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ARTIFICIAL RECHARGE OF GROUNDWATER

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ABSTRACT

Development of the groundwater resources in various parts of the world has been increasing in recent years as development of surface water resources approaches the point of full potential. The increasing use of ground water for municipal, industrial and irrigation supply has emphasized the need for recharging the groundwater by artificial means. For last several years, the practice of artificially recharging the ground water reservoir has been quite successfully used in the USA and in many countries of Europe. In India, a declining trend of ground water regime has been observed in the parts of Gujarat, Tamilnadu, Rajasthan etc. due to over exploitation of groundwater. It is, therefore, important to study the various aspects of artificially recharging the groundwater which will not only help in controlling the declining trend of ground water but will also ensure its effective utilisation.

This technical note gives summary of various developments in the field of artificial recharge of ground water at national and international levels. Various methods of recharge have been discussed in detail with reference to their design criteria, application, economic feasibility etc. The planning, design and execution of an artificial recharge project have been discussed giving details of data requirement. A brief description of an artificial recharge project taken up in Mehsana area of

Gujarat is given. The basic guidelines involved in modelling an artificial recharge system have been described. A detailed bibliography is also given at the end.

1.0 INTRODUCTION

Artificial recharge of ground water basins may be defined as the augmentation of the natural infiltration of precipitation or surface water into underground formations by appropriate methods. A variety of methods have been developed, including water spreading, recharging through pits and wells, and pumping to induce recharge from surface water. Often groundwater is the only source of water in arid and semi-arid regions and natural recharge to groundwater by rainfall is not significant especially in view of the fact that for most of the year the rainfall is relatively small compared to the potential evaporation and during the days when the rainfall exceeds evaporation and the storm intensity is sufficient to cause surface runoff, the potential water for recharge moves to locations downstream where it either gets lost by evaporation or joins the sea. The river flow in dry periods reduces in these regions which can be augmented by artificially storing the increases discharge of river during wet periods and using it later during dry periods.

A total of 1370 x 10^{15} m^3 water is available on the earth surface out of which 97.3 percent is salt water not useful for agriculture,domestic and industrial consumption. Out of remaining 2.7% of water, only 0.6% in fresh liquid water and the rest 2.1% being present as snow or ice. The fresh liquid water, 0.6% of total water available on earth's surface, corresponds to 8.5 x 10^{15} m^3 out of which 98% is groundwater of which half occurs at a depth more than 800 m below ground surface. From such a greater depths the recovery of water becomes expensive hence the fresh water resources available at shallow depths become quite precious commodity and demands for careful utilisation (Huisman and Olsthoorn,1983).

With the increase in population and other processes like urbanisation,industrialisation the water demand is on a constantly increasing trend. In some places the water table is declining regularly because of over pumpage of water. This situation can be tackled by artificially recharging the ground water using various recharging methods. Selection of specific method of artificial recharge based on local hydrogeological situation and evaluation of its technical and economic feasibility necessitates detailed investigations including experimental studies. The present note is an attempt to describe the various aspects of artificial recharge including various methods, their planning,design,construction,operation and maintenance.

2.0 REVIEW

Aritificial recharge has been practiced for quite some time for checking the decline in ground water table. A brief review of various aspects associated with artificial recharge is given in following sub-sections.

~~2.1~~ 2.0 History of Development

Artificial recharge had begun early in the last century in the Europe. Bowen (1980) has reported that first infiltration basin for recharging was constructed at Goteborg, Sweden in 1897 and subsequently several basins were developed. Infiltration rates ranging from 7 to 52 feet/day have been reported for these basins (Jansa,1952). In Germany, the first artificial recharge unit composed of a sand filled infiltration canal and a periodically flooded field, started operation in Chemnitz in 1875. It was only in 1900, however, after the publication of experiments by the Swedish scientist Richert, artificial ground water recharge using infiltration tanks made a real breakthrough. The first recharge tanks in the Ruhr area in Germany were built in Essen-Steele in 1902. In The Netherlands, surface water had been infiltrated in the dune area near the Dutch Coast at the North sea for almost for fifty years. Since 1955, this had been carried out on a large scale at different places in the dunes of North and South Holland by infiltration of pretreated Rhine water in behalf of the drinking-water supply of Amsterdam, the Hague,Leiden and North Holland (Puffelen,1979). In Australia,where much of the continent is semi-arid with sparse population, it is mainly in eastern highlands, where there is high rainfall, the urban, industrial and intensive agricultural development exist. In these areas the increase in demand for water combined with the national propensity towards drought mitigation has meant a shift to increased groundwater use and conjunctive use of surface and groundwater. In order to artificially recharge the ground water a number of schemes have been tested or applied since 1960. Only a few minor schemes have been implemented for drinking water and the major ones are being used for agriculture. In general, the state of art of artificial recharge in Australia is at an early stage (Lawrence,1985). In the USSR the problem of artificial recharge is of considerable interest in arid regions, in heavily urbanised areas with no potential for the extension of water intakes and in some mountain regions where the length of the sites suitable for construction of shore intakes is limited. Approximately, 60 systems of artificial ground water recharge are implemented at water intakes in some regions of the USSR (Riga,Kaunas,Tbilsi,Novokuznetsk,Kursh, Tashkent, the Urals,Kazakhstan etc.). During last 10-15 years the problem of artificial recharge has been intensely studied in the USSR(Sychev and Polkanov,1985). In Switzerland,because of heavy usage of water in great urban areas like Basle,Geneva and Zurich,artificially recharging ground water acquires a special significance. In 1979, there were 12 plants running for artificially recharging ground water in Switzerland. The water board of Basle, a city of Switzerland, started using artificial recharging of ground water since 1911 (Trueb,1979). Shelef (1979) has reported that in Israel over 95 percent of the conventional surface and groundwater resources are already in full utilisation and hence artificial recharge of ground water by treated effluents acquires a special significance. In Spain, the ground water recharge was started in 1953 in Besos area with a special well,surrounded by a crown of 16 small diameter tube-wells, in order to accomplish an intense back washing of the coarase sand and gravels that form the water table aquifer. In the Llobregat area of Spain, artificial recharging of coarse and gravel confined aquifer has been done by treated river water in excess of city distribution using tube-wells since 1969. During the period of shortage of water, the injected water is abstracted by other wells (Custodio et al.1979). In Poland, infiltration is conveniently practiced for ground water enrichment. While natural infiltration for enriching ground water is common in Poland, artificial infiltration is usually applied without pretreatment. However, the infiltration units that are designed in Poland now,involve sedimentation and periodical coagulation processes (Kowal,1979). In the coastal zone of Israel, due to intensive evaporation and over exploitation of ground water, it was required to store low salt content winter flood waters to be used in the practically dry summer periods months of high water demand. Shigma project,in the Southern part of Israel, between Ashquelon and Gaza, was the first step in this direction which was commissioned in 1958-60 and aimed to conserve episodic waters of winter stream Shigma by impoundment, followed by artificial recharge of regional aquifer. In 1966 another plant, the Nahaley Menashe work, in the centre of the coastal strip, was started to harvest the water of four periodical winter weeks (Katz,1979). As regards the U.K., artificial recharge was attempted first in the Lee River Valley near London where, before 1965, a scheme' started and became operational later. In 1970-71, a recharge borehole and eleven observation boreholes were made in the Bunter sandstone (Triassic) near Clipstone,Nottinghamshire, and experiments were made in them during the period June,1971 to March,1974 (Bowen,1980). Edworthy and Downing (1979) have described artificial ground water recharge and its relevance in Britain and concluded that : (i) the technqiue is applicable to main aquifers in the U.K., ii) an average recharge rate of 0.3 - 0.5 m.per day can be expected where lagoons are used to recharge aquifers, for instance the Permo-Triassic Sandstones iii) the quality of water is improved by recharge through an unfissured aquifer. Practices of artificial recharge in the U.S.A. began near the end of nineteenth century. Water spreading as a means of artificial recharge was first tried by Denwer Union Water Company in 1889 which tried to spread water over the gravel cone of the souht Plattee near the mouth of its canyon. In 1896, flood waters of San Antiano Creek in southern Calofornia were conserved by spreading on the alluvial fan at the mouth of San Antiano Canyon. The State of California has developed the finest network of artificial recharge projects, numbering around 276, to augment its underground water resources. In Long Island, New York, the recharge of storm water through basins has been in practice since 1935 and for last five years recharge of reclaimed wastewater has also been practiced (Bradley,1985).

In India, the ground water resources are declining in certain places due to its overexploitation in uncontrolled manner. These places are mainly in the States of Gujarat, Tamilnadu,Maharashtra,Andhra Pradesh,Punjab,Rajasthan and Haryana. Studies have been taken up at these places by Central/State Govt.Organisations. A pilot project on artificial recharge in Mehsana area and coastal Saurashtra in Gujarat State started in April,1980. In the Ghaggar river basin in Haryana, artificial recharge studies were carried out during the period 1976-78. Studies on artificial recharge were also carried out in Maharashtra,Andhra Pradesh,Tamilnadu and Kerala (Pathak, 1985).

2.2 Recharge Mound

Water percolating beneath a spreading basin forms a mound, the dimensions of which are governed by basin size and shape, recharge rate and duration,water table position, and aquifer characteristics. If the spreading area is such that its length is much more than its width e.g.a canal or a stream the mound so formed can be considered two dimensional. When spreading area is more or less equal in length and breadth such as in square basins, the mound is considered three dimensional. When the mound has just begin to form while the recharge through spreading continues, the shape of mound changes with time and is in an unsteady state. The mound shape can achieve a steady state if the recharge from surface occurs at a constant rate (Arya,1964). The expressions for finding out mound geometries have been derived for following idealised conditions:

i) aquifer is homogeneous and istropic

ii) height of mound is small in relation to initial saturated thickness

iii) vertical recharge is at a uniform rate

Baumann (1965) has presented a mathematical model of two-dimensional flow of ground water under steady and unsteady flow conditions based on an idealized aquifer. Theoretical aspects of the two and three dimensional mound phenomenon are presented with model test results for two dimensional flow for comparison. Bouwer (1963 a) discussed the flow system below a water spreading basin. The flow system between a recharge basin and the lower mound may consist of a number of perched mounds and percolation zones. The flow conditions governing formation and recession of individual mounds can be of considerable complexity. With a resistance network analog, non-uniformities and complexity in soil and boundary conditions can be taken into account. Hantush (1967) has discussed growth and decay of ground-water mounds in response to uniform percolation. According to the author, in the artificial recharge of irrigation water , the response of ground water mounds to deep percolation is of practical interest. Where the underlying aquifer is infinite in areal extent, the solution of rise and fall of the water table for the circular recharging area is given in terms of a function easily tabulated for a practical range of parameters.

Jacob (1960) has discussed ground-water mounds in two-layered aquifers. The top layer has low permeability and high storativity and both the layers are coupled hydraulically across their common interface. The author obtained partial differential equations for non-steady flow in such a two-layered system into which water is recharged at non-uniform rates over all or part of the aquifer. Todd (1961) studied the time and space distribution of ground water below artificial recharge areas for idealized conditions. Model techniques for studying flows from recharge areas where analytical approaches cannot be applied are described and results from experiments in progress are presented for illustration. Bianchi et al.(1978) have given a dimensionless graph defining the rise and horizontal spreading of a water table mound with time beneath a square recharge area. To use this graph recharge rate, basin size, transmissivity of aquifer, storage coefficient and length of time are required to be known in order to find height of mound at any point within the basin.

2.3 Variations in Recharge Rates

Todd (1985) reported that most recharge facilities display a reduction in recharge rate with time. According to him, a typical recharge rate curve with time may show three phases namely i) an initial reduction due to dispersion and swelling of soil particles after wetting ii) a subsequent increase water and iii) a final gradual reduction resulting from microbial growths that clog the soil pores. Bear (1979) has presented a typical curve as shown in figure 1 showing the reduction in infiltration rate with time in an infiltration basin. He

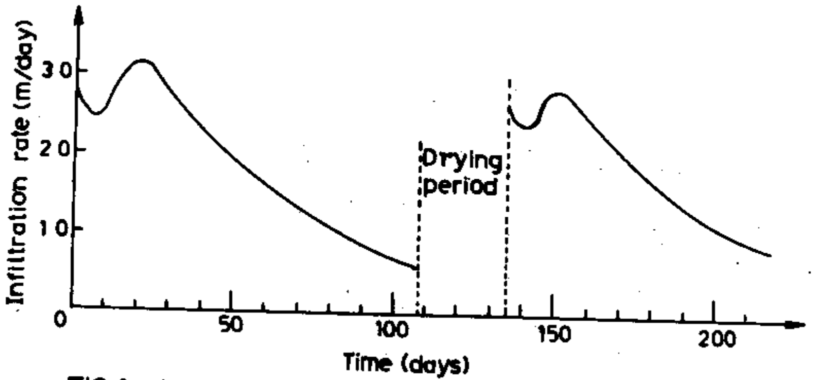

FIG.1-VARIATION OF INFILTRATION RATE WITH TIME
(BEAR,1979)

further reported that economy of artificial recharge by surface spreading techniques depends to a large extent upon the maintenance of high infiltration rates. Depending on the type of soil, rates of 3-15 m/day have been observed in gravel, upto 3 m/day in gravel and sand, upto 2 m/day in fine sand and sand stone, and upto 0.5 m/day in sand and silt (Bear,1979). Many chemicals and various types of organic matter have been studied in efforts to increase recharge rates. Chemical soil conditioners which tend to aggregate the soil have sometimes proved beneficial. It is also reported that in spreading basins, a cycle of drying and wetting yields in more recharge rates rather than the basin being continuously flooded with water. Drying kills microbial growths and creates cracks in the soil surface which consequently increases the water intake rates. In situations where less pervious strata lie below ground surface, the recharge rate depends on the rate of subsurface lateral flow. Todd (1983) has reported recharge rates in spreading basins for various projects at different locations in the U.S.A. For example, in Los Angeles county in California, USA the recharge rates were reported as 0.7-1.9 m/day while for Richland,Washington, the recharge rate was reported as 2.3 m/day. Todd (1985) has reported recharge rates for recharge pits at Peoria,Illinois which have been in operation since 1951, as 23 m/day initially. After 13 years of operation, the recharge rates have gone down to about 12 m/day which according to the author was attributed to silt penetration into the upper part of the aquifer. Berend (1967a) has reported that suspended mineral matter in recharge water was the dominant factor in reduction of infiltration rate in flood water spreading operations,through the creation of an impervious film on the soil surface. The author has recommended that the flood water should be desilted prior to spreading in order to keep the effectiveness of spreading grounds on a high level. Johnson (1957) has discussed utilisation of decomposed organic residues to increase infiltration rates in water spreading. He has concluded that percolation rates of soil mixed with organic residues varied with the amount of material applied,decomposition rate of the material, and the length of incubation period. Warner (1985) has reported average well injection rates for several locations within U.S.A. as given in Table 1.

Table 1 - Average Well Recharge

Location	Rate m^3/day
Fresno.Calif.	500-2200
Los Angeles,Calif.	2900
Manhattan Beach.,Calif.	1000-2400
Orange Cove.,Calif.	1700-2200
San Fernando Valley.,Calif.	700
Tulare County.Calif.	300
Orlando.Fla.	500-51,000
Mud Lake.Idaho	500-2400
Jackson County.Mich.	200
Newark,N.I	1500
Long Island,N.Y.	500-5400
El Paso.Texas	5600
High Plains.Texas	700-2700
Williamsburg.Va.	700

Source : Warner,D.L. (1985)

2.4 Water Quality Aspects of Artificial Groundwater Recharge

Sometimes the main reason of artificial recharge is to improve the quality of recharging water by underground flow, removing, for instance, turbidity and E.Coli so as to obtain clear drinking water which is bacteriologically safe. During the downward flow of recharge water the soil of the vadose zone acts as a natural filter and removes pollutants and other impurities from it. The water quality further improves as the water moves through the aquifer although most of the quality improvement takes place in the vadose zone (Bouwer,1985). If the recharging water contains potential pollutants of physical,chemical,baterial, and radioactive nature, these may also pollute the ground water. Harmeson (1963) has described use of recharge pits for recharging ground water after the water is chlorinated to avoid pollution of ground water. Warner (1965) has discussed the technical and economic feasibility of deep well injection of liquid waste in the U.S. The author has stressed proper planning and implementation of deep well injection of liquid waste to avoid pollution of ground water.

Katz (1979) has reported improvement in water quality in an artificial recharge project and attributed this improvement to sedimentation,percolation through a 5 M sand layer, retention time of water underground, and mixing of recharge water with aquifer water. The Author reported following changes in various chemical constituents influencing water quality before and after recharging operations.

Table 2 - Changes in chemical constituents

	From (before discharge)	To (in pumped water)
$\overline{Cl}$, mg/l	60-80	30-50
NO_3,mg/l	20	10-20
ABS,mg/l	0.2	0.02-0.04
El.Contd.	600	400-500
$KMNO_4$ Demand mg/l O_2	3.3	1-2
Coliform counts/100 ml	10^2	2.2

Bize (1979) has described use of artificial recharge for treatment of river water in France. The concept used is in the areas with large alluvial deposits the river water could be infiltrated through these deposits which act as slow sand filters and the infiltrated water could be recovered from well batteries at small distances. The designed and usually achieved aim is production of tap water or water needing only a final sterilization.

Edworthy and Joseph (1979) have discussed some effects of artificial recharge in the Lea Valley,London,England. In the early 70s the Lea Valley in north London was chosen for artificial recharge experiments because of the good transmissive qualities of the Chalk there, and the large volume, 175 x $10^6 m^3$, of dewatered aquifer available. During 1972-74, at one recharge site, recharge of fully-treated water resulted in very high concentrations of some determinands in samples from observation boreholes in the sands; SO_4 rose to more than 3000 mg/l. Richard and Capan (1979) have suggested pretreatment of water before it is used for recharging purposes. According to them pretreatment of water shall improve the quality of recharge water such that only a finishing role is left to soil. Examples of pretreatment of Seine river water in Paris,France have been cited by the author.

Boochs and Barovic (1979) have stated that all ground water in coastal areas of northern Germany has to be prepared before using it for human or industrial purposes, because of its high concentration of iron and mangnese. It has been reported that concentration of these substances is diminished by oxidation processes in special devices which can be removed then by filtration. In order to initiate oxidation in the aquifer itself, water concentrated with oxygen was injected into a natural aquifer by a single recharging well. By initiating oxidation in the aquifer the usual surface preparations are not required.

Baxter and Edworthy (1979) have described the impact of sewage effluent recharge on ground water quality for an area in South East England. The recharging of chlorinated domestic effluent disposal area and the public supply borehole. The chemical analysis of interstitial water, extracted from core samples by centrifuge, and standing water for choloride,nitrate and ammonia show the pattern of effluent infiltration to the water table. The virus concentration in the effluent was reduced by three orders of magnitude within 300 m and the E. Coli count reduced by four orders of magntidue within the same distance of underground travel. The water quality profile along the ground water gradient away from the area of infiltration is shown in figure 2.

In Scandinavia, the ground water generally contains iron and manganese because of prevailing geological and climatological conditions. Consulting engineers at VIAKAB in Sweeden have developed a simple method called re-infiltration for separating iron and manganese from groundwater. By this method water is pumped into a suitable area of aquifer where it is aerated in an overflow cascade and infiltrated to the ground water reservoir through basins. The sand beds in the basins are designed for a filtration rate upto 0.5 m/hr.to get retention time for breaking humid iron complexes and complete the oxidation of manganese. The infiltrated water from sand beds will form volume of purified water in the aquifer which can be used directly for water supply by pumping from wells in the infiltration area (Agerstrand,1979).

Piet et al.(1979) have observed behaviour of organic micropollutants during passage of the soil. It was reported that chemical compounds like tetrachloromethane,tetrachloroethene, trichloroethene,chloroanilines,chlorinated ethers, if introduced into the soil, persist for long time and can deteriorate water quality. The industrial chemicals if discharged to ground, can pollute ground water unless their residence time in the soil is sufficiently long. The processes which modify or remove organic chemicals in the soil are filtration of particulate matter with adsorbed sustances, adsorpotion and ion exchange,co-precipitation with carbonates and sulphides,hydrolysis, microbial decomposi-

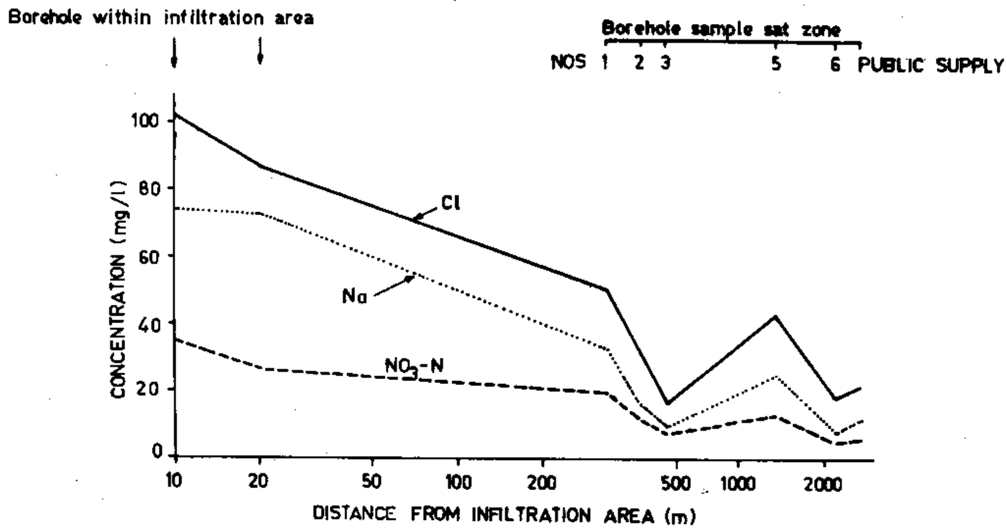

FIG. 2- QUALITY PROFILE DOWN GROUNDWATER GRADIENT AWAY FROM AREA OF INFILTRATION

SOURCE: BAXTER, K.M. AND K.J. EDWORTHY (1979) tion under aerobic and unaerobic conditions and a combination of these processes. In a similar study in Federal Republic of Germany, Kubmaul (1979) reported the behaviour of organo-halogen compounds during underground passage. It was stated that removal of these compounds during artificially recharging ground water occurs mainly in the direct surroundings of the infiltration area.

Rizet et al. (1979) have studied the influence of artificial recharge on water quality using a pilot installation of 10 m depth and 9 m diameter basin. The possible pollutants in, industrial, domestic and agricultural wastes presumed to pollute ground water were heavy metals, phenols, hydrocarbons, ionic and non-ionic detergents and pesticides or compounds formed during pretreatment like organochlorine or other derivatives. Experiments were carried out near Paris, France to measure concentration of these products upon introduction at upstream of the holding basin, during retention in this basin, then by sampling at various ground levels down to the ultimate point at which the water would be tapped by wells. At Peoria, Illinois, USA recharge pits have been in operation since 1951. These pits penetrate a sand and gravel aquifer and recharge water drawn from Illinois river with Chlorine added to it (3-5 mg/litre). Laboratory studies of coarse-grained filtering materials concerning recharge pits demonstrated that the amount of suspended solids removed by the media can be determined by the following equation:-

$$R = -34.5 + 29.8 \log D - 44.0 d - 35.2 \log V$$

where,

R = percent of total suspended solids of the recharge which is removed by the filter medium

D = depth of filter layer, inches

d = mean diameter of filter particles, inches

V = recharge rate, gal./min./ft^2

3.0 PROBLEM DEFINITION

The steady rise in urban population and abnormal demands of upcoming industries have brought about a steady increase in overall water use which has resulted in overpumpage of ground water in regions where it is the main source of water supply for municipal,industrial and agricultural purposes. As a result, the problem of falling water table is being faced in some parts of the country like Gujarat,Tamilnadu,Rajasthan etc. Also in drought prone areas where the condition of low and erratic rainfall, high temperature, low humidity,higher rate of potential evapotranspiration, light soils, sparse vegetation etc. are existing, the natural replenishment of rainfall is not assured and water table declines at an alarming rate as the rate of withdrawal exceeds the rate of replenishment. In order to control the continual decline of water table in such regions, the ground water reservoir needs to be recharged artificially.

The regions which are prone to flash floods like semi-arid and arid parts of Haryana and Rajasthan adjoining Aravali Hills, the flood water can be spread over the flood plains to recharge the groundwater. By conserving the runoff and flood water during rainy period, extra water is made available for dry periods. The aquifer acts as a storage reservoir with a larger capacity. In some cases, the artificial recharge techniques may be required to raise the ground water levels from the existing ones for agricultural purpose for pushing back the sea water in coastal areas which will also reduce the well construction cost. The artificial recharge of water may also be used to improve the quality of water as the water infiltrates through soil zone, it gets purified to certain extent. The formations through which recharge water passes to reach ground water reservoir act as slow sand filters. When the water stays long enough in the ground and travels long distance,the overall quality of water (bacterial population,suspended inorganic or organic impurities etc.) gets improved. Recharging at one place has effects in the ajoining areas which in other words acts as water transporation means. Over pumpage of water may cause land subsidence problem which can also be tackled by recharging the ground water artificially. Of late, idea of conserving energy by either artificially recharging the hot or cold water has also been thought over by researchers, however, extensive use of this is yet to be practiced.

In view of the above, the use of artificial recharge method is becoming more and more common day after another. However, there is not set pattern of planning , design,execution,operation and maintenance of artificial recharge projects. It is intended in this report to review the various aspects associated with artificial recharge projects and provide guidelines for planning, design, execution,operation and maintenance of the same.

4.0 ARTIFICIAL RECHARGE METHODS

Several methods have been developed to recharge the ground water artificially which are being described as foll-ows:-

4.1 Water Spreading

This involves releasing water over the ground surface in order to increase the quantity of water infiltrating into the ground and them percolating to the water table. The basic concept of this method is to increase area and length of time for water to remain in contact with soil that will tend to increase the rate at which water enters into the soil. The efficiency of the process is measured by the recharge rate which is expressed as the velocity of downward movement of water over the relevant wetted area. Water spreading is practised on a large and fast increasing scale all over the world. Various means may be utilised in order to accomplish the water spreading activity which include the following:

4.1.1 Flooding

In relatively flat topography,water may be diverted so as to evenly spread over quite a large area so that water moves in a thin sheet over the land avoiding disturbance of soil and thereby increasing the intake rate of the soil. This method of water spreading costs minimum as compared with other methods and is recommended at places where sufficient quantity of water is available but there are not much monetary resources available to go for more effective techniques of artificial recharge.

32 3.1.2

~~4.1.2~~ Basin injection

The water available for recharge can be released into specially made basins constructed by dikes or levels or by excavation. This is most widely used method for recharging water artificially. Depending upon the land surface slope, the basin size and shapes are adopted and the number of basins will depend upon the quantity of water available for recharge e.g. where local storm runoff is used for recharge, a single basin will normally suffice while if streamflow is diverted for artificial recharge, a series of basins (multiple basins) often parallel to the natural stream channel becomes more beneficial. Sealing of the basins is one of the problems encountered in this method for which scraping or disking of the bottom surfaces is required. Multiple basins provide continuity of operation when certain basins are removed from service for drying and maintenance. In cases where the recharging water carries a lot of sediments, the uppermost basins can be used as settling basins where the sediment will settle and clean water will flow to the lower basin for recharging. A study of artificial recharge projects in California, USA indicated that natural ground slope can serve as a convenient guide for estimating long-time infiltration rates in recharge basins. Todd (1983) has suggested that for alluvial soils in the slope range of 0.1 to 10 percent, the long-time infiltration rate (w) in meters per day is given by:

$$w = 0.65 + 0.56\,i$$

where,

i = natural ground slope in percent

The Recharge sites should have sufficient saturated zone between ground surface and the water table to provide storage space for recharged water. The surface soil should be permeable enough to allow adequate infiltration rates and the sub-surface geology should permit water to percolate readily downward and laterally away from the basins. In order to prevent clogging of basing surface, the water should be diverted into the basins during non-flood periods when suspended sediment is low. The sediment load can also be reduced by adding flocculating agents and subsequently passing the water through sedimentation basins before it reaches to recharge basins. In general, basin method has the following advantages in operation (Raymond and Robert , 1961).

i) basins utilise the maximum area for spreading. They permit water contact over 75-80% of the gross area. This advantage makes it favourable where land values are very high.

ii) irregular and gullied surfaces can be used with minimum preparation

iii) silt ladden water can be used in multibasin system

iv) considerable surface storage capacity is available to store flash floods

v) local materials can be used for construction of dikes and levees

vi) the basins are easy to maintain.

4.1.3 Stream channel method

This method involves operations that will increase the time and area over which water is recharged from a stream channel. In order to increase infiltration in the channel, both streamflow management and channel modifications are required. The erratic runoff rates can be regulated by up-stream reservoirs so that the stream flows do not exceed the absorptive capacity of downstream channels. Channel modifications may include its widening, levelling, and ditching. Small check dams and dikes are frequently used to reduce velocities and spread the flow over the entire width of the channel. These checks may be simply temporary earth structures protected by wires, vegetative cover, rip rap etc. Temporary earth structures are built so that they could collapse when the flow in the stream exceeds a certain limit. Whatever method is adopted the purpose is to extend the time and area over which water is recharged from a naturally influent channel.

4.1.4 Ditch and furrow method

In areas of irregular topography it is easier to recharge water by ditches and furrows. Water is distributed to a series of ditches or furrows which are shallow, flat bottomed and closely spaced. A number of systems for orientation of furrow and ditches have been devised. In general, the following three types of orientation are common:

i) contour type in which ditch follows the ground conto

ii) lateral type in which water is diverted from the main canal to a series of small furrows

iii) tree shaped in which water is diverted from the main canal into successively smaller canals and ditches.

The width of the ditch may vary greatly, but generally ranges from 1/3 - 5/3 meter depending on the terrain and velocity desired. Gradients of major feeder ditches should be sufficient enough to carry suspended material through the system since deposition of fine grained material clogs soil surface openings. However, velocities should not be too high which will cause erosion in the channels. On very steep slopes checks are frequently constructed for minimising erosion as well as increasing the wetted area. A collector ditch is neede at the lower end of each area to carry excess water back to the main channel. For economic reasons, rough ditches are first constructed by using ordinary tools and then are modified and developed during operation. This method has the following advantages:

i) it can be used to supplement a basin spreading project

ii) it can be successfully applied to rough stoney terrain

iii) water with fairly high silt content can usually be used if adequate velocities can be maintained to transport a large part of the silt through the spreading system and deposit in the main channel.

From there, it can be removed mechanically or by washing during floods.

The disadvantage of this method is that percentage of total spreading grounds in direct contact with water is very low,usually 10-12% as compared to 75-80% in the basins(Arya, 1964).

4.1.5 Irrigation method

Application of excess water during non-irrigation or irrigation season can be used as a means of artificially recharging ground water. However, the excess application must consider the crop characteristics to avoid its adverse effects on yield. The seepage from irrigation canals can also lead to raise ground water table. Leaching of soil nutrients and salt to ground water may occur in this case.

4.1.6 Pit method

In regions where shallow subsurface strata restrict the downward movement of water, pits penetrating such layers, can supply water directly to underlying materials with higher infiltration rates. As the silt being carried with water settles to the bottom of the pit, the sides of the pit provide unclogged surface for infiltration of water.

Besides the above mentioned methods, incidental recharge occurs from cesspools, septic tanks, water mains, waste-disposal facilities, sewers,canals, reservoirs etc.

4.2 Recharge Well Method

A recharge well may be defined as a well which admits water from the surface to fresh-water aquifers. Its flow is the reverse of a pumping well,however, its construction may or may not be the same. It is quite useful method for recharging deep confined aquifers. Unlike pumping wells, a recharge well tends to be self sealing. Water has to be very clean to be used for recharging purposes by recharge wells. Todd (1983) has reported average well recharge rates in the USA varying from 200-51,000 m^3/day at different places. Recharge wells served as convenient means for disposal of septic tank effluent,excess irrigation water and surface runoff into the permeable volcanic terrains of the north western USA. Selection of the recharge well method should be preceeded by an evaluation of site geology and geohydrology including; aquifer type, depth,thickness, distribution,hydraulic conductivity, storativity and head distribution. The recharge well can be clogged by suspended particles in the injection water, gas bubbles in the water, proliferation of bacteria, in and around injection water and the well, formation of chemical precipitates in the soil, swelling and dispersion of clay and erosion of soil structure and jamming of the aquifer. Studies conducted in field and laboratories have shown that fresh water can be stored in saline water aquifers through wells first recharged and then pumped.

4.3 Indirect Methods of Artificial Recharge

The common one called induced recharge method is applicable close to a river or lake where a line of wells can be set up parallel to the bank of river or lake. With the abstraction of ground water, the water table level falls below the water level in the river near the shore-line and so, the river water will move towards the line of well which will keep on increasing with more water abstracted through wells. The method is effective in permeable formations which are hydraulically connected between the stream and the aquifer. The stream velocity should be sufficient to prevent sediment deposition from sealing the stream bed. The stream banks act as filters so that normally water entering into the aquifer due to induced recharge is free of organic matter and bacteria even though the river water is not. Also surface water typically contains less total dissolved solids than ground water, therefore, the pumped water will have a better quality than natural ground water (Todd,1985).

5.0 PLANNING AND DESIGN OF ARTIFICIAL RECHARGE PROJECT

Once the over pumpage of ground water because of increased demand of water in various sectors is ascertained, it is necessary to replenish the ground water to control the continous decline in ground water level. It can be achieved by planning and executing an artificial recharge project in the region. The planning process includes selection of suitable recharge sites and recharging method 5.1.

Various factors that need to be considered for selecting the recharging site and method are being described as follows:

5.1 Selection of Recharging Site

Site selection involves consideration of following factors:

- Availability of land and topography
- Hydrogeological conditions
- Possible sources of water for recharge
- Operation and maintenance problems
- Economic considerations

5.1.1 Availability of land and topography

Generally it is considered better to choose flat or gently sloping land for artificial recharge purposes especially if the spreading methods are adopted. Such lands will allow even small amounts of water to spread widely and reduces cost of earth movement in case of basin construction. The topographical maps, low-altitude aerial photographs and informations collected during the site visits could be used for assessing the availability of land and its suitability for artificial recharging.

5.1.2 Hydrogeologic conditions

Analysis of local soil, geologic and ground water conditions is a key element in site selection for artificial recharge. Geologically suitable sites for ground water recharge are found in flood plains, alluvial fans, sand dunes, and places of deep sandy soils, permeable vadose zones and unconfined aquifers. The soil surface should be such that it gives high infiltration rates which could be maintained over long periods. Usually, infiltration basin soil should be sandy loams or still coarser to produce acceptable infiltration rates e.g. more than 20 cm/day. In case the recharge water is polluted, too coarse soil may not be desirable as it also has to filter recharging water for removing impurities. Fine textured soils are more liable to clog and hence infiltration rates in such soils tend to decrease rapidly. Hard crust at the surface is detrimental to infiltration as it has got to be scrapped and removed or harrowed before starting recharging operations. The various characteristics of soil surface which affect the infiltration rates can be summarised as follows :-

- soil permeability: higher the soil permeability more will be the infiltration and percolation rates.
- depth of soil profile: the depth of soil profile determines the thickness of saturated zone. With the increase

in thickness of saturated zone, the infiltration rates decrease for the same depth of water above the soil. It is generally observed in infiltration basins that the suspended material in water (silt, clay or organic particles) etc. accumulates at the bottom of the basin and thus reduce the infiltration rates even by 50% in some cases. Thus, the hydraulic conductivity of bottom soil largely governs the maximum sustained infiltration rates in infiltration basins.

Organic matter - The microbial activities in the soils rich in organic matter get increased with the application of water. Upon drying, the microbial cells contract tending to put the soil particles together into aggregates and resulting in formation of large pores which permit more rapid water movement upon flooding. In general, the organic matter treatment of soils improves its infiltration characteristics. The degree of compaction of soil surface also affects the infiltration rates.

The sub-surface hydrologic conditions are needed to be analysed in order to ensure proper conditions of sub-surface soils from hydrogeologic point of view. It is the sub- strata hydrogeologic conditions that control the percolation rates down below once the water has infiltrated from soil surface. Percolation rates will be high in coarse textured and more permeable subsurface deposits. The greater the specific yield, transmissivity and thickness of sub-surface aquifers, the more will be the percolation rates. The water movement opportunity or the percolation rate is higher with higher hydraulic gradients. The percolation rates are also affected by presence or absence of impermeable layers or lenses that can impede percolation. These impermeable lenses will influence the capacity of recharged area to transmit water to well fields. The information regarding such barriers can be obtained by geologic reports, groundwater resource studies, soil surveys and geologic logs of the existing wells. Field studies including test drilling and percolation tests can be undertaken for defining the type, depth and sequence of the subsurface materials that the recharge water will pass through. Completed test holes can be used to monitor ground water levels, and to collect samples for quality tests to conduct percolation tests to define the recharge capability of the site. After selecting a proper site, the land acquisition process begins which involves land surveys, mapping, title searches, negotiations for purchase etc.

5.1.3 Possible sources of water for recharge

The sources of water for recharging purpose may include local surface water, water brought from other regions known as imported water and reclaimed water. Each source should be considered in terms of cost of water, location relative to recharge sites, quantity and quality. The time-distribution of water sources should be documented to determine seasonal variations in flow. In general, two distinct types of water sources should be considered for water supply. The first one could be perennial supply in which the discharge rate is relatively constant and operation is continuous. This type of source can be realised when surface storage is utilised in conjunction with ground water reservoir. The second one is the erratic supply in which the discharge rate keeps varying with time. In such case, provision has to be made for handling large volumes of water in short periods of time by temporarily storing the excess flows. Sampling of the quality of source water should include determination of mineral and inorganic constituents, physical characteristics, organic chemicals and other pollutants and suspended sediment concentrations.

5.1.4 Operation and maintenance problems

Before selecting a recharge site, it is desirable to assess the likely operation and maintenance problems which greatly vary with the purpose of recharge, method of recharge, quality of water being used for recharge and location of the project. The common problems that arise in an aritificial recharge project for maintaining high recharge rates, for maintaining or improving ground water quality etc. are listed as follows :

a) Spreading basin silting : This depends on the silt load of the recharge water, velocity of water through recharge basin, depth of water on the basin etc. The silt load can be removed by scrapping and harrowing the ground surface.

b) Maintenance of recharge rates : In situations where sub-soil conditions are not favourable , it may turn to be difficult to maintain the desired recharge rates. Maintenance of recharge rates may involve water treatments, use of settling basin, use of filter beds, periodic drying of basins to allow the sealing skin to curt and crack and scrapping of basins for silt removal. The recharge rates are assessed by continously monitoring the water inflow.

c) Spread of diseases: Due to large areas continuously put under submerged conditions, some diseases may spread in the vicinity of the recharging sites. Specially, if recharging is done by polluted water, the atmospheric conditions may get adversely affected. Thus, the sites are avoided to be located in highly inhabitated areas.

d) Construction and maintenance of diversion structures: The site selection process must include consideration of problems that are asociated with construction and maintenance of diversion structures which are used for diverting recharging water from various sources.

e) Pest control: Maintenance of standing water can cause insect problems. Insects and nuisance aquatric plants can be treated by periodic dewatering or stocking with fish.

5.1.5 Economic considerations

The economic feasibility of the artificial recharge project is needed to be established before taking up the construction and operation of the project. The benefits from recharge could be obtained in the forms of relief of overdraft on the ground water basins, use of ground water basins as reservoirs and distribution systems and purification of water obtained after recharge. Due to rise in ground water table, the immediate benefits that are realised are : the pumping cost of water gets reduced; the well construction cost also decreases; in some cases irrigation water requirements of crops get reduced as ground water contribution in the crop root zone increases;

in coastal areas sea water intrusion is prevented etc. A ground water reservoir may be used for the storage and regulation of surface supplies as this reservoir can be recharged in periods of surplus water supply which can be used during dry periods. In this way, the cost of surface storage reservoir which would have been required in absence of ground water storage is saved. Also evaporation losses of water will reduce to nil with no contamination when ground water reservoirs are used for water storage purpose. In the process of water movement through soils, the vadose zone acts as a natural filter that removes pollutants and other impurities from the percolating water. In this process the quality of water gets improved. But since aquifers usually consist of coraser materials than vadose zone, most of the quality improvement takes place in the vadose zone. Bouwer (1985) has referred such water purification system as the Soil Aquifer Treatment (SAT) system.

The United Nations has brought out a report on ground water storage and artificial recharge in 1975 which has given a check-list summarising the planning phase of an artificial recharge project which is given in table 3.

Table 3 Planning a Surface Recharge Project
(source : United Nations,1975)

1. Source of water and pricing policy
2. Water rights
3. Potential liability (flooded gravel mining operations, raising ground water levels too close to the ground

surface and jeopardising surface improvements.

4. Effects on ground water basin management

5. Effects on ground water quality

6. Investigations (involving exploration of the geological and hydrological conditions) to prove feasibility of scheme.

7. Environmental impacts

8. Rights of way

   a) Surveys b) Maps c) Title search d) Condemnation (including legal and court fees) e) Rezoning

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5.2 Selection of Recharge Methods

Once a suitable site has been identified, the next step is to select a suitable method of recharging the ground water. The broad categories of recharge methods as described earlier are :

i) Spreading methods

ii) Injection methods

iii) Induced infiltration

To select one out of these broad categories, a thorough study of surface and sub-surface characteristics of recharge site and quality of the recharge water is required to be done. The induced recharge method is least expensive out of these, however, it is possible only if there is a stream or lake in the vicinity of the area where artificial recharging is required. Moreover, the bank and bed of the stream or lake should be made of pervious material as also the underground formations between the source of water and the area where ground water level is required to be raised.

The choice between spreading and injection methods is based on hydrogeologic conditions of soil substrata. If there is continuous impervious layer of large areal extent intervening between the ground surface and ground water reservoir, it is always desirable to go for injection method. However, if lenses of less permeable soils are present at shallow depths or a continuous but thin less permeable layer is underlying the surface soils, the use of spreading methods like ditches and furrows is more effective than using injection methods. Generally, spreading methods are used when the soil is homogeneous throughout the soil strata upto ground water table. The choice between broad categories of recharge methods is quite obvious in most cases,however, the choice between various methods of a particular category is not always clear.

In case of spreading methods, the recharging is preferred by flooding method in areas where the land slopes are gentle and uniform and surface and sub-surface soils are homogeneous and coarse textured. Flooding method will also be preferred in areas where recharge water is relatively cheaper compared to costs involved in construction of recharge facilities. When a large flexibility in operation and maintenance of recharging facilities is required, the basin method of recharging is preferred as number of basins with necessary control structures give the desired flexibility of operation. A high rate of infiltration can be expected in basins so in areas where land values are high, recharging should preferably be done by basin method of spreading. As the basins can store water too, these are also suitable in regions where flash floods occur frequently. In areas where not much area is available for recharge purposes ditches and furrow methods of water spreading prove more useful. In areas of rough and stony terrains with steep slopes, the basin construction may not be easy so, furrows, and ditches may be more useful from recharge point of view. If the recharging water contains a lot of silt, it could be recharged through ditches with stable soil conditions by making the water flow at a velocity which prevents silting. In regions where streams are subjected to flash floods of short duration, artificial recharge by modified stream bed method is more economical.

In situations where recharge by injection method is more suitable, the choice is required to be made among various injection methods i.e. pits, shafts, tunnels and recharge wells. In general, recharge pits are used in conditions where the impervious layer does not extend too far below the ground surface. When the top impervious layer is too thick to be penetrated by a pit, shafts are used for recharge purposes. When a very deep lying impervious layer is to be penetrated, recharge wells are used for ground water recharge. This method requires clean water for recharging otherwise, the recharging wells may get clogged. A line of recharge wells along coastal line is quite commonly used to build a fresh water pressure ridge to repel and check the sea water intrusion in confined coastal aquifers.

5.3 Design of Artificial Recharge Systems

The design of any recharge project is largely governed by the amount of overdraft,surface and sub-surface characteristics of soils, geologic and hydrologic conditions of sub-surface, mound levels desired after recharge,pattern of surface drainage, availability of construction material etc. After selection of method of recharge,it is needed to find the dimensions, number and spacing of different recharge units. The design of a particular method of recharge varies depending upon the site conditions. The design of recharge method is unique for a particular site condition. However, the broader outline of procedure to be followed and design criteria of different types of recharge systems are described as follows:

5.3.1 Design of spreading system

In order to maintain mound level below ground surface a certain quantity of water is required to be recharged at a uniform rate which will pass through the mound and will ultimately be discharged at the lateral control which may be a drainage stream, sea shore, pumping through or a collecting gallery. Total amount of water to be recharged for maintaining the mound level and allowing pumpage can be calculated with the help of equations. Based on the quantity of water to be recharged, the dimensions, number and spacing of recharge units can be established for getting a particular recharge rate. To find total quantity of water to be recharged, the surface losses like evaporation and transpiration and leakage from aquifers to underground formations should also be given due consideration.

The flooding method of spreading involves flooding of a large extent of area with a low water depth. The total area to be flooded can be found out by dividing the required recharge rate (volume per unit time) by the average infiltration rate (depth per unit time). As the recharging process advances, the infiltration rate decreases due to clogging effects of fine materials collected over the recharge area. It is,therefore, an average rate of infiltration used to find out the flooding area. However, the value of design infiltration rate also depends on the operation schedule of the flooding area. For example, if the recharge water is available in larger quantity for shorter duration i.e. during high flood flow, higher values of infiltration can be taken for finding flooding area as the decrease in infiltration rate is not very significant during the short flooded period. However, if the ground is kept flooded for longer time, an average value of infiltration rate should be used for finding the area to be flooded.

In case of basin method of spreading, the area of basin can be found by assuming a representative value of infiltration rate as in case of flooding method. Basins are preferred in cases when less pervious soil underlies the more pervious soil strata and overlies the ground water reservoir. In such cases the size of spreading basin is governed by the depth of less pervious layer below ground surface. It has been experienced that if the less permeable layer is deep lying, use of large spreading basin is economical. In the USA, use of multi-basin for recharge purposes is in vogue. This is particularly suitable in cases when high silt ladden water is available for recharge operations. The upper one or two basins can be used for removal of silt from the recharging water. Todd (1985) has described a nomograph for determining the dimensions of spreading and settling basins which is shown in figure 3. The basin area can be found by this nomograph based on the pumping rate, retention time of water, and infiltration rate. Higher rates of infiltration can be obtained in case of basins as compared to flooding grounds because water depths that are maintained in basins are relatively more. Therefore, in regions where land values are high, the use of basin spreading is advantageous compared to flooding method. Infiltration rates in different basins have been observed to vary from 1.67 - 16.7 m./day with higher values in basins where height of basin above water table is appreciable.

The ditch and furrow method of spreading is used where only a fraction of the total surface area is required for spreading and the land slopes are too steep to construct basins. Recharging with water having fairly high silt content can also be done by ditches provided these are made in stable soil. The efficient recharging is obtained by placing the collectors or locating the pump for withdrawing water in a line exactly in between and parallel to the adjacent dithces. The design of ditches involves finding out the dimensions of the ditches with a given spacing or vice-versa. The ditch design is governed

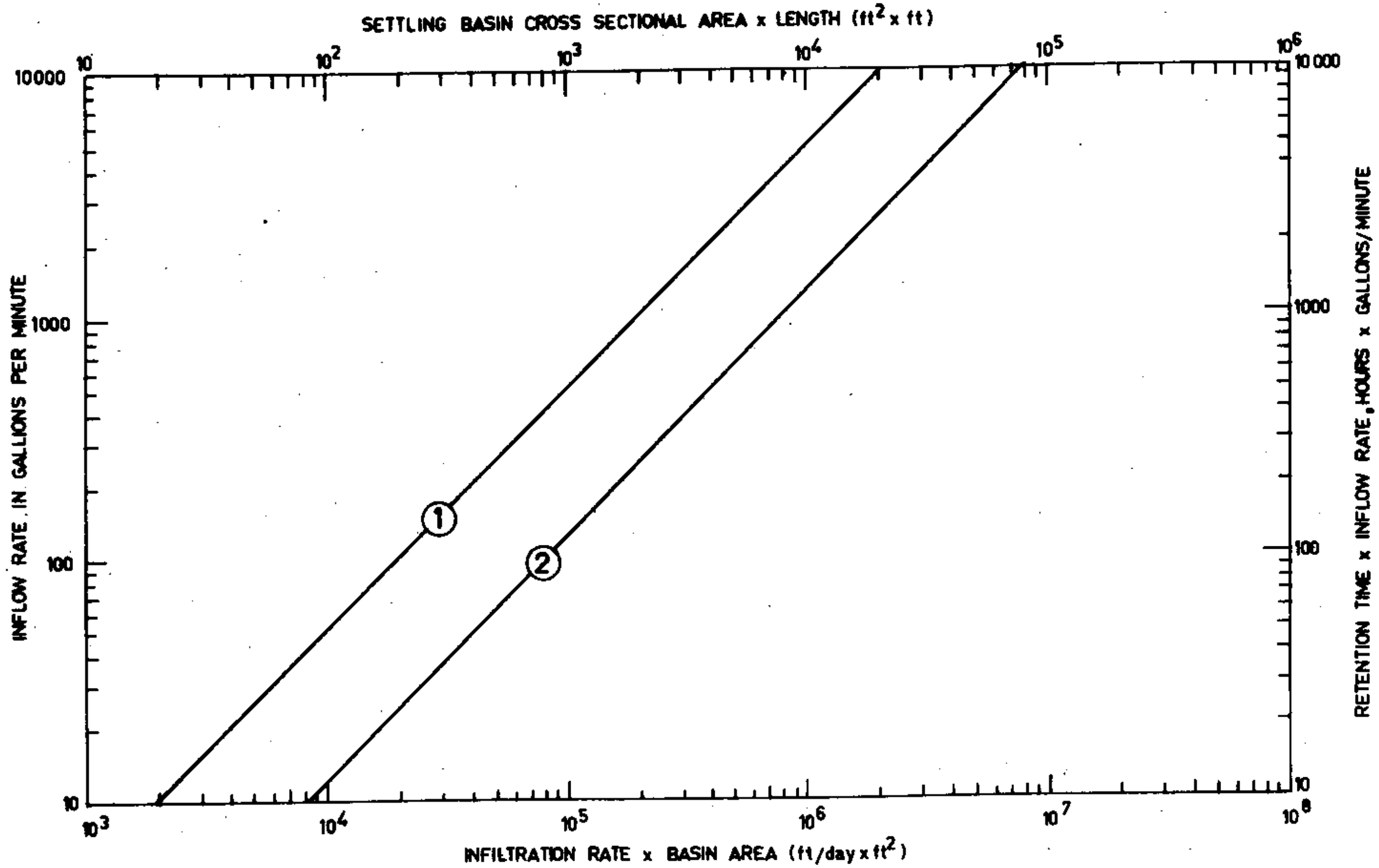

FIG.3-GRAPH FOR DETERMINING THE DIMENSIONS OF SPREADING AND SETTLING BASINS

SOURCE: TODD, D. K. (1985)

by the sub-surface geological conditions.

5.3.2 Design of injection systems

Design of injection systems require knowledge of geo-hydrological constants such as permeability, transmissivity etc. of the aquifer. These can be determined by carrying out pumping tests. A broad outline of design procedure to be followed in different injection systems is as follows :

A recharge pit is used to penetrate through a less pervious or impervious layer and it may be continued in the pervious formation in order to increase the area of infiltration. A recharge pit having larger length as compared to width may be designed in similar way as the spreading ditches. If the length and breadth of the pit are comparable, the approximate mound shape, pumpage capacity of the area can be used to find the total quantity of water to be recharged in a given time which can be used to find the dimensions of the pit.

The design of recharge well involves an evaluation of site geology and geohydrology including aquifer types, depth, thickness, distribution hydraulic conductivity, and head distribution. Grain size distribution of granular aquifers is important design information. During injection by a recharge well, a cone of recharge will be formed that, theoretically, will be reverse of the cone of depression for a pumping well. The equation that describes the shape of the recharge cone during steady-state conditions for a well fully penetrating a confined aquifer is :-

$$Q_r = \frac{2\pi \; Kb(h_w - h_o)}{l_n \; (r_o/r_w)} \qquad \ldots (4)$$

In case of fully-penetrating well recharging an unconfined aquifer, the equation is :

$$Q_r = \frac{\pi K(h_w^2 - h_o^2)}{l_n (r_o/r_w)} \qquad \ldots(5)$$

The symbols are identified in figure 4. Based on equations 1 & 2, the diameter of recharge well and the injection heads to be maintained can be found out for confined and unconfined aquifers respectively. The diameters of injection wells differ from those of production well in that there is no need to accommodate a pump and it is the pump size that usually controls the well diameter in production wells.

5.3.3 Induced recharged systems

The design of induced recharge systems involves finding out suitable distance of the collectors from the stream and their spacing for a known water requirement so that river water is induced to recharge the aquifer in sufficient amount to maintain water table levels within desirable limits. The distance of the collectors from the stream is decided based on two considerations namely, this distance should be such that during the travel of water from stream to the collector it gets sufficiently purified and also the proportion of the total quantity of water induced through direct infiltration should satisfy collector capacity; hence the distance chosen should be such which will yield in high percentage of induced recharge. Once the location of collector with reference to stream is fixed, the dimensions of the collector can be decided based on quantity of water which is expected to flow towards the

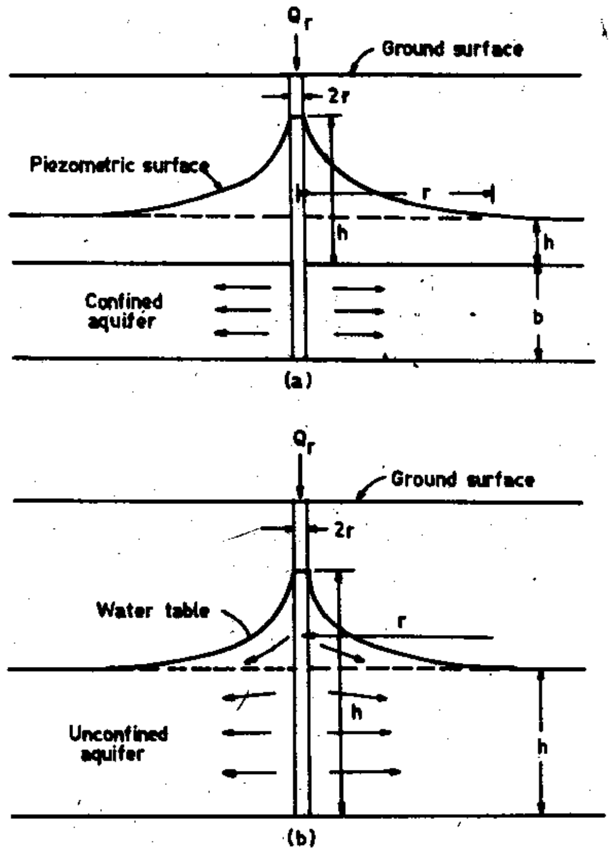

FIG. 4-RADIAL FLOW FROM RECHARGE WELLS PENETRATING (a) CONFINED AND (b) UNCONFINED AQUIFERS.
SOURCE: WARNER, D. L. (1985)

collector.

5.4 Engineering and Construction of Recharge Facilties

These involve surveying and detailed mapping of the site design and construction of recharge facilities, supervision of construction, inspection and testing. A check-list summarising engineering and construction of surface recharge projects has been given in table 4.

Table 4 Engineering and Construction of Surface Recharge Projects (from United Nations, 1975 ; 97-98)

Engineering

1. Surveys and mapping
2. Design
3. Contract administration
    a) Supervision
    b) Inspection
    c) Testing

Construction

1. Spreading facilities (basins, levees, check dams)
2. Diversion structures (dams, head gates)
3. Control structures (weirs, gates)
4. Monitoring facilities (gauge stations, monitor wells)
5. Water treatment (Chlorination, fluctuation)
6. Access
7. Fences
8. Sheds for equipment.
9. Landscaping

In case of injection method, any drilling method that is used for construction of production wells can also be used for drilling injection wells. Performance of drilling methods in various types of geologic formations is given in table 5. The usual criteria for selecting gravel packs for production wells, the well development processis also done with injection wells with the help of various methods including pumping, surging, air surging, air backwashing, hydraulic testing, chemical treatment and hydraulic fracturing.

5.5 Operation and Maintenance of Recharge Facilities

In order to maintain high recharge rates, provide water compatible with the aquifer, maintain or improve ground water quality, it is required to have a proper control on operation and maintenance of recharging facilities. The recharging water can be treated by screening or filtration to remove suspended sediment and floating debris, chlorinating or treating with copper sulphate to eliminate algal growths and flocculation to reduce suspended sediments. In case of spreading methods, the deposition of sediment on ground causes drastic reduction in recharge rates which needs to be controlled by various methods including water settling basins, use of filter beds, periodic drying of basins to allow the sealing skin to curl and crack, and to disrupt growth of algal and scrapping of basins or silt removal. In standing water measures to control pests etc. are also needed. The recharge rates can be monitored by recording amounts of water inflow and outflow from the

Table 5 - Performance of Drilling Methods in Various Types of Geologic Formations

Type of Formation	Drilling method		
	Cable Tool	Rotary	Rotary Percussion
Dune sand	Difficult	Rapid	NR
Loose sand and gravel	Difficult	Rapid	NR
Quicksand	Difficult, except in thin streaks. Requires a string of drive pipe	Rapid	NR
Loose boulders in alluvial fans or glacial drift	Difficult; slow but generally can be handled by driving pipe	Difficult frequently impossible	NR
Clay and silt	Slow	Rapid	NR
Firm shale	Rapid	Rapid	NR
Sticky shale	Slow	Rapid	NR
Brittle shale	Rapid	Rapid	NR
Sandstone,poorly cemented	Slow	Slow	NR
Sandstone,well cemented	Slow	Slow	NR
Chert nodules	Rapid	Slow	NR
Limestone	Rapid	Rapid	Very rapid
Limestone with chert nodules	Rapid	Slow	Very rapid
Limestone with small cracks or fractures			Very rapid
Limestone cavernous	Rapid	Slow to impossible	Difficult
Dolomite	Rapid	Rapid	Very rapid
Basalts,thin layers in sedimentary rocks	Rapid	Slow	Very rapid
Basalts,thick layers	Slow	Slow	Rapid
Metamorphic rocks	Slow	Slow	Rapid
Granite	Slow	Slow	Rapid

* NR : Not recommended

Source : Warner,D.L.(1985)

recharging sites. Observation wells, one at the centre of the recharge area to monitor the maximum mounding effect and another down-gradient of the facility to determine impacts on the surrounding water table are at least needed. In case of injection wells, the injection rate can be predicted based on local experience, subsurface geologic data and aquifer tests. To drive the recharge water into the receiving aquifer, a head of water is required called injection head for confined aquifers, which is limited by the head that will cause fracturing of confing strata. The wells are needed to be monitored for injection rate, injection head and the quality of injection water. The injection capacity of recharge wells gets decreased as the well is clogged because of various factors including suspended particles in the injection water, gas bubbles in the water, proliferation of bacteria in and around the well, formation of chemical precipitates in the injection water and the well, formation of chemical precipitates in the soil, swelling and dispersion of clay, and erosion of soil structure and jamming of the aquifer. The clogging of wells and groundwater contamination can be prevented by treating recharging water for removal of suspended solids and by chemical stabilization and bacterial control.

5.6 Costs

The total cost incurred in an artificial recharge project can be divided as capital cost and the annual cost. The capital cost includes the money involved in land acquisition and construction of recharging facilities. Annual costs include cost of water, operation and maintenance costs, taxes,insurance, if any and salaries and other benefits of operating staff. Priestaf (1985) reported that for San Jose Creek Recharge basins in California, total capital costs amount to US Dollars 5,120,000 ; and unit capital cost as U.S. Dollars 512/1000 m^3. The unit cost for operation and maintenance is reported as Dollars 186/1000 m^3 which makes total unit cost of recharge as Dollar 700/1000 m^3. For injection wells, Warner (1985) has reported construction costs for the Los Angeles county west coast Basin barrier project for 1964-1969 as given in table 6. He also reported the operational cost of the Los Angeles County Alamitos barrier injection project during 1982-83 as Dollar 77.58/acre-feet of injected water.

Table - 6 West Coast Basin Barrier Project Construction Costs

Unit	Facilities	Completion date	Construction cost*
1	31,200 Pipleline,pressure regulation and chlorination station	1-64	$ 1,482,185.06
1A	12 Injection Wells	9-64	337.793.67
1B	14 Observation Wells	5-64	55,580.82
1C	13 Observation Wells	12-64	70,739.58
1D	19 Injection Wells	6-65	409,371.66
2	14,200 Pipeline,pressure regulation and chlorination station	6-68	646,961.52
2A	8 Injection Wells	5-68	145,787.81
2B	9 Observation Wells	12-65	71,749.41
2C	9 Observation Wells	11-66	48,594.88
2D	6,000 Pipeline	7-67	124,974.09
2E	11 Injection Wells	5-68	186,154.84
3	8,200 Pipeline	3-66	349,416.14
3A	9 Injection Wells	3-66	
3B	6 Observation Wells	12-64	31,885.39
3C	7,000 Pipelines,21 Vaults	12-66	161,458.85
4	9,300 Pipeline	12-64	182,297.05
4A	17 Injection Wells	2-66	549,254.03
4B	26 Observation Wells	9-64	198,339.80
4C	5 Injection Wells	4-66	170,044.07
5	9 Observation Wells	5-68	82,286.50
5A	6 Observation Wells	5-69	53,209.28
		Total Cost	$ 5,358,084.45

* Amount paid to contractor,does not include LACFCD expenses associated with construction.

6.0 MATHEMATICAL MODELLING OF RECHARGE SYSTEMS

Mathematical models of aquifers are a means of understanding the flow mechanisms within an aquifer. Mathematical models are especially convenient to devise for simulating the mechanics of flow through porous media such as seepage through dams, salt water intrusion in aquifers etc. A mathematical model is a mathematical expression or group of expressions, that describes the hydraulic relations within the system. It is usually in the form of a differential equation or a set of differential equations, together with the auxiliary conditions.

Two types of information must be available to prepare a mathematical model of any flow system, namely, the laws governing the system variables such as flows or potentials and the auxiliary conditions describing the system constraints. Three types auxiliary conditions are of interest, namely, the system geometry, the hydraulic characteristics of the system matrix or system parameters and the initial and boundary conditions.

In order to model a ground water flow problem, good data is essential in respect of following parameters:

i) Values of hydraulic conductivity

ii) Values of the confined storage coefficient

iii) Values of specific yield

iv) Inflows to the aquifer (and how they change with time). In addition, if artificial recharge is to be presented by the model,changes in the parameters may occur due to :

i) clogging of the spreading channel

ii) deterioration of the recharge well

iii) water logging

It is usual to describe a groundwater problem in terms of groundwater head mainly because the head can be measured directly in the field and the head is a convenient quantity for the mathematical calculation. Although the groundwater head is a convenient parameter, the quantity flowing is often more important. Once the solution has been obtained in terms of the groundwater head, it is always possible to calculate the distribution of flows.

All groundwater problems are truely three dimensional in space (x,y,z or r,z,θ) plus the time dimension. However, it is not usually practicable or necessary to obtain solutions in each of these four dimensions because :

i) Mathematical and numerical solutions are difficult to obtain,

ii) There is often insufficient field data to justify the detailed solution, and

iii) One or more dimensions can be eliminated

Therefore, solutions are often obtained using the following approximations:

i) Groundwater flow from spreading channels(x,z,t)

ii) Groundwater flow from recharge wells (r,z,t)

iii) Regional groundwater flow (x,y,t)

General Groundwater flow equations

Darcy (1856) worked with flow of water in sand and developed the well known Darcy's law which states that the velocity of ground water flow is proportional to the hydraulic gradient. Later, various researchers developed the ground water flow equations by combining the Darcy's equation with the principle of mass balance. Mass balance involves consideration of inflow, outflow and changes in groundwater storage. A general governing differential equation could be writen as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K} \frac{\partial h}{\partial t} \qquad \ldots(6)$$

where,

h = head above datum, L

S_s = specific storage, L

x, y, z = space coordinates, L

K = hydraulic conductivity, $L\ T^{-1}$

The above equation holds good for aquifers with isotropic a homogeneous conditions. In case of steady state flow, equation 6 becomes,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad \ldots(7)$$

which is same as the Laplace equation and describes the steady flow.

Multiplying the r-h-s of equation 6 by saturated thickness of aquifer(b) and using the Laplacian operator, it can be written as :

$$\nabla^2 h = \frac{S}{T} \frac{\partial h}{\partial t} \quad \ldots(8)$$

where,

S = storage coefficient (dimensionless)

T = Transmissivity, $L^2 \; T^{-1}$

S and T in equation 8 are defined as aquifer parameters. Equation 8 is basically derived for confined aquifer. However, the same equation can also be used for unconfined aquifers provided vertical component of the flow is negligible and the saturated thickness of the aquifer is large enough to the drawdown. In case of unconfined flow, the storage coefficients, will be replaced by specific yield (S_y) term.

The solutions of ground water flow problems can be found out by analytical methods, methods based on the use of models and analogs, and numerical methods. When more than one method can be applied to a given problem, the selection of most suitable one depends on the availability of skilled manpower and on time and costs required for reaching a solution.

The analytical solutions of ground water flow problems are obtained under simplified assumptions otherwise in real life ground water system because of complex boundary conditions, non-homogeneous and anisotropic nature of the system and wide variations in space and time of the external recharge/discharge (Q) term, the analytical solutions become practically impossible to obtain. However, in literature there are analytical solutions available for different types of defined boundary conditions which help in understanding the ground water flow systems. Though analytical solutions can give useful information,however, there are two warnings that need to be given about analytical methods, namely,

i) Often simplification and idealisations have to be made to fit the exact mathematical solutions which are available.

ii) The idealisations which have to be introduced in analytical solutions may mean that certain critically important features cannot be included.

Analog models can either viscous flow models or electrical analog models and can represent hydrologic nature of an aquifer system. However, due to advent of fast digital computers this method has been outdated.

The numerical methods of solving groundwater flow problems gained momentum sometime during early 1970s. The main advantages of numerical methods are the flexibility of application and accuracy of solutions that are obtained. There are several numerical techniques available in literature (Remson et al.,1971) the most common being the finite difference and finite element methods. In case of finite difference methods, the governing differential equation is replaced by difference equation. The region is discritized into rectangular grids or polygons with each grid/polygon centering about a nodal point with the basic assumption that over the area represented by a grid, the recharge, abstraction, hydrogeologic properties remain unchanged and are represented at its nodal point. Thus, the aquifer parameters are discritized and the governing differential equation involving the head values at the nodal points is solved by applying suitable boundary conditions and solving the set of equations.

The finite element method essentially consists of following steps :

i) Discritization of the region and defining the nodal points and elements.

ii) Defining the flow matrix and flow load vector corresponding a single element derived on the basis of appropriate choice of element type and basis function.

iii) Assembly of element matrices and load vectors to obtain global matrix

iv) Solution of the systems of equations for nodal values.

Though finite element approach is more powerful than finite difference method, the application models using finite element approach for real life situations still lack momentum.

Initial and Boundary Conditions

Each partical differential equation of ground water flow describes a class of phenomena, the equations themselves contain no information (e.g., the shape of the flow domain) related to any specific case of flow through a porous medium. Therefore, each equation has an infinite number of possible solutions, each of which corresponds to a particular case of flow through a porous medium domain. In order to get solution of a certain specific problem of interest, it is necessary to provide supplementary information like the geometry of the domain in which the considered flow takes place values of relevant physical coefficients, initial conditions which describe the initial state of the fluid in the considered flow domain and conditions on the boundaries of the considered flow domain (Bear ,1979).

Initial conditions include the specification of piezometric head (H) at all points within the domain D at some initial time, usually denoted as

t = 0 or,

H = f (x,y,t,o)

for all points x,y,z included ;

f is a known function.

The various types of boundary conditions generally encountered in flow through porous media are the following:

i) Boundary of prescribed potential or head controlled boundary: This is a boundary with a known potential or hydraulic head, which may or may not be a function of time or,

$H = f_1 (x,y,z)$, or $H = f_2(x,y,z,t)$

where f_1 and f_2 are known functions.

A boundary of this kind occurs whenever the flow domain is adjacent to a body of open water, e.g.lakes,oceans,water courses and irrigation canals.

ii) Boundary of prescribed flux or flow controlled boundary

It is a boundary through which a certain volume of ground water enters/leaves the basin per unit of time from/to adjacent basin. At a boundary of this type the flux normal to the boundary surface is prescribed for all points. Flow controlled boundaries are simulated by setting up hydraulic conductivity at the boundary equal to zero and considering the under flow in the model as a recharge/discharge term.

iii) No flow boundary:

A no flow boundary could be an impermeable base or in mathematical terms a boundary across which the hydraulic gradient is zero, or at no flow boundary:

$$\frac{\partial h}{\partial x} = 0$$

where,

h = hydraulic ahead

x = direction normal to the boundary

After discussing the basic ground water flow equations methods of solving them, various boundary conditions, a complete statement of groundwater flow problem could be as given in following steps :

i) specify the geometry of the flow-domain in the aquifer.

ii) determine which dependent variable (or variables) is to be used.

iii) state the continuity equation describing the flow in the aquifer.

iv) specify the initial conditions

v) specify the boundary conditions which the hydraulic head (H) or its derivatives have to satisfy on the boundaries specified.

In artificial recharge problems besides finding out the temporal and spatial distribution of piezometric head, the quality of water is often a significant feature. Certain modelling techniques are available to represent both quantity and quality of the groundwater but there are some disadvantages associated with such modelling, namely, parameters related to quality are difficult to measure, solutions require complex numerical techniques which are often unstable, the true variable nature of an aquifer can not be represented, and many, of the chemical reactions cannot be included in the solutions.

7.0 FIELD APPLICATION

Artificial Recharge Project in Mehsana Area of Gujarat State India :-

In order to control the aquifer depletion in Mehsana alluvial areas of Gujarat state, the Central Ground Water Board carried out a project in collaboration with the UNDP for finding out suitable methodology for artificial recharge. The main objectives of the project were (i) to examine technical feasibility and economic vaiability of storing the available surplus flow of the Saraswati and the Rupen rivers in the ground water reservoir and to examine its effect on counteracting overdraft conditions in the Mehsana alluvial areas (ii) to examine technical feasibility and economic viability of artificial recharge of ground water and its effect on regional ground water quality near coastal area (iii) to study long term and short term socio-economic benefits of such endeavour in regular recharge cum development program (iv) to evaluate biological activities affecting recharge and (iv) to evaluate environmental impact of recharge.

Mehsana area has alluvial deposits extending over a distance of 330 km. from the foothills of the Aravalli mountains in the north to the Gulf of Cambay in the South with an average width of 150 km. Sabarmati river forms the eastern boundary while the western boundary is obliterated by the sands of the little Rann of Kutch. The extent of the most overexploited area from groundwater point of view is limited to central and eastern parts of the Mehsana district. The alluvial plain in Mehsana area slopes very gently towards south west and the presence of sand dunes has resulted in rolling topograph in the region with the height of dunes ranging from 3-15 meters above the surrounding areas. The sandy nature of the soil, the semi-arid climate and the physiographic control by the sand dunes, all contribute to the development of internal drainage in the form of small streams which is found in different parts of the Mehsana area. Normal mean annual rainfall in the area of 672 mm and the temperature varies from 13 to 40^{o}C depending upon the season. Being close to the great Rajasthan desert, the storm in the desert cause frequent dust storms in the alluvial tract during winter and summer months. During the dust storms, the accumulation of dust is as high as 40 tons/sq.km./day. The mean annual potential evaporation is about 1627 mm. The soils in Mehsana area can be classified as light sandy, particularly in recharge zone they are calcic, brown and deep loamy sands with good permeabilities. Soils do not have water retention and fertility status. As per the geological conditions, the alluvium comprise several sand and clay zones both varying in thickness from few meters to as much as 20 m and in exceptional cases upto 60 meters. The hydrogeological section across Mehsana alluvial area as reported by Phadtare (1985) is shown in figure 5. The chronological sequence of the alluvial formations at the project experiment site is as follows:

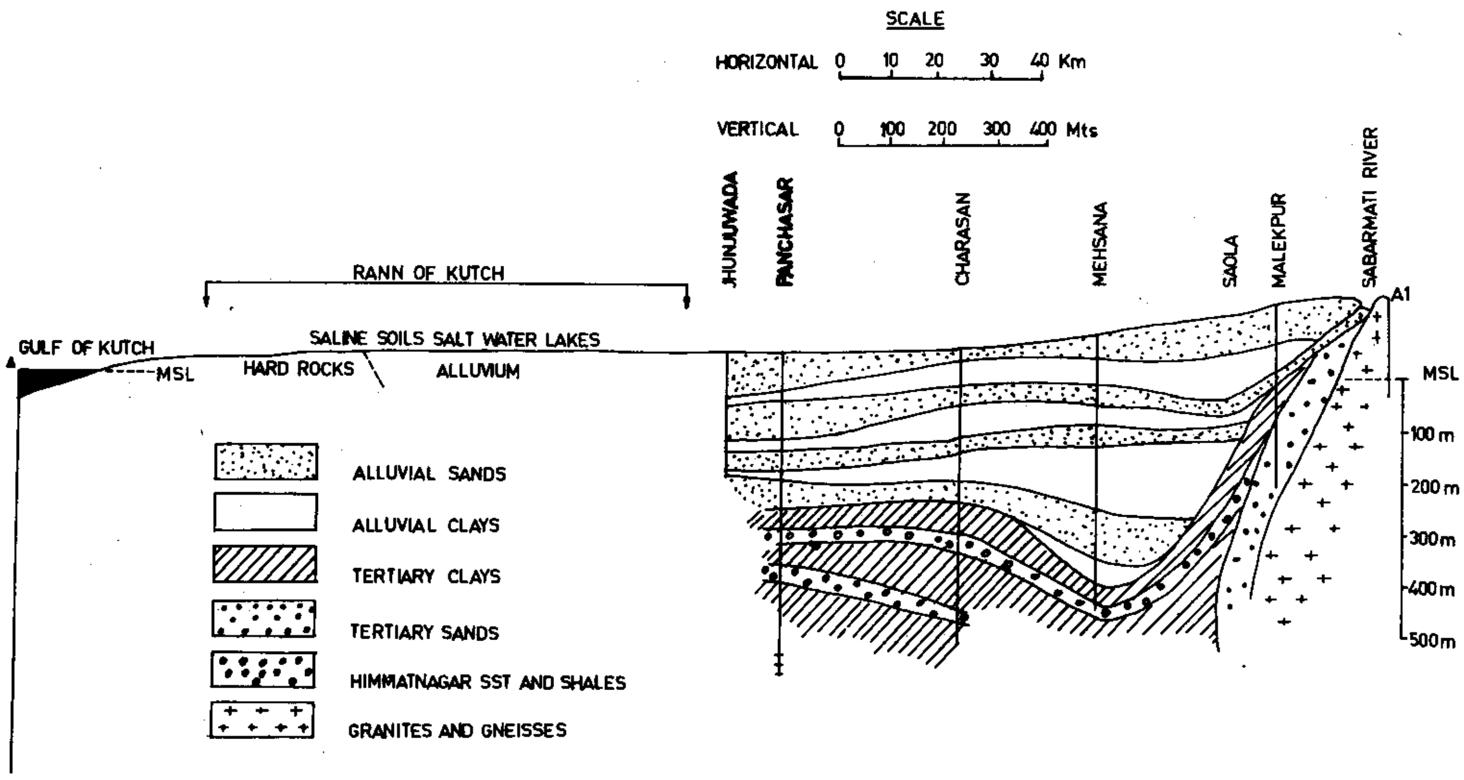

FIG. 5 - HYDROGEOLOGICAL SECTION ACROSS MEHSANA ALLUVIAL AREA
SOURCE: PHADTARE, P. N. (1985)

Table 7 - Chronological Sequence of Alluvial Formations at the Project Experiment Site

Formation	Thickness in meters	Depth Range in meters	Remarks
Phreatic Aquifer(A1)	5-30	0-35	Comprising of flood plain deposits, shallow alluvial deposits in common zone and blow sand deposits over entire alluvial area
Aquitard I	5-30	10-60	Sandy clays
Confined Aquifer (A 2)	20-30	35-90	Alternate bands of medium to five grained clayey sands with gravel
Aquitard II	10-15	55-110	Yellowish sticky sandy clays with clayey sand lenses
Confined aquifer (A 3)	15-25	110-160	Lithology same as aquifer A 2 above

The piezometric levels in confined aquifers exhibit large declines during post-monsoon period due to heavy withdrawal for irrigation and this trend continues till the later half of February when the winter crop is harvested. As there is not much cultivation during summer, the withdrawal reduces considerably and the piezometric levels start raising gradually. The annual ground water draft in the year 1983,from the shallow aquifer system upto the depth of 130 meters was of the order of 554.90 MCM against annual ground water recharge of 876.60 MCM (Phadtare,1984). In six blocks namely Kadi,Kalok,Mehsana, Sidhpur,Visnagar and Viapur the total draft is of the order of 27.5 m/ha/year. These six blocks comprise of the 4200 sq.kms out of which 1600 sq.km. come within the Dharoi canal command and rest 2600 sq.km. needs immediate remedial measures to the check the decline in ground water levels. The source of water for artificially recharging the ground water reservoir is selected from the surface water resources available in the immediate vicinity of the affected area. Keeping this in view, availability of water from Saraswati river just north of the overexploited area, Rupen river and its tributaries like Pushpawati and Khari in the central Mehsana area and the tail end releases from the Dharoi canal system between Mehsana and Vijapur are being evaluated. Rupen and its tributary discharge about 53 MCM of water by way of flash floods during the 4 month monsoon period. On an average, flow of 2.25 m^3 to 10.7 m^3 is available for about 12 days in a month. This surface run-off is at present not utilised and gets discharged into the saline tracts of Rann of Kutch. The flood plain deposits of Saraswati river between the towns of Patan and Sidhpur, about 26 sq.km. in areal extent have dynamic ground water resources of 13 MCM upto shallow depth of 5 meters. These resources could be utilised for artificial recharging of ground water in over-exploited zones.

The moderate to high permeability of the blown sand deposits which are present over the entire area and the increase in permeability of the alluvial formations from below the depth of 2 meters, make the entire alluvial area suitable for artificial recharge by spreading methods. The results of artificial recharge in Dhabu location of Mehsana are given below:

Table 8 - Artificial Recharge in Dabhu Location at Mehsana

Recharge Structure	Test Period	Source Water	Recharge Rate	Build up	Dissi-pation
Spreading Channel 3.3 m wide 400 m. long with 1:1 side slope, wetted pari-meter 1520 m	28.8.84 to 17.6.84 (46 days)	canal water (silt free)	260 m^3 (17 cm/ day)	1.84 to 2.0 m in 46 upto 15 m from the channel and 20 cm at 200 cm from channel	1.42 m in 15 days
Recharge pit 1.70 m x 1.70m x 0.75m	18.4.84 to 17.6.84 (60 days)	canal water (no silt)		total 4.13 m in piezo-metric levels at a distance of 5 m	80 cm in 20 days

8.0 CONCLUSION

Artificial recharge can be an effective water management technique provided hydrologic conditions of the aquifer system are quantified and rational design criteria are established. The main source of ground water recharge is natural precipitation and the areas of scarce rainfall and high groundwater withdrawal exhibit continuous depletion of ground water reservoir thus specifying need for artificial recharge. Conceptually, an artificial recharge project is brought about to combat adverse conditions such as lowering of ground water levels, unfavourable salt balance, pollution migration and sea water intrusion. The conservation of runoff and flood waters which would otherwise be wasted can also be done by providing aritificial storage in underground reservoir. Of late, artificial recharge practices are being used for conserving energy of hot and cold water by storing it underground and extracting it at the time of need. For artificial recharge to be considered as an effective water management technique, it is necessary to know that :

i) How much rechargeable water is available when, and at what rate ?

ii) What is the quality of the recharge wzter,dissolved solid content,temperature, ionic ratios,suspended solids, and bacterial content ?

iii) How much under ground storage space is available and at what depth ?

iv) How readily will the aquifer accept the recharge water and how readily can it be recovered ?

v) How will the quality of water change after recharging ?

vi) How quickly will the aquifer plug due to chemical, physical or bacterial action ?

In order to develop an effective design criteria for artificial recharge, each of these factors need to be evaluated properly. Though the artificial recharge methodology is comparatively simple, but it will be different in different hydrologic conditions. Hence the selection of suitable methodology for artificial recharge would be a key for the successful operation. In arid areas where deep confined aquifers are to be recharged, recharge wells from the most suitable method while in alluvial flood plains where sub-surface soils are permeable, spreading method of recharge is useful. In arid and semi-arid areas where surface water is scarce, waste water can be used for recharge purposes. In order to analyse the flow mechanism within an aquifer, mathematical modelling of aquifer can prove to be very much effective. This will help in finding the temporal and spatial effects of artificial recharge in piezometric head and also the amount of water that leaves a basin can be assessed as a result of development of mathematical model. Proper monitoring of ground water conditions is required to demarcate areas where artificial recharge is essentially required. Particularly health aspects of artificial recharge with special reference to waste water recharge have to be carefully studied. In order to get more comprehensive information on artificial recharge, it will be desirable to document artificial recharge practices in different countries of the world giving details about hydrogeological conditions of the area,methodology followed and the results obtained. The artificial recharge methods deployed in India were largely connected with irrigation projects, hence were inexpensive however, specific projects for recharge has now to be taken up to recharge the depleting ground water resource in basins where ground water is the prime source for irrigation. In general, the artificial recharge projects are expensive and therefore need to be very carefully planned and operated.

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