Implementation of managed aquifer recharge techniques in India

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Rapid rise in population and urbanization have caused excessive groundwater exploitation which is a major concern. Therefore, technologies to replenish the groundwater are necessary for its conservation and sustainable development. Storage of freshwater in shallow aquifers using different techniques has become the practice worldwide to restore the depleting groundwater and improve water quality. This article addresses the implementation of managed aquifer recharge (MAR) in six zones of India, viz. North, South, East, West, Central and North East along with a brief scenario of the geologies of these zones. The prevalence of percolation tanks, check dams, recharge shafts and rainwater harvesting methods is found to be feasible and beneficial in most parts of India due to their efficiency and easy application. The adversities of MAR like clogging of porous media are also highlighted along with their mitigation strategies.

Keywords: Check dams, managed aquifer recharge, recharge shafts, rooftop rainwater harvesting, percolation tanks.

MANAGING freshwater resources worldwide has become critical in recent years. Due to rising population, improvement of living standards and industrial activities, there is a constant rise in the demand for water. Moreover, due to climate change and unpredictable rainfall scenarios, a large part of the world is already facing a strain from water shortage and periods of extended drought. Groundwater is the primary source of freshwater for drinking and irrigation in many parts of the world, including India[1], and its depletion is recognized as a global phenomenon[2]. Groundwater fulfils the demand of nearly 2 billion people worldwide and more than 40% of it is utilized for irrigation[2]. Therefore, monitoring and conserving the groundwater has become imperative and of utmost necessity. The principal objective of water conservation is to capture and store excess freshwater and extract it when supply is scarce and/or demand is high.

An aquifer offers a huge reservoir space for conveying and storing excess freshwater for a long span of time. The recharge of aquifers can be subdivided into three categories: unintentional, unmanaged and managed. Instances of unintentional recharge include clearing of deep-rooted vegetation or mechanical agitation of soil for crop production, spate irrigation and irrigation techniques which cause seepage and infiltration of water underground. Unmanaged recharge of groundwater includes infiltration through drainage wells, septic tanks, leach fields, and various mining and industrial wastewater disposal activities. These practices are extremely harmful since the water is untreated, which may lead to groundwater pollution. The pollutants can even be carcinogenic and thus can affect human health if consumed. Managed aquifer recharge (MAR) on the other hand, is the purposeful recharge of water to subsurface porous media or aquifers for subsequent recovery to meet water demands and provide environmental benefits. MAR as a technique has been in practice worldwide for several decades. In 1960, one of the oldest MAR projects was practised in Berlin, Germany. Three infiltration ponds of area 8700 m^2 and 3 m depth were used to meet the growing demand for drinking water supply near Lake Tegel area in Berlin. The infiltration rate at the beginning of the operation cycle was recorded to be 3 m/day, which eventually reduced to 0.3 m/day owing to clogging[3]. Similarly, in 1969, in Orange County, California, USA, percolation tanks and extraction wells were used to improve water quality. The primary objective was to prevent intrusion of saltwater by creating a hydraulic barrier by injection of freshwater. The river water was desilted and recharged into the aquifer through percolation tanks. Few additional recovery wells, 3 km away from the coast were used to pump out the saline/brackish water and return it to the ocean. Twenty-three recharge wells were placed further inland for injecting freshwater and 25 wells were available for monitoring water quality[3]. In recent times, effluents released from wastewater treatment plants are being used as the aquifer recharge source, where pollutants present in the wastewater (nitrogen and organic pollutants) are removed by biodegradation and sorption[4]. In Andarmadam, Tamil Nadu, India, recharge shaft in combination with a percolation tank is being used as a method of MAR to improve water quality in the coastal aquifer[5].

Need of MAR in India

Rapid urbanization, industrialization and growth in agriculture have caused a significant increase in water

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demand in India[6]. The country possesses 16% of the world's total population but only 4% of the world's freshwater resources. Here, the groundwater demand for the industrial, domestic and agricultural sectors is approximately 2%, 9% and 89% respectively[7]. Introduction of high-yielding crop varieties and use of fertilizers have enhanced the overall agricultural production in India[8]. For instance, in the last four decades, the net irrigated area through groundwater has been increased roughly by 84%. The North Indian states like Punjab and Haryana account for maximum use of groundwater in agriculture[7]. Therefore, technologies must be implemented to restore the groundwater quantity and improve its quality. Figure 1 shows the exploitation of groundwater in various parts of India. We can observe the overexploited and critical zones to be maximum in the Northwest region due to rainwater scarcity and agriculture. Using data from NASA Gravity Recovery and Climate Experiment (GRACE) satellites Rodell *et al.*[1] estimated that over Punjab, Haryana, Rajasthan and the national capital Delhi, the groundwater level is depleting at an annual average of 4.0 ± 1.0 cm, accounting for a total depletion of $17.7 \pm 4.5\ km^3$ of water in a year. In recent times, India has emerged as a global leader in artificial recharge contributing to 4 km^3/yr of water restoration, and 85 km^3/yr of surplus run-off has been identified to further boost groundwater recharge technologies[9]. The Government of India also initiated various funding schemes like the Central Sector Scheme and Rural Employment Guarantee Programme to finance the construction of MAR structures[10]. Nearly INR 791,780 million has been allotted for artificially recharging an area of approximately 941,541 km^2 in the country[11].

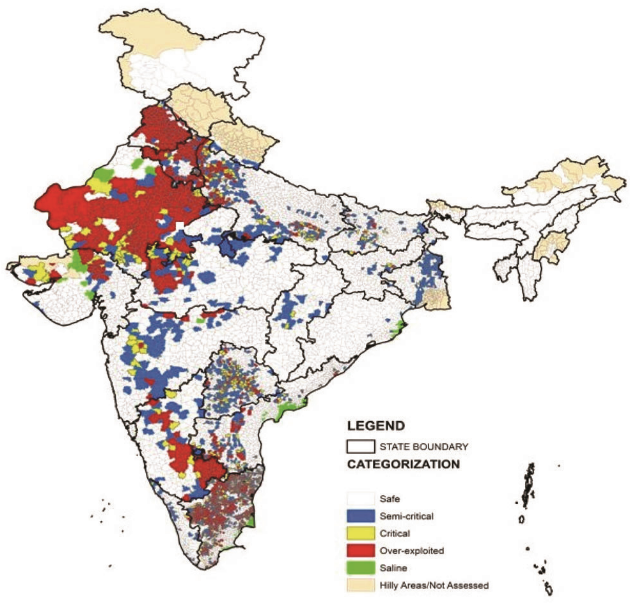

Figure 1. Groundwater exploitation scenario in India[28].

Ancient and modern artificial recharge practices in India

In ancient India, several efforts were made for rainwater harvesting. In the Trans and western Himalayan regions of Jammu and Kashmir, small tanks/ponds or surface channels for collecting or diverting melted glacial water and natural flowing streams were used[12]. In the Eastern Himalayan region, the slopes of the valleys were bifurcated by constructing earthen dams for the collection of rainwater. In the North East region, pond-like structures were used to collect the surface run-off, or small channels/bamboo pipes to divert the run-off into agricultural lands[13]. In the Indo-Gangetic plains, square or circular reservoir or step wells were constructed for the collection of rainwater. Covered underground circular wells or kunds, which had saucer-shaped catchment areas, were popular in Rajasthan. The Bundelkhand region and some parts of central, western and southern India used man-made lakes, check dams and percolation tanks to store water. The eastern part of the country mainly used strong earthen embankments which were curved at either ends and were built across a drainage line. South India witnessed the construction of small lake-like structures and check dams. Underground canals were also used here for connecting groundwater and surface water bodies. In 2015, the global reported MAR capacity of India was 30.9%, which is the highest percentage in the world even though only five states were documented, namely Andhra Pradesh (including Telangana), Gujarat, Jharkhand, Karnataka and Uttarakhand[14]. The contemporary artificial recharge methods can be segregated into four main categories: infiltration, direct injection, filtration and rooftop rainwater harvesting.

Infiltration method

This method uses infiltration basins (ponds or tanks) to facilitate percolation of water into the aquifer naturally. This is the most cost-effective method, and is easy to implement and maintain. Table 1 presents the various infiltration methods used in India. All these methods enable passing of water through the unsaturated zone, thus causing natural purification of water and elimination of inorganic and organic contaminants as well as harmful pathogens.

Direct injection method

This method includes aquifer storage and recovery (ASR) and aquifer storage, transfer and recovery (ASTR). ASR is a technique which involves conveying surplus freshwater into a suitable aquifer which is required to be stored for a certain period of time and recovered in future to cater the demand of agricultural, industrial, urban,

Table 1. Different methods of infiltration and their features

Infiltration methods	General features and advantages
Surface spreading and percolation tanks	• Surface spreading is an artificial recharge technique which is performed by dispersing water over an area for a certain period of time such that the entire water percolates and recharges the groundwater. • It is suitable for unconfined aquifers where there are no impervious layers and the topsoil is porous. • Percolation tanks are small water-harvesting structures constructed across a natural stream to store rainwater. • The rainwater is retained for a longer time and thus facilitates natural percolation. • The tanks should be ideally constructed on highly fractured or weathered rocks to accelerate the infiltration process. • They facilitate recharge into the surrounding ground which in turn enhances soil moisture, improves agricultural productivity and prevents drought.
Recharge pits and recharge shafts	• Recharge pits are constructed in various shapes: circular, rectangular or square provided with stone or masonry wall with weep holes at regular intervals. • The pits may be furnished with perforated covers. • The dimensions of the pits are selected on the basis of rainfall intensity, recharge rate of soil and the catchment area. • Generally a pit can be 2–3 m deep and 1–2 m wide depending on the depth of the pervious strata. • Recharge shafts are provided where the topsoil is alluvial or less permeable. These are bored holes of 10–15 m depth and 30 cm diameter. The depth of the holes depends on the depth of the pervious layer. The bores must be lined with slotted/perforated PVC/MS pipes for preventing collapse of the vertical sides.
Drainage trenches	• These are constructed where the top impermeable layer of the soil is shallow. • The trenches are drilled into the ground and packed with porous media like boulders or pebbles. • These are usually built for conservation of the surface run-off. • The depth and size of a recharge trench vary from 1.0 to 1.5 m and 0.50 to 1.0 m respectively, depending on the quantity of the expected run-off. • This technique is suitable for small houses, parks, roadside drains and playgrounds.

emergency and other water uses[15,16]. ASTR implies injection of water in one well and recovery by pumping from a second well located several hundred metres down-gradient from the injection well. The injected water is thus transported through the aquifer before being abstracted. This process requires the aquifer be of relatively good quality as the abstracted water is mainly used for drinking. Table 2 shows the various ASR methods which are most prevalent in India.

Filtration methods

These include riverbank filtration and dune filtration. Riverbank infiltration involves construction of a number of wells parallel to or near the river. The pumping action in the wells lowers the water table, creating a difference in head between the groundwater and the river which draws the surface water through the riverbank. The basic aim of this technology is to use the geo-purifying capacity of the riverbank to filter and purify the recharged water. Dune filtration involves infiltration of water from ponds constructed in dunes. The water is then extracted from wells or ponds at lower elevation. For example, in the city of Nainital, Uttarakhand, India, nine vertical filter wells have been installed in less than 100 m vicinity from Nainital Lake of depth 26.6–31.7 m for riverbank filtration, from which around 24,000 m^3/d water is extracted[17].

Rooftop rainwater harvesting

This method is common in India. In this system, the roof becomes the catchment for capturing the rainwater which is later diverted for storage in a tank or an artificial recharge system. This process is effective in urban areas where there is scarcity of land. Rainwater is safe from pathogens, free from organic matter, soft in nature and therefore it can be stored easily for future use. Figure 2 shows the schematic of different MAR techniques.

Zone-wise study of MAR techniques in India

This section highlights the geological diversities of different states in India and the feasibility of MAR structures. The country has been subdivided into six zones: North, South, East, West, Central and North East, and different MAR structures are discussed for each zone.

MAR in the North Zone

The North Zone comprises Punjab, Haryana, Uttarakhand, Uttar Pradesh and Himachal Pradesh[18], where groundwater depletion is highest due to extensive agriculture and thus artificial recharge is essential here. Punjab is highly dominated by paddy/wheat monoculture leading

Table 2. Different ASR methods and their features

ASR methods	General features and advantages
Check dams	• Check dams are small, permanent or temporary dams constructed across a stream, channel, gully or drainage line to reduce the velocity of flows for certain design storm events. • They are constructed from logs of wood, stone, bricks and cement. • They are beneficial in soil moisture restoration, thus helping in crop production. • They also reduce soil erosion and sediment transport, and help in the recharge of shallow wells.
Contour bunding	• Contour bunding is the construction of narrow-based trapezoidal embankments (bunds) along contours to confine water behind them, which then percolates into the soil resulting in groundwater replenishment. This is provided in areas where rainfall is scanty and sloping agricultural lands are available. • The soil must be permeable and the slopes must be long for its better implementation. • This method helps prevent soil erosion and increase water infiltration.
Dug wells	• Dug wells are constructed by digging bore holes of desired diameter and depth with hand or by mechanical power. • The bore holes may be shored, lined or cased depending on the depth. • The wells are used where water from the canal or excess water can be diverted to recharge the aquifer. To avoid entrapment of bubbles in the aquifer, the recharged water should be transported by pipes to the bottom of these wells.
Gully plugs	• Gully plugs are structures which are built across small gullies and streams to conserve run-off and enhance aquifer recharge. • They are built using local stone, clay and bushes along the hill slopes. They are beneficial in conservation of soil moisture and help prevent soil erosion.
Injection wells	• Injection wells are constructed for subsurface groundwater recharge, where the water is directly injected into the deep aquifers. • They are preferred in areas where a thick impermeable layer exists between the soil surface and the target aquifer which is required to be replenished. • They are also beneficial in areas where the availability of land is scarce.
Bench terraces	• Bench terraces are constructed by cutting and filling to construct a sequence of level steps or benches. • This is a soil and water conservation technique used on sloping land to retain water and control erosion. • They allow water to percolate slowly into the soil, thus causing groundwater replenishment. • Bench terraces are supported by retaining banks of soil or stone on the forward edges.
Groundwater dams	• Groundwater dams are structures that hinder the natural flow of groundwater to provide storage of water underground. • The fundamental principle of a groundwater dam is storage of water underground instead of surface reservoirs and thus preventing evaporation losses. • Further, the risk of contamination of the stored water is decreased because microorganisms contaminating surface water cannot breed in the groundwater. • The problem of land inundation normally associated with surface dams is absent with subsurface dams.

to overexploitation of groundwater. In 2015, out of 20 million tube wells in India, almost 1.3 million were in Punjab contributing to rapid groundwater depletion[12].

Recharge shafts are mainly used in North India as they acquire smaller lands and have practically no evaporation losses. They are simple to construct and even unused dug wells can be converted into recharge shafts. Check dams are also abundantly used in this zone. We observed the construction of recharge shafts and check dams of recharge capacity 0.015 and 0.04 MCM in Punjab and Haryana respectively (Figure 3)[13]. Uttar Pradesh is characterized by vast alluvial fill of the middle Ganga drainage system, whereas the southern part is dominated by rocky upland. In this state, diverse MAR structures like percolation tanks, nala bunds/check dams/cement plugs and recharge shafts/dug wells/tube wells for aquifer recharge are used. Nala bunds or cement plugs are embankments built across large streams and provided in areas having gentle slopes. They are temporary structures constructed with locally available materials like stone, brick, cement, etc. The primary objective is to capture the surface run-off, allowing water percolation into the substrata and enhancing soil moisture conditions. In the district of Agra, Uttar Pradesh, we observed the use of 83 percolation tanks, 2179 nala bunds/check dams/cement plugs and 1361 recharge shafts/dug wells and tube wells[13]. In Himachal Pradesh, the major source of recharge is from rainwater harvesting. The geology of the state can be divided into valley fills, semi-consolidated Siwalik low hill ranges and igneous, crystalline high hill ranges. In the valley fills, construction of check dams cum subsurface dykes is feasible whereas in the low and high hill ranges, gabion structures are more prevalent. Gabion structure is a type of check dam which is constructed across a small stream. Boulders are assembled in a mesh of steel wires and anchored to the stream banks. These are useful for retaining surface water run-off for a considerable amount of time, resulting in groundwater recharge.

MAR in the South Zone

The South Zone consists of Andhra Pradesh, Telangana, Karnataka, Kerala, Maharashtra, Goa and Tamil Nadu. We observed the abundance of percolation tanks and check dams in all the states of South India, where rocks are predominantly weathered and fractured (Figure 4). Andhra Pradesh consists of igneous, sedimentary and metamorphic formations. Precambrian sedimentary formations are found in the districts of Kadapa, Anantapur and Chittoor, whereas Deccan Traps are found in the East and West Godavari districts. Tertiary formations are found in the East and West Godavari and Visakhapatnam districts, whereas alluvium deposits are found in river valleys, deltas and along the east coast. The geology of Telangana can be broadly subdivided into two physiographic units, namely Gondwana Graben and the Deccan Plateau forming a wide expanse of flat to low-undulatory terrain of plains and small hills[11]. In Karnataka, we observed the use of subsurface dykes or underground dams to curb siltation and evaporation losses. Geologically, Kerala can be distinguished into hard rock and alluvial regions. Apart from the common MAR structures, we observed the construction of gully plugs, nala bunds, subsurface dykes and contour bunds in this state. The entire region of Maharashtra forms a part of the ‘Peninsular shield’, which consists of rocks from diverse origins that have undergone considerable metamorphism. More than 80% of the area of the state falls under the Deccan Trap region which has concealed geologically older formations. In the districts of Nasik and Pune, the gross storage capacity of percolation tanks is 200 TCM, of check dams is 30 TCM and of recharge shafts is 60 TCM respectively[13] (Figure 4). Goa situated on the western coast of India has porous lateritic aquifers and the groundwater gets discharged quickly due to steep hydraulic gradient leading to water scarcity in summer. In this state, we observed the feasibility of bhandaras and vented dams, which allow the run-off to escape during heavy rainfall and arrest the non-monsoon run-off. Bhandaras are basically check dams built across a river provided with canals for carrying water into agricultural fields. Rooftop harvesting of rainwater is also common due to heavy rainfall in this state. In Tamil Nadu, crystalline rocks of Archean era dominate about 73.52% of the total area, whereas sedimentary rocks cover only 26.48% along the east coast. Recharge tube wells, recharge trenches, farm ponds/recharge pits are predominant along with the common MAR structures owing to diverse climatic, physiographic and hydrogeological conditions. The farm ponds are small tanks or reservoirs which are constructed for storing the surface run-off generated from the catchment area.

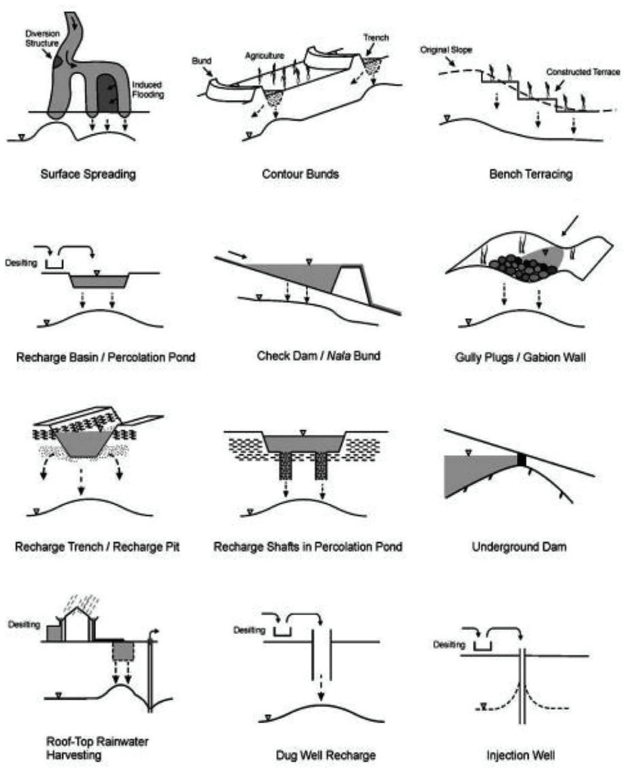

Figure 2. Most common MAR practices in India[29].

MAR in the East Zone

The East Zone consists of West Bengal, Sikkim, Odisha, Jharkhand and Bihar. Bihar can be categorized into hard rock areas of Jamui district and marginal alluvial region of Gaya district respectively[18]. In both Bihar and Jharkhand we observed the construction of nala bunds in the hard-rock areas along with common MAR structures (Figure 5 *b*). In these states, priority has been given to the renovation of old contour bundings or ahar systems. Ahar is a traditional irrigation system consisting of reservoirs with embankments on three sides commonly used by the local farmers. The hydrology, hydrogeology and physiography control the feasibility of MAR structures constructed in Odisha. In the hilly regions and highland areas, we observed the construction of nala bunds in abundance. West Bengal is sub-categorized into two broad segments: soft/alluvial and hard-rock areas respectively. In hard-rock areas, the capacity of percolation tanks, check dams, gabion structures/contour bunds, subsurface dykes and dug well recharge/recharge shafts is 0.5, 0.05, 0.005, 0.01 and 0.05 MCM respectively (Figure 5 *a*), whereas in the alluvial areas the capacity of percolation tanks, re-excavation of existing tanks with recharge shafts and injection wells is 0.01 and 0.3 MCM respectively[18]. River Teesta flows through most parts of Sikkim and has an annual rainfall of about 2500 mm, but there is still scarcity of water in the rain-shadow regions of East, West and South Sikkim during the lean periods. Even though no significant development of groundwater recharge has

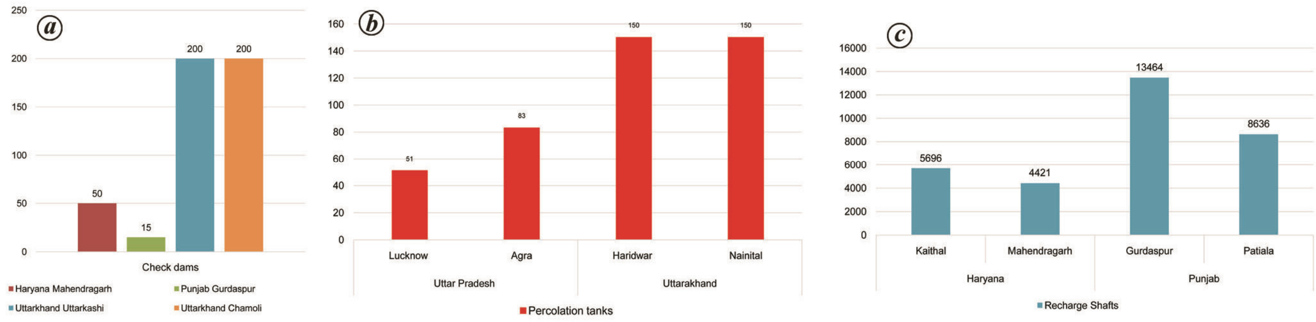

Figure 3. ***a***, Total number of check dams in some districts of Punjab, Haryana and Uttarakhand. ***b***, Total number of percolation tanks in some districts of Uttar Pradesh. ***c***, Total number of recharge shafts in some districts of Punjab and Haryana (all data collected from ref. 13).

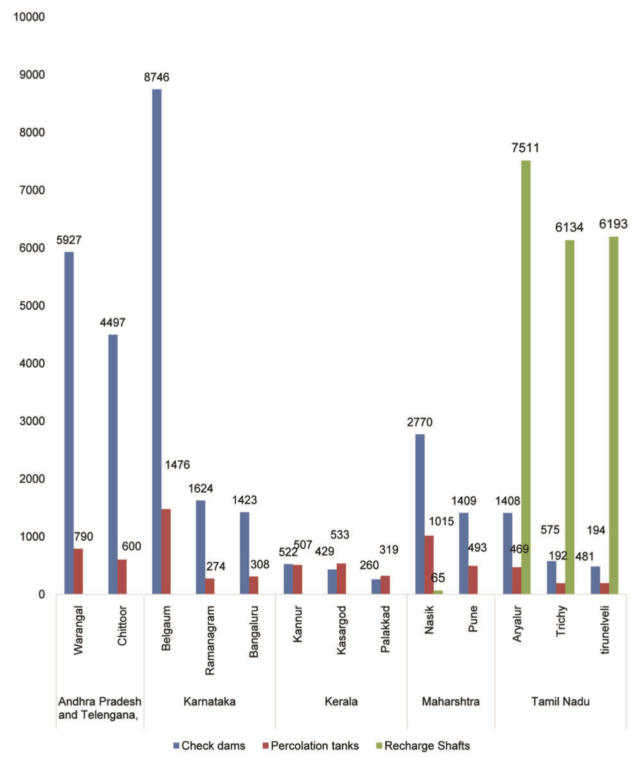

Figure 4. Total number of common MAR structures in various districts of states in the South Zone[13].

been observed, there is a huge potential for spring augmentation through the establishment of gabions, contour trenches, nala bunds, slope terracing, etc. Rooftop rainwater harvesting has a huge potential in this state as well.

MAR in the West Zone

The West Zone comprises Rajasthan and Gujarat, and accounts for the maximum water scarcity zone in India. Rajasthan is subdivided into 14 river basins which spread to the northern, eastern and southern river catchments. Luni is the only river originating from the west of the Aravallis and in the remaining western region of the state, internal drainage is predominant which culminates into the desert sand after flowing for a short distance. In several districts, anicuts which are dams built on a stream for maintaining and regulating irrigation are used along with percolation tanks. In the districts of Chittorgarh, Jhalawar and Jaipur, we observed the construction of around 700 percolation tanks, 185 anicuts (Figure 6 *a*), and 1130 recharge shafts of 0.02, 0.01 and 0.03 MCM recharge capacity respectively[13] (Figure 6 *a*). Aquifer storage and artificial recharge is an integral part of the water conservation technique in Gujarat, since it is a drought-prone area and frequently faces sharp decline in the groundwater table. The aquifers can be broadly classified into three hydrogeological units – consolidated rock units of igneous and meta-sediments, unconsolidated alluvial deposits and semi-consolidated units of other sedimentary rocks. Weirs/check dams are mostly feasible in the hard-rock areas with moderate relief and in semi-consolidated formation, whereas percolation tanks are more appropriate in plateau and plain areas that are occupied by hard rock and alluvium. In the district of Ahmedabad, we observed the construction of around 476 percolation tanks of capacity 0.14 MCM and 1746 check dams of capacity 0.05 MCM (Figure 6 *b*)[13].

MAR in the Central Zone

The Central Zone consists of Madhya Pradesh and Chhattisgarh. The geographical area of Madhya Pradesh can be subdivided broadly into alluvial and hard rock regions[18]. In both regions, the most familiar MAR structures are prevalent (Figure 7). Additionally, structures like gabion and contour trenches may be implemented accordingly for soil and moisture conservation. It is estimated that rooftop rainwater harvesting may be adopted as a MAR technique in approximately 6 lakh houses, institutions, etc. in municipal and urban areas of the state. The most feasible MAR structures in the upper parts of the watershed areas in Chhattisgarh are contour bunds, gully plugs and gabions. Percolation tanks and nala bunds are effective in the run-off zones, whereas in the downstream areas gravity head wells and recharge shafts can be efficiently implemented. Percolation tanks of filling capacity 0.1525 MCM are found in most parts of Chhattisgarh for utilizing surplus monsoon rainfall effectively. Nala bunds of average capacity 0.457 MCM can effectively be constructed in various second-order streams for storing 25% of the monsoon run-off[13]. From Figure 7, it is clearly evident that the Central Zone is predominated by the widely accepted MAR structures.

MAR in the North East Zone

The North East States of India are Manipur, Assam, Mizoram, Meghalaya, Arunachal Pradesh, Nagaland and Tripura. This zone comprises hilly topography and the enormous alluvial plains of Barak and Brahmaputra rivers in Assam. Small intermundane valleys are dispersed across the other states of this zone[18]. Even though Mawsynram near Cherrapunji, Meghalaya records the world's highest rainfall, various segments of the zone succumb to acute shortage of drinking water, especially during the arid periods. Considering the physiography, rainfall and hydrogeology check dams, weirs and gabion structures are feasible in this zone (Figure 8). Rooftop rainwater harvesting is highly beneficial along with development of springs for delivering safe drinking water to the village areas. Figure 8 depicts the total number of MAR structures dispersed throughout the entire topography in this zone. There are approximately 2640 check dams, 6100 gabion structures and 5100 weirs in the NE zone.

Cost allocation for MAR structures

The Central Groundwater Board of India has developed a plan to implement area-specific artificial recharge techniques depending on the type of aquifer, geology and source water availability. Table 3 shows the total cost allocated to each state in each zone for the construction and development of MAR structures depending on the geographical area and the regions feasible for artificial recharge.

Problems associated with MAR and techniques to resolve them

MAR techniques may prove to be crucial for groundwater replenishment, especially in arid and semi-arid regions. However, they have certain disadvantages. The primary disadvantage of MAR includes relatively large land area requirement. This problem can be solved by simply using recharge shafts and underground dams/reservoirs for

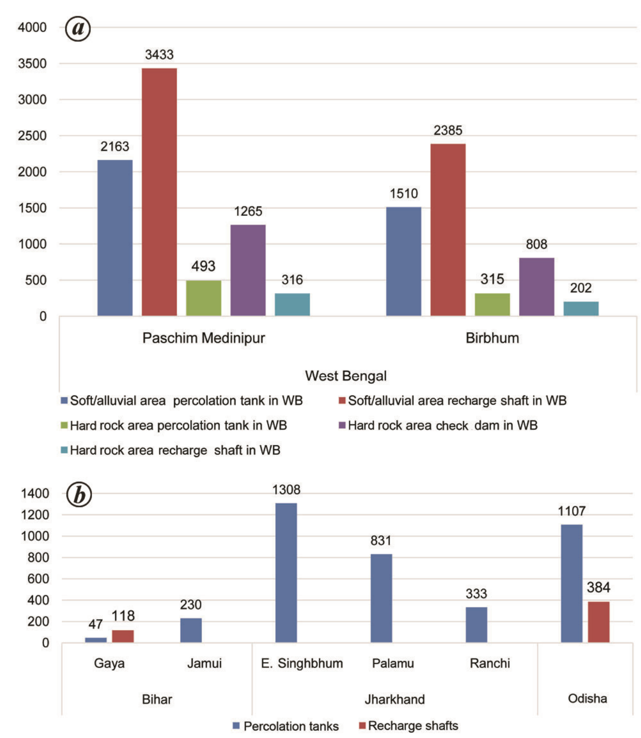

Figure 5. ***a***, Number of recharge shafts, percolation tanks and check dams in hard-rock areas and soft/alluvial areas of West Bengal. ***b***, Familiar MAR structures in Bihar, Jharkhand and Odisha[13].

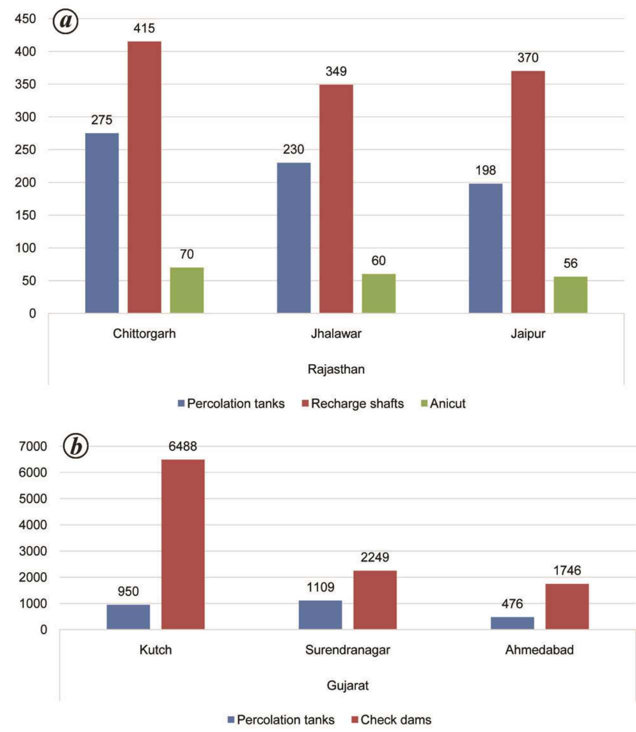

Figure 6. ***a***, Number of percolation tanks, recharge shafts and check dams in some districts of Rajasthan in the western region[13]. ***b***, Number of percolation tanks, recharge shafts and check dams in some districts of Gujarat[13].

Table 3. Zone-wise cost allocation of MAR structures

States	Geographical area (km^2)	Area suitable for recharge (km^2)	Total allotted cost of the structures (INR in crores)
North Zone			
Punjab	50,362	43,340	3671.47
Haryana	44,212	37,029	2930.30
Uttar Pradesh	240,928	110,783	9597.28
Uttarakhand	53,483	13,542	483
Himachal Pradesh	55,673	2500	655.47
Total	444,658	207,194	17,337.52
South Zone			
Andhra Pradesh and Telangana	275,068	43,743	3933.15
Karnataka	191,791	74,007	3146.66
Kerala	38,863	10,849	5914.47
Maharashtra	307,713	130,011	10,692.09
Goa	3702	2027	99.98
Tamil Nadu	130,058	68,839	9284.63
Total	947,195	329,476	33,070.98
East Zone		Geographical area (sq.km)	
West Bengal	88,752	36730.4	3972.06
Sikkim	7096	500	67.33
Odisha	155,707	5339	1024.50
Jharkhand	79,714	7864	2023.34
Bihar	94,163	760.3	292.81
Total	425,432	51,193.7	7380.04
West Zone			
Rajasthan	342,239	160,589	2386.07
Gujarat	196,024	19,407	1494.00
Total	538,263	179,996	3880.07
Central Zone			
Madhya Pradesh	308,144	119,409	11,701.60
Chhattisgarh	136,034	22,401.4	2165.21
Total	444,178	141,810.4	13,866.81
North East Zone			
Manipur, Assam, Mizoram, Meghalaya, Arunachal Pradesh, Nagaland and Tripura	255,083	25,508	1421.90
Total	255,083	25,508	1421.90

water recharge. Rooftop rainwater harvesting can be a major boon in MAR, where no excess land is required. Several factors like precipitation, aquifer thickness, hydraulic conductivity, hydraulic gradient and aquifer anisotropy need to be estimated before construction of a MAR structure[19]. Previously, test drillings, stratigraphy analyses, on-site field studies and statistical methods (logistic regression, frequency ratio, etc.) were some of the time-consuming and tedious techniques used for identifying locations suitable for the construction of MAR structures and accessing their recharge efficiencies[20]. In recent times, multicriteria decision analysis (MCDA) combined with geographical information systems is used for site feasibility assessment. The analytical hierarchy process is applied to allow consistency check in MCDA, which reduces bias in the decision-making process[21].

Evaporation losses of water in surface spreading pose a disadvantage. Silting is also a persistent problem associated with MAR, especially for check dams and percolation tanks. Deposition of silt and growth of vegetation in MAR structures can significantly decrease the infiltration capacity of the soil[22]. Mitigation of this adversity requires pre-treatment of water through sand filters, sedimentation tanks or metal screens.

Another major issue of MAR is the clogging of recharge systems which can be grouped into three categories: physical, chemical and biological. Physical clogging results from the accumulation of microorganisms and algae cells, silt and clay particles in the source water[23]. Certain fine particles detach from the respective soils in aquifers, and tend to accumulate and move downwards resulting in this type of clogging. Therefore, even though source water with low suspended solids is injected into the aquifer, the silt and clay particles present in receiving aquifers may be disoriented causing physical clogging. The biological clogging includes the growth of microorganisms and agglomeration of biomass like polysaccharides and other metabolic products[24]. Biofilms are predominantly composed of microbial cells and extracellular polymeric substances. Chemical clogging happens due to the precipitation of phosphates, calcium carbonates, sulphates and other minerals[25]. Clogging can be reduced by reduction in the concentration of the contaminants responsible for it. First, screening of oily matter, suspended particles, debris, litter and aquatic life is required, followed by sedimentation in order to allow the suspended particles to descend by using dams, sedimentation basins and aqueduct systems. For better controlling of physical clogging in the injection wells, sedimentation and filtration sand beds must be used simultaneously. Several bio-filtration methods may be implemented for effective removal of organic carbon and other nutrients (phosphorus and nitrogen) from the contaminated water which will result in the reduction of algal growth and other forms of biological clogging. Filtration process using granular activated carbon which has considerable affinity for both inorganic nutrients and organic carbon can also be effective in reducing the biological clogging.

Groundwater pollution is also a major shortcoming of MAR which happens due to the application of contaminated water and aquifer–groundwater interactions[26]. Therefore, the injected water must be properly pre-treated and water quality parameters must be within permissible limits before using it for recharge. However, in India the benefits of MAR are not distributed evenly in all the communities, especially the people without lands of their own[27]. Therefore, rooftop rainwater harvesting can be a more feasible method for MAR in the country owing to no land requirement and better water quality.

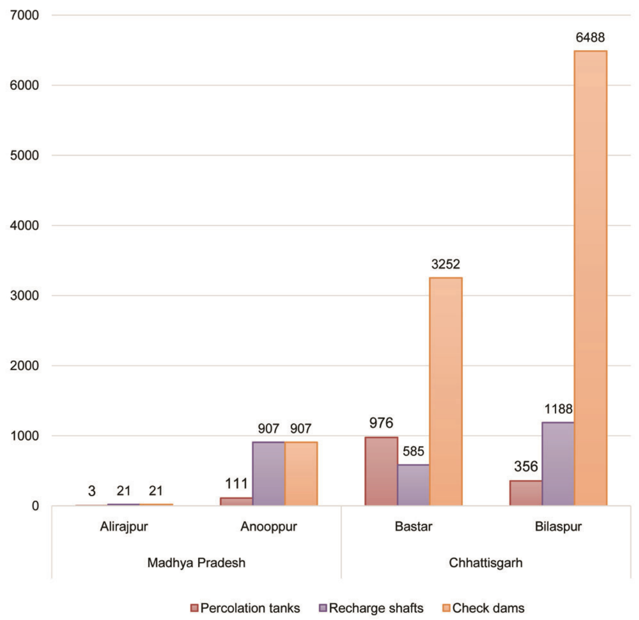

Figure 7. Total number of percolation tanks, recharge shafts and check dams in some districts of Madhya Pradesh and Chhattisgarh in the western region[13].

Figure 8. Total number of check dams, weirs and gabion structures in the North East Region[13].

Conclusion and future scope

In the contemporary era, factors like population growth, concentration in urban areas, the requirement of increased food production, enhanced industrialization and increase in living standards have all contributed towards groundwater depletion and contamination. Thus, the implementation of MAR, which refers to the techniques that are used to secure, maintain and enhance the groundwater systems has become crucial. Rainwater was used as the primary source in India for several decades, but now with the advent of MAR, even effluents from wastewater are being used to recharge the aquifers. The zone-wise division of India shows the use of percolation tanks, check dams and recharge shafts in most of the states due to their efficiency and diverse benefits. The geology of the area, rainfall patterns and, most importantly, the aquifer characteristics are the primary factors that determine the feasibility of any MAR structure. However, we need to monitor the structures frequently to prevent groundwater contamination, silting and clogging. The structures located on the coastlines need to be checked frequently to monitor salt-water intrusion and soil erosion in the groundwater, especially during monsoon and post-monsoon periods. Water quality analysis needs to be done at regular intervals to meet the environmental and health standards. With proper monitoring and maintenance, purposeful recharge of aquifer can prove to be beneficial for restoration of the depleting groundwater and thus implement sustainable development in an efficient manner.

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