Artificial recharge pilot projects in Gujarat, India

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Abstract Artificial recharge is a possible means of alleviating the over exploitation of aquifers. This paper describes artificial recharge experiments in both alluvial and limestone aquifers using spreading channels, percolation tanks and injection wells. The importance of understanding the conditions in the aquifer is stressed and the economic viability of the alternative techniques is considered.

Projets-pilote de recharge artificielle à Gujarat, Inde.

Résumé La recharge artificielle est l'un des moyens possibles pour réduire la surexploitation des aquifères. Cette étude décrit des expériences de recharge artificielle dans les deux aquifères alluvial et calcaire, au moyen de bassins d'extension, de réservoirs d'infiltration et de puits d'injection. L'importance de la compréhension du fonctionnement hydrodynamique de l'aquifère a été soulignée et la viabilité économique des alternatives techniques a été prise en considération.

INTRODUCTION

Intensive exploitation of an aquifer frequently leads to deteriorating conditions, especially in highly progressive agricultural areas where the quantity of water withdrawn for irrigation purposes is usually several times the recharge. This over-exploitation can lead to declining water levels and severe falls in pumping levels. In other situations, the consequence is the ingress of poor quality water.

Once deteriorating conditions have occurred there are few opportunities for remedial action. However, unless remedial measures are introduced, failure of the groundwater source is likely to occur. Artificial recharge is one possible means of alleviating the conditions.

Artificial recharge is important in groundwater management since it provides storage space free of cost, avoids evaporation losses and allows the use of the stored water during dry periods. There are, however, severe practical limitations to the development of artificial recharge schemes.
There are three main methods of artificial recharge:

- spreading method
- induced recharge method
- injection method.

In selecting which method should be implemented, account should be taken of the hydrogeological conditions, quality of the source water and proposed use of the recharged water. Although the main concern of this paper is major artificial recharge schemes, it is important to recognize that the natural recharge processes can be enhanced by the construction of bunds and levees in stream and river beds and by the de-silting of reservoirs to increase infiltration (CGWB, 1985).

Gujarat State in India has experienced a rapid agricultural development. In the Mehsana alluvial aquifer, which has a long history of irrigation from shallow wells, the drilling of numerous tubewells during the past decade has resulted in falling water tables and even more serious declines in pumping levels. Artificial recharge appeared to be a feasible method of controlling the decline and pilot project studies have been carried out into the suitability of injection wells spreading channels and percolation tanks. Different problems have been encountered in the coastal limestone areas where saline encroachment into the aquifer has occurred in the coastal belt. The possibility of reclaiming the coastal belt by means of artificial recharge has been examined.

For each of these investigations there have been three important issues which required detailed study:

- an improved understanding of the hydrogeology
- the development of reliable recharge techniques
- consideration of the economics of the schemes.

By considering each of these issues, decisions can be made on the viability of artificial recharge.

MEHSANA ALLUVIAL AQUIFER

Agricultural practice has been revolutionized in the Mehsana alluvial aquifer following the drilling of deep tubewells to tap the lower permeable strata of the Mehsana alluvial aquifer. The flow mechanism which was assumed to occur in this alluvial aquifer was that recharge occurred in the "common recharge zone" on the higher ground, Fig. 1, with water moving laterally through the more permeable zones to the heavily exploited agricultural regions such as central Mehsana.
Fig. 1  Typical cross-section, Mehsana alluvial aquifer.
This proposed mechanism ignores the fact that vertical flow can occur through the low permeability clay zones in addition to the horizontal flow through the sand zones. Due to the large drawdowns in the deeper pumped aquifers of 20 to 40 m, vertical gradients across the clay zones can exceed unity. With vertical hydraulic conductivities of these zones in the range of 1 to $3 \times 10^{-3}$ m/d, vertical flows of 1 to 5 mm/d can result. These flows are of the same order as the crop water requirements. However, although horizontal flows from the common recharge zone do occur, they only supply a small proportion of the abstraction due to the limited horizontal hydraulic gradients and the competition between the wells to intercept this horizontal flow. Consequently, in the central Mehsana area, about 90% of the abstracted water results from vertical flows.

Due to the efficiency of the deep tubewells at drawing water vertically downwards through the less permeable zones, the abstraction rate from the aquifer is several times larger than the annual recharge rate. Hence the need for artificial recharge.

**Artificial recharge using spreading channels**

Spreading channels can be used in unconfined aquifers as a means of increasing the inflow of water above the natural recharge rate. The spreading channels used in the Pilot Project were typically 2 m deep with a width of the base of the channel of 2 m and side slopes of 45°. Water was supplied from nearby canals and although initial injection rates approaching 1.0 md⁻¹ were achieved, the rates fell until they reached steady values of around 0.25 md⁻¹. To maintain a recharge of this order of magnitude for several years, periodic cleaning and scraping of the bed of the channel is necessary. Because the aquifers in the spreading channel areas are largely clay free, most of the water which infiltrates through the beds and sides of the spreading channels moves freely to the underlying water table. The recharge rate was highest in the spreading channel with the least clay in the aquifer.

The viability of spreading channels as a device for mitigating the effect of heavy abstraction due to irrigation demands can be assessed by determining the amount of water that is likely to enter the aquifer through the spreading channel. Assuming that, on average, the spreading channel can operate for 30 days each year (the duration will be longer in years with a high rainfall but may be zero during years with below average rainfall), the average annual recharge for each 100 m length of spreading channel equals the cross sectional area times the recharge rate times the duration:

$$\text{artificial recharge} = 100 \times 4.0 \times 0.25 \times 30 = 3000 \, \text{m}^3 \, \text{y}^{-1}$$
If the water is to be used for irrigation, each irrigated crop is likely to require at least 500 mm of water, consequently the area that could be irrigated through this artificial recharge is 0.6 ha. Since the area of the spreading channel is more than 0.04 ha, almost 10% of the irrigated area must be set aside for spreading channels. This indicates the high cost of using artificially recharged water to meet irrigation demands.

**Artificial recharge using injection wells**

There are a number of alternative approaches for artificially recharging aquifers using injection wells (Todd, 1980); in the Mehsana area injection wells were used to transfer water from a river bed into the deeper aquifers. Therefore the injection well acts as a connection between the shallow and deeper aquifers. A connector well experiment in Florida is described by Bush (1977) in which a high transmissivity deep limestone aquifer was recharged from a shallow sandstone aquifer. No difficulties were encountered in recharging the deeper aquifer. However, the recharging of the deeper aquifers in the Mehsana area proved to be more difficult due to the lower hydraulic conductivity of the recharged zones.

**Fig. 2 Layout of injection well experiment.**

Details of the pilot project are indicated in Fig. 2. Water from a shallow source well in the phreatic aquifer, A1, is fed by syphon into the injection well which has a slotted casing in Aquifers A2 and A3. There are two observation piezometers close to the injection well and two observation wells at about 150 m.
Prior to the long term injection test a number of pumping tests were carried out and these indicated that a discharge of 1730 m$^3$d$^{-1}$ could be abstracted for four days with a pumped drawdown of 15 m. Analysis of this test presented some difficulty since the observation well in Aquifer A3 responded almost immediately to the pumping, but the observation well in Aquifer A2 did not respond for 15 mins. A more detailed review of the groundwater head distribution during the "at rest" conditions showed that the groundwater heads in Aquifer A2 were about 8 m above those in Aquifer A3, hence flow occurs from Aquifer A2 down the injection well to Aquifer A3. From a numerical model simulation it was deduced that the "at rest" flow from Aquifer A2 to A3 equalled 300 m$^3$d$^{-1}$. When the pumping test was analysed using the numerical model, transmissivities of Aquifers A2 and A3 were estimated as 50 and 130 m$^2$d$^{-1}$ (Rushton & Srivastava, 1988).

The main injection test continued for 250 days; the injection rate equalled 225 m$^3$d$^{-1}$. For the first 40 days of the test, water continued to flow from Aquifer A2 into the injection well since the groundwater head in the injection well was below that in Aquifer A2; consequently the amount of water entering the deeper Aquifer A3 equalled the injection rate plus the contribution from Aquifer A2. As the test continued, the water level in the injection well increased until at the end of the test it was almost 20 m higher than the groundwater heads in Aquifer A3.

Eventually the flows into the Aquifer almost ceased due to clogging in the vicinity of the injection well. A step pumping test was carried out after the completion of the injection test and, for a discharge rate of 430 m$^3$d$^{-1}$, the pumped drawdown after 8 mins exceeded 13.5 m. In a similar test prior to the injection experiment, the same discharge led to a pumped drawdown of 2.3 m after two hours of pumping. Following thorough cleaning and re-development of the well, a third test at the same pumping rate led to a drawdown of 1.46 m after two hours.

From this information it is apparent that a severe deterioration occurred in the vicinity of the well. Numerical modelling suggested that the hydraulic conductivity within 1 m of the well was reduced to 2% of its normal value (Rushton & Srivastava, 1988). Although the well can be cleaned, the deterioration of the hydraulic conductivity in the vicinity of the injection well means that this method of artificial recharge is likely to be expensive.

**Artificial recharge using percolation tanks**

During the monsoon rainfall, water is stored in man-made reservoirs which are called tanks. Some of the tanks cover little more than a hectare, others extend over areas of more than 10 km$^2$. Water from these tanks is used for domestic and agricultural purposes and the aim is to ensure that some water remains in the tanks for the whole of the dry season. These tanks lose
substantial quantities of water due to evaporation approaching 2 m each year. If, however, these tanks are used as a means of collecting water which subsequently recharges the aquifer, the same amount of water can be stored without the high evaporation losses. In areas where the presence of sub-surface clay layers is not extensive, the tanks can be used as percolation tanks which recharge the aquifer.

By cleaning the beds of the tanks, recharge rates as high as 150 mmd$^{-1}$ can be achieved although the rate is likely to drop to about 15 mmd$^{-1}$ as the build up in silt occurs in the bed of the tank. Even this low rate of percolation is higher than the evaporation losses. Percolation tanks are proving to be a viable method of artificial recharge. To overcome the effect of the siltation, connector wells have been constructed in the bed of some tanks. In hard rock areas where the well can feed into fissure zones encouraging results have been obtained. However, in alluvial areas, the connector wells tend to clog.

Recharge due to losses from canals

From the above discussion it is apparent that the spreading channel is an efficient means of artificially recharging the aquifer system. However, the large land requirements of the spreading channels are likely to limit the development of this technique. Nevertheless, the extensive canal development in part of the Mehsana area does provide a form of spreading channel which should lead to significant recharge. Furthermore, because there is still heavy pumping from the deeper aquifers, this should lead to induced artificial recharge from the canals.

Significant losses do occur from both unlined and lined canals (Wachyan & Rushton, 1987); in the more permeable soils the losses can exceed 2 m$^3$ d$^{-1}$ per cent length of canal. These high losses should result in an improvement in the conditions in the deeper aquifers with either stabilised or rising pumping heads in the deeper wells. No such improvement has been observed and in certain areas the pumped levels continue to fall whilst water-logging extends in the vicinity of the canals and water courses.

The reason for this response is apparent from an examination of the lower permeability zones which lie under the canals. Figure 3 shows the manner in which these lower permeability zones restrict the downwards movement of the water lost from the canals. In Fig. 3 the hydraulic gradient across the less permeable layer equals 1.3; with a vertical hydraulic conductivity of 0.0015 md$^{-1}$, the quantity of water moving downwards equals 1.95 mmd$^{-1}$.

Even if the canal losses are spread over a width of 50 m, the loss from the canal is equivalent to 40 mmd$^{-1}$ which is far higher than the quantity that can move through the underlying clay zones. This result indicates that unless
the aquifer is largely free from the presence of clay layers, any form of recharge into the deeper aquifers is severely restricted.

COASTAL MILIOLITE LIMESTONE AQUIFER

Saline intrusion has occurred along much of the coast limestone belt; for this discussion attention will be restricted to an area of 90 km$^2$ as indicated in Fig. 4. The intrusion of saline water is indicated by the electrical conductivity contours which are above 4000 $\Omega$ /cm for a distance of 2 km from the coast. Further information is contained in the generalised cross-section of Fig. 5. Underlying the Miliolite formation is the Gaj formation of clays and limestone; due to the low permeability it can be approximated as a lower impermeable boundary.

The upper part of the Miliolite limestone formation contains major fissures and cavities. This is illustrated by two pumping tests carried out in the same well but with different rest water levels. When the water levels are just below ground level, a discharge of 3000 m$^3$ d$^{-1}$ caused drawdowns of less than 1 m. However, with rest levels 10 m below ground level, discharges of 300 m$^3$ d$^{-1}$ caused excessive drawdowns. Hence, the aquifer can be idealized as having a lower permeability zone of about 10 m thickness overlain by a higher permeability zone. The transmissivity of the lower permeability zone varies from about 500 m$^2$ d$^{-1}$ at the coast to 50 m$^2$ d$^{-1}$ on the highest ground. The transmissivities of the upper zone can be five to ten times these values.
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INDEX
-4000-- E.C. contour in micromhos/cm

M Mioliolite outcrop
G Gaj limestone outcrop
S Coastal ridge
S Springs

Fig. 4 Study area of the coastal Mioliolite limestone aquifer
The average annual precipitation for the area is 620 mm with 90% of the rainfall occurring during the three monsoon months. In one year the rainfall was only 62 mm, in another it approached 1400 mm. The fluctuations in groundwater levels equals 10 m in typical years and during years with above average rainfall water leaves the aquifer from springs, Figs 4 and 5. Extensive exploitation of the aquifer has continued for many years to irrigate the crops after the end of the monsoon rains. The wells provide good yields for the first few months following the rains but as the water table falls the yield decreases. In the coastal region, abstraction at times of low water table has caused the ingress of saline water. Artificial recharge has been proposed as a means of flushing out the saline water in the coastal region.

Artificial recharge to this highly transmissive aquifer presents no technical difficulties; the water freely enters the aquifer. Three alternative recharge structures have been selected:

- a canal section, 700 m long in the Miliolite limestone
- a recharge basin, area 80 m² and depth 1 m
- an injection shaft 0.45 m in diameter tapping two major cavities

Each of these structures is within 4 km of the coast at the tail end of a canal system. Due to a shortage of canal water only limited field tests were possible but they did provide valuable information.

To identify the consequences of this artificial recharge, detailed interpretation of the field evidence was necessary; this was supplemented by a groundwater model (Rushton & Rao, 1988). These studies indicated that, instead of flushing out the saline water, the farmers are the main beneficiaries of this artificial recharge; they can maintain abstraction from their wells over a longer time period. If artificial recharge continued for a long period, water would eventually flow from the springs. Conditions in the coastal region would hardly be affected by the artificial recharge.

The reason for the small response in the coastal region is that the artificially recharged water moves primarily in the overlying high permeability zone with little water moving into the low permeability saline zone. Consequently, excess recharged water leaves from springs rather than displacing the saline water. By pumping out the saline water from the coastal zone and using artificial recharge to ensure that high groundwater heads are maintained on the landward side, the saline water could slowly be displaced by fresh water but this would be a costly procedure.

DISCUSSION

Although the Pilot Project studies showed that artificial recharge is feasible, note must be taken of the costs of construction and operation to determine
Fig. 5 Typical cross-section of the Miliolite aquifer system.
whether it is economically viable. Table 1 lists the initial costs and operational costs for the various schemes. The most expensive scheme, the injection well in an alluvial aquifer, is allocated initial and operating costs per unit volume of recharged water of 100; the cost of the other schemes are expressed relative to these maxima.

Table 1 Relative Costs of Various Artificial Recharge Schemes (Indian Costs)

<table>
<thead>
<tr>
<th>Artificial Recharge Structure</th>
<th>Initial Cost</th>
<th>Running Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection well (alluvial area)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Spreading channel (alluvial area)</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Percolation tank (alluvial area)</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Injection well (limestone area)</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>Spreading channel (limestone area)</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

From the results of the table it is apparent that the injection well in an alluvial area is very expensive. Injection wells in hard rock areas are less expensive since they tend to be shallower and they do not suffer from the same risks of clogging. Percolation tanks are the cheapest in terms of construction costs but this is because the tanks already exist and the initial cost only involves the cleaning of the bed of the tank.

A second issue is the way in which the artificially recharged water is to be used. As illustrated in the discussion of the spreading channel in the alluvial aquifer, the demands for irrigation are very high. Consequently in most situations it is not viable to use artificial recharge to provide irrigation for a total crop. However, artificially recharged water can be used for supplemental irrigation to a rainfed crop. When there is a shortage of water, additional water at a crucial stage in the growing process can dramatically improve the yield of the crop.

The main use for artificially recharged water should be to provide for domestic needs, livestock and possibly industry. In areas of acute water shortage, even small amounts of artificial recharge can greatly improve the reliability of the supply. Although it is proposed that artificially recharged water should be used primarily for domestic purposes, it is not possible to subdivide an aquifer into regions which can be used for domestic purposes, and other parts to be used for irrigation. Consequently there must be a responsible attitude by all water users.
Availability of water is a third issue of great importance. In Gujarat, there have been a series of years with very low rainfall during which no water was available for artificial recharge. This has delayed the continuation of the investigations and has also demonstrated that the artificial recharge should not be planned on the basis of annual replenishment. It will be difficult to persuade the villager and farmer that the replenished groundwater resource should be used sparingly in case there is a poor rainfall in future years, but these issues must be tackled if the artificial recharge schemes are to be widely introduced.

CONCLUSIONS

This paper has demonstrated that the first step in promoting an artificial recharge scheme is to perform experiments which can lead to an understanding of conditions in the Aquifer system. These pilot schemes provide information about the physical conditions in the Aquifer and also indicate the economic and management aspects which need to be considered. The projects in Gujarat have shown that artificial recharge is technically feasible using a number of alternative structures but the results also indicated that the effects of overexploitation and saline intrusion which have occurred due to heavy irrigation demands cannot be overcome solely by artificial recharge.

REFERENCES
