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Groundwater irrigation over the past few decades has improved stability in cropping but resulted in aquifer depletion in semi-arid regions of India. To minimize decline of groundwater levels, Managed Aquifer Recharge (MAR) interventions are widely adopted, supported by local communities, state and central governments. Albeit a desirable intervention, there is overwhelming evidence that many of the MAR structures are excessively designed, poorly located and therefore reflect poor investment of valuable human and financial resources. This paper identifies hydro and hydrogeological factors which dictate the performance of MAR intervention. The influence of annual rainfall, available land and water, river-aquifer interaction, soil, and aquifer types on MAR is discussed.

Water Policy Research

HIGHLIGHT

Hydro, Hydrogeological Constraints to Managed Aquifer Recharge in the Indo Gangetic Plains

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HYDRO, HYDROGEOLOGICAL CONSTRAINTS TO MANAGED AQUIFER RECHARGE IN THE INDO GANGETIC PLAINS[1]

INTRODUCTION

In many parts of India especially in the arid- and semi-arid regions, due to vagaries of monsoon and scarcity of surface water, dependence on groundwater resource has increased tremendously in recent years (Sakthivadivel 2007). While groundwater use over the past few decades has improved stability in cropping, there are increasingly serious issues with aquifer depletion, as groundwater tables are rapidly falling in a number of states (Rodell et al. 2009; Shah 2009). In particular, states of Punjab, Rajasthan and Haryana witness more groundwater withdrawals than net recharge, resulting in groundwater level decline. It has resulted in dry dug wells and low yielding tube wells, especially in summer. The drinking water crisis prevalent in most of the villages in summer imposes serious health hazards to the rural masses and is responsible for the loss of livestock population for the want of drinking water and fodder. Decline in groundwater levels has also led to higher pumping costs, seawater intrusion in coastal aquifer systems and land subsidence in various parts of India.

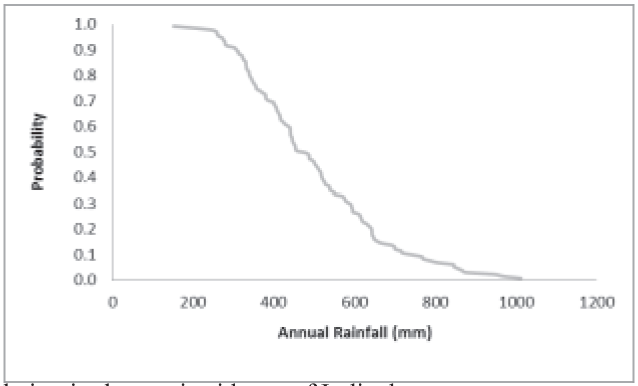
To minimize decline of groundwater levels, Managed Aquifer Recharge (MAR) interventions are widely adopted across India, supported by local communities, state and central governments. MAR is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefits. Fundamentally, surface methods of MAR detain runoff water and increase opportunity time for infiltration.

There is overwhelming evidence that many of the MAR structures are excessively designed, poorly located and therefore reflect poor investment of valuable human and financial resources. In this Highlight, we identify hydro and hydro-geological constraints often overlooked by planners and implementers.

IN SEMI-ARID REGIONS, WATER FOR MAR IS VERY LIMITED

Before proceeding with installation of MAR structures, an analysis of historical rainfall data is necessary. Importance of such analysis is illustrated using 130 years of rainfall data (1871-2000) from Punjab, India. The average rainfall of the State is 500 mm during this period, and it ranged from 150 mm in 1987 to 1012 mm in 1971. Figure 1 shows a probability of annual rainfall in this state. Accordingly, in any year, the probability of receiving 150 mm rainfall is 0.99, but the probability of receiving 1012 mm rainfall is 0.01. The median rainfall of this state is 480 mm, suggesting that at least 50 percent of the time, being in the semi-arid part of India, has an average potential evaporation of over 1800 mm. Under such circumstances, it is highly unlikely that there will be runoff on a regular basis providing the possibility of MAR on an annual basis.

Figure 1 Probability of annual rainfall in Punjab



IN NORTHWESTERN INDIA LAND AND WATER ARE SCARCE FOR MAR

In north-western regions of India where groundwater levels are falling, not only water, but land is also under constraint for installation of MAR structures. We illustrate this constraint using data from Sangrur District, Punjab.

Sangrur lies between 29°- 4' & 30°- 42' North latitude and 75° -18' and 76° -13' East longitude. It is 5024 km^2 in extent, with a population of 551476 of which 432966 (79 percent) belong to rural areas in 2011 (GoI 2011). The average annual rainfall in the district is about 590 mm, about 73 percent, falling between July and September, coinciding with rice growing season. The rainfall in the district increases from south-west towards the north-east

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and varies from about 490 mm, at Sunam, to about 670 mm at Malerkotla. On an average, there are 27 rainy days (i.e. days with rainfall of 2.5 mm or more) in a year in the district. This number varies from about 24 at Sunam to about 31 at Malerkotla (NIC n.d.).

The CGWB (2007a) reported that 4400 km^2 of the district was sown, and area irrigated in both seasons was 8710 km^2, implying that crop production is carried out throughout the year (irrigation and cropping intensity- 198 percent). Major *rabi* crop is wheat, and minor *rabi* crops include barely, gram, oilseeds (*sarson, taramira, alsi and toria*), and winter vegetables (peas, cabbages, cauliflower, turnip, carrot). Major *kharif* crop is rice, but sugarcane, cotton, groundnut, maize, *jowar, bajra,* vegetables (tomato and lady's finger), pulses (*moong, mash, arhar,* and soyabean). Grapes, pears, peach, guava etc. are also grown in small areas in the district (Government of Punjab 1980).

Rainfall and irrigation from canal and groundwater meet evapotranspiration (ET) requirements of these crops. As the climate changes continuously, rainfall remains an unpredictable source of water. Although the average annual rainfall in Sangrur is 590 mm, it has ranged between 121 mm in 2002 and 1012 mm in 1983. The supply of canal water on the other hand is restricted due to existing allocation and irrigation infrastructure constraints. It is groundwater, at its own decline, which has prevented crop failures to ensure prosperity. Groundwater is pumped by over 127200 shallow tube wells, tapping the unconfined aquifers at depth between 30 and 70 m below ground level, and irrigate 4110 km^2 (CGWB 2007a). Deep tube wells tap confined aquifers at depths between 100 and 150 m.

It appears that the potential for net recharge of excess rainfall and irrigation water under irrigated fields is very low. ET requirements and net irrigation requirement (NET) of major crops in an adjacent district of Sangrur, named Moga District, were estimated by Amarasinghe et al. (2010). They estimate that, ET of rice and wheat are 673 and 268 mm, and NET are 268 and 259 mm respectively. Hence the total irrigation requirement is 527 mm. Assuming a specific yield of 0.25 and an average decline in groundwater level of 0.5 m, the net discharge from groundwater per annum is 125 mm. Therefore, of the total ET requirement, contributions from rainfall, canal water and groundwater are 414 mm, 402 mm and 125 mm respectively. This net discharge of 125 mm from groundwater is not available either from rainfall or from canals in the district.

In Sangrur, the total area sown is 4400 km^2, and the total irrigated area was 8710 km^2 (CGWB 2007a). It implies that almost every field had at least two crops within a year, and therefore the chances are that, actual evaporation from these fields would have been greater than the effective rainfall, requiring farmers to irrigate with canal and/or groundwater. If the irrigation water was drawn from groundwater, then it would have resulted in net discharge and lower groundwater levels.

CGWB (2007a) reports that pre-monsoon depth to water levels in the district ranged between 8.77 – 23.89 m, and post-monsoon they ranged between 9.95-24.52 m, indicating a net discharge from the aquifer, even during the monsoon of 2007.

Therefore in an average rainfall year there ought to be a net decline in groundwater level in Sangrur district. This interpretation is supported by CGWB (2007a), which estimated the average annual decline during a ten year period ranged between 0.47 and 0.76 m.

However, there are aspects related to rainfall and land use, which warrant adoption of rain water harvesting and artificial recharge practices in Sangrur district.

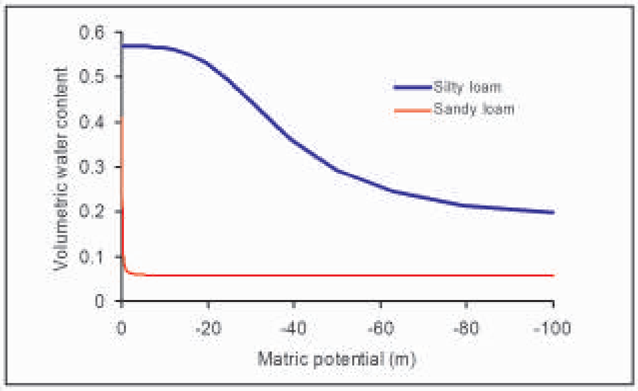
1. Approximately 624 km^2 within the district is not under agriculture. For such partially covered ground catchments, the runoff coefficient ranges from 0.3 for soil surface to 0.9 for roof surfaces (CSE n.d.). Hence rainfall runoff from non-agricultural land may be channeled into local ponds for artificial recharge. Such ponds are generally available in the close vicinity of most villages.
2. Although the average annual rainfall is 590 mm, its annual variation tends to be wide. During recent period, it has ranged between a low 121 mm in 2002 and a high 1012 mm in 1983 (CGWB 2007a) in thirty years prior to 2007. During the 17 year period from 1954 to 1970, the annual rainfall was less than 80 percent of the average in five years, and was between 450 and 750 mm in 10 years (NIC n.d.). This implies that there had been excessively wet years occasionally, resulting in runoff suitable for recharge.
3. Occasionally, the district has experienced rainfall events of very high intensities, capable of resulting in large volumes of runoff, even from irrigated fields. Records show, that in 1976, Barnala block of the district received 377.5 mm within 24 hours (NIC n.d.).
4. Since rice is the major crop during monsoon season when high intensity rainfall is received, raised bunds of the rice fields will minimise runoff and detain water. This will reduce groundwater pumping following high intensity rainfall, and it will also recharge the aquifer.

In summary, it may be concluded that although the land and water for artificial recharge in Sangrur district is very limited, there is some scope to increase recharge to groundwater, which warrants limited interventions at field and village scale.

SOILS ABOVE THE WATER TABLE COULD RETAIN RECHARGING WATER

Following infiltration, water percolates through an unsaturated soil to recharge the water table. Energy gradient facilitates this process. The relationship between water content and energy status is unique for each soil as

Figure 2 Soil moisture characteristic curves of silty loam and sandy loam



Source: Schaap et al. 2001.

it depends on texture, particle size distribution, aggregation, and pore size distribution. This unique relationship is called the Soil Moisture Characteristic, or Water Release Curve (Figure 2), and expresses the matric potential energy as a function of volume water content. The curve illustrates that for the soil types considered, at -20 m suction, a silty loam profile of 1 m could hold 50 cm of water, while at the same suction, a sandy loam soil profile of 1 m could hold only 0.05 cm. Hence if a MAR structure is installed on top of a silty loam profile, recharge to groundwater will be low because percolating water will be retained by the profile. On the other hand, if the MAR is installed on top of a sandy loam profile, most of the percolating water will reach the water table.

IN THE EASTERN GANGETIC PLAINS RIVER-AQUIFER INTERACTION LIMIT SCOPE FOR MAR

District Vaishali lies between 25°- 28' and 26°- 5' North latitude and 85° -5' and 85° -40' East longitude (Figure 2). It has two sub-basins, namely, Gundak and Burhi Gandak. Gandak river flows in south-easterly direction, and forms the western boundary of the district. It disgorges into River Ganga near Hajipur. In addition, Gandaki and Baya rivers which flow parallel to Gandak river, also flow into River Ganga. This extensive presence of river activity indicates the possibility of them behaving as surface drains during monsoon, and subsurface drains when intersecting groundwater during remainder of the year. Hydro and hydrogeological responses are monitored by seven Hydrograph Network Station and seven piezometers within the District (CGWB 2007b).

The district is 2015 km^2 in extent with a population of 3495249 in 2011 of which 3262715 (93.3 percent) belong to rural areas and 232534 (6.7 percent) in urban areas (GoI 2011). Approximately 1219 km^2 was sown at least once and 731 km^2 was sown more than once. 19.8 km^2 is identified as uncultivable land, and 393 km^2 is identified as cultivable waste. The district has approximately 90.4 km^2, which remain permanently waterlogged. Remaining land is not available for cultivation or used for grazing animals (CGWB 2007b).

Major crops in this district are paddy, maize, wheat, vegetables, tobacco and oil crops (CGWB 2007b). The average annual rainfall in the district is 1168 mm, about 85 percent, falling between mid-June and September, during south-west monsoon region (CGWB 2007b). During the dry period, canal water and groundwater are used to irrigate these crops.

The district is underlain with high yielding unconfined and confined aquifers. Depth to groundwater ranges between 3 to 9 m pre-monsoon, and 2 to 5 m post-monsoon. Potentiometric head of the confined aquifers rests at approximately 5 m below ground level (Government of Punjab 1980), indicating that the deeper aquifers are not necessarily confined, and possibly recharged by leakage from shallow aquifers.

The potential for MAR is limited in these regions because:

1. Groundwater levels are already shallow, limiting additional storage capacity of aquifers. For example during pre-monsoon in Vaishali district the maximum depth is 9 m, which reduces to 5 m post monsoon.
2. The direction of current hydraulic gradient suggests that groundwater flows in the same direction as the river. This, in conjunction with shallow depths near rivers suggests that the water table intersects the river bed and possibly discharges into the river during low flow seasons.
3. The groundwater level drops from 1 m to 4 m following monsoon, during the dry period. This drop is due to (a) groundwater pumping for irrigation, (b) bare soil evaporation supported by capillary up-flow in areas with shallow water tables, (c) through-flow to regional aquifers and (d) base flow discharge to rivers. Of these possible processes, the extent of bare soil evaporation is limited, when the water table drops below a meter or when the surface soil is closer to its residual water content, resulting in discontinuity of capillary up-flow. Though flow to regional aquifers will also be less because of poor potentiometric gradients across the aquifer, therefore, only pumping for irrigation, and base flow discharge to rivers will cause the drop in groundwater levels. Hence, even if MAR activities are successful in recharging the aquifer, a significant part of it will be discharged to the rivers.

GEOLOGY OF THE AQUIFER DETERMINES THE RESPONSE

In India, two-thirds of the total surface of the country is occupied by hard rocks; that is nearly 2.4 million km^2. Hard rock is a term coined by drillers to indicate poor drillability. They are characterized by insignificant primary porosity and primary permeability. Due to weathering and fracturing, such rocks contain secondary porosity and permeability which are not constant in every location. Fractures in hard rocks create porosity but for permeability, interconnectivity of fractures, fracture aperture and other such properties are very important (Singhal 2007). In general effective porosity of crystalline rocks is less than 5 percent. On the other hand, porosity of alluvial aquifers (of sand and gravel) is in the range of 40-50 percent (Freeze and Cherry 1979). Therefore per unit volume of recharge, groundwater level in a hard rock aquifer will rise by about 20 units or more, but in an alluvial aquifer it will rise by only two folds. It should also be noted that hard rock aquifers, having low permeability, will not transmit water widely, but they will release water stored easily when pumped (see discussion on soil type).

CONCLUSIONS

As a measure to mitigate declining groundwater levels MAR activities are widely promoted by communities and governments across India. It appears, in their haste to address this potential calamity, human and financial resources are not always invested prudently. This paper identifies hydro and hydro-geological constraints to MAR, and appeals to decision makers that due consideration is given to them.

Currently, most of the NREGA resources are used to develop watersheds to increase water storage in surface ponds or groundwater. However, there is very little scientific and technical input in the design of these structures. There has to be a concentrated effort to increase hydro hydrogeological awareness among those involved in planning and implementing these activities. A comprehensive feasibility study, assessing the probability of rainfall, supported by land and water availability and the nature of underlying should be a pre-requisite. Local government agencies responsible for land and water management should be required to guide and regulate these interventions, without becoming bureaucratic or restrictive.

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The IWMI-Tata Water Policy Program (ITP) was launched in 2000 as a co-equal partnership between the International Water Management Institute (IWMI), Colombo and Sir Ratan Tata Trust (SRTT), Mumbai. The program presents new perspectives and practical solutions derived from the wealth of research done in India on water resource management. Its objective is to help policy makers at the central, state and local levels address their water challenges – in areas such as sustainable groundwater management, water scarcity, and rural poverty – by translating research findings into practical policy recommendations. Through this program, IWMI collaborates with a range of partners across India to identify, analyze and document relevant water-management approaches and current practices. These practices are assessed and synthesized for maximum policy impact in the series on Water Policy Highlights and IWMI-Tata Comments.

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