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Study on the effect of groundwater recharge through water harvesting structures in semi-arid red soil region of south India

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ABSTRACT

A study was conducted to investigate the effect of Water Harvesting Structures (WHS) on groundwater (GW) recharge during 2004-08 in red soil watershed of semi arid region, namely K.D. Pally watershed (920 ha) in Kambadur Mandal of Anantapur district, Andhra Pradesh. Four WHS namely, P. Reddy Check Dam (PRCD), G. Reddy Percolation Tank (GRPT), Small Check Dam (Small CD) and Village Percolation Tank (VPT) of storage capacity 1.67, 4.36, 0.33 and 3.93 ha-m, respectively having a total capacity of 9.4 ha-m. One time filling were selected to assess their effect on GW recharge. In the present study, structure wise simple linear and multiple regression equations with API as an additional factor were developed to predict the runoff expected in a particular rainfall storm, for all four structures. The hydrological analysis showed that curve number (CN) was found to be less and storage (S_t) was higher in case of computed values from observed data using methodology prescribed in the present study compared to Hydrologic Soil Cover Complex method. Potential recharge has been estimated and empirical relationships were developed between cumulative potential recharge and cumulative rainfall. Changes in ground water utilization pattern was also studied and found that the irrigated area expanded up to 113.5 ha in post-project as against 37.2 ha pre-project. The present study showed that the WHS had very good impact on ground water recharge in the study area. Therefore, it is recommended that the study can be applied for similar other region for approximate quantification of surface storage and ground water recharge.

1. INTRODUCTION

It has been estimated that irrigation through ground water resources would account for 40 m ha for the country as a whole apart from 58 m ha from major and medium irrigation projects. Surface water resources are inadequate and costly to develop for intensive agriculture and generally result in water logging and salinity problem. Hence it is of paramount importance to devise suitable techniques to augment ground water reserves, which have many advantages over the surface resources (Singh *et al.,* 2005).

Climate and soils are the two dominant factors in deciding whether or not water harvesting system will be possible and sensible. The hyper arid zone (P/ETP<0.3) is too dry for viable runoff farming, while sub humid zone (P/ETP 0.5-0.75) will be too wet. The runoff 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/EPT 0.2-0.5). The watershed under study is falling under semi-arid red soil zone of Andhra Pradesh, hence this area is having highly potential for rain water management including water harvesting through soil and water conservation measures (Adhikari *et al.*, 2008; Singh and Khan, 1999).

Currently in India, the average potential surface flow is estimated as 1869 km^3, out of which, total live storage of 174 km^3 has already been created, and projects to create another live storage of 721 km^3 are under construction (Agrawal and Goel, 2002; Singh *et al.,* 2014). It includes live storage of 25 km^3 in minor irrigation and traditional tanks in India. Sustainable protection or management of surface and sub surface water resources is one of the most pressing needs of the nation. This issue is closely related to surface and sub surface flow in the minor gullies at micro level to major river systems at macro level (Samra *et al.*, 2003; Singh *et al.,* 1997; Kumar *et al.,* 2011). In view of above, the present study was conducted at K.D. Pally watershed in red soils region of Andhra Pradesh state, which showed the effect of drainage line treatment with right intensity and sequence of conservation structures in cascading effect on surface and sub-surface water resources at micro level. Such studies will help in formulating guidelines for planning, designing and utility of different WHS and to establish empirical/statistical relationship.

2. MATERIALS AND METHODS

Study Area

A study was initiated in K.D. Pally watershed located at Latitude 14^{0}24'N, Longitude 77^0 12'E and Altitude 556 msl in Kambadur Mandal of Anantapur district in Andhra Pradesh state during 2002-03 to assess and quantify the effect of WHS on surface and subsurface water hydrology. The area of the selected micro catchment was 920 ha with red soils (alfisols) derived from granite and gneisses, having average slope of 2.0-9.0%. In the watershed, the area under cultivation was 459.3 ha. The mean (19 years) annual rainfall of the area was 575 mm. The transmissivity of aquifers in the area is of the order of 10-290 sq m day^{-1} (Anon. 2002). The watershed programme was implemented during 1998-2003, which included construction of continuous and staggered contour trenches, WHS of various size, loose boulder structures in drainage line, field bunding and horticulture plantation in agricultural land. Four water harvesting structures were considered for this study (Fig.1).

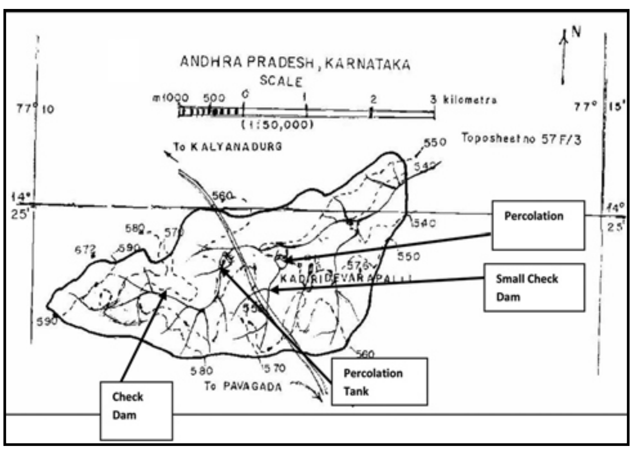

Fig. 1. K.D. Pally Watershed delineated from the toposheet

Relationship between Stage Storage Capacity and Stage Water Spread Area

Two percolation tanks and two check dams were selected to monitor the surface runoff and storage. Initially, capacity survey of all four WHS was conducted and the relationships between stage level water spread area and stage level- storage capacity were developed, which are given below:

	Storage capacity	Water spread area
PRCD	V_t=1000	WS_t=1000
	(0.230 $h_t^{3.262}$)	(0.768 $h_t^{2.369}$)
GRPT	V_t=1000	WS_t=1000
	(0.799 $h_t^{3.272}$)	(2.460 $h_t^{2.536}$)
Small CD	V_t=1000	WS_t=1000
	(0.945$h_t^{3.291}$)	(2.065 $h_t^{1.480}$)
VPT	V_t=1000	WS_t=1000
	(0.762-4.459h_t+8.307h_t^2)	(0.731-4.55h_t+8.21h^{t2})

Where, V_t is the storage capacity (cum), h_t is the stage level (m), and WS_t is the water spread area (sq m).

The maximum storage capacities and water spread areas were calculated after detailed survey and are given in Table 1. Staff gauge were installed to record depths of the stored water in these WHS for calculation of water spread area and capacity with respect to depth. Daily rainfall, evaporation and storage depth in WHS were measured to quantify different losses. Fortnightly water table levels were also measured from the open wells existing in the influence zone of WHS. Infiltration tests were also conducted in arable areas and bed surface of WHS. Well logs were collected to know the type of fractured aquifers. One recharge filter consists of pit of size 5 m length, 5 m width and 1.5 m depth connected with 200 mm bore well having depth of 50 m was also constructed in each ponding area of WHS to induce artificial recharge.

Table: 1
Maximum storage capacities and water spread areas of different WHS at K.D. Pally

Sl.No.	Water harvesting structures	Water spread area (sq m)	Storage capacity (ha-m)
1	PRCD (Check dam)	1460	1.67
2	GRPT (Percolation tank)	4230	3.46
3	Small CD (Check dam)	840	0.33
4	VPT (Percolation tank)	4140	3.93

Estimation of Curve Number and Watershed Storage

The Soil Conservation Service (SCS) runoff prediction model has been used for estimating potential retention for which St (storage in mm) for events with runoff was expressed as a function of P and Q (Ponce and Hawkins, 1996).

$$S_t = 5[P+2Q-(4Q^2+5PQ)^{½}]$$

Where, P is the rainfall depth in mm, Q is the runoff depth in mm, and S_t is the potential retention in mm.

Using this equation with data on rainfall runoff depth, values of S_t were computed for all runoff events. These were then used to compute CN using following equations:

$$CN = 25400/(254+S_t)$$

Where, CN is the curve number. S_t and CN were computed for all the runoff events of all the four structures.

Runoff was estimated from the potential maximum retention and one-day maximum rainfall of 10 year return period by using equation given below:

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)}$$

Where, P is the storm rainfall (mm) and Q is direct runoff (mm).

$$Q = \frac{(P-0.3S)^2}{(P+0.7S)} \text{ for } I_a = 0.3S,$$

Rainfall-Runoff Relationship

An attempt was made to develop simple and multiple linear regression equations to predict runoff from rainfall and antecedent precipitation index (API) (Adhikari *et al.*, 2003). The equations are:

Y = ax+c

Y = ax+bz+c

Where, Y is the runoff in mm, x is rainfall in mm, z is API, a dimensionless factor, and a,b,c are the regression constants.

3. RESULTS AND DISCUSSION

Hydrological Analysis

Annual rainfall data from 1985 to 2003 (19 years) of the study area were analyzed. It was found that the average rainfall of past 19 years was 575 mm and runoff producing rainfall was 357 mm (62% of total rainfall) spreading over 9 runoff producing rainy days out of total 32 rainy days. Average runoff depth was estimated to be 72.3 mm (12.57% of total rainfall) based on SCS method for red soils.

Curve Number and Watershed Storage Analysis

Datewise rainfall, runoff, S_t and CN computed for all four WHSs are presented in Table 2. The S_t and CN were computed based on the observed rainfall and runoff data for all the rainy storms of all four structures. The average computed values of CN and S_t were found to be 69.15 and 122.2 mm, respectively.

The values of CN and S_t were also estimated based on the land use pattern of watershed using CN table (Conventional Hydrologic soil cover complex method, Anonymous 1972.) for comparison. The estimated values were found to be 78 and 73 mm for CN and S_t, respectively. This method does not take into account the effect of soil and water conservation practices on estimation of these parameters.

The results showed that CN was found to be less and S_t was higher in case of computed values from observed data using methodology prescribed in the present study compared to Hydrologic soil cover complex method. Hence the results clearly indicated the effect of conservation measures since year 2003 were responsible for decrease in CN and runoff and increase in S_t, which in turn helped to increase ground water recharge.

Rainfall - Runoff Relationship

Data of storm wise rainfall events and runoff produced were collected for the period of four years (2004-08) from the K.D. Pally watershed. APIs were computed using methodology described above for all the storms. Storm wise rainfall, runoff and corresponding API are given in Table 2. It revealed that the maximum storm occurred was 179 mm and minimum of 29.00 mm during the period which could produce runoff in all the structures.

To predict the runoff expected in a particular rainfall storm, structure wise simple linear and multiple regression equations with API as an additional factor were developed for all four structures. The structure wise coefficients, constants, r^2 and standard error of simple and multiple regressions are presented in Table 3a and Table 3b. It can be seen from the table that multiple linear regression equations got better 'r^2' value and less standard errors compared to simple linear regression equations. Hence multiple linear regression equations can be recommended to predict runoff for this watershed.

Table: 2
Date wise rainfall, API, runoff, storage and curve number of K.D. Pally watershed

Date	Rainfall (mm)	API	PRCD			GRPT			Small CD			VPT		
			Runoff (mm)	St (mm)	CN	Runoff (mm)	St (mm)	CN	Runoff (mm)	St (mm)	CN	Runoff (mm)	St (mm)	CN
28.5.04	46.50	25.3	5.20	103.0	71.14	5.90	97.1	72.34	4.40	110.6	69.66	5.40	101.3	71.49
23.5.05	42.50	1.6	2.69	116.9	68.49	2.55	118.8	68.12	3.24	109.8	69.83	3.47	107.1	70.35
30.5.05	72.50	29.1	5.60	186.4	57.68	5.60	186.4	57.68	8.06	161.8	61.19	6.93	117.8	59.65
16.7.05	44.20	28.9	2.92	119.9	67.94	3.18	116.5	68.56	6.75	83.9	75.16	8.47	73.4	77.58
15.9.05	40.50	73.1	5.23	83.9	75.17	6.47	75.0	77.20	8.06	65.6	79.47	8.63	62.7	80.21
3.11.06	179.00	65.0	21.20	386.6	39.65	22.90	372.5	40.54	3.10	316.0	44.56	26.86	343.1	42.54
9.6.07	48.00	53.0	4.61	113.5	69.11	5.10	108.8	70.01	6.67	95.8	72.61	7.02	93.3	73.14
18.9.07	50.00	67.0	5.11	115.2	68.79	5.98	107.4	70.28	7.88	93.3	73.14	8.15	91.5	73.51
4.6.08	61.00	32.0	5.73	145.6	63.57	3.91	167.5	60.32	4.97	153.8	62.29	4.96	153.9	62.27
27.8.08	46.00	2.0	4.01	113.0	69.20	3.24	122.1	67.53	3.87	114.6	68.91	4.33	109.7	69.84
4.9.08	29.00	21.0	2.32	73.6	77.53	2.66	69.9	78.43	1.78	80.5	75.93	2.22	74.8	77.25
9.9.08	39.00	29.3	2.92	101.4	71.48	3.56	94.1	72.96	2.95	101.0	71.55	3.75	92.2	73.37
16.9.08	30.50	45.4	2.84	73.0	77.67	3.21	70.3	78.33	2.95	71.9	77.93	2.79	73.6	77.54
10.11.08	45.50	3.6	3.81	113.5	69.11	3.56	116.4	68.57	3.70	114.8	68.87	3.30	119.6	67.99
28.11.08	31.20	9.60	2.32	81.3	75.76	2.55	82.2	75.56	2.31	81.4	75.73	2.69	77.0	76.74
Average	53.70	32.4	5.10	128.5	68.1	5.36	127.0	68.43	4.71	116.9	69.79	6.60	116.3	70.23

Table: 3a
Structure wise coefficients, constants, r^2 and standard error of simple regression equation

Structure	Coefficient (a)	Constant (c)	r^2	Std. Error
PRCD	0.124	-1.573	0.964	0.912
GRPT	0.133	-1.800	0.919	1.494
Small CD	0.189	-3.548	0.935	1.875
VPT	0.156	-1.762	0.888	2.096

Table: 3b
Structure wise coefficients, constants, r^2 and standard error of multiple regression equation

Structure	Coefficient (a)	Coefficient (b)	Constant (c)	r^2	Std. Error
PRCD	0.118	0.024	-2.021	0.976	0.764
GRPT	0.122	0.044	-2.267	0.955	1.157
Small CD	0.173	0.062	-4.715	0.972	1.286
VPT	0.139	0.065	-2.984	0.943	1.550

Ground Water Recharge Potential

An empirical relationship between cumulative potential recharge versus cumulative rainfall was developed and used for estimation of potential recharge of each WHSs. The equation is stated below $\text{Log}_{10}\,(\text{CPR})=a\{b-e^{-c(\text{CRF})}\}$ and details of equation parameters are given in Table 4 for all the four WHSs. It is reveled from the Table that the threshold rainfall to trigger 1mm potential recharge (82.44 mm) was found to be higher in case of small CD and lowest (28.00 mm) in case of GRPT. It means that lesser the threshold rainfall higher the recharge which was evident from the data of maximum recharge. The maximum recharge was found to be higher (28.60 mm) in case of GRPT and minimum in case of small CD.

The transmitivity of aquifers of the watershed was also computed to know the behavior towards flow of water within the aquifer and found to be 10-290 sq m day^{1}. These results showed that aquifer is well drained. The level difference was more than 1.15 m between water table in WHS-influenced bore well (depth to ground level 13.5415.50 m) and 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 indicated recharge efficiency of WHSs. The rise in water table in wells due to water harvesting structures was found greater towards the valley of watershed.

Ground Water Utilization Pattern

The above storage spreading over 12.6 ha of contact area for about 90 days resident time would provide considerable scope for GW recharge. Thus, longer resident period and wider contact area by means of WHS is created for GW recharge improvement. Further, well-drained subsurface zone enhanced impact of surface storage on groundwater recharge. Well logs revealed that the depth of fractured zones ranged from 17.85-61.40 m. The impact of use of ground water on increase in irrigated area after implementation of this project of WHSs for ground water recharge has been given in Table 5. It can be seen from table that the number of wells increased from 24 in pre-project (1995) to 41 in the post project period, which expanded irrigated area up to 113.5 ha in post project as against 37.2 ha. This was also evident from the increased area under horticulture plantation which could be possible only when the ground water is available through out the year. The horticulture area increased from 17.8 ha in pre- project to 53.4 ha in post project period. In rainy season, the irrigated crops depended on rainfall except during long dry spell period. In winter and summer, the crops were grown entirely by irrigation from wells. Results clearly indicated that the irrigated area in post- project period has remarkably increased by 143.22 % over that of pre- project period.

Table: 4
Cumulative potential recharge (CPR) structure-wise versus cumulative rainfall (CRF) relationship along with WHS performance

WHS	Statistical parameters				WHS performance		
	a	b	c	r^2	Threshold rainfall to trigger 1 mm potential recharge	Maximum recharge (mm)	Maximum % of recharge to rainfall
PRCD	1.821	0.7274	0.0049	0.88	64.86	21.1208	2.97
GRPT	1.57	0.9274	0.0027	0.81	28.00	28.61	2.36
Small CD	2.63	0.4542	0.0096	0.81	82.44	16.72	3.92
VPT	2.033	0.6296	0.0068	0.81	68.00	19.0463	3.53

Table: 5
Increase in irrigated area and use of ground water

Situation	No. of Wells	Irrigated area (ha)			Weighted depth of irrigation (m)		Groundwater used (ha-m)		
		Season		Total					
		R	W		R	W	R	W	Total
Pre-project	20	27.8	9.4	37.2	0.5	0.9	13.9	8.5	22.4
2004	41	23.4	38.2	61.6	0.63	0.9	14.7	36.7	51.4
2005	41	51.6	44.8	96.4	0.38	0.8	19.6	35.8	55.4
2006	41	60.2	53.3	113.5	0.35	0.8	21.1	42.6	63.7
2007	41	60.3	53.0	113.4	0.35	0.8	21.14	42.4	63.54

R - Rainy, W - Winter

4. CONCLUSIONS

In this study, various hydrological parameters related to ground water recharge have been estimated. API based rainfall - runoff relationship have been developed. Multiple regressions were found to be better than simple regression model. Runoff curve number from observed data and by Hydrologic Soil Cover complex have been computed and compared. The results showed that CN was found to be less and S_t was higher in case of computed values from observed data using methodology prescribed in the present study compared to Hydrologic soil cover complex method. Potential recharge has been estimated and empirical relationships were developed between cumulative potential recharge and cumulative rainfall. Changes in ground water utilization pattern was also studied and found that the irrigated area expanded up to 113.5 ha in post project as against 37.2 ha pre-project. The study showed that the water harvesting structures in semi arid red soil region, helped in improving the ground water recharge. The results of the study can be applied for similar Agro climatic region for approximate quantification of surface storage and ground water recharge.

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