ARTIFICIAL GROUND WATER RECHARGE WITH A SPECIAL REFERENCE TO INDIA

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ABSTRACT

Artificial groundwater recharge is a process by which the groundwater reservoir is augmented at a rate exceeding the augmentation rate under natural conditions of replenishment. In some parts of India, due to over-exploitation of groundwater, decline in groundwater levels resulting in shortage of supply of water, and intrusion of saline water in coastal areas have been observed. In such areas, there is need for artificial recharge of groundwater by augmenting the natural infiltration of precipitation or surface-water into underground formations by methods such as water spreading, recharge through pits, shafts, wells et cetera The choice of a particular method is governed by local topographical, geological and soil conditions; the quantity and quality of water available for recharge; and the technological-economical viability and social acceptability of such schemes. This paper discusses various issues involved in the artificial recharge of groundwater.

1. INTRODUCTION

Groundwater recharge is the replenishment of an aquifer with water from the land surface. It is usually expressed as an average rate of mm of water per year, similar to precipitation. In addition to precipitation, other sources of recharge to an aquifer are stream and lake or pond seepage, irrigation return flow (from both canals and fields), inter-aquifer flows, and urban recharge. In contrast to natural recharge (which results from natural causes); artificial recharge is the use of water to replenish artificially the water supply in an aquifer. Of all the factors in the evaluation of groundwater resources, the rate of recharge is one of the most difficult to derive with confidence. Estimates of recharge are normally subject to large uncertainties and spatial and temporal variability.

The increasing demand for water has increased awareness towards the use of artificial recharge to augment ground water supplies. Stated simply, artificial recharge is a process by which excess surface-water is directed into the ground – either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration – to replenish an aquifer. It refers to the movement of water through man-made systems from the surface of the earth to underground water-bearing strata where it may be stored for future use. Artificial recharge (sometimes called planned recharge) is a way to store water underground in times of water surplus to meet demand in times of shortage.

Some factors to consider for artificial recharge are (O'Hare et al., 1986)

- Availability of waste water
- Quantity of source water available
- Quality of source water available
- Resultant water quality (after reactions with native water and aquifer materials)
- Clogging potential
- Underground storage space available
- Depth to underground storage space
- Transmission characteristics of the aquifer
- Applicable methods (injection or infiltration)
- Legal / institutional constraints
- Costs
- Cultural / social considerations

2. ARTIFICIAL RECHARGE PROJECTS

The goal of most artificial recharge projects is to convey water to the saturated zone. Evaluation of the viability of proposed projects and of the effectiveness of existing projects requires an understanding and predictive capability of their hydraulic and chemical effects. It focuses on the potential hydraulic consequences of altering the saturated flow system through artificial recharge, which are largely controlled by the geological and hydrological characteristics of the aquifer system. A combination of field, laboratory, analytical, and simulation methods generally are used to develop an understanding of the hydro-geological system as a basis for predicting potential consequences. Optimisation techniques may be coupled with predictive models of ground-water flow and other processes to create an effective tool for planning and management of artificial recharge projects. Pre-project and long-term monitoring of key aspects of a flow system is an essential part of a successful management plan.

Artificial recharge projects are undertaken for many purposes in a variety of aquifer systems. Regardless of the initial distribution and trend of hydraulic heads in these systems, artificial recharge will alter these heads and associated conditions. Characterisation of the geology is important in determining the viability of an artificial recharge project, particularly where significant lateral and (or) vertical ground-water flow is required between recharge and discharge locations.

Hydrological considerations for the saturated-flow component of an artificial recharge project typically include the distribution of head and stress prior to and during project operations, hydraulic properties, the fate of artificially recharged water, and off-site effects. The prediction of saturated flow during artificial recharge projects requires information on the distribution of stress, or recharge and discharge. These stresses can include a variety of natural and artificial processes that can be measured in a variety of ways. The hydraulic properties of an aquifer system, along with the distribution of stress, determine the direction and rate of saturated flow. Given the distribution of head, stress, and hydraulic properties, simulation models can be developed to help address the fate of artificially recharged water and off-site effects. Monitoring and simulation are both used to address off-site effects; however, simulation can also be used to design an efficient monitoring network prior to full-scale implementation.

Successful planning and management of an artificial recharge project often requires consideration of many water management objectives, water routing capabilities, economics, off-site effects, as well as other factors. Optimisation techniques are designed to identify an optimal way to meet an objective given a set of constraints. The linkage of a predictive ground-water flow model with optimisation techniques, or a simulation / optimisation model, allows for simultaneous consideration of the flow system and physical and (or) economic constraints determined by water-resource managers.

Simulation / optimisation models have been applied to ground-water problems for decades and have been used to plan and manage artificial recharge projects. Monitoring of hydraulic conditions prior to and during an artificial recharge project is an essential part of a management plan, and often is an integral part of project operations. Measurement of project performance is clearly one goal of a monitoring programme. A second goal is to provide the information needed for future improvement of predictive modelling capabilities and adjustment of optimisation constraints. Reduced uncertainty in model results translates directly to increased confidence in management decisions based on these models.

Artificial recharge projects can be a valuable component of a groundwater management and conjunctive use strategy, for long-term reliability of groundwater supply, improvement of basin water quality, and for banking of water.

2.1. Artificial Recharge programmes are typically conducted in three phases:

2.1.1. Feasibility

This entails evaluation of the dynamics of groundwater flow and basin recharge, and consideration of options for artificial recharge techniques that can be used. A primary concern is the identification of basin compartmentalisation or impermeable layers within the aquifer that inhibit recharge to the basin aquifers. Also important are concerns about chemical mixing of surface waters and native groundwater, hydrological variability within the aquifers, and the nature of probable migration of recharged water. Different sources of surface-water, together with potentially different regulatory concerns are also evaluated as part of the feasibility programme. Where applicable, prepare necessary feasibility and hydrological reports for regulatory oversight and permitting agencies.

2.2.2. Test programme Design and Operation

Based on results of the feasibility analysis, a test programme is designed, using existing facilities if possible. This work includes chemical and physical modelling of recharge options, detailed chemical analyses of co-mingled waters that have different initial chemical signatures, and measurement of recharge rates in the test programme.

2.2.3. Full-Scale Project Implementation

Test programme results are used to recommend final, full-scale programme parameters, including sites for additional wells or infiltration ponds (if necessary), potential future options for sourcing of surface-water, planning of recharge management during regular operations, and necessary monitoring. Focus is kept on keeping the system design flexible, so that changing needs of the client can be integrated with existing recharge operations and facilities.

3. METHODS OF ARTIFICIAL RECHARGE

Artificial recharge methods can be classified into two broad groups (i) direct methods, and (ii) indirect methods.

3.1. Direct Methods

(a) Surface Spreading Techniques
The most widely practised methods of artificial recharge of groundwater employ different techniques of increasing the contact area and resident time of surface-water with the soil so that maximum quantity of water can infiltrate and augment the groundwater storage. Areas with gently sloping land without gullies or ridges are most suited for surface-water spreading techniques.

Flooding
The technique of flooding is very useful in selected areas where a favourable hydro-geological situation exists for recharging the unconfined aquifer by spreading the surplus surface-water from canals / streams over large area for sufficiently long period so that it recharges the groundwater body. This technique can be used for gently sloping land with slope around 1 to 3 percentage points without gullies and ridges.

Ditches and Furrows
In areas with irregular topography, shallow, flat-bottomed and closely spaced ditches and furrows provide maximum water contact area for recharging water from the source stream or canal. This technique requires less soil preparation than the recharge basin technique and is less sensitive to silting.

Recharge Basins
Artificial recharge basins are either excavated or enclosed by dykes or levees. They are commonly built parallel to ephemeral or intermittent stream-channels. The water contact area in this method is quite high which typically ranges from 75 to 90 percentage points of the total recharge area. In this method, efficient use of space is made and the shape of basins can be adjusted to suite the terrain condition and the available space.

Run-off Conservation Structures
In areas receiving low to moderate rainfall, mostly during a single monsoon season, and not having access to water transferred from other areas, the entire effort of water conservation is required to be related to the available 'insitu' precipitation.

Gully plugs are the smallest run-off conservation structures built across small gullies and streams rushing down the hill slopes carrying drainage of tiny catchments during rainy season. Usually, the barrier is constructed by using local stones, earth and weathered rock, brushwood, and other such local materials.

Sloping lands with surface gradients up to 8 percentage points having adequate soil cover can be levelled through ***bench terracing*** for bringing under cultivation. It helps in soil conservation and holding run-off water on terraced area for longer duration giving rise to increased infiltration recharge.

Contour barriers involve a watershed management practice so as to build up soil moisture storages. This technique is generally adopted in areas receiving low rainfall. In this method, the monsoon run-off is impounded by putting barriers on the sloping ground all along contours of equal elevation. Contour barriers are taken up on lands with moderate slopes without involving terracing.

In areas where uncultivated land is available in and around the stream-channel section, and sufficiently high hydraulic conductivity exists for sub-surface percolation, small tanks are created by making stop dams of low elevation across the stream. The tanks can also be located adjacent to the stream by excavation and connecting them to the stream through delivery canals. These tanks are called "***percolation tanks***" and are thus artificially created surface-water bodies submerging a highly permeable land area so that the surface run-off is made to percolate and recharge the groundwater storage. Normally, a percolation tank should not retain water beyond February in the Indian context. It should be located downstream of a run-off zone, preferably towards the edge of a piedmont zone or in the upper part of a transition zone (land slope between 3 to 5 percentage points). There should be adequate area suitable for irrigation near a percolation tank.

Stream-channel Modification
The natural drainage channel can be modified with a view to increase the infiltration by detaining stream flow and increasing the stream-bed area in contact with water. This method can be employed in areas having influent streams (stream-bed above water table) which are mostly located in piedmont regions and areas with deep water table (semi-arid, arid region and valley fill deposits). stream-channel modification methods are generally applied in alluvial areas.

Surface Irrigation

Surface irrigation aims at increasing agricultural production by providing dependable watering of crops during gaps in monsoon and during non-monsoon period. Wherever adequate drainage is assured, if additional source water becomes available, surface irrigation should be given first priority as it gives a dual benefit of augmenting groundwater resources.

(b) Sub-Surface Techniques

When impervious layers overlie deeper aquifers, the infiltration from surface cannot recharge the sub-surface aquifer under natural conditions. The techniques adopted to recharge the confined aquifers directly from surface-water source are grouped under sub-surface recharge techniques.

Injection Wells

Injection wells are structures similar to a tube well but with the purpose of augmenting the groundwater storage of a confined aquifer by “pumping in” treated surface-water under pressure. The aquifer to be replenished is generally one that is already over exploited by tube well pumping and the declining trend of water levels in the aquifer has set in. Artificial recharge of aquifers by injection wells is also done in coastal regions to arrest the ingress of seawater and to combat the problems of land subsidence in areas where confined aquifers are heavenly pumped. Due to higher well losses caused by clogging, the injection wells display lower efficiency (40 to 60 percentage points) as compared to a pumping well of similar design in the same situation. The source water and the water in the aquifer should be compatible to avoid any precipitation, causing clogging of well. Injection-cum-pumping wells are more efficient because the well can be cleaned during pumping operation.

Gravity-Head Recharge Wells

In addition to specially designed injection wells, ordinary bore wells and dug wells used for pumping may also be alternatively used as recharge wells, whenever source water becomes available. In certain situations, such wells may also be constructed for effecting recharge by gravity inflow. In areas where water levels are currently declining due to over-development, using available structures for inducing recharge may be the immediately available economic option.

Connector Wells

Connector wells are special type of recharge wells where, due to difference in potentiometer head in different aquifers, water can be made to flow from one aquifer to other without any pumping. The aquifer horizons having higher heads start recharging aquifer having lower heads.

Recharge pits

Recharge pits are structures that overcome the difficulty of artificial recharge of phreatic aquifer from surface-water sources. Recharge pits are excavated of variable dimensions that are sufficiently deep to penetrate less permeable strata. A ***canal trench*** is a special case of recharge pit dug across a canal bed. An ideal site for canal trench is influent stretch of a stream that shows up as dry patch. One variation of recharge pit is a ***contour trench*** extending over long distances across the slope and following topographical contour. This measure is more suitable in piedmont regions and in areas with higher surface gradients. As in case of other water spreading methods, the source water used should be as silt free as possible. In case of hard rock terrain, a canal bed section crossing permeable strata of weathered fractured rock or the canal section coinciding with a prominent lineament or intersection of two lineaments, form ideal sites for canal trench.

Recharge Shafts

In case, poorly permeable strata overlie the water table aquifer located deep below land surface, a shaft is used for causing artificial recharge. A recharge shaft is similar to a recharge pit but much smaller in cross-section.

3.2. Indirect Methods

(a) Induced Recharge

It is an indirect method of artificial recharge involving pumping from aquifer hydraulically connected with surface-water, to induce recharge to the groundwater reservoir. In hard rock areas, the abandoned channels often provide good sites for induced recharge. The greatest advantage of this method is that under favourable hydro-geological situations, the quality of surface-water generally improves due to its path through the aquifer materials before it is discharged from the pumping well.

Pumping Wells

Induced recharge system is installed near perennial streams that are hydraulically connected to an aquifer through the permeable rock material of the stream-channel. The outer edge of a bend in the stream is favourable for location of well site. The chemical quality of surface-water source is one of the most important considerations during induced recharge.

Collector Wells

For obtaining very large water supplies from river-bed, lake-bed deposits or waterlogged areas, collector wells are constructed. The large discharges and lower lift heads make these wells economical even if initial capital cost is higher as compared to tube well. In areas where the phreatic aquifer adjacent to the river is of limited thickness, horizontal wells may be more appropriate than vertical wells. Collector well with horizontal laterals and infiltration galleries can get more induced recharge from the stream.

Infiltration Gallery

Infiltration galleries are other structures used for tapping groundwater reservoir below river-bed strata. The gallery is a horizontal perforated or porous structure (pipe) with open joints, surrounded by a gravel filter envelope laid in permeable saturated strata having shallow water table and a perennial source of recharge. The galleries are usually laid at depths between 3 to 6 metres to collect water under gravity flow. The galleries can also be constructed across the river-bed if the river-bed is not too wide. The collector well is more sophisticated and expensive but has higher capacities than the infiltration gallery. Hence, choice should be made by the required yield followed by economic aspects.

(b) Aquifer Modification

These techniques modify the aquifer characteristics to increase its capacity to store and transmit water. With such modifications, the aquifer, at least locally, becomes capable of receiving more natural as well as artificial recharge. Hence, in a sense these techniques are artificial yield augmentation measures rather than artificial recharge measures.

Bore Blasting

These techniques are suited to hard crystalline and consolidated strata. Through hydro-geological investigation, suitable sites are fixed where the aquifer displays limited yield that dwindles or dries in winter or summer months. All the blast holes reach the depth of the aquifer required to be benefited, whether unconfined or confined. All the charges of row or circle are exploded at a time.

Hydro-Fracturing

In many cases, blasting has given indifferent results. Hydro-fracturing is a recent technique that is used to improve secondary porosity in hard rock strata. Hydro-fracturing is a process whereby hydraulic pressure is applied to an isolated zone of bore wells to initiate and propagate fractures and extend existing fractures. The water under high-pressure break up the fissures cleans away clogging and leads to a better contact with adjacent water bearing strata. The yield of the bore well is improved. In hydro fracturing, vertical fractures are initiated which inter-connects aquifers at different levels in addition to extension of existing fractures. This leads to better conditions for artificial recharge. The technique may be applied at bore well sites located in hard crystalline rock or other massive consolidated strata including metamorphic and sedimentary formations. Generally, a bore well giving low or poor yield is treated, but the technique can also benefit other wells.

(c) Groundwater Conservation Structures

The water artificially recharged into an aquifer is immediately governed by natural groundwater flow regime. It is necessary to adopt groundwater conservation measures so that the recharged water remains available when needed.

Groundwater Dams / Underground Barriers

A groundwater dam is a sub-surface barrier across stream that retards the natural groundwater flow of the system and stores water below ground surface to meet the demands during the period of greatest need. The main purpose of groundwater dam is to arrest the flow of groundwater out of the sub-basin and increase the storage within the aquifer. The sub-surface barriers need not be only across the canal bed. In some micro watersheds, sub-surface dykes can be put to conserve the groundwater flow in larger area in a valley. Sites have to be located in areas where there is a great scarcity of water during the summer months or there is a need for additional water for irrigation. Technical possibilities of constructing the dyke and achieving large storage reservoirs with suitable recharge conditions and low seepage losses are the main criteria for sub-surface dyke. It directly benefits up-gradient area and hence care should be taken that a large number of users are not located immediately downstream.

Fracture-Sealing Cementation Technique

In many hard rock areas, the groundwater circulation to deeper levels is governed by shear, fault or fracture plane indicated by lineaments. The boreholes located on such zones prove productive but due to dissipation of the limited storage along preferred flow planes, in case of adverse topographical situation, these become dry by the end of winter or summer. Fracture-sealing cementation is a suitable water conservation measure in such situations. This measure can also be used to prevent ingress of saline or polluted water from a known source. The groundwater flow system at the site should be adequately known to establish the outflow direction and the preferred fracture planes along which the flow occurs under the influence of the natural hydraulic gradient.

Under certain hydro-geological conditions, a combination of several surface recharge and sub-surface recharge methods and groundwater conservation techniques, can be used in conjunction for optimal recharge of groundwater.

4. ARTIFICIAL GROUNDWATER RECHARGE IN INDIA

Technological developments in well construction and pumping methods have resulted in large-scale exploitation of groundwater in India and elsewhere. In many parts of India, due to the vagaries of the monsoon, and, in the arid and semi-arid regions, due to the lack or scarcity of surface-water resources, dependence on groundwater has increased tremendously in recent years. Thus, given the possibility of the available groundwater resources to be over-exploited in these areas, it is essential that proper storage and management of available groundwater resources be instituted.

Replenishment of groundwater by artificial recharge of aquifers in the arid and semi-arid regions of India is essential, as the intensity of normal rainfall is grossly inadequate to produce any moisture surplus under normal infiltration conditions. Although artificial groundwater recharge methods have been extensively used in the developed nations for several decades, their use in developing nations, like India, has occurred only recently. Techniques such as canal barriers, construction of percolation tanks, and of trenches along slopes and around hills, et cetera, have been used for some time, but have typically lacked a scientific basis (e.g., knowledge of the geological, hydrological and morphological features of the areas) for selecting the sites on which the recharge structures are located.

Various techniques for artificial groundwater recharge have been employed in the states of Maharashtra, Gujarat, Tamil Nadu and Kerala. In Maharashtra, studies were carried out on seven percolation tanks in the Sina and the Main River basins. The average recharge volume of these tanks was 50 percentage points of the capacity of the tank, provided the tank bottom was maintained by removing accumulated sediment and debris prior to the annual monsoon. Best results were obtained from systems located in areas of vesicular or fractured basalt. Canal barriers, where the recharge structure was situated within the course of the canal, was found to be most effective and economical as the surface area exposed to evaporation was, on average, 10 percentage points of that of an average-sized percolation tank. Within canal barriers, the rate of infiltration varied from 50 percentage points to 70 percentage points of the capacity of the reservoir. Infiltration was aided by a connector well linking the phreatic, alluvial aquifer at 6 metre depth with the deeper, confined basaltic aquifer at 63 metre depth, allowing the free flow of water by gravity from phreatic aquifer to the confined aquifer at the rate of 0.19 million cubic metres per year. The water level in the phreatic aquifer, which was saturated due to infiltration from the surface reservoir, was 3 metre below ground level, and the piezometric level in confined aquifer was 30 metre below ground level.

In Tamil Nadu and Kerala, studies were carried out on nine percolation tanks in the semi-arid regions of the Noyil Ponani and Vattamalai River basins. Rates of percolation were as high as 163 mm per day at the beginning of the rainy season, but diminished thereafter mainly due to the accumulation of silt in the bottoms of the tanks. Periodic de-silting, therefore, was determined to be an essential element in the maintenance of these tanks. In contrast, sub-surface dykes of 1 metre to 4 metre in height were found effective in augmenting groundwater resources, particularly in the hard rock areas underlain by fractured aquifers.

Studies of artificial recharge using injection wells were carried out in the Ghaggar River basin, using canal water as the primary surface-water source. The injection rate was initially 43.8 litres per second at an injection pressure of one atmosphere. The pressure was increased to two atmospheres after 5 hours, and was kept constant thereafter, although the recharge rate gradually diminished to 3.5 litres per second after a few days. The reproducible recharge rate obtained using the pressure injection system was found to be about 10 times greater than the rate obtained using gravity flow. The increase in pressure during injection was due to clogging of the interstitial spaces within the aquifer, which can be minimised by careful control of the quality of source water. Periodic cleansing of well was also required, whenever the pressure increased beyond six atmospheres or showed a sudden rise. Further studies were conducted on induced recharge from the Ghaggar River using a well field, with individual wells spaced at 200-metre intervals, within 100 metre of the riverbank. As with the injection wells, periodic removal of the clay film deposited in the floodplain above the natural recharge areas of the aquifer was required to improve recharge efficiency.

In Gujarat, studies of artificial recharge were carried out in two areas. In the Central Mehsana area of North Gujarat, artificial recharge was carried out using injection wells, connector wells, and infiltration channels and ponds. Surplus groundwater from the floodplain aquifers of the major rivers in Mehsana area and tail end releases from the Dharoi Canal System were utilised as the water sources. In addition, the injection of water from the phreatic aquifers into the deeper, overexploited aquifers was investigated in the Central Mehsana area. In the coastal areas of Saurashtra, artificial recharge was carried out using injection wells and recharge basins. Storm-water run-off and tail-end releases from the canal system of the Hiran Irrigation Project were used as the water sources, and the studies included an evaluation of the effectiveness of the existing tidal regulators and check dams, designed to limit the extent of seawater intrusion. Of the methods studied in the Central Mehsana area, spreading methods, using

techniques such as spreading channels, recharge pits and ponds, were found to be more economical than injection methods, although dual purpose connector wells were found to be more economical for recharging the deep aquifer. The dual-purpose connector wells not only supplied water by gravity to the deep aquifer, but also abstracted water by periodic pumping, which reduced the extent of clogging of the wells. In contrast, the coastal Saurashtra area where the aquifers are highly porous and drain to the coastal zone, the rapid outflow of recharged water to the sea did not make artificial recharge a viable proposal. However, the tidal regulators that created barriers of freshwater along the creeks and in coastal depressions effectively prevented seawater intrusion in these areas. Also in Gujarat, studies of sub-surface storage were carried out. In the Jamnagar District, naturally occurring basaltic dykes were known to retain groundwater. However, it was also known that the surface soils in the District were not waterlogged. The studies indicated that, while the lower portion of the dyke acted as a barrier to the passage of groundwater, the top few metres of the dyke, composed of fractured basalt, allowed the passage of groundwater through the soil profile, preventing waterlogging in the aquifer area. This design feature was subsequently incorporated into the specifications of sub-surface dykes.
Elsewhere in India, watershed management practices adopted in some states to minimise soil loss in erosion gullies also contribute to groundwater recharge. Check dams not only store surface-water during portions of the year, but also encourage infiltration into the surface aquifers, providing a threefold benefit to communities (i.e., prevention of soil loss, provision of water for livestock watering and human use, and groundwater recharge). Such works have been implemented on an extensive scale in Gujarat, Maharashtra, Madhya Pradesh, and Rajasthan since 1960.

5. ADVANTAGES AND DISADVANTAGES

Artificial recharge has several potential advantages, namely:

- The use of aquifers for storage and distribution of water and removal of contaminants by natural cleansing processes that occur as polluted rain and surface-water infiltrate the soil and percolate down through the various geological formations.
- The technology is appropriate and generally well understood by both the technologists and the general population.
- Very few special tools are needed to dig wells.
- In rock formations with high structural integrity, few additional materials may be required (concrete, soft stone or coral rock blocks, metal rods et cetera) to construct the wells.
- Groundwater recharge stores water during the wet season for use in the dry season, when demand is the highest.
- The quality of the aquifer water can be improved by recharging with high-quality injected water.
- Recharge can significantly increase the sustainable yield of an aquifer.
- Recharge methods are environmentally attractive, particularly in arid regions.
- Most aquifer recharge systems are easy to operate.
- In many river basins, control of surface-water run-off to provide aquifer recharge reduces sedimentation problems.
- Recharge with less-saline surface waters or a treated effluent improves the quality of saline aquifers, facilitating the use of the water for agriculture.

Artificial Recharge has some disadvantages too, namely:

- In the absence of financial incentives, laws, or other regulations to encourage landowners to maintain drainage wells adequately, the wells may fall into disrepair and ultimately become sources of groundwater contamination.
- There is a potential for contamination of the groundwater from injected surface-water run-off, especially from agricultural fields and road surfaces. In most cases, the surface-water run-off is not pre-treated before injection.
- Recharge can degrade the aquifer unless quality control of the injected water is adequate.
- Unless significant volumes of water are injected in an aquifer, groundwater recharge may not be economically feasible.
- The hydrogeology of an aquifer should be investigated and understood before any future full-scale recharge project is implemented. In karst terrain, dye-tracer studies can assist in acquiring this knowledge.
- During the construction of water-traps, disturbance of soil and vegetation cover may cause environmental damage to the project area.

6. OPERATION AND MAINTENANCE

Periodic maintenance of artificial recharge structures is essential because infiltration capacity is rapidly reduced because of silting, chemical precipitation, and accumulation of organic matter. In the case of injection wells and connector wells, periodic maintenance of the system consists of pumping and / or flushing with a mildly acidic solution to remove encrusting chemical precipitates and bacterial growths on the well tube slots. By converting the injection or connector wells into dual-purpose wells, the time interval between one cleansing and another can be extended, but, in the case of spreading structures, except for sub-surface dykes constructed with an overflow or outlet, annual de-silting is necessary. Unfortunately, because the structures are installed as a drought-relief measure, periodic maintenance is often neglected until a drought occurs, at which time the structures must be restored (the 5 to 7 year frequency of droughts, however, means that some maintenance does take place). Several agencies and individuals normally carry out structural maintenance.

7. CONCLUDING REMARKS

- The cost of a recharge scheme, in general, depends upon the degree of treatment of the source-water, the distance over which the source-water needs to be transported, and the stability of the recharge structure, and resistance to silting and / or clogging.
- Artificial recharge of ground water should be licensed and controlled by competent authorities according to specific requirements laid down in an appropriate permit system that should be flexible to adapt to site-specific conditions. The question of ground-water exploitation should be clarified on a case-by-case basis, taking into account all relevant aspects, including ecological ones. The relevant regulations should establish the extent to which exemptions are allowed.
- Authorisation for artificially recharging the aquifer should be granted only if the hydro-geological situation, environmental condition and the recharge-water quality permit injection, percolation or infiltration of water by artificial means into aquifers for storage and retrieval.
- Appropriate measures should be taken to combat saline water encroachment into coastal aquifers. In such areas, special regulations for ground-water abstraction should be enforced to avoid over-pumping and the resultant lowering of the ground-water table.

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