Effectiveness of Artificial Recharge Structures in Enhancing Groundwater Storage: A Case Study

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Abstract

Objectives: The effectiveness of recharge structures in enhancing the recharge process has been evaluated for different recharge structures, namely, check dam and percolation pond with percolation wells, individually as well as in a combined manner. **Methods:** These structures have been constructed and monitored for their effectiveness through field pilot scale studies in a watershed in Tamil Nadu. The effectiveness was assessed in terms of increase in groundwater table, improvement in the quality of groundwater and the percentage of recharged quantity in terms of water storage created by the recharge structures using water level fluctuation method and mass balance approach. Natural recharge was estimated by water balance method. **Findings:** An average increase in water level of the order of 2m to 3m was observed in the surrounding areas of individual recharge structures, whereas in the area surrounding the combined recharge structures, an increase of around 5m in the groundwater table was observed after 2 years of artificial recharge. According to mass balance study the percentages of the volume of water contributed for recharge of the aquifer was worked out to be 79 percent and 92 percent for check dam and percolation pond with percolation wells respectively. The Total Dissolved Solids (TDS) and hardness were observed to be considerably reduced after the construction of artificial recharge structures. Percolation pond with percolation wells was found to be the most favorable structure in the watershed studied. **Applications:** This paper has demonstrated the comparison of situations with and without artificial recharge structures and these recharge structures are highly effective in enhancing groundwater resource.

Keywords: Artificial Recharge, Check Dam Groundwater, Mass Balance, Percolation Pond, Percolation Well

1. Introduction

Recharge can either be natural, from precipitation that falls on the earth's surface and moves on its way underground or it can be artificial, from human activities that deliberately or inadvertently replenish an aquifer. Artificial recharge may be defined as the process of replenishing groundwater by augmenting the natural infiltration of rainwater or surface water into underground formations through various methods designed depending on the topographic, geologic and soil conditions.

The previous studies[1-3] showed that the most commonly used method for natural recharge estimation is the mass balance approach. In[4] analyzed groundwater flow in an unconfined aquifer under seasonal artificial recharge schemes of variable duration and found that variations in storage and outflow from the aquifer apart from the silting of recharge well were highly dependent on both the aquifer characteristics and the duration of recharge.

The influence of percolation pond in artificial recharge in a granitic gneissic terrain of a semi-arid region of India was assessed using environmental chloride method[5]. It was observed that 30-35 percent of the impounded water was recharged through the pond.

The response of two percolation ponds in Tamil Nadu, India was studied[6] to assess their potential influence zones. They observed that the strongly influenced wells were located within 400m from the ponds whereas moderately influenced wells were located up to 800m from the ponds.

Investigation of artificial recharge basins of different shapes and assessment of their effect on underlying

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aquifer system showed a lower groundwater build-up for higher perimeter basin shapes[7].

In[8] studied the water balance of reservoirs for Indian sites and found that 96 percent of the water in a basin was recharged and 4 percent was lost to evaporation in the most favorable case and 45 percent was recharged and 55 percent was evaporated for the worst scenario.

In a numerical model developed for calculating the groundwater mounding for an artificial recharge basin of size 175m x 450m in Gaza strip in the Middle East, where the unsaturated zone was about 60m thick[9]. From the model it was found that the maximum rise of mound was 14m at the center of the artificial recharge basin and about 12m at the edges, after 100 days of recharge.

In[10] artificial recharge study was carried out through roof top rain water harvesting methods during 2004 to 2007 at St Peter's Engineering College Campus, Avadi, and Tamil Nadu. Aquifer parameters were assessed using pumping test. A three layer hydro geological model of the aquifer was applied in Visual Mod flowver. 4.1 and significant increase in water level in the top aquifer was recorded during 2007. The study concluded that rainwater harvesting and recharges studies form important part in groundwater restoration and management.

Water quality issues in artificial recharge became prominent in the last decade and were studied by a few researchers. In a study on geochemical transformations during artificial recharge found that F, Ba and as were leached in appreciable concentrations, whereas leaching of B, Cr, Pb and Se were minimal[11]. It was also observed that concentrations often peaked during the first few days of operation and then declined.

In[12] studied the removal of microorganisms by deep well injection into a sandy aquifer in Netherlands. Injection water was seeded with microorganisms for 5 days. Within the first 8m of soil passage concentrations of microorganisms were found reduced logarithmically.

There are many methods proposed for groundwater recharge estimation, but there is no systematic study on the comparison of different methods and on assessment of artificial groundwater recharge with combination of recharge structures including recharge wells.

2. Study Area

The watershed taken up for study is located in Nadiyapattu village of Cuddalore District, Tamil Nadu state, India which falls within latitudes 11°15' to 11°45' N and longitudes 79° 15' to 79° 45' E in Survey of India toposheet 58M/6. The watershed lies in one of the sub-basins of Gadilam River in Tamil Nadu state, India and has an aerial extent of 420 km². The general topography consists of highlands in the Northwest and a flat terrain in Southeast. Maximum rainfall in the region occurs during the North-East monsoon (October to December) i.e. 60 percent of the average annual rainfall is brought by the North-East monsoon, 25 percent by the South-West monsoon (June to September) and the rest in summer showers. The highest rainfall has occurred in the month of November with a monthly average rainfall value of 268.5 mm and the minimum rainfall usually occur in the month of February with an average value of 10.7 mm. The climate is tropically humid. The area is warmer in summer months (March to May) with a maximum temperature of 40°C recorded during the month of May. During the monsoon months, the normal temperature varies between 20°C and 25°C. The area is cold in winter months (January to February) and the normal temperature during the period varies between 18°C and 21°C and January is the coldest month. This sub-basin is characterized by heavy pumping for agricultural, industrial, domestic and mining purposes. The pumping is tending to exceed the average recharge rates, causing depletion of water levels in the region. For the system to be sustainable, the pumping and recharge should be balanced either by minimizing the pumping or by increasing the recharge. The only possible alternative solution is replenishing the groundwater through artificial recharge by different arrangements.

3. Field Experimental Work

The watershed has two major drains and flows towards North East and finally join the Gadilam river which flows further about 30 km to reach the sea. However in this distance there is no beneficial use of the drained water than joining the sea without any beneficial use. Thus, by providing rainwater harvesting structures, if one could speed the excess water into the aquifer, it can be beneficially used in the aquifer, during the water-deficit season.

The artificial recharge due to different structures namely check dam, percolation pond with percolation wells and combined structures (percolation pond with percolation wells and check dam with recharge well) have been assessed through field experiments. A percolation pond with a surface area of 15000 m² has been constructed and three Percolation Wells (PW1, PW2 and PW3) were

drilled in the percolation pond area. A pond of 2800 m² area with three Percolation Wells (PW4, PW5 and PW6) was constructed in another location along with a check dam with a Recharge Well (RW0) and called as combined structure area. A Thus the combined structure area consists of a check dam with a recharge well, one percolation pond and three percolation wells. In the second phase the size of the pond in the combined structure area was also extended to 15,000 m². A single check dam was also constructed on the northern side of combined structure area. The second phase was completed in April 2005.

Percolation wells having a diameter of 45 cm penetrated up to the bottom of permeable strata (i.e., around 75 m) and the pit was filled with gravels and pebbles to allow the free flow of filtered water. Recharge well was ordinary well having 15 cm diameter and around 75 m depth with a slotted length of 24 m. Observation wells had a diameter of 10 cm and extended up to 75 m with a slotted length of 24 m. To monitor the groundwater level fluctuation and quality a total of 15 observation wells were constructed.

The location plan of the bore holes is shown in Figure 1. Groundwater levels were monitored and recorded on a daily basis from all the observation wells from September 2003 to February 2006 and groundwater quality was monitored pre and post monsoon on selected observation wells to study the artificial recharge effects of check dam, percolation pond and combined structure on the quantity and quality of groundwater. Water level fluctuation data collected from the observation wells (seven for percolation pond area PO1, PO2, PO3, PO4, PO5, RO1 and RO2; six for combined structure area CS1, CS2, CS3, CS4, CS6 and RO3; two for check dam area CS5 and CS7) within the influence zone was used to draw the water

level contours to study the water level fluctuations and compared the same with the water table levels before the construction of these artificial recharge arrangements. Basin scale mass balance approach was used to find the individual effectiveness of check dams, check dam with recharge well and percolation pond with percolation wells as well as combined effectiveness of various artificial recharge arrangements.

The construction of recharge structures was completed in April 2004 and thus the water from the rainfall of July 2004 onwards got collected in these structures and got recharged into the groundwater aquifer system. Water levels were recorded on a daily basis from September 2003. Water samples were collected seasonally from four typical observation wells (two from percolation pond area i.e., PO4, PO5 and one each from check dam area i.e.,CS7 and Combined Structure area i.e., CS6) and analyzed in the Environmental and Water Resources Engineering laboratory of Indian Institute of Technology, Madras as suggested by[13]. Water quality was analyzed for pre and post monsoon periods in a year.

4. Methodology

In the context of sustainable groundwater management, it is essential to assess the effectiveness of artificial recharge arrangements in terms of their ability to recharge the aquifer. The artificial recharge due to different structures namely check dam, check dam with recharge well and percolation pond with percolation wells were studied using different methods. Natural recharge was estimated by water balance method. Water level fluctuation data collected from wells within the influence zone was used to study the water level fluctuations before and after the construction of artificial recharge arrangements. Mass balance approach was used to find the individual effectiveness of check dam and percolation pond with percolation wells.

4.1 Natural Recharge Estimation

Natural recharge was estimated by conventional water balance method. The study of water balance is the systematic accounting of water within a geographic region for a specified period. The basic elements of water balance include inflows such as precipitation and outflows like evapotranspiration, runoff, interception losses and soil moisture storage. In water balance model the significant components were first identified and independently
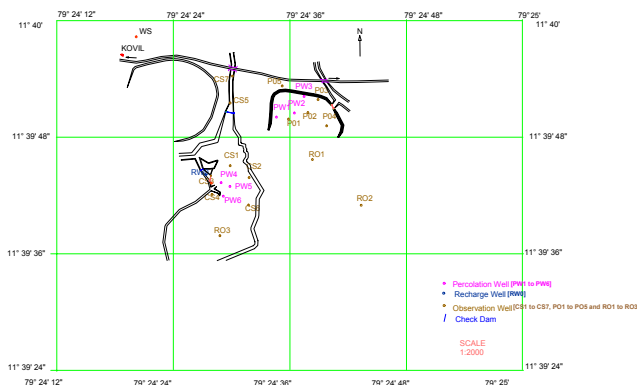
Figure 1. Location of bore holes in the Artificial Recharge Site.

evaluated and then substituted in the water balance equation to find out the natural recharge. For the recharge estimation the soil water balance equation is written as

$$R_e = P - R - I_a - ET_a \pm \Delta S \qquad (1)$$

where

R_e = Recharge (mm).
P = Precipitation (mm).
R = Runoff (mm).
I_a = Interception loss (mm).
ET_a = Actual Evapotranspiration (mm).
ΔS = Change in soil water storage (mm).

If the balance is carried out annually, the change in soil moisture storage is negligible[14]. The individual components of the water balance model such as runoff and interception loss were calculated using SCS method[15] and Evapotranspiration (ET) values were estimated by Penman-Monteith method[16]. Change in soil water storage was neglected. Natural recharge values were calculated by substituting the different components in the water balance model.

4.2 Artificial Recharge Estimation

The amount of artificial recharge through the different structures have been estimated by two methods namely, Water level fluctuation method and the mass balance method. These methods are briefly explained below.

4.2.1 Water Level Fluctuation Method

Water level fluctuation data collected was used to study the effectiveness of artificial recharge structures. Water level fluctuations in the observation wells give the combined effect of artificial and natural recharge. As already explained, the natural recharge has been estimated using the water balance method. For an effective understanding about the recharge phenomena, daily water levels in all observation wells were monitored for a period of one year prior to and two and half years after the construction of the artificial recharge structures. The first year data, from September 2003 to August 2004 was taken as base data i.e., water levels without artificial recharge structures. The water level recorded from each month was subtracted from the base data values (water levels for the same months in the previous year) to get the effect due to artificial recharge. This way, the water level without artificial recharge structures was subtracted from the water level in the same observation well with artificial recharge structures. These differences or the increase in water levels were noted as the effect due to artificial recharge.

4.2.2 Mass Balance Approach

A detailed water balance study provides a quantitative estimate of the contribution of a structure to groundwater recharge. Even though it only provides a relative assessment, it would still be an immensely useful aid in making management decisions. At the recharge basin scale, the rise or decline in water levels over time is an indicator of the performance of the recharge structure.

During periods of no inflow to a pond and no outflow from a pond, the decline in the pond water level is attributable to the algebraic sum of recharge and evaporation losses. The balance between these two losses determines, whether the structure is fit for and the site is suitable for recharging purpose.

To estimate the water balance between evaporation and recharge losses from the percolation pond/check dam, the change in pond water level with time was monitored. For periods without direct abstraction and rainfall, this is translated into groundwater recharge rates after subtracting open pan evaporation rates. The water balance for a reservoir can be simplified if losses due to leakage, abstraction etc. can also be neglected and if the pond is under effluent conditions in relation to the aquifer, then the water balance can be written as follows[9].

Groundwater Recharge=Change of volume of water in the pond-Evaporation   (2)

Under such conditions, the balance between evaporation and groundwater recharge will determine the effectiveness of the artificial recharge scheme.

5. Results and Discussion

5.1 Data Analysis

5.1.1 Water Level Data Analysis

Daily water levels in the observation wells in the vicinity of the recharge structures were plotted along with the corresponding rainfall data and the recharge pattern was analyzed. From the water level fluctuation data analysis it was found that there was 45 to 60 days lag time for the rainwater to join the groundwater storage. Thus the effective water table increase due to artificial recharge started from September 2004. The peak water levels were obtained in

the months December and January in most of the cases. Water level variations with rainfall for representative observation wells for check dam area, percolation pond area and combined structure area are given in Figures 2, 3 and 4 respectively. From these Figures, it can be observed that there is an overall rise in water level of 2 to 3 m, after the construction of recharge structures.

5.1.2 Water Quality Analysis

The potential for water quality improvement of an aquifer is a major criterion for any artificial recharge project. Water quality parameters were analyzed during pre-monsoon and post monsoon periods before and after artificial recharge. Figure 5, Figure 6 and Figure 7 depict the water quality improvement after artificial recharge near check dam, percolation pond and combined structure areas respectively. There was considerable improvement in the groundwater quality especially in the case of TDS and hardness after artificial recharge. It was found that the concentration levels did not rise after the monsoon as the recharge structures helped in diluting the native water by the huge volume of surface water stored in them, which wouldn't have been possible by natural recharge alone. It was observed that there was 50 to 80 percent reduction in the concentration of TDS in the observation wells considered. It was also observed that the groundwater quality improvement was maximum near the percolation pond area. Water quality could not be analyzed after January 2005, as samples were not collected.
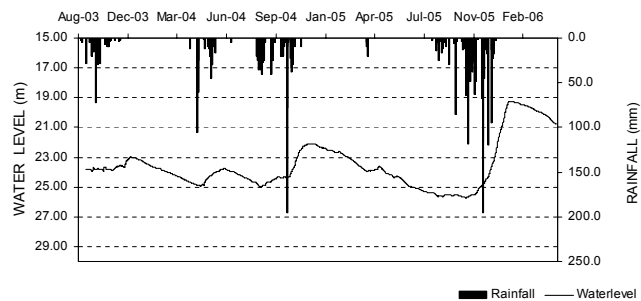
Surface water, which was used for artificial recharge was also analyzed for pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Total Suspended Solids (TSS)
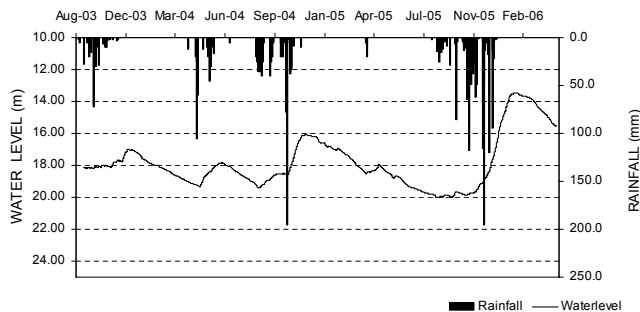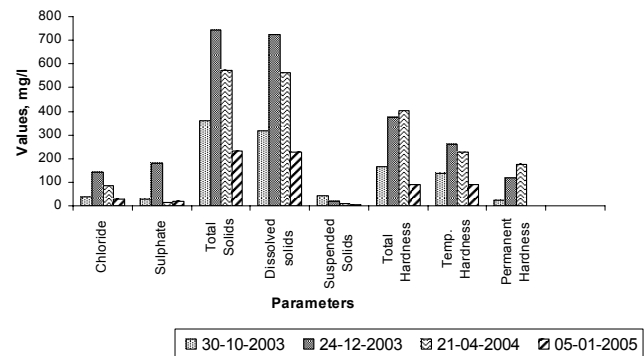

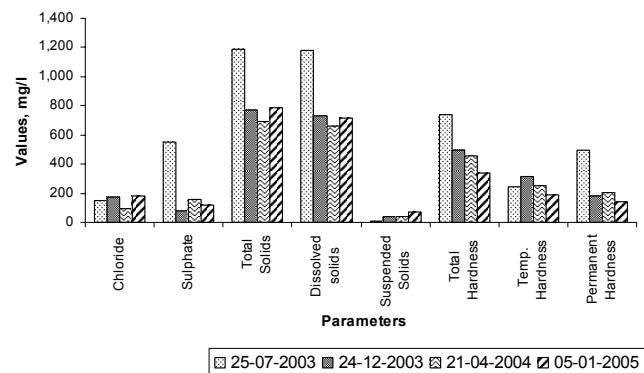**Figure 2.** Water level variation in check dam area.
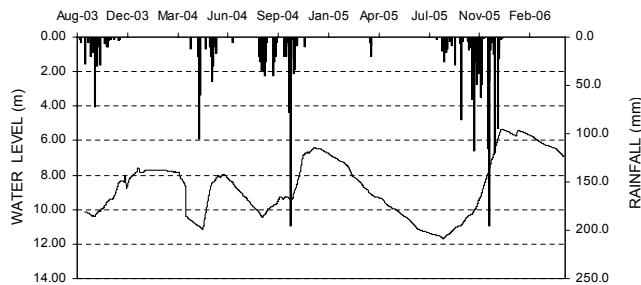
Figure 3. Water level variation in percolation pond area.

Figure 4. Water level variation in combined structure area.

Figure 5. Comparison of water quality before and after artificial recharge near check dam (observation well CS7).

Figure 6. Comparison of water quality before and after artificial recharge in percolation pond area (observation well PO4).

in the water quality lab of Indian Institute of Technology, Madras. The samples were collected from six sampling points and the analysis results are tabulated in Table 1.

5.2 Natural Recharge Estimation

Natural recharge was estimated by water balance method. The various components of water balance were calculated on a daily basis for each rainfall event and subtracted from the rainfall, as per the Equation 1. Water balance model was applied on a daily basis and daily recharge values were calculated, and from these values, monthly recharge quantities were calculated by summation of daily recharges. Figure 8 shows the monthly variation in natural recharge by water balance method along with the corresponding rainfall data. The average annual recharge for the study area during the study period came to 256.97 mm which was 17.17% of the total rainfall.
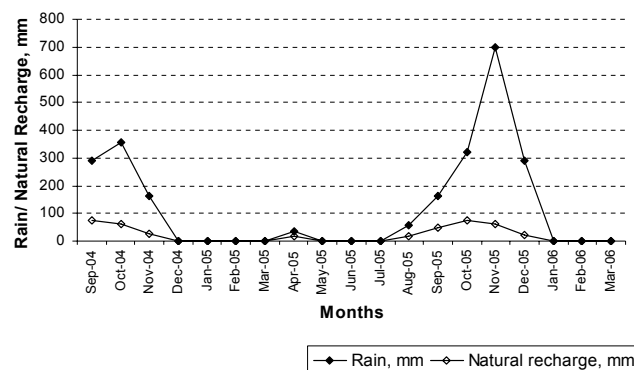
5.3 Artificial Recharge Estimation

The quantity recharged after construction of artificial recharge structures such as check dams, check dams with recharge well and percolation pond with percolation wells
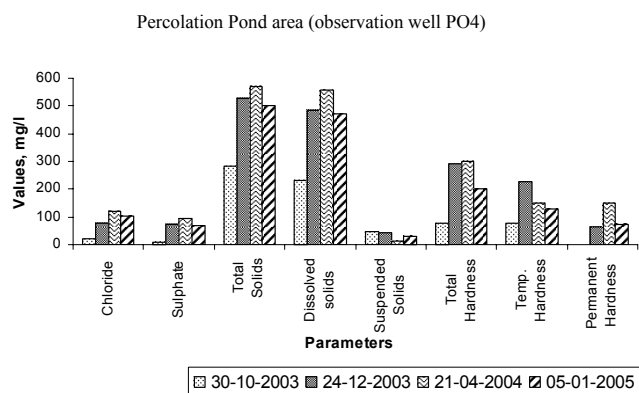
Figure 7. Comparison of water quality before and after artificial recharge in combined structure area (observation well CS6).

Table 1. Surface water quality in monsoon season in the study area

Sl. No	Parameters	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
1	PH	6.3	6.3	6.7	6.3	6.4	6.7
2	EC μmho	15.3	13.5	33.8	32.9	97.8	29.5
3	TDS mg/l	9.7	8.64	21.63	21.05	62.58	18.85
4	TSS mg/l	11288	5987	1249	4232	1970	5132

**Figure 8.** Monthly variation in natural recharge by water balance method.

at Nadiyapattu was estimated using water level fluctuations method and mass balance approach.

5.3.1 Water Level Fluctuation Method

The amount of artificial recharge was estimated using both the water level fluctuation method and the mass balance method, on a daily basis. Water level fluctuations in the observation wells give the combined effect of artificial and natural recharge. Average monthly water levels were calculated from the daily data. Water level data before the construction of artificial recharge structures was subtracted from the water level data in the same observation well after the construction of artificial recharge structures. The average increase in water levels due to artificial recharge was determined at the check dam area, percolation pond area and the combined structure area. The increase in groundwater level is an indication of the volume of water added to the groundwater reservoir. The results are discussed in the following section on the structure wise.

5.3.1.1 Check Dam Area

The monthly water level before the construction of check dam was subtracted from the monthly water level values after the construction to get the effective increase in water level due to artificial recharge. A graphical representation of rainfall, natural recharge and artificial recharge in the check dam area is given in Figure 9. The contribution from natural recharge is negligibly small in the study area compared to the contribution from artificial recharge. It was observed that there was an average water level increase of 1 m and 4 m due to artificial recharge near the check dam in the first and second year respectively.
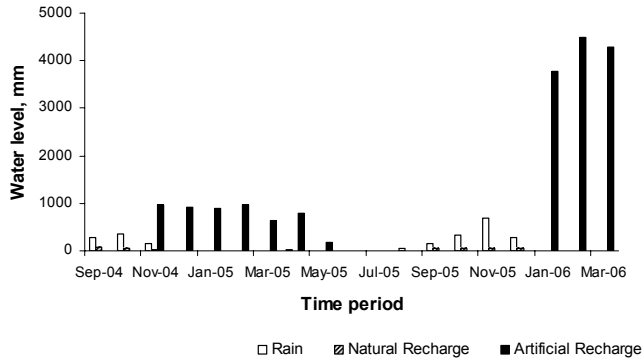
Figure 9. Water level increase due to artificial recharge in check dam area.

5.3.1.2 Percolation Pond Area

In the percolation pond area, the monthly water level values of the previous year was subtracted from the monthly water level values after the construction of percolation pond to get the effective increase in water level due to artificial recharge. A graphical representation of rainfall, natural recharge and artificial recharge for percolation pond area is shown in Figure 10. A considerable increase in water level in percolation pond area could be observed after the construction of recharge structures. In the study area, the contribution from natural recharge is very small when compared to the contribution from artificial recharge. It can be seen that water table rise due to artificial recharge is much more than the depth of rainfall in the locality. The rainwater from the nearby areas also got collected in these structures and got recharged into the aquifer. It was observed that there was an average recharge in the range of 2 to 3 m in the observation wells in the vicinity of the percolation pond. The natural recharge process lasted only for a short period after the rains whereas the effect due to artificial recharge persisted for several months after the rains. The heavy rain in November 2005 had remarkable contribution for artificially recharging the aquifer. The rise in water level due to artificial recharge reached nearly 4 m in February 2006 and March 2006, which is two years after the construction of the structures.
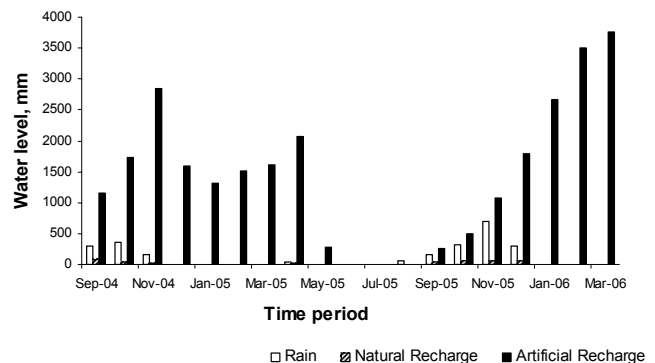
5.3.1.3 Combined Structure Area

In the combined structure area, the observed contribution due to artificial recharge was less compared to that of percolation pond area in the first year. The monthly recharge in 2004 was around 1 m only in the observation wells in the vicinity of the combined structure area. The small percolation pond constructed in the area during the first phase of construction was extended in the second phase during April 2005. Due to this, the heavy rains in November 2005 could be effectively stored in the extended pond area and thus contributing for a considerable increase in water level in January to March during the year 2006 shown in Figure 11. In February 2006, the contribution due to artificial recharge went up to 5.8 m. This also explains the contribution of percolation ponds in recharging the aquifers.

5.3.2 Mass Balance Approach

The change in pond water level with time was monitored to find the area and volume of storage which in turn used to estimate the water balance between evaporation and recharge from the percolation pond/check dam. For periods without direct abstraction and rainfall, these data was translated into groundwater recharge rates after subtracting pan evaporation rates. The water bal-

Figure 10. Water level increase due to artificial recharge in percolation pond area.
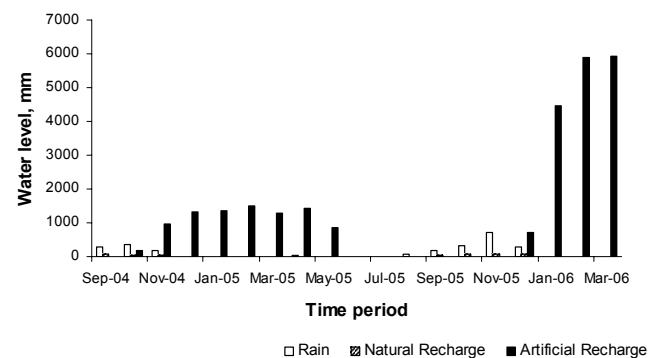
Figure 11. Water level increase due to artificial recharge in combined structure area.

ance for a pond can be simplified if losses due to leakage, abstraction etc. can also be neglected. If the pond is under effluent condition in relation to the aquifer, then the water balance can be written as follows[9].

$$R_e = \Delta V_P / \Delta V_{CD} - E \qquad (3)$$

R_e = Groundwater Recharge.
ΔV_P = Change in volume of water in the pond.
ΔV_{CD} = Change in volume of water in the check dam
E = Evaporation.

Under such conditions, the balance between evaporation and groundwater recharge will determine the effectiveness of the artificial recharge scheme on a basin scale. The responses of individual structural arrangements were evaluated based on the data collected once in two days. Recharge was assumed to be distributed uniformly within the recharge structure at rates specified in m^3/day/ m^2 of ponding area. The model then calculated water levels in the aquifer and volume balances. This basin scale analysis was done for check dams and percolation pond.

5.3.2.1 Check Dams

The response of check dam was evaluated based on the data collected once in two days and the average monthly details were obtained. The effect of the check dam in recharging the aquifer was computed per unit of ponding area of the recharge structure. The effectiveness of check dam is found to be 0.30 m^3/square meter of ponding area/month with 79 percent of the stored water being used for recharging the aquifer. This gives individual effectiveness of check dam in the study area. Since check dams remain dry during several months in a year the efficiency of check dams in recharging the aquifer was comparatively low.

5.3.2.2 Percolation Pond with Percolation Wells

The response of percolation pond with three percolation wells were evaluated for data collected once in two days and the average monthly details were tabulated. The effect of the percolation pond arrangement was assessed per unit of ponding area of the recharge structure. The average effect of percolation pond with three percolation wells arrangement was obtained as 0.69 m^3/square meter of ponding area/month. The volume of water contributed for the recharge of the aquifer was worked out to be 92 percent of the ponding water in the case of percolation pond with percolation wells arrangement.

The basin scale study showed that on an average 80-90 percent of the change in volume of water got infiltrated and about 10-20 percent only was lost due to evaporation. This shows that these structures are effective in recharging the aquifer and the site is favorable for artificial recharge. Recharge effect of different structures by mass balance approach is given in Table 2. The effect of check dam was less compared to the percolation pond with three percolation wells in recharging the aquifer.

5.4 Performance Evaluation of Various Structural Arrangements

Individual performances of check dam, percolation pond with three percolation wells and combined structure were evaluated with the help of water level fluctuations and water balance method. Head values before and after the construction of artificial recharge structures were compared for different time periods and the increase in head was noted.

The water level rise obtained after rains due to check dam, percolation pond with percolation wells and combined structure in the 1st and 2nd year after the construction of the structures was compared individually with that of the water level before the construction of the recharge structures. The increase in head due to check dam in the 1st and 2nd year after artificial recharge is obtained as 1 m and 4 m respectively. In percolation pond area, an increase of 2 m and 4 m was observed during the same time period. The increase in head at combined structure area was found to be 1 m in the first year and around 5 m in the end of second year. In percolation pond area, the increase in water table due to artificial recharge arrangement was visible after the first rains after the construction of the recharge structures. The increase in water level near the combined structure area was not considerable in the first year. It may be due to the fact that the size of the

Table 2. Effectiveness of various recharge arrangements by mass balance approach

Sl. No.	Recharge arrangement	Effectiveness	Inference
1	Check dam	0.30 m^3/sq.m of ponding area/month	There is no other recharge structure in the proximity of the check dam.
2	Percolation pond with 3 percolation wells	0.69 m^3/sq.m of ponding area/month	Percolation pond with percolation wells had good impact on increasing the recharge capacity.

initial pond in the combined structure area was small in the first year and extended to the size of the other pond only in the second year. Unlike the pond area, the mound below the check dam went down after a short period, as the ponding was not perennial.

The performances of check damand percolation pond with three percolation wells in recharging the aquifer were evaluated using a mass balance approach, by subtracting the evaporation losses from the change in volume of ponding in the recharge structure. The effectiveness of artificial recharge due to a single check dam was found to be 0.30 m³/square meter of ponding area/month. The effect of percolation pond with three percolation wells was obtained as 0.69 m³/square meter of ponding area/month. The percentages of the volume of water contributed for recharge of the aquifer was worked out to be 79 percent and 92 percent for check dam and percolation pond with percolation wells respectively. Mass balance study showed that the structures were effective in recharging the aquifer and the sites were favorable. The effect of check dam was less compared to the percolation pond with three percolation wells in recharging the aquifer.

Groundwater quality improvement after artificial recharge near check dam, percolation pond and combined structure areas were analyzed from samples collected during pre and post monsoon period. Remarkable water quality improvement was noticed after artificial rechargein the case of TDS and hardness. It was found that the concentration levels did not rise after the construction of recharge structures even in the dry months. From the samples analyzed it was found that quality improvement was maximum near the percolation pond area followed by check dam area and combined structure area. Quality parameters could be collected only up to one year after the construction of recharge structures. This can be the reason for the poor groundwater quality improvement in the case of combined structure areas where water level rise was considerable in the second year. It was observed that there was 50 to 80 percent reduction in the concentration of TDS in most of the observation wells considered.

6. Conclusions

The effectiveness of different artificial recharge arrangements, namely check dam, percolation pond with percolation wells and combined structure were evaluated through the field pilot scale experimental studies and reported in this paper. Water level and quality data were collected from wells within the influence zone and the fluctuations were analyzed before and after artificially recharging the aquifer. Water level fluctuations and water balance approaches were used to quantify the individual and combined effectiveness of various artificial recharge structures in recharging the groundwater aquifer.

From the results of the study, it can be concluded that among the different artificial recharge structures studied, the percolation pond with percolation wells was found to be more effective in recharging the surface water into the aquifer. Combined structure was also very effective after the expansion of the percolation pond. It was observed that groundwater quality has considerably improved by artificial recharge as evident from the analysis of different water quality parameters, namely total dissolved solids and hardness. Maximum water quality improvement was near the percolation pond area. The average annual natural recharge was found to be 17.17% of rainfall during the study period. The maximum water level increase was found to be around 4 m, 4 m and 5.8 m respectively for check dam, percolation pond with three percolation wells and combined structure arrangement after two years of artificial recharge. The recharge rate of a check dam alone and percolation pond with three percolation wells were estimated as 0.30 m³/m² of ponding area/month and 0.69 m³/m² of ponding area/month respectively. Mass balance approach showed that on an average 80-90 percent of the change in volume in the case of ponding structures was contributing to the recharging of the aquifer rather than being lost to evaporation. An average increase in water level of 2 to 3 m was noticed after two years of artificial recharge in most places in the study area. It was also observed that there was considerable variation of water level with time and location. From the study it was found that artificial recharge is a viable solution for sustainable development of water resources in general and for the development of groundwater resources in particular.

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Appendix

Notation

E	Evaporation	RO	Observation well at Recharge area
EC	Electrical Conductivity	RW	Recharge Well
ET	Evapotranspiration	R_e	Recharge
l	liter	TDS	Total Dissolved Solids
m	Meter	TSS	Total Suspended Solids
mg	milligram	ΔV_P	Change in volume of water in the Pond
PO	Percolation pond area Observation well	ΔV_{CD}	Change in volume of water in the Check Dam
PW	Percolation Well		