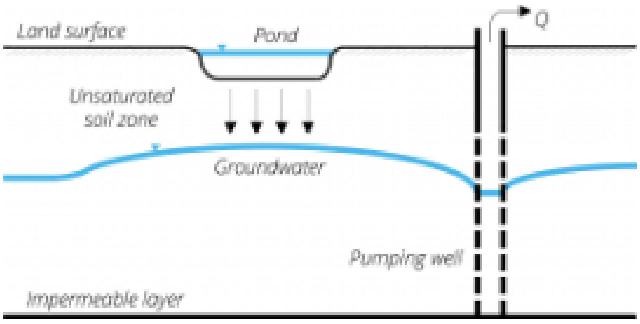

Figure 11. Surface spreading. After Stefan, INOWAS.

Percolation tanks or ponds are small structures/reservoirs constructed to store harvested rainwater or other water sources allowing it to slowly percolate into the ground. Sakthivadivel (2007) reports that more than 500,000 tanks and ponds dispersed through-out India have been constructed.

There are numerous publication on the pros and cons of percolation tanks - rather easy construction at low cost but with some maintenance requirements - often in combination with other installations such as recharge shafts (Raicy & Elango, 2020).

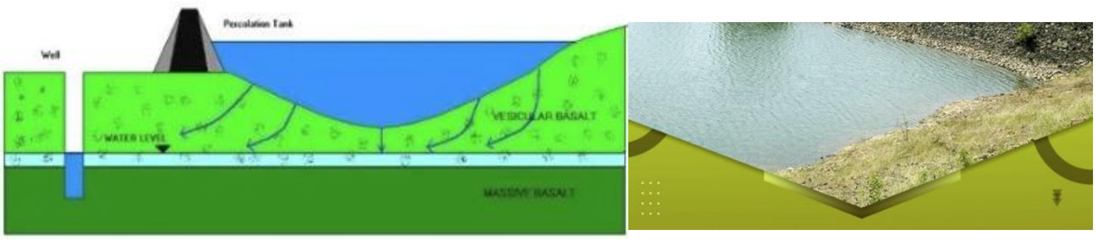

Figure 12. Percolation tank.

Recharge shafts are provided where the topsoil is alluvial or less permeable. These are lined boreholes with a diameter of 1 – 3 m and of 10–15 m depth, depending of the depth of the impermeable layer. A combination of percolation tanks and recharge shafts has been proposed by Water Resources Department in Tamil Nadu in a recent MAR proposal to prevent saltwater intrusion and at the same time provide more water for the water supply for various purposes, including irrigation and domestic drinking water (TNWRD 2024).

5.4.2.1 Check dams

Check dams are small, temporary or permanent dams built across streams and drainage channels to slow down water flow, control erosion, and trap sediment. One way to establish a barrier across a stream or cannel is by gabions, which are structures made from boulders enclosed in wire mesh Since the 1960s more than 200,000 check dams have been constructed on ephemeral streams in India to enhance groundwater recharge and help sustain irrigation supplies (Dashora et al. (2018).

Check dams are together with percolation tanks and other techniques using harvested rainwater as the source water the most frequently applied MAR technologies in India (Mozzi et al. 2021; Djuma et al. 2017). They are installed for different purposes, mostly for providing more water for domestic water supply or agricultural practices at different scales ranging from medium sized installations to small scale installations at farm level for agricultural purposes (Dashora et al. 2018).

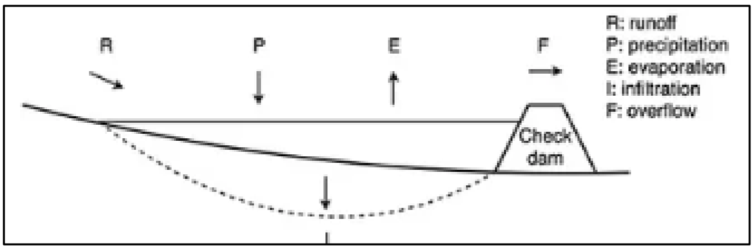

Figure 13. Check dam

There are many reports on the impact of check dams on water quantity and quality. According to Gowrisankar et al. (2017), establishing a check dam led to a significant reduction in groundwater fluoride concentration in downstream due to the dilution with the freshwater recharge. In another earlier study in Tamil Nadu near Chennai, water samples were collected from a check dam and a number of wells nearby and analysed for a number of chemical parameters to check the effect of the of the water source on the groundwater quality (Renganayaki & Elanga, 2014) showed the same improvement of the quality.

5.4.2.2 *In-stream and in-channel modifications*

There is a lot of focus on large scale in-stream structures, since it has been shown that there is a lot of extra groundwater storage capacity in many rivers and streams across India. In-channel modifications are essentially MAR projects capturing floodwater from ephemeral streams to remedy quality and quantity issues affecting aquifers in hydraulic connection with temporary streams, thereby increasing water storage to mitigate flooding and provide more drinking water, which has been accelerated by recent plans in states, i.e. Odisha, to establish such facilities. According to Standen et al. (2020), in-stream or in-channel structures in India are mostly in the form of small dam structures across small streams, i.e. check dams.

There are many examples of studies of in-stream structures across India. Gale et al. (2006) studied three streambed structures and more recently Dashora et al. (2018) studied four and reviewed studies of 20 more revealing that infiltration rates from in-stream water detention are one to two orders of magnitude less than that reported for off-stream infiltration basins where flow and quality of water can be controlled.

5.4.3 Direct injection methods

Injection wells (also called recharge wells), gravity head recharge wells, recharge pits, and recharge shafts are methodologies used to recharge often deeper (confined) aquifers. Groundwater recharge through wells, shafts and boreholes sums up all methods that utilize gravitational recharge through shallow constructed shafts, pits, boreholes or recharge by direct injection of water through wells.

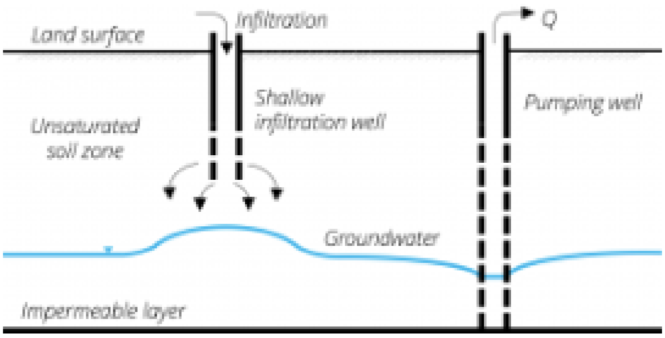

Figure 14. Well injection. After C Stefan INOWAS.

MAR using injection wells or well galleries are widely used in many countries to create a hydraulic barrier to prevent saltwater intrusion or simply to provide more water to over-exploited aquifers. In India, such schemes have also been applied (Mukherjee, 2016). However, it is not that common to use well injection compared to infiltration technologies, although some types of injection wells, i.e. recharge shafts, are often installed in combination with percolation tanks. However, a number of cases have been reported, including Kumar et al. (2008), Soni et al. (2021),

In a recent study, three piezometer wells were drilled in proximity to the high-salinity zone within the unconfined aquifer, one injection well and two observation wells. Different volumes were injected in the injection well at a similar recharge rate, and the results indicated that MAR has the potential to mitigating saltwater intrusion in freshwater zones to some extent in the short term. (Tripathi et al. 2024).

In another study in Ganges, water quality testing showed that groundwater having received stormwater through a number of injection wells was tested for inorganic chemicals, heavy metals, and coliforms, and it was found that the groundwater could not be used directly as drinking water but for irrigation (Jha et a. 2021).

Two approaches are employed for injection and recovery: (i) aquifer storage and recovery (ASR) (Bandyopadhyay et al. 2021; Holländer et al. 2009; Tiwari & Yadav, 2023) and (ii) aquifer storage, transfer, and recovery (ASTR). In ASR, injection and recovery occur through the same wells, while in ASTR two wells are installed, an injection well and an extraction well. It is techniques which are used with asymmetrical precipitation with a surplus fresh-water to be injected to a suitable aquifer to be stored for a certain period of time and recovered during periods with less freshwater available for various purposes.

5.4.4 Filtration methods

In Europe, river bank filtration (RBF) have been used since 1870, providing about 50% of the public water supply of Slovakia and Hungary, 9% in Germany, 7% in Netherlands and 25% in Switzerland. Budapest (Hungary) is fully supplied with bank filtrate from the Danube River, and in the US, bank filtration systems have been in use for more than 60 years.

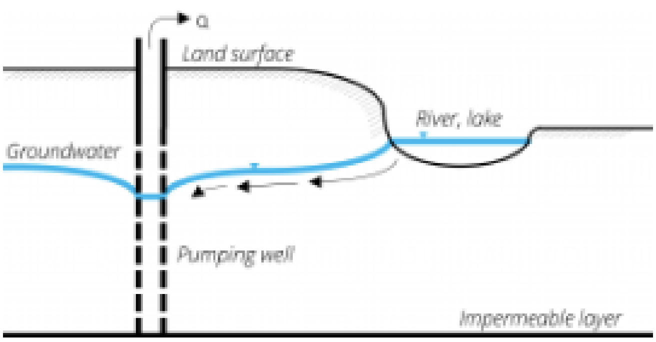

Figure 15. Bank filtration. After C Stefan INOWAS.

In India, There are a number of RBF sites in the alluvial deposits along the Ganga River and various tributaries, since the hydrogeology of many riparian cities in India makes RBF both feasible and attractive as this hydrogeology makes it possible to readily extract large quantities of water from riverbanks (Dash et al. 2010; Sandhu et al. 2011). An EU-Indian and a German-Indian RBF project were started in 2005 and 2008, respectively, and the Co-operation Centre for Riverbank Filtration was established in 2007 at the RBF site Haridwar (India). In 2011, the Indo-German Competence Centre on RBF was founded under the guidance of the National Institute of Hydrology, Roorkee, following the approval by the Indian Ministry of Water Resources.

In the study by Sandhu et al. (2011), an attempt is made to review the studies carried out on River Bank Filtration in India. The geological conditions, well types and the effect of bank filtration on physical, chemical and biological quality of water were adressed. Also a review by Jeyakumar et al. (2017) confirmed that physical, chemical and biological contaminants were decreased dramatically during the bank filtration process. Thus, the potential of RBF to treat the surface water during flow through the aquifer is very evident. Thus, it was found that a large potential for RBF exists in many riparian locations throughout India..

6. Key findings

India is the country in the world with the world's highest extraction of groundwater for water supply, accounting for app. 25 % of the extraction of groundwater worldwide. Most of this amount has been used, 87 %, for agricultural purposes, which is in the same level – although somewhat higher - to the rest of the world.

Using of MAR for replenishing over-exploited aquifers goes back hundreds of years in India, and there is a lot of local experience gained among farmers, NGOs and local communities. MAR installations are dominated by small scale decentralised MAR schemes, such as check dams and percolation tanks, often using harvested rainwater as source, which is very much different from the experience with MAR in the rest of the world, which are mainly large scale installations.

Because of these features, rather few MAR installation have been monitored and evaluated after installation in terms of long-term efficiency and performance, although it must be assumed, that most installations have been functioning sufficiently well. In recent years, however, a growing concern on the sustainability of MAR schemes has been witnessed, and such monitoring and evaluation has been reported in a number of cases.

Like in many other countries there has not been much focus on long-term sustainability, i.e. on how to ensure availability of a long-term stable water source for MAR and how to avoid adverse effects using MAR, such as clogging and the risk of groundwater pollution. It might be related to the fact that most schemes are small-scale installations Likewise, there is only few reports on tools and measures taken to ensure sustainable MAR before design and installation of the MAR scheme.

MAR is a supply management tool – to provide more water of a quality fit for the purpose -, but there is very little focus in India on demand management tools going hand in hand with MAR to save water. It would require initiatives to create incentives, i.e. financial incentives in terms of pricing regimes, to save water both in agriculture and for domestic use as well as deploying technologies for measuring use of water within different sectors.

Summarising the current expertise and experience in India based on the scientific literature on the different technical aspects of MAR, as described in chapter 5, a rough picture can be shown as in Figure 16.

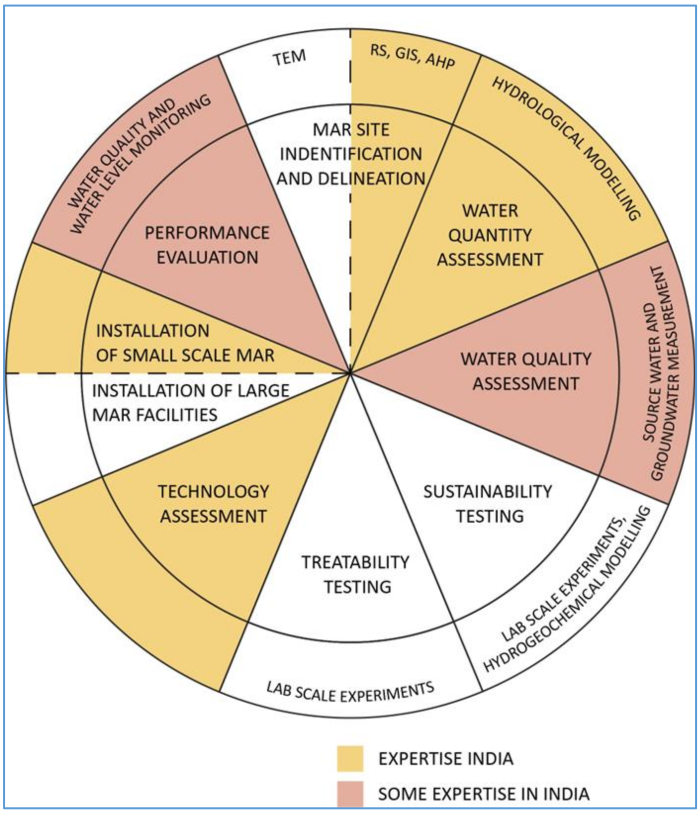

Figure 16. Expertise on different aspects of MAR in India based on the scientific literature.

There is a lot of experience on installing and operating small-scale MAR facilities, but if the ambitions reflected in the CGWB master plan from 2020 should be fulfilled, there is a need for achieving more expertise on establishing and management of larger MAR plants and also to improve feasibility practices in terms of higher degree of pre-investigations to ensure sustainability of such plants. There will still be a major focus on smaller schemes, but with time the MAR structures will probably develop in the same direction as in the rest of the world with more digitalised and automated high-tech MAR technologies.

In Table 3, a comparison of the main characteristics on MAR practices between India and the rest of the world is shown. The table shows that the main characteristics in India in many ways are quite different from the rest of the world. An explanation of this observation could be, that there has been a much longer tradition for MAR in India, and that the development hare has been rooted in the countryside with very little cooperation with other countries – maybe except for Australia. The country which is most similar to India in terms of technologies and focus areas is South Africa.

Table 3. Differences in some basic characteristics of MAR between India and the rest of the world.

		India	Europe				USA	Australia	South Africa
			Spain	Germany	France	The Netherlands			
Purpose	Irrigation	+++	+++	++	+++	+++	+++	+++	++
	Domestic supply	++	+++	+++	+++	+++	++	+++	++
	Saltwater intrusion	+	++	+	+	++	+	+	+
Techno-logies	Large facilities	+	+++	+++	+++	+++	+++	+++	++
	Small scale MAR	+++						+	+++
Focus areas	Water quantity	+++	+++	++	++	++	+++	+++	+++
	Water quality	+	++	+++	+++	+++	++	++	+
	Sustainability		+	+	++	++	+	++	+

7. Selected institutions involved in MAR projects in India

Below, a number of institutions and/or professional contacts with expertise in various aspects of MAR is listed. The list is composed based on the current literature survey, and thus there might be some experts, who are not in the list.

Anna University, Department of Geology, Chennai, (L. Elango, Professor)

Central Groundwater Board, Chennai (Dr. N. Ramesh Kumar, Scientist-D)

CSIR-National Geophysical Research Institute, Hyderabad (Dr. Prakash Kumar, Director)

Indian Institute of Technology, Department of Earth Sciences, Roorkee 247667 (Dr. Basant Yadav, Ass. Professor)

International Water Management Institute (IWMI), New Delhi 110012 (Dr. Alok Sikka, Senior fellow, country representative, Dr. Paul Pavelic, Senior Hydrogeologist)

Jadavpur University, School of Water Resources Engineering, Kolkata, India, (Dr. Subhasish Das, Assistant Professor)

Shiv Nadar Institution of Eminence, Faculty at School of Humanities and Social Sciences (Himanshu Kulkarni, Professor of Practice)

Unnat Bharat Abhiyan (Dr. Pradeep Singh, Project director)

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