STUDY OF PERCOLATION PONDS FOR ARTIFICIAL RECHARGE: DEVELOPMENT OF CHLORIDE MASS BALANCE METHOD

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ABSTRACT

The hard rock aquifers of southern and western India, receive less than 10% precipitation as natural recharge, and are witnessing over-exploitation. Consequently measures are being adopted to augment groundwater resources artificially. Percolation ponds (tanks), the most popular artificial recharge structures in India, are constructed across monsoon streams for the above purpose. However no detailed study was carried out to evaluate their performance quantitatively in different hydrogeological environs. This paper reports the development and testing of chloride mass balance method to determine the efficacy of percolation ponds situated in different geological terrains. Depending on the location of the percolation tank, varied percolation fractions (of impounded water) were obtained; Basalts: 0.20-0.30; Granite-gneisses: 0.30-0.45; and Sandstones: 0.60, thus conforming to the transmission properties of rocks. In addition to geologic and climatic controls, the study also demonstrates enhancement of percolation (capture recharge) as a result of higher abstraction of groundwater in the downstream area of the tank. Thus the study demonstrates the potential use of chloride mass balance method for reliable estimate of efficacy of percolation ponds.

1.0 INTRODUCTION

Ever increasing exploitation of groundwater for varied usages, and the continuously declining groundwater levels necessitate deployment of artificial recharge structures/techniques, such as percolation ponds (tanks), check dams, sub-surface dams, injection of water into wells, surface spreading etc. to augment the groundwater resources. Percolation tanks involving very heavy investments are being constructed in hard rock semi-arid regions of southern and western India to enhance the recharge (input) to groundwater by harnessing surface run-off of monsoon streams. These structures are simple earthen dams constructed across the first or second order natural streams to impound surface run-off. Due to evaporation losses only a certain fraction of impounded water (defined as efficacy of the Percolation Tank) is subsequently expected to percolate through the tank bed to augment the groundwater and improve the well yields in the downstream. However the efficacy of such tanks are expected to be governed by the geologic, climatic and ageing factors.

Despite a large spectrum of problems (ex: basin management, groundwater response, pretreatment process, wastewater reclamation, water quality, aquifer modelling etc.) associated with artificial recharge are addressed worldover (Asano, 1985; Central Groundwater Board, 1998), hardly any information about techniques for evaluating the efficiency of percolation ponds is available except for conventional water balance method. Of late emphasis is on the use of environmental chloride for natural recharge studies (Eriksson & Khunakasem, 1969; Allison & Hughes, 1978; Edmunds & Walton, 1980; Sharma & Hughes, 1985; Sukhija et al., 1988; Dettinger, 1989; Edmunds et al., 1990; Tariguchi & Sharma, 1990; Wood & Sanford, 1995; Wood, 1999) basically due to two reasons : (1) chloride is a conservative tracer (Hem, 1985), and (2) it can be measured using a simple technique. However no such attempt was made for artificial recharge studies.

In India through water balance studies Raju (1985) , Sharma (1985) and Sharma & Mehta (1998) reported 85% tank efficiency in hard rocks, which is based on the questionable use of extrapolated pan-evaporation data. Nair et al. (1978, 1980) employed stable isotopes (deuterium and oxygen-18) and artificial tritium to study percolation tanks, but could only get qualitative results pertaining to tank influence area. Sukhija and Reddy (1987) based on low chloride levels but progressively increasing chloride concentration in the groundwater flow direction showed utility of the environmental chloride in qualitatively demarcating the area influenced by a percolation pond. Subsequently the environmental chloride balance method (Sukhija et al., 1997) was developed for quantitative evaluation of efficiency of percolation tanks. Its validity and applicability in tanks situated in varied hydrogeological environs (such as granites-gneisses, basalts, sandstones) in arid and semi-arid conditions is demonstrated. Also the geologic, geohydrologic and climatic controls on the performance of tanks, and the merit of the chloride method vis-a-vis conventional water balance method is discussed in this paper.

2.0 DEVELOPMENT OF ENVIRONMENTAL CHLORIDE MASS BALANCE METHOD FOR EVALUATING EFFICACY OF PERCOLATION TANKS

Assuming no additional sources like insignificant dry fallout or sinks of chloride in the percolation tank after impounding, and loss of water is through evaporation and/or percolation (seepage from the dam, if any, should also be accounted), the mass balance of chloride in the tank water can be used in estimating the percolated fraction of impounded volume of water. Since chloride studies start at the end of rainy season i.e. after three or four months of water collection and lasts till the tank completely dries up, we expect the effect of residual chloride in the top soil unimportant. The total chloride content of tank water at any time is estimated from the volume of tank water at that time and its chloride concentration. As there is no loss of chloride by evaporation, the chloride concentration of the tank water should increase with time because of evaporation. The percolating water, however, takes the chloride with it. Thus, by measuring the chloride concentration and the volume of water in tank at different times (after the monsoon), the percolation fraction of tank water can then be calculated (Sukhija et al., 1997). The chloride balance in the tank water between times t1 and t2 can be written as follows:

$$V1*C1 = V2*C2 + (1-f)*(V1-V2)*Cp \quad (1)$$

where V1 = volume of water in the tank (after monsoon) at time t1; C1 is the chloride concentration in the tank water at time t1; V2 is the volume of water in the tank at time t2; C2= chloride concentration in the tank water at time t2; (V1-V2)-loss of water between time t1 and t2; f-the fractional loss of water by evaporation; (1-f)-percolation fraction/efficiency; f(V1-V2)-loss of water by evaporation; (1-f)*(V1-V2) loss of water by percolation; and Cp is time weighted average concentration of chloride in percolated water (written as $Cp = \sum Ci*Vi/\sum Vi$, where Ci and Vi are chloride concentration and volume of tank water respectively measured at regular intervals between times t1 and t2) . The percolated fraction is then,

$$1-f = (V1*C1-V2*C2)/Cp*(V1-V2) \quad (2)$$

3.0 METHODOLOGY

The volume of water in tank at any instant can be estimated from the depth of the water column and the area occupied by the water body at that time. In order to obtain this, a rating curve (stage vs volume) is required. A detailed (~5 m grid) topographic survey of the tank bed has to be made and volume of water (also provides water spread area) for each centimeter height to be calculated. The chloride measurements are to be carried out at regular intervals, say over week, and water level in the tank has to be recorded daily using the installed staff gauge. Low chloride concentration in water sample can be measured by the mercuric thiocyanate and ferric nitrate method (colorimetric method; Navada, 1982), using a Spectrophotometer or by ion chromatograph.

The efficiency of tank i.e., (1-f), is generally determined on five to seven weekly values of water volumes and chloride concentrations so that during this time some significant changes in chloride concentration can be observed. In case of any significant rainfall event, which can be recorded as well as can be identified by the sudden change in water level in the tank or change in chloride concentration, the chloride balance has to be obtained for the dry period only, so as to justify the assumption of no additional source or sinks of chloride for working the balance on which this method is based.

4.0 RESULTS

Out of four selected percolation tanks, two tanks in Granite-gneisses are located in Southern India (near Hyderabad, Andhra Pradesh) and the other two tanks are situated in different hydrogeological terrains of basalt and sandstone but in similar climatic conditions (Surendra Nagar Dist., Gujarat). Details of the studied tanks are mentioned in Table 1.

Table 1 : Details of the Studied Percolation Tanks

Sl. No.	Geologic formation	Tank Name	State/ Dist.	Water Spread) area (sq.km)	Earthen dam length/ height (m)	Tank full capacity (MCM)	Average percolation fraction									
							1992-93		93-94		94-95		95-96		96-97	
							1	2	1	2	1	2	1	2	1	2
1.	Granite Gneisses	Kalwakurthy	AP (Mahbubnagar)	0.123	600/5	0.133	-	-	-	-	.45	.29	.44	.42	.58	.43
2.	"	Singaram	" (Ranga Reddy)	0.015	170/2.5	0.01	.35	.50	.22	.50	-	-	-	-	-	-
3.	Deccan Traps (Basalts)	Lakanka	Gujarat/ (Surendra Nagar)	0.161	600/5	0.21	-	-	-	-	-	-	.36	-	.20	.55
4.	Cretaceous Quartzite (Sandstone)	Saper	" "	0.268	600/5.5	0.312	-	-	-	-	-	-	-	-	.60	.68

1. Chloride mass balance method; 2. Water balance method.

4.1 Kalwakurthy Tank in granites/gneisses (Andhra Pradesh)

The experiments were conducted for about 19 to 20 weeks each year, for three successive years from 1994 - 1997. Fig.1 shows the weekly chloride concentration in the tank water in relation to the quantity of water in the tank. Average percolations, estimated using equation 2 for 1994-95 and 1995-96 years, are almost same (0.45 and 0.44 respectively) but for 1996-97, it is some what higher (0.58). Percolation fraction estimated using water balance method is lower (0.29) during 1994-95 than the 1995-96 and 1996-97 values (i.e., 0.42 and 0.43 respectively). The above difference in percolation fractions is attributed to the effect of climatic factors as discussed later.

4.2 Singaram Tank in granites/gneisses (Andhra Pradesh)

The Singaram tank in granites is studied from November 1992 and lasted till Feb. 1993. The progressive seven weekly percolation fraction is calculated for two consecutive hydrologic years 1992-93 and 93-94. The average seven weekly percolation fraction of the tank volume is about 0.35 for 1992-93 and 0.22 1993-94 using the chloride method and about 0.50 for both the years using water balance for this percolation tank.

4.3 Lakanka Tank in basalts (Gujarat)

Very limited available data for the year 1995-96 is processed to estimate percolation fraction using chloride mass balance method for the Lakanka Tank in Basalts. Five weekly percolation fraction is estimated as 0.36 and 0.37 (only two values). For the year 1996-97, because of

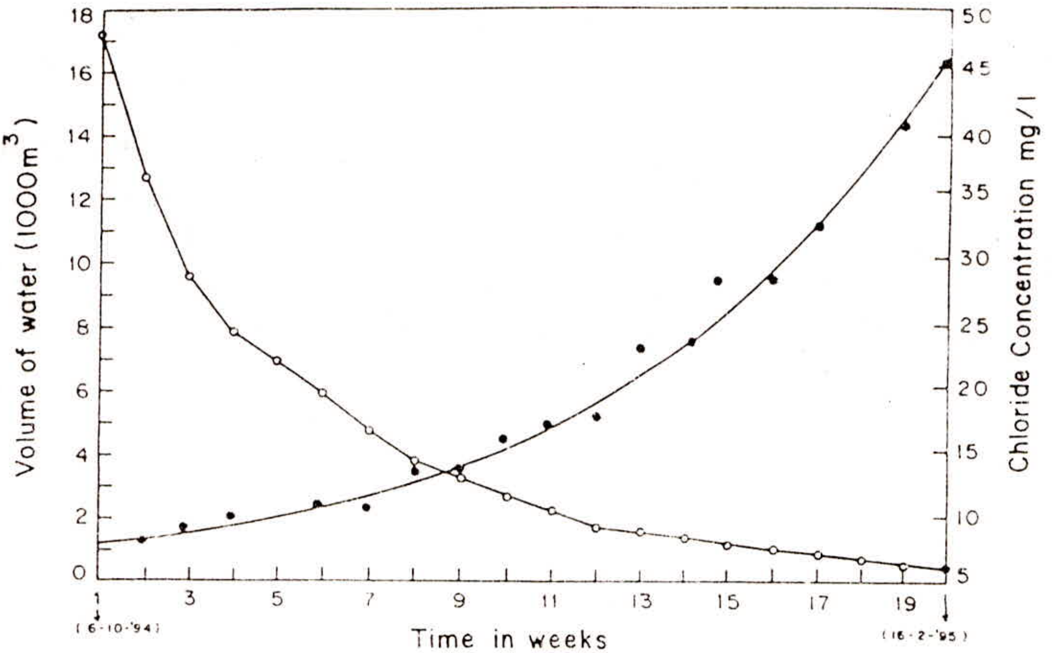

Fig. 1 : Volume of water and chloride concerntration in the percolation tank in Granites (Kalwakurthy Tank) as a function of time (from 6.10.1994 to 16.2.1995)

rainfall in between, the data is processed only for September and October, which gives percolation fraction of about 0.20. With available data the percolation efficiency is evaluated to be 20 - 30% for the tank located in basalts. For the same period, using water balance method percolation fraction is estimated as 0.55.

4.4 Saper Tank in Sandstones (Gujarat)

Because of the limited rainfall duration, the data for three months time (Oct-Dec.'1996) is made use of for the Sapar tank in sandstones. The estimated percolation fraction using chloride method in this tank is higher than other tanks, it has a value of 0.60. Using water balance method the percolation fraction ranged from 0.63 to 0.74

5.0 DISCUSSIONS

5.1 Qualitative Verification of Percolation from Tanks using Groundwater Level Data

Long term monitoring of the groundwater levels before and after construction of percolation tank can lead to qualitative verification of contribution from the percolation tank. Such an attempt was made for Kalwakurthy tank situated in Granites. The normal rainfall for the area is ~ 600 mm/a, and the 1985 was a normal rainfall year which can be considered as a base year before construction of the tank. Fig. 2 shows that during normal and above normal rainfall years of 1989-91, the water level in the downstream wells increased by 5-6 m primarily due to contribution from the tank. It was also observed that the groundwater levels in two open wells close to the dam rose close to the ground surface during the above hydrologic years. Such a situation never arose prior to construction of the percolation tank. Notwithstanding the low (200-300 mm) rainfall during 1992 & 1993, the wells near the tank did show higher water levels than the pre-tank construction period groundwater levels. Thus the groundwater level data qualitatively verifies that the percolation tank is effective in augmenting the natural groundwater recharge. No quantitative assessment was possible because of lack of specific yield data.

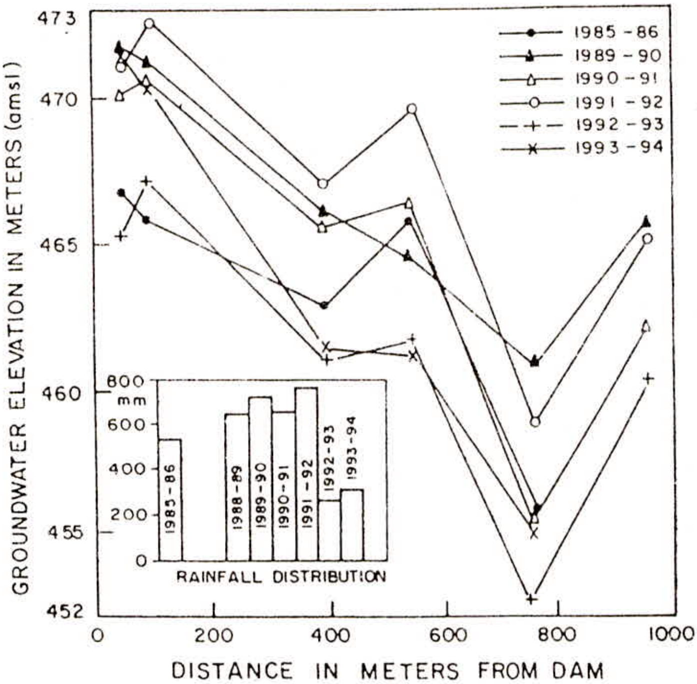

Fig. 2 : Spatial and temporal response of groundwater levels in the down-stream before and after construction of the tank (Kalwakurthy) in Granites. Inset diagram shows distribution of ainfall in the area during 1985-86 to 1993-94.

5.2 Ascertaining the Validity of Percolation Data using Chloride Concentration in Groundwater

The groundwater chloride concentration get reduced in the tank influence zone than wells unaffected by tank. So, the mixing phenomenon can be utilised to compute artificial recharge fraction in terms of natural recharge rate in different segments of the tank influence area.

In case of Kalwakurthy tank in granites/gneisses, the upstream well measures a chloride concentration of 49 mg/l, determined by natural precipitation recharge. The natural recharge rate can be determined by the inverse ratio of chloride in precipitation and that in groundwater. Average chloride concentration of precipitation in the area during 1995-96 was 3.5 mg/l, thus natural groundwater recharge turns out to be 7.5 percent of precipitation (4.5 cm). Other three wells progressively 100 m, 300 m and 400 m away in the down stream, indicate chloride concentrations of 18, 26 and 30 mg/l respectively and well far away (600 m down stream from dam) indicates 50 mg/l almost equal to the upstream well chloride concentration. Using the weighted average chloride concentration of percolated water (Cp = 11.5 mg/l) as one end member of the mixing line equation and the chloride concentration (50 mg/l) of natural recharge of groundwater at the other end of the mixing line equation, the above chloride concentrations respectively yield artificial recharge fractions to be 0.82, 0.61 and 0.51 from the tank to the groundwater, and the remaining fraction due to natural recharge. Thus artificial recharge fractions when considered in terms of natural recharge (4.5 cm) would provide a factor of 4.55, 1.56 and 1.04 with an overall weighted factor of 1.78 of natural recharge in the tank influence area. The total artificial recharge value turns out to be 8 cm of water column over an area of 400 m * 600 m (tank influence area considering reduced chloride concentration in groundwater), which would provide a percolation value of 19,200 cu. m from the tank to the aquifer. For the same period (1995-96), using chloride balance in the tank the percolated fraction is 0.44 and the percolated quantity is about 21,000 cu. m which is quite close to the value (19,200 cu. m) estimated using dilution method (mixing equation).Thus the two different approaches provide quite a good agreement in percolation efficiencies.

6.0 GEOLOGIC CONTROL

The percolation fraction from the tank situated in basalts, in Gujarat, is in the range of 0.20-0.30. The black clayey soil which is the weathered product of basalts has poor hydraulic conductivity and is responsible for the lower efficiency. On the other hand, the percolation tank situated in the Sandstone formation in the same area has shown fairly large percolation value (0.60), because of reasonably good hydraulic conductivity (3.1 m/day). This shows the important role played by underlying strata for percolation. The important point which emerges from the comparison of percolation rates of two tanks is that the two percolation tanks situated in same climatic environs (i.e., Saurashtra region) but in different geological terrains (basalt and sandstones) have wide variation in percolation. This shows that the role of geological strata outweighs the climatic factors in the performance of percolation tanks.

7.0 GEOHYDROLOGIC CONTROL

In our study the two tanks situated in granitic region, have shown fairly good percolation efficacies (30 -45%), whereby it can be construed that beneath the tank bed good transmitting weathered medium followed by well connected fracture network exists. However there is a variation in percolation efficiency between the two tanks; one tank (Singaram tank) has an efficiency of 30% and the other (Kalwakurthy tank) has about 45%. An important point to be noted is that in case of the latter tank, about 20 wells are being operated for irrigation of paddy and other crops in comparison to 3 wells for the former tank which are also located away from the tank. Thus, higher withdrawal rate of groundwater in the down stream of the tank results in additional recharge considered as "Capture recharge"(Bredehoeft, 1997), which other-wise would not have been available.

8.0 CLIMATIC CONTROL

Temporal behaviour (yearly changes in percolation) of percolation tanks can be related to climatic variation in addition to geologic control. We have observed temporal variation in percolation efficiency (chloride method) for the Kalwakurthy tank in granites during 1994-95 and 1996-97 to be 0.44 and 0.58 respectively though the initial volume of water in tank and observation period (October to February) for both the times remained same. This variation is attributed to relatively lesser evaporation measured during 1996-1997.

9.0 CONCLUSIONS

The escalating number and huge investments involved in the construction of percolation tanks as artificial recharge structures necessitated development of a reliable method for estimating and the factors controlling the functional efficacies. The developed chloride mass balance method is validated for tanks situated in different hydrologeological environs. Using chloride method we have obtained percolation efficacies as 20 - 30% for basalts, 30 - 45% for granite/gneisses; and about 60% for the sandstones of the impounded water. We compared the results with those obtained by the dilution and water balance techniques. The water balance method in general provided higher percolation values than the chloride method, which can be attributed to improper usage of pan-evaporation data for the tanks. Further the percolation efficiencies obtained through chloride method also illustrate the important role hydrogeology plays in siting of the tanks. The results also illustrate enhanced recharge in case of the percolation tanks associated with higher groundwater withdrawal in the downstream. Thus the developed chloride mass balance method is simple, sensitive and provides reliable data on percolation efficiency of tanks.

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