Contribution of percolation tanks to total aquifer recharge: the example of Gajwel watershed, southern India

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Abstract

Hard rock aquifers located in semi-arid climatic conditions are especially prone to overexploitation because of limited storage and recharge. In Andhra Pradesh (southern India), such geological and climatic settings prevail and rapid increase in groundwater abstraction for irrigation has led to aquifer overexploitation in many districts. As a response to overexploitation, Central and State governments have launched watershed development programmes aiming at augmenting aquifer recharge using different man-made structures such as percolation tanks, check dams, defunct dug wells.

The objective of the present study is to determine the contribution of percolation tanks to the total aquifer recharge in a typical semi-arid hard rock watershed of southern India (Gajwel, 84 km^2) and develop a simulation tool to test the impact of various climatic scenarios/tank management strategies on tank percolation fluxes and overall groundwater balance. The modelling approach consists in a first component which simulates runoff from daily rainfall as well as volumetric storage in tanks. A second component computes deep percolation from tanks based on a tank water balance approach. The model is validated by field observations in part of the watershed (temporal variations of tank volumetric storage). Estimation of the recharge with the water table fluctuation method is about 21% of the monsoon rainfall whilst estimations of the additional artificial recharge, inferred from the tank water balance and the runoff model, range from 5 to 8%.

Keywords: tanks; hard rock aquifer; semi-arid climate; water management; model; India

Introduction

In most regions of southern India, groundwater resources are constituted by shallow hard-rock aquifers with modest yield and thickness limited to a few tens of meters (weathering layer). With the development of groundwater irrigated agriculture, these aquifers have become intensively pumped and water levels are on a decreasing trend in many areas which is indicative of alarming consequences on future water resources if no adequate management response is implemented.

A possible management solution, encouraged by Government agencies over the recent years, is to intervene on the supply side of the groundwater balance, i.e. by artificial recharge. For instance, the State of Andhra Pradesh set the objective to increase aquifer recharge from 9% of total rainfall under natural conditions to 15% by the year 2020 (Government of Andhra Pradesh, 2003).

Artificial recharge structures encompass percolation tanks, check dams, injection wells, defunct dug wells. In many places, a high density of tanks exists as they were the traditional water source for many centuries. The conversion of these traditional tanks into purely percolation tanks is increasing day by day (Sakthivadivel 2007). Several studies have looked at the hydraulic functioning of these tanks and their contribution to recharge augmentation (Muralidharan et al. 1995, Selvarajan et al. 1995, Sukhija et al. 1997, Gore et al. 1998, Sudarshan 2003, Machiwal et al. 2004, Sharda et al. 2006). The efficiency (i.e., volume percolated compared to total volume stored) of these artificial recharge structures ranges from 30% (Sukhija et al. 1997) to 57% (Mehta and Jain 1997).

The present study focuses on a representative hard-rock (Archean granite) semi-arid watershed where groundwater is intensively pumped for irrigated agriculture (Gajwel watershed, 84 km^2, Medak district, Andhra Pradesh, Figure 1). Over 30 tanks are distributed within the watershed and no surface runoff is observed at the outlet except in the case of exceptional monsoon rainfall (once every 5-10 years).
The objective is to compare the contribution of artificial recharge to the overall recharge computed at the watershed scale and discuss alternative management options.

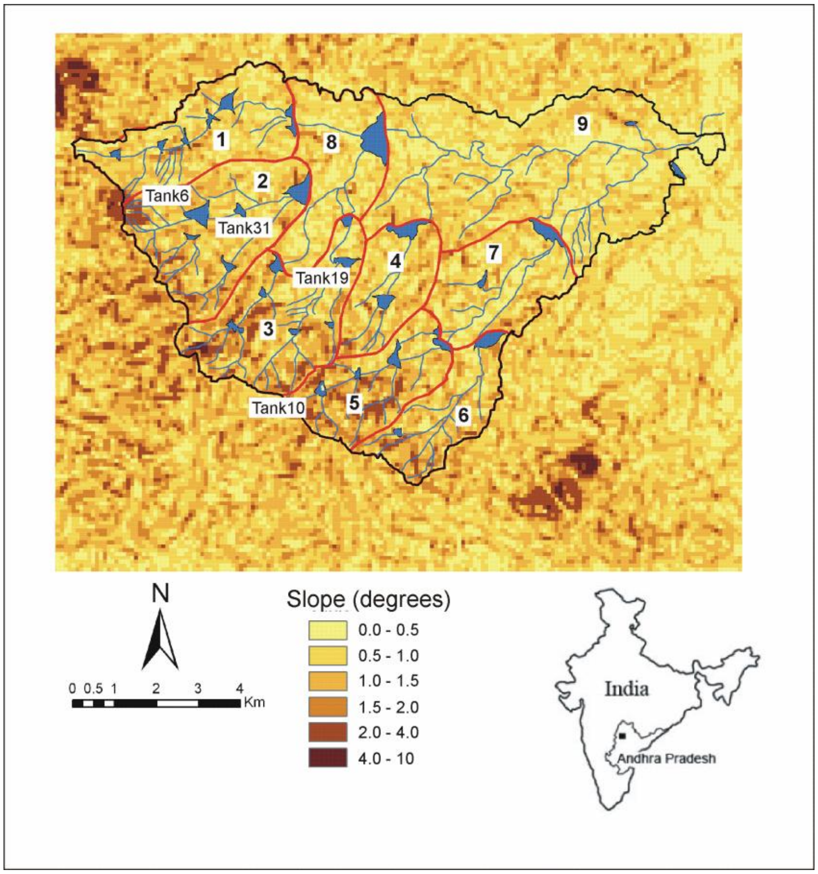

Figure 1: Location of Gajwel experimental watershed in southern India and slope map of the watershed with tanks in blue and drainage network. The watershed is split into 9 sub-watersheds numbered 1-9.

Computation of total aquifer recharge using groundwater balance

The groundwater balance is given by (e.g., Marechal et al. 2006):

$$R + RF + Q_{in} = E + PG + Q_{out} + Q_{bf} + \Delta S_{gw} \tag{1}$$

where R is groundwater recharge, RF the return flows, Q_{in} and Q_{out} the groundwater flows across the watershed boundaries, E the evaporation from the water table, PG the abstraction of groundwater by pumping, Q_{bf} the baseflow (groundwater discharge to streams) and ΔS_{gw} the change in groundwater storage:

$$\Delta S_{gw} = S_y \cdot \Delta h \tag{2}$$

With S_y the specific yield of the aquifer and Δh the water table fluctuation.

In Gajwel watershed (and other intensively exploited hard-rock watershed of southern India), Q_{in} balances Q_{out} across aquifer boundaries because in the upstream parts of the watershed, the piezometric surface describes a ridge-line (i.e., no flow boundary) which matches the surface watershed boundary (i.e., topographic ridge-line) and in the downstream part of the watershed intensive pumping is present on both

sides of the watershed limits thus strongly limiting lateral groundwater flows; Q_{bf} is non-existent as the water table is disconnected of the stream beds.
Therefore equation (1) can be simplified into:

$$R + RF = E + PG + S_y \cdot \Delta h \tag{3}$$

Estimation of PG
A landuse interpretation from satellite imagery (ResourceSat MX-LISS IV, 5 m resolution) has been used to obtain the surface area for the different irrigated crops (rice, vegetables, mangoes orchards) for both the dry season (rabi) and the rainy season (kharif) (Perrin et al. 2008). Field surveys were carried out to estimate the average daily irrigation for the different crops. On this basis, it is possible to compute the seasonal groundwater abstraction per irrigated crop. To obtain the total groundwater abstraction, other uses such as poultry farms and domestic uses have to be accounted for (Table 1). Total annual groundwater abstraction is 248 mm (of which 243 mm is for irrigation).
As per 2008 statistics (Mandal Revenue Office Gajwel, comm. pers.), the number of irrigation wells within Gajwel watershed is 1134. Taking an average discharge of 12 m^3/hr (average from 37 wells measured in the watershed), a daily pumping of 6 hrs (Massuel et al. 2008), and a yearly pumping of 270 days (two paddy cultivations), annual abstraction is 262 mm (22.0 x 10^6 m^3), estimation which compares well with the abstraction computed from landuse.

Table 1: Computed groundwater abstraction, Gajwel watershed. Stars indicate inferred values.

	Irrigation_mm/day		Irrigated area_ha		Groundwater abstraction_mm	
	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif
Rice	12	9	412	693	89	112
Vegetables	9	6*	113	113*	18	10
Orchards	9*	0*	93	93	14	0
Domestic					2.8	2.0
Poultry					0.2	0.2
Total					124	124.2

Estimation of RF
Irrigation return flows (IRF) have been calculating using a similar methodology than Dewandel et al. (2008) with a combination of water balance at the field scale and 1-D vertical variably saturated model so as to estimate average IRF at the seasonal scale. It is found that irrigation return flow coefficients C_f ($C_f = IRF/PG$) are comprised between 37-58% for rice and 36-55% for vegetables. For mangoes orchards, IRF is negligible as mostly drip irrigation is used. For domestic use and poultry, C_f is estimated to be 20% (Marechal et al. 2006).

Estimation of Δh and E
Piezometric campaigns were conducted after the monsoon has ended to obtain the highest water table (November) and at the end of the dry season to obtain the lowest water table (June). Between 40 and 55 piezometers (i.e., abandoned borewells) were measured for each campaign. The depth to water table is also used to estimate the evaporation flux from the water table using the relationship of Coudrain-Ribstein et al. (1998).
Equation (3) is solved twice a year, once for the dry season when recharge R is nil and therefore (3) is solved for S_y and once for the monsoon season for computing R (Marechal et al. 2006). On this basis, the groundwater budget at watershed scale has been computed for the years 2006-2009 (Table 2).

Table 2: Gajwel watershed groundwater budget, years 2006-2009. The star indicates that recharge had taken place in April 2008 due to cyclonic conditions during the dry season, thus invalidating the water fluctuation method for this period.

Year 1	Rainfall [mm]	ΔWT [m]	R[mm]	RF [mm]	E [mm]	PG [mm]	Balance [mm]
Jun2006-Oct2006	972	4,6	200	64	0,4	124	139
Nov2006-May2007	130	-2,1	0	59	0,4	124	-66
Annual data				122	0,8	248	73
Year 2							
Jun2007-Oct2007	493	0,8	101	47	0,3	124	23
Nov2007-May2008	235	-2,0	*	65	0,4	124	
Annual data				112	0,7	248	
Year 3							
Jun2008-Oct2008	730	3,0	147	59	0,4	124	82
Nov2008-May2009	100	-2,5	0	55	0,4	124	-70
Annual data				114	0,8	248	12

Estimation of tank storage capacity

For tanks 6 and 10 (Figure 1), the reservoir capacity has been computed based on GPS tracking around the tank shores at regular interval during their depletion so as to obtain the tank elevation contours. The final tank bottom topography was obtained by geostatistical interpolation (kriging).

Tank surface areas can be easily determined using satellite imagery and topographical maps. However, for water balance calculation, a relationship linking the observed area with the tank storage capacity (i.e., water volume stored) need to be established. In Gajwel watershed, tanks are located along drainage axes in a quite homogeneous landscape (no large change in topographic gradients, valley size, etc.). Therefore it is hypothesised that tank geometry is quite similar across the watershed and a single relationship may be used to compute tank storage volume from tank area (Figure 2). The relationship can reproduce storage volumes of tanks 6 and 10 within 20% of their actual volumes.

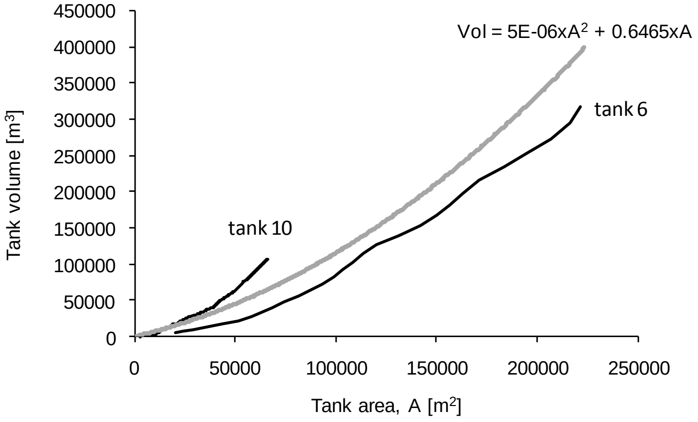

Figure 2: model used to compute tank storage volume from tank area.

Estimation of runoff

The detailed monitoring of rainfall (automatic tipping bucket rain gauge) and tank 10 filling (15 min interval pressure datalogger) during the 2007 and 2008 monsoons brings insight on the rainfall-runoff processes in Gajwel watershed. At the onset of the monsoon in June, the first 40-50 mm of rainfall replenish the soil moisture deficit (SMD) developed during the dry season. Then the first floods are observed, with surface runoff resulting from Hortonian overland flow, namely by infiltration excess but also saturation excess later in the monsoon season. On a daily basis, a simple linear relationship is proposed (Eq. 4) with runoff (Q) occurring when the total rainfall (R_d) exceeds the threshold (T). T decreases as the cumulative monsoon rainfall ($\Sigma Rain$) increases.

for $\Sigma Rain > 50mm$
and $T_{\min} \leq \Sigma Rain < T_{\max}$

$$Q(t) = C_r \cdot R_d(t) \tag{4}$$

with C_r the runoff coefficient.

The calibrated model with C_r=0.22, *T*=30mm for Σ*Rain* <200mm, *T*=15mm for Σ*Rain* between 200mm and 400mm, *T*=10mm for Σ*Rain* >400mm, reproduces quite well the progressive filling of tank 10 (Figure 3). Simulated versus observed water inflow in tanks 6 and 10 are plotted on figure 4 with a Nash coefficient of 0.994.

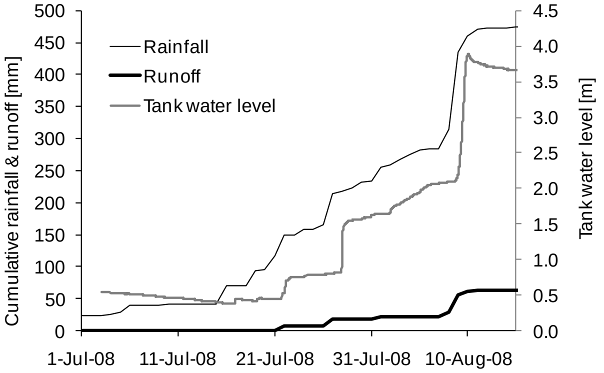

Figure 3: cumulative runoff from simulated daily runoff and observed tank water level, monsoon 2008.

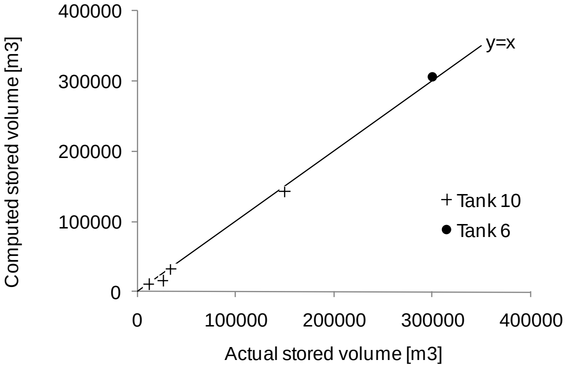

Figure 4: comparison of computed stored water volume in tanks 6 and 10 using the runoff model with observed stored volume (monsoon 2007, rainfall event spring 2008, monsoon 2008 including tank 6), Nash coefficient is 0.994.

Estimation of artificial recharge from tanks

Observed tanks depletion

Earlier studies (e.g., Sukhija et al. 1997, Mehta and Jain 1997, Perrin et al. 2009) have shown that the main fluxes out of tanks are evaporation (including transpiration by plants within the tank) and recharge; additional minor outflows are domestic and livestock uptakes and overflow.

Depletion rates of the four monitored tanks (Figure 1) are quite similar (Figure 5) and range between 16 and 20 mm/day. As evaporation rate is assumed to be more or less the same (tanks are within a few km), it means that recharge rates are in the same range. This observation indicates that observed depletion rates may be extended to all the tanks of the watershed.

Daily tank balance computation shows that percolation efficiency is between 40-65 % (56% tank 6 depletion 2008, 40-63% tank 10 2007-2009) of the tank capacity, similar to earlier studies (Sukhija et al. 1997, Mehta and Jain 1997, Perrin et al. 2009).

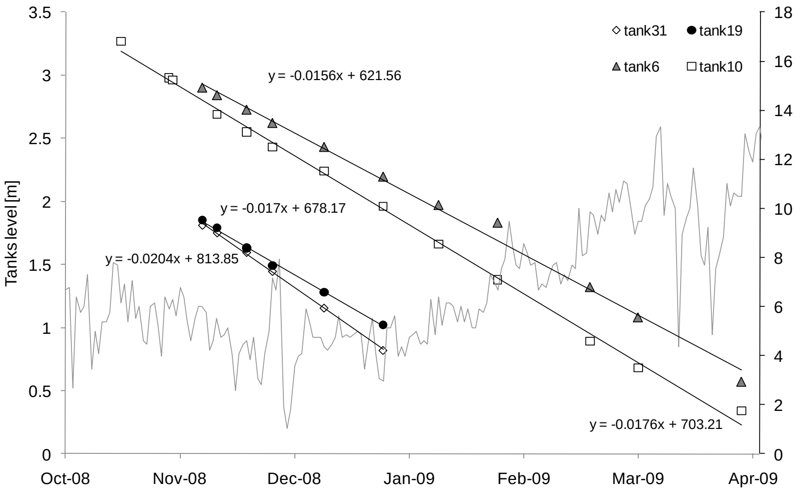

Figure 5: Tank depletion curves for the dry period October 2008 to April 2009, Gajwel watershed. Daily pan evaporation from ICRISAT meteorological station is also shown.

Computing artificial recharge from percolation tanks

For each sub-watershed (Figure 1), volumetric runoff is computed on a daily basis using the calibrated rainfall-runoff model and the respective sub-watershed surface areas. Then a daily tank water balance is computed taking into account loss by evaporation, recharge, overflow (after tank maximum storage capacity has been reached), uptakes and gain due to additional runoff. Water fluxes are computed for each sub-watershed for two values of percolation efficiency (0.4 and 0.6) which cover the range found in this study and other studies.

Sub-watersheds 1-6 are headwaters and will only overflow; sub-watersheds 7 and 8 have their own catchment and in addition will receive the overflow of respectively sub-watersheds 5, 6 and sub-watersheds 1, 2, 3. It is hypothesised that no runoff occurs in downstream sub-watershed 9 as slope is negligible and thick black soils with high storage capacity dominate.

Results (Table 3) show that most of the runoff is captured by existing tanks with outflows occurring only during the rainy years 2006 and 2008 (less than 10% of total runoff). The main fluxes are evaporation and percolation with evaporation higher than percolation for simulation with percolation efficiency of 40% and the reverse for simulation with percolation efficiency of 60%.

Table 3: Water budgeting of tanks at watershed scale for the lower (0.4) and higher (0.6) bounds of percolation efficiency. The year 2008-2009 budget is slightly truncated as model was run until end of April (May-June missing due to absence of meteorological data).

Perc.efficiency: 0.4					
	Runoff [mm]	Evap. [mm]	Recharge [mm]	Outflow [mm]	Uptake [mm]
year06-07	123.0	54.5	40.1	12.9	1.7
year07-08	54.6	30.1	20.7	0.0	1.7
year08-09	75.3	35.9	29.5	4.7	1.4
Perc.efficiency: 0.6					
year06-07	123.0	40.3	65.4	9.2	1.7
year07-08	54.6	20.5	29.9	0.0	1.7
year08-09	75.3	25.3	45.3	2.2	1.4

Discussion and conclusions

Recharge computed with the water table fluctuation method represents about 21% of monsoon rainfall and artificial recharge from tank computed using tank water balance and runoff model is comprised between 5 and 8% of monsoon rainfall (Figure 6). The remaining fraction of monsoon rainfall (71-74%) is mostly consumed by evapotranspiration and limited outflows in case of high monsoon. These results indicate that there is limited scope to build additional recharge structures as most runoff is already captured; however increased recharge may be achieved by improving the performance of existing percolation tanks. For instance if percolation efficiency is increased from 0.4 to 0.6, 10-20 mm more artificial recharge is generated (Table 3). This improvement may be achieved by increased hydraulic gradients near tanks and/or tank desilting. Another more efficient way to manage tanks would be to use directly tank water for irrigation so as to decrease irrigation pumping which represents a large share of the groundwater budget (Table 2) (Perrin et al. 2009).

The water table fluctuation methods used to estimate recharge assume that no recharge occurs during the dry season. This is not true in the vicinity of tanks as between 35-55% of artificial recharge occurs during dry season. For the method to remain valid, it is strongly advisable to use piezometers away from tanks so that they are not influenced by artificial recharge. If this condition is respected, the total recharge to the aquifer will be the sum of the recharge from the water table fluctuation and artificial recharge. In Gajwel, total recharge is therefore between 26-29% of monsoon rainfall (Figure 6).

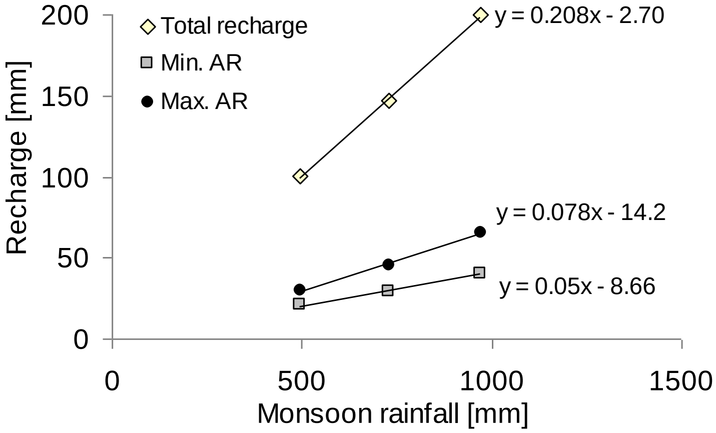

Figure 6: linear relationship between monsoon rainfall and recharge (total recharge from groundwater budget calculation, minimum artificial recharge (AR) with percolation efficiency at 0.4, maximum AR with percolation efficiency at 0.6).

The presented approach represents a preliminary estimate of the artificial recharge at the small basin scale but provide enough information to carry out further investigations. A larger panel of reservoirs has to be monitored within different soil conditions (i.e. red soil and black soil) for a proper rainfall-runoff model to be developed. Additional time series are required to improve the reliability of the results since, as shown by year 2008, the climate variability is very high.

In the framework of a new project, it is planned to apply a SWAT modelling approach to the watershed which will further consolidate the water budget estimates. Based on the modelling efforts, it will then be possible to test different water management strategies for planning sustainable scenarios.

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