Augmentation of groundwater recharge and water quality improvement by water harvesting structures in the semi-arid Deccan

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The effect of water harvesting structures on groundwater recharge and water quality was evaluated in a watershed situated in a semi-arid region in Andhra Pradesh, India. Two percolation tanks and two check dams with a total storage capacity of 4.209 ha m were selected to assess their effect on groundwater recharge and water quality within the influence zone of the water harvesting structures. Daily rainfall, evaporation and storage depth in structures were measured to quantify percolation. Using rainfall–run-off relationship with antecedent precipitation index as a factor, complete water budgeting was carried out. Results show that the threshold value of rainfall for ensuring 1 mm potential recharge is 61 mm. Potential recharge is only 3% of annual rainfall received. Water quality analysis revealed that except pH, all other water quality parameters like electrical conductivity, sodium adsorption ratio, residual sodium carbonate, total hardness, nitrate and fluoride content reached desirable limits in close vicinity (< 100 m) to the water harvesting structures. Increased availability of groundwater led to subsequent over-exploitation in below-normal rainfall years and the number of bore wells increased by three times.

Keywords: Check dam, groundwater, percolation tank, semi-arid regions, water quality.

INCREASING demand for water in the semi-arid regions has led to rapid groundwater depletion in almost all regions of the globe. These dry and environment-stressed regions represent nearly 30% of the global surface area[1]. A review by Scanlon *et al.*[2] covering Australia, China, Africa and SW North America indicated that average recharge rates in these regions vary from 0.2 to 35 mm/year representing 0.1–5% of long-term average precipitation. They suggested that land-use practices significantly influenced groundwater recharge.

Assessment of groundwater recharge is one of the key challenges in determining the sustainable yield of aquifers, as recharge rates are generally low in comparison with average annual rainfall or evapotranspiration, and thus difficult to determine precisely[3]. Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir'[4]. Reliable estimates of groundwater recharge are needed for a number of reasons, including assessing the surface water–groundwater interactions, total availability of water resources, groundwater vulnerability (for both quantity and quality aspects), and formulation of regional-scale artificial recharge and rainwater harvesting programmes. The National Water Policy-2002 of India states that 'there should be a periodical reassessment of the ground water potential on a scientific basis, taking into consideration the quality of the water available and economic viability of its extraction'[5]. Exploitation of groundwater resources should be so regulated as to not exceed the recharging possibilities, and also to ensure social equity[4]. Climate and soil are the two dominant factors in deciding whether or not a water harvesting system will be possible and economically viable. The hyper-arid zone (P/ETP < 0.3) is too dry for viable run-off farming, whereas the sub-humid zone (P/ETP 0.5–0.75) will be too wet. The run-off farming zone is primarily situated in the arid zone (P/ETP 0.03–0.2) and to some extent in the semi-arid zone (P/ETP 0.2–0.5)[6].

Farmers in many areas are using groundwater faster than nature is replenishing it, causing continuous decline in water levels. In India, as in other developing countries, agriculture accounts for most water use, as much as 85% of total annual draft. Natural recharge measurements carried out in about 20 river basins across India suggest that about 15–20% of seasonal rainfall is the contribution to groundwater recharge in the Indo-Gangetic Basin, which drops to just 5–10% in the peninsular hard-rock region. In the semi-arid regions of Karnataka, Shivanna *et al.*[7] estimated that about 33 mm (6%) of groundwater was recharged from an annual rainfall of 550 mm during 1992. Weathered granitic and gneissic complexes of southern India have neither hydrogeological nor hydrometeorological factors in their favour, which results in their small recharge rates[8]. Consolidated aquifers consist-

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ing of the basaltic and granitic–gneissic complexes have natural recharge rate of only 3–15% (20–100 mm).

An earlier study in the semi-arid tract of South India revealed that integrated soil and water conservation measures on a watershed basis had improved the groundwater regime. Reduction in surface run-off from 27.4% to 57.4% induced higher infiltration due to enhanced opportunity time. This led to increased water levels in wells by 0.5–1.0 m, thereby increasing the area irrigated by the wells by 172% compared to the pre-project period, which in turn improved crop yields by 70% (ref. 9).

Accurately estimating the current rate of groundwater recharge is a pre-requisite for efficient and sustainable groundwater management in semi-arid regions, where such a resource is the key to economic development. In arid and semi-arid areas, where potential evapotranspiration equals or surpasses average precipitation, recharge is difficult to estimate. Projections for the year 2025 indicate that all of northwestern India, the southern plateau and southeastern coastal regions will face water deficit[10].

The total annual groundwater withdrawals in India (251 billion cm^3) is the highest for any nation. Depletion of groundwater resources is increasingly common in many parts of India, and farmers bear significant costs and greater vulnerability resulting from the loss or reduction of a reliable irrigation source. This study is an attempt to quantify the effect of water harvesting structures on groundwater recharge, the consequent utilization patterns and impact on water availability[11].

Materials and methods

Study area

The study was carried out during 2004–08 in the K. D. Pally watershed (lat. 14°24′N, long. 77°12′E, altitude 556 m amsl) situated in Mallapuram–Kadlur sub-basin of Pennar river basin in Ananthapur district, Andhra Pradesh (Figure 1). The selected micro watershed covers 920 ha, an average slope ranging from 2% to 9%, and consists mainly of red soils (alfisols) derived from granite and gneisses. The mean (17 years) annual rainfall of the area is 543 mm. The watershed programme was implemented by the State Government during 1995–2003, which included construction of continuous and staggered contour trenches, water harvesting structures (WHS) of various sizes, loose boulder structures in drainage line, field bunding and establishment of horticulture plantation. The resource estimation report[5] for groundwater recharge revealed that the area for recharge is 107 ha of command area and 16,876 ha of non-command area in Mallapuram–Kadlur sub-basin in which this watershed is situated. The other features are:

(1) Net annual groundwater availability is 54 (ha m) in the command area and 1109 in the non-command area.
(2) Current gross annual groundwater draft for all uses is 15 (ha m) in the command area and 1463 in the non-command area.
(3) Current annul draft for irrigation is 13 ha m in the command area and 1438 ha m in the non-command area.
(4) Categorization – command area (safe), non-command area (over-exploited).

Four WHS (two percolation tanks and two check dams) were identified for this study (Figures 2 and 3). Staff gauges were installed to monitor the depths of stored water in these structures for calculation of waterspread area and capacity with respect to depth. Daily rainfall, evaporation and storage depth in WHS were measured to quantify losses caused by percolation and evaporation. Water-table levels were measured fortnightly from open wells and bore wells existing in the influence zone of WHS. Infiltration tests were conducted in arable areas and bed surface of WHS. Well logs were collected to determine the type of fractured aquifers. Monitoring was done for stage levels in WHS and water table in observation wells as described by Adhikari *et al.*[12]. Capacity survey of WHS was conducted and relationships between stage level and waterspread area and storage were developed (Table 1). Bore-well water samples were analysed for their physico-chemical constituents such as pH, electrical conductivity (EC) and important cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+),

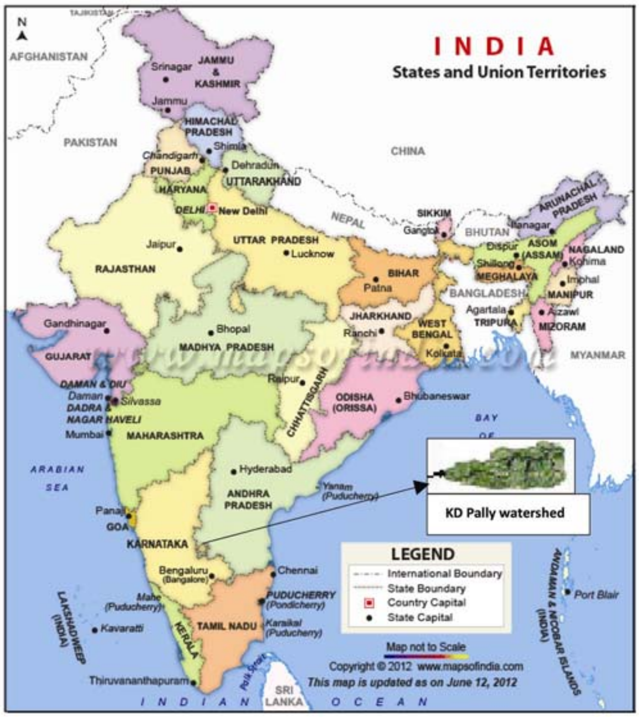

Figure 1. Location map of K. D. Pally Watershed, Ananthapur district, Andhra Pradesh, India.

Table 1. Stage–storage and stage–planer area relationships for water-harvesting structures (WHS) at K. D. Pally Watershed, Ananthapur district, Andhra Pradesh

WHS	Storage (in ’000 m^3)	Planer area (in ’000 m^2)	Planer area (in ’000 m^2)	Storage capacity (ha m)
Check dam-1 (CD-1)	$V_t = 0.945\ ht^{3.291}$	$WS_t = 2.065\ ht^{1.480}$	0.84	0.33
Check dam (CD-2)	$V_t = 0.230\ ht^{3.262}$	$WS_t = 0.768\ ht^{2.369}$	1.46	1.67
Percolation tank-1 (PT-1)	$V_t = 0.762–4.459\ h_t + 8.307\ ht^2$	$WS_t = 0.731–4.55\ h_t + 8.21\ ht^2$	4.14	3.93
Percolation tank-2 (PT-2)	$V_t = 0.799\ ht^{3.272}$	$WS_t = 2.460\ ht^{2.536}$	4.23	3.46

V_t, storage (in ’000 m^3); *ht*, Stage level (in m); WSt = Planer area (in ’000 m^2).

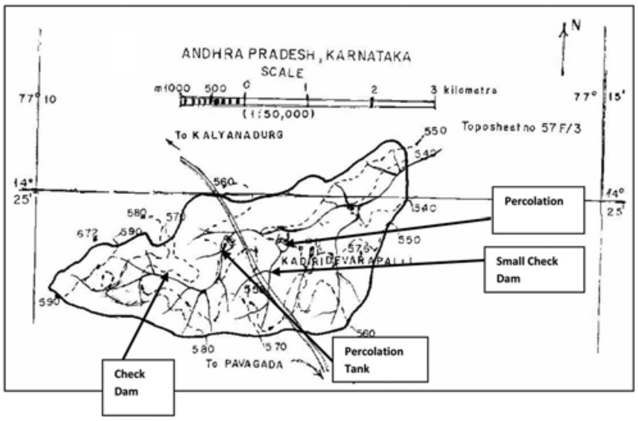

Figure 2. Watershed (contour map) delineated from the toposheet map showing latitude, longitude, altitude amsl and location of the water harvesting structures.

potassium (K^+) as well as anions such as chlorides (Cl^{-1}), sulphates (SO_4^{-2}), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-). All the physico-chemical parameters mentioned above were assessed using the standard procedures[13].

Results and discussion

Hydrological analysis

Annual rainfall data from 1985 to 2003 (18 years) of the project area were analysed for distribution and probability. It was observed that the average annual rainfall of the past 18 years was 575 mm and run-off-producing rainfall was 357 mm (62% of total rainfall) spread over nine run-off producing rainy days out of a total of 32 rainy days. Average run-off depth was estimated to be 7.23 cm (12.57% of total rainfall) based on SCS method for red soils. Since 2004, the watershed has been treated with soil and water conservation measures. Storm-wise rainfall, antecedent precipitation index (API), run-off, evaporation and percolation for all the structures and detailed water budgeting for predicting run-offs, including overflows are presented in Table 2.

Rainfall-run-off relationship

Structure-wise simple linear and multiple linear regression equations with API as an additional factor have been developed earlier[14] for similar agro-ecological situations and these were observed to be useful in predicting the run-off. Based on the data collected from K. D. Pally watershed during 2004–08, the following two equations have been developed.

$$Y = ax + c,$$

$$Y = ax + bz + c,$$

where *Y* is the run-off (in mm), *x* the rainfall (in mm), *z* is API, a dimensionless factor, and *a*, *b*, *c* are the regression constants.

It is observed that multiple linear regression equations had higher correlation compared to simple linear regression equations (Table 3); hence the former can be recommended to predict run-off, including overflows for this watershed. In 2006, overflow for each structure has been predicted based on the equations developed.

Groundwater recharge potential

Water storage spread over 3.91 ha of contact area for about 15–45 days residence time provides considerable scope for groundwater recharge. Thus, longer residence period and wider contact area by means of WHS was created for enhanced groundwater recharge. Further, well-drained subsurface zone enhanced impact of surface storage on groundwater recharge. Well logs revealed that the depth of fractured zones ranged from 50 to 195 ft (Figure 4). The water is initially struck at 50–95 ft, while full yields (1.5–2.0 inches) are realized at a depth of 140–215 ft. Structure-wise potential recharge has been estimated from the equations (Table 4) which were developed for this watershed.

Amount of percolation was also calculated and it was assumed that the remaining water has been absorbed by the sub-soil layer. Pump testing was carried for two wells at K. D. Pally during June 2006 by the Groundwater Department. The results of pumping tests indicated that the transmitivity (m^3/d/m) was found to be 94.34 and 144.84, whereas specific capacity (lpm/m) was 41.57 and 64.71 and discharge (lpm) 222 and 143, with the coefficient of storage being 0.03246.

Table 2. Storm-wise rainfall, antecedent precipitation index (API), run-off, evaporation and percolation in the influence zone of all the structures

			CD-2			PT-2			CD-1			PT-2		
Date	Rain fall (mm)	API	Run-off (mm)	Evaporation (mm)	Percolation (mm)	Run-off (mm)	Evaporation (mm)	Percolation (mm)	Run-off (mm)	Evaporation (mm)	Percolation (mm)	Run-off (mm)	Evaporation (mm)	Percolation (mm)
28.5.04	46.50	25.30	5.20	0.48	4.70	5.90	0.50	5.40	4.40	0.80	3.60	5.40	0.48	4.92
23.5.05	42.50	1.60	2.69	0.20	2.20	2.55	0.20	2.30	3.24	0.70	2.50	3.47	0.60	2.80
30.5.05	72.50	29.10	5.60	0.60	5.00	5.60	1.20	4.40	8.06	1.00	7.00	6.93	1.20	5.70
16.7.05	44.20	28.90	2.92	0.30	2.60	3.18	0.65	2.50	6.75	0.70	6.00	8.47	1.40	7.00
15.9.05	40.50	73.10	5.23	0.61	4.80	6.47	1.20	5.20	8.06	0.90	7.10	8.63	0.90	7.70
3.11.06	179.00	65.00	21.2	0.40	4.70	22.9	0.40	5.50	31.1	0.60	16.30	26.86	0.85	23.00
9.6.07	48.00	53.00	4.61	0.30	4.30	5.10	0.40	4.70	6.67	0.20	6.40	7.02	0.10	6.70
18.9.07	50.00	67.00	5.11	0.40	4.60	5.98	0.40	5.50	7.88	0.30	7.58	8.15	0.10	7.70
4.6.08	61.00	32.00	5.73	0.40	5.30	3.91	0.50	3.40	4.97	0.30	4.60	4.96	0.20	4.50
4.9.08	75.00	21.00	6.33	0.30	5.70	5.90	0.30	4.40	5.65	0.50	5.00	6.55	0.30	5.20
16.9.08	69.50	45.40	5.76	0.40	5.30	6.68	0.30	6.50	5.90	0.30	5.60	6.54	1.10	4.80
10.11.08	45.50	3.60	3.81	0.20	3.60	3.56	0.20	3.30	3.70	0.20	3.40	3.30	0.70	2.60
28.11.08	31.20	9.60	2.32	0.10	2.20	2.25	0.20	2.00	2.31	0.10	2.20	2.69	0.40	2.10

1. Storm in 2006 was very intense. It was observed that considerable amount of water flowed over the storage structure. Run-off is shown as entire amount of water (stored + overflow), but evaporation and percolation have been calculated only from the full storage capacity, i.e. 5.11, 5.98, 16.92 and 23.85 mm for CD2, PT2, CD1 and PT1 respectively.
2. Annual rainfall of 2004, 2005, 2006, 2007 and 2008 is 423, 626, 516, 486 and 657 mm respectively.
3. CD, Check dam; PT, Percolation tank.

Figure 3. A view of water harvesting structures.

Table 3. Structure-wise coefficients, constants, R^2 and standard error of simple and multiple regression equations

Structure	Coefficient (*a*)	Constant (*c*)	R^2	Std. error
Simple regression				
CD-2	0.124	–1.573	0.964	0.912
PT-2	0.133	–1.800	0.919	1.494
CD-1	0.189	–3.548	0.935	1.875
PT-1	0.156	–1.762	0.888	2.096

Structure	Coefficient (*a*)	Coefficient (*b*)	Constant (*c*)	R^2	Std. error
Multiple regression					
CD-2	0.118	0.024	–2.021	0.976	0.764
PT-2	0.122	0.044	–2.627	0.955	1.157
CD-1	0.173	0.062	–4.715	0.972	1.286
PT-1	0.139	0.065	–2.984	0.943	1.550

Table 4. Structure-wise average recharge function

WHS	Potential recharge function
CD-2	$Y = 26.45X^{1.6133}$
CD-1	$Y = 71.22X^{2.4752}$
PT-2	$Y = 83.352X^{1.5667}$
PT-1	$Y = 335.53X^{1.1292}$

X is average height (in m) of stored water in two consecutive days. *Y* is the potential recharge (in m^3).

Relationship between cumulative rainfall and cumulative potential recharge

The relationship between cumulative rainfall (CRF; in mm) and cumulative potential recharge (CPR, in mm) has been developed using the following function[15].

$$\log 10\,(\mathrm{CPR}) = a\{b - e^{-c(\mathrm{CRF})}\},$$

a, *b*, *c* are constants of the equation.

An attempt has also been made to calculate maximum potential recharge, percentage of maximum potential recharge to cumulative rainfall and cut-off rainfall to produce 1 mm recharge. The results are presented in Table 5. It can be observed from Table 5, that an average threshold rainfall to produce 1 mm recharge is 28–82.4 mm. Potential recharge is around 3% of rainfall. The level difference was more than 1.15 m between water table in WHS-influenced bore well (depth to ground level 13.54–15.50 m) and WHS-uninfluenced bore well (depth to ground level 14.77–17.24 m). Due to influence of WHS, rise in water table level was 3.4 m in open wells and 1.6 to 2.4 m in bore wells. This indicates recharge

Table 5. Structure-wise cumulative potential recharge versus cumulative rainfall relationship along with WHS performance

		Statistical parameters				WHS performance		
WHS	Equation used	*a*	*b*	*c*	R^2	Threshold rainfall to trigger 1 mm potential recharge	Maximum recharge (mm)	Maximum % of recharge to rainfall
CD-2	$\log10(\text{CPR}) = a\{b - e^{-c(\text{CRF})}\}$	1.821	0.7274	0.0049	0.8825	64.86	21.1208	2.97
PT-2	-do-	1.5706	0.9274	0.0027	0.81	28.00	28.6098	2.36
CD-1	-do-	2.6930	0.4542	0.0096	0.81	82.44	16.7148	3.92
PT-1	-do-	2.0328	0.6296	0.0068	0.81	68.00	19.0463	3.53

Table 6. Water quality parameters of K. D. Pally watershed from June 2004 to January 2009

	Rainy season			Winter season			Summer season		
Parameter	Upper region	Middle region	Lower region	Upper region	Middle region	Lower region	Upper region	Middle region	Lower region
pH	8.29	8.27	8.20	8.64	8.72	8.60	8.53	8.44	8.42
Electrical conductivity (EC) (dSm^{-1})	1.52	0.62	0.56	1.56	0.61	0.55	1.34	0.62	0.54
Sodium adsorption ratio	3.06	3.13	5.54	2.86	3.01	5.04	3.61	3.45	5.64
Residual sodium carbonate	1.62	1.45	0.27	1.14	0.95	0.58	1.75	1.49	1.38
Total hardness (mg/l)	79.3	97.4	169.36	89.1	106.08	216.95	74.08	102.39	203.92
Nitrate (ppm)	27.10	35.64	79.69	30.79	51.40	109.13	33.55	43.30	100.97
Fluoride (ppm)	2.40	1.89	1.81	3.55	2.69	2.29	2.67	2.03	2.15

All values are average of 13 wells studied in the watershed.

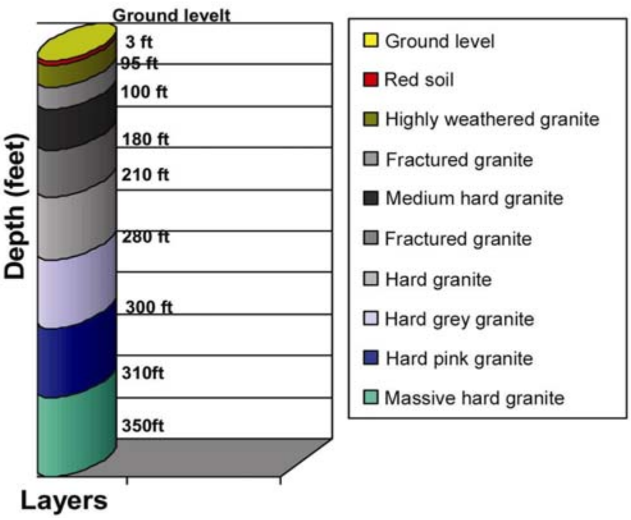

Figure 4. Lithological log of bore well at K. D. Pally.

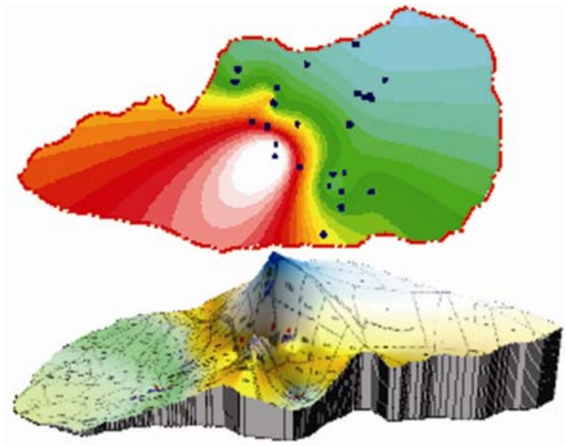

Figure 5. Isometric view of difference in water-table-level grids due to WHS.

efficiency of WHS. The rise in water table in wells due to WHS was observed to be greater (Figure 5).

The increase in water level in the wells is further evident from the observation of date-wise variation in the water table of influenced wells by storage structure (Figure 6) eventually harvesting rainwater from the catchment area, which shows that in the initial year (2004–05 with a rainfall of 423 mm) water level from the ground surface varied between 5 and 25 m, whereas in the project period (2008–09 with rainfall of 657 mm) it was between 3 and 8 m, proving that there is a clear-cut increase in water table in the wells.

Structure-wise potential recharge (Table 6) has been computed from the observed storage data (four years) and catchment area. Based on this potential recharge (Rp), weighted average of maximum potential recharge is estimated to be 23.66 mm/ha/year for the selected four WHS. Two more WHS with 27 and 58 ha catchment areas situated in the watershed also influenced groundwater recharge. Hence, the total potential recharge from six WHS within the watershed was estimated to be 8.9 ha m/year.

Quality of groundwater

Water samples were collected from 13 bore wells situated in the upper, middle and lower regions of the watershed

Table 7. Average quality of well water at different distances from WHS during 2008–09

Distance of wells from WHS (m)	pH	EC (dSm^{-1})	SAR	RSC	Total hardness (mg/l)	Nitrate (ppm)	Fluoride (ppm)
0–100	8.28	0.69	3.07	1.74	136.83	62.44	0.97
101–300	8.24	0.79	3.32	2.06	140.59	74.74	1.09
301–800	8.36	0.94	3.70	2.12	145.90	118.47	1.26

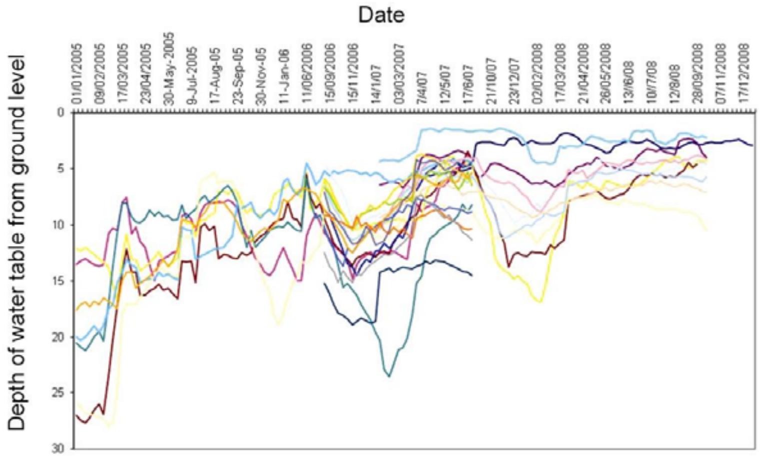

Figure 6. Date-wise variation in water table of WHS-influenced wells by storage structure.

at monthly intervals from June 2004 to January 2009 and analysed for quality parameters. Results (Table 6) indicate that there is an increase in pH values from rainy season to winter season. Not much change was observed in EC values during three different seasons. However, lower EC values (0.54–0.56 dSm^{-1}) were observed in the lower region of the watershed during all the seasons. Total hardness of water was lower in the rainy season, while it increased during winter and summer seasons in the middle and upper regions. Sodium adsorption ratio (SAR) values are less than 6 and within permissible limits. Similarly, residual sodium carbonate (RSC) values are within the safe limit of 2.5. Well waters in lower regions show decrease in RSC values during winter followed by rainy season. There is an increase in concentration of nitrate and fluoride values during summer followed by winter. During rainy season, lower concentration of nitrates and fluorides was observed in all the regions of the watershed. This clearly highlights the dilution effects in the concentration of nitrates and fluorides during rainy season in all the regions, because of the impact of WHS on groundwater.

From Table 7 it is evident that during 2008–09, WHS influenced the quality of water in the wells by diluting the salt content. The EC, RSC, nitrates and fluoride values were less in the wells located near (0–100 m distance) the WHS compared to those located away (101–300 and 301–800 m distance) from WHS. Similar trend was observed in total hardness and SAR values. So, it can be confirmed that recharge from WHS has strong influence in diluting the salt content of groundwater in nearby wells. During the year, water samples were collected from eight bore wells located outside the watershed and analysed. Higher concentration of nitrates and fluorides was observed in well waters outside the watershed compared to those within the watershed. Groundwater recharge had increased with WHS in the watershed and the quality of water also improved.

Groundwater availability vis-à-vis utilization

The Andhra Pradesh State Government Ground Water Department has reported that 6.6 m^3 (53.4 ha m) of net groundwater availability exists in the non-command area of Mallapuram–Kadlur basin in which the study area is situated. Sukhija *et al.*[8] reported that hydraulic conductivity of this basin is 3–6.3 m/d, specific yield of major aquifer (granite and gneiss) is 2.5–3.0% with average recharge of 6.5 mm and average % of recharge to rainfall ranges from 1.2 to 6.9.

During rainy season, the irrigated crops depend on rainfall, except during periods of long dry spell. In winter, the crops are grown entirely by irrigation from wells.

Groundwater use in pre-project period

In the pre-project period (2003–04 without WHS), total irrigation water requirement for kharif and winter irrigated area (37.2 ha) was 21.42 ha m. This requirement

Table 8. Increase in groundwater use for irrigation with time

Period (years)	Rainfall (mm)	Irrigated area (ha)	Irrigation quantity required (ha m)	Water availability* (ha m)	Over-exploitation (ha m)	Percentage of excess exploitation in low rainfall year over normal year
Pre-project		37.2	21.42	53.94	0	
Post-project						
2005	626.0	96.4	61.64	58.41	3.23	
2006	516.0	113.5	72.74	58.27	14.47	99.8
2007	489.0	113.3	72.55	58.40	14.15	95.4
2008	657.0	102.9	65.76	58.52	7.24	
Average of post-project		106.5	68.17	58.40	9.77	

*Sources of water availability include rainfall, natural recharge and recharge from WHS both within and outside the watershed.

was met by rainfall (0.5 ha m) and by the net availability of groundwater quantity (53.4 ha m) due to existing percolation tanks in the vicinity. This resulted in a desirable situation of groundwater surplus to tide over drought years, which is a common occurrence (once in three years) in this arid to semi-arid tract.

Groundwater use in post-project period

In the post-project period (2005–2008 with WHS), the average irrigated area increased to 106.5 ha compared to 37.2 ha in the pre-project period. Correspondingly, the average groundwater draft increased from 37.3 ha m (pre-project period) to 68.2 ha m (average of five years in post-project period). Out of this, 53.9 ha m of irrigation water was met by direct rainfall and natural recharge plus recharge due to existing WHS in the vicinity. In addition, six more WHS, constructed in the post-project period, have created a potential recharge of 4.5 ha m. Yet, there is an average deficit of groundwater (9.8 ha m; Table 8).

This implies that over-exploitation of groundwater is continuing to an extent that may exhaust the buffer reserves in deep aquifers, which will place the assured sources of drinking water at stake. This over-exploitation was 95–99% (14.15 and 14.5 ha m) higher in ‘below normal’ rainfall years (2006 and 2007) compared to 3.2–7.2 ha m in the normal rainfall years (2005–08). Over-exploitation in scanty rainfall years aggravates the drinking water problem in this non-command area, which depends entirely on groundwater sources for drinking and domestic needs. However, local WHS could moderate the drinking water requirements, if not irrigation needs, to some extent, as these WHS store whatever rainwater is received as run-off, even in years with scanty rainfall and help recharge the groundwater for drinking-water purposes, as was apparent in the case of the K. D. Pally watershed (Table 2).

Consequently, the deepening of bore wells has been profound with the depth increasing from 30 m in 1995–2000 to 106 m in 2004. This trend of increase in well intensity and deepening of bores has had an adverse effect on the functioning of old open wells and also subsurface inflows into water bodies. Eighteen open wells (average depth 15 m) existing from 1975 have dried up since 2006 due to the indiscriminate drilling of bore wells. Further, failure rate of the bore wells commissioned since 2000 was three for every successful bore well and resulted in increasing the financial liability of the farmer.

The above situation suggests that authorities should take up measures for groundwater recharge and exploitation simultaneously and should issue guidelines for groundwater exploitation. The buffer groundwater in deep aquifers, that is supposedly meant for meeting drinking water requirements in lean years, should not be drawn. Watershed projects actually lead to increased water use for irrigation, because extending the area under irrigation is often an explicit objective or an unintended outcome. WHS, and soil and water conservation measures are welfare programmes, as they ensure rural water requirements and also provide opportunities for groundwater recharge, for subsequent use in life-saving irrigation.

Conclusion

In this study various hydrological parameters related to groundwater recharge have been estimated. Relationship between API-based rainfall and run-off has been developed earlier[14]. The results show that the threshold value of rainfall for ensuring 1 mm potential recharge is 28–82 mm in this dry region. Potential recharge has been estimated to be 3% of rainfall. The study clearly indicates that WHG, in semi-arid red soil region helped in improving groundwater recharge, but also led to its subsequent over-exploitation. The results of the study can be applied for similar agro-climatic regions for approximate quantification of surface storage and groundwater recharge. However, there is an urgent need to review legislation and develop local-level institutions (water user’s society) to ensure sustainable water availability.

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RETRACTION

Cotton leaf curl virus resistance transgenics with antisense coat protein gene (*AV1*)

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