Rainwater Harvesting to Augment Groundwater Levels: A Case Study

Deepesh Machiwal[1], Santosh Ojha[2] and R.C. Purohit[3]

ABSTRACT

Rainwater harvesting-cum-artificial groundwater recharge is the most-promising tool for enhancing water availability in semi-arid regions by augmenting groundwater levels. The present study evaluates a rainwater harvesting structure in the Rajsamand district in semi-arid region of Rajasthan by rainfall-water level dynamics, surface-ground water interaction and potential/actual groundwater recharge. Daily rainfall and evaporation, water level of the water harvesting structure weekly groundwater levels of ten wells and pre- and post-monsoon groundwater quality were monitored during 2007-10 and analysed. The results revealed that the rainfall has strong influence on the surface water and groundwater levels. The groundwater quality is found to be satisfactory for drinking and irrigation purposes. The potential recharge rate in the area is determined as 1 m/day. However, the actual groundwater recharge varied from 4.3 to 30.4 cm (8.3-26.1% of monsoon rainfall). Thus, the study reaffirms that the rainwater harvesting structures have adequate potential in rainwater recharging to augment the groundwater levels in the study area.

Key words: Rainwater harvesting structure; Rainfall-water level dynamics; Surface water-groundwater interaction; recharge; water table rise.

For past few years, the inhabitants of Khamnor block of Rajsamand district of Rajasthan are facing problems of declining water table, which has led to a situation that the old shallow wells with average depth of 20-30 m have become inoperative. The study area does not have any perennial source of water. The whole area surrounded by the Aravalli hills, is largely dependent on rainfall, which occurs mainly during the monsoon season, i.e., from June to September. However, the erratic nature of rainfall often create problems not only for drinking purpose but also for agriculture, industry, livestock and other miscellaneous uses. Moreover, very few attempts have been made to highlight the problems related to the management of water resources of the region and their possible solutions. Almost all the dug wells get dry and hand pumps also become inoperative in the years experiencing below average rainfall, thereby culminating the water problem in the study area. Thus, the study area is severely affected by water shortages, which in turn threaten agricultural production as well as health, hygiene and sanitation of the local people. Rainwater harvesting and artificial groundwater recharge are the two most important tools for ensuring enhanced water availability in a region and thereby sustain shallow dug wells and/or tubewells. Groundwater supply is more reliable and provides better control to farmers. Therefore, sustainable groundwater management is a key for sustained crop production and improved economy of the beneficiaries in the area.

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Considering the growing water shortage in the study area, it is necessary to harvest rainwater for supplemental irrigation to kharif crops during their critical growth stages and/or pre-sowing irrigation to low water requiring crops grown in winter season as well as to use for artificially recharging groundwater. Moreover, *in situ* rainwater harvesting can also induce groundwater recharge, control of soil/nutrient losses from cropped fields, and reduction of surface drainage congestion in low-lying areas. Therefore, the present study was undertaken to investigate the impact of one water harvesting structure (WHS) in augmenting groundwater levels in Salor village of Khamnor block in Rajsamand district of Rajasthan.

MATERIALS AND METHODS

The Study Area and Experimental Setup

The study was conducted in Salor village (73°33' - 74°00' E longitude and 24°43' - 25°05' N latitude) of Khamnor block in Rajsamand district of Rajasthan (Fig.1). The area is characterized by semi-arid climate with an average annual rainfall and rainy days of 501.1 mm and 31 days, respectively. The monsoon season prevails from June to September and August as the wettest month. May and January are the hottest and coldest months of the year with average daily maximum and minimum temperatures of 38.6 and 7.8 °C, respectively (CGWB, 2009). Relative humidity ranges from 60% during the rainy/monsoon season to as low as 20% during summer (GWD, 2005; Singh, 2006). The dominant soil type is clay loam.

The occurrence of groundwater in the study area is mainly controlled by topographical and structural features present in the geological formations of the area. The major water bearing formations are phyllite-schist and granite-gneiss hard-rocks. In hard rocks, the occurrence and movement of groundwater is controlled through the foliation/bedding planes, fissures, joints, solution cavities and other structural weak planes. The weathered mantle of the hard rocks yields good discharge of water. The groundwater occurs under unconfined to semi-confined conditions in hard-rock area.

A low-cost earthen WHS having cement masonry surplus weir constructed in the study area was selected through reconnaissance survey for this study (Fig. 2). A wooden scale with a least count of 5 mm was installed in submergence area of the WHS to monitor water level of the harvested water. A raingauge and an evaporation pan were installed at the site to record rainfall and evaporation, respectively. A total ten dug wells in the downstream side of the WHS were selected as observation wells to monitor groundwater levels.

Data Collection and Analysis

Daily rainfall and evaporation data were recorded during August 2007-December 2010. The depth of rainwater stored in the WHS was recorded on daily basis during monsoon season in 2010. Furthermore, weekly groundwater levels of the ten observation wells were monitored for three years (August 2007-December 2010) by using acoustic water level indicator. The groundwater levels were plotted on monthly time scale to understand seasonal groundwater fluctuation. The groundwater samples from observation wells were collected during pre- and post-monsoon season to examine its quality for the drinking purpose. The collected water samples were analyzed in the laboratory to determine EC, TDS, pH, HCO_3, CO_3 and Cl.

The earthen WHS was constructed at the site in the year 2008. However, only 255 mm rainfall (about 50% of the average annual rainfall) occurred during 2009 that failed to generate adequate quantities of the surface runoff in catchment area of the WHS. This resulted in negligible depth of the harvested water in submergence area of the WHS, and therefore, the harvested runoff water could not be monitored. On the contrary, excessive amount of the annual rainfall (1167 mm) in the year 2010 produced sufficient runoff water that submerged ample depth of the WHS which was monitored on daily basis for 104 days (July 2 to October 13, 2010). Dynamics of the rainfall and surface water levels of the harvested runoff water was investigated by plotting rainfall barcharts and surface water levels for the year 2010. Like-wise, rainfall-groundwater dynamics was explored by plotting groundwater hydrographs along with rainfall barcharts for four years (2007-2010).

In order to estimate potential recharge rate, a total ten infiltration tests were conducted using double ring infiltrometer in submergence area of the WHS. The duration of the infiltration tests ranged between 208 to 315 minutes with an average of 267 minutes. In order to evaluate effectiveness of the earthen WHS, patterns of both surface water and groundwater levels were explored by plotting them on the same graph for the year 2010.

In this study, groundwater recharge was estimated at ten sites by using the widely-used water table fluctuation technique (Healy and Cook, 2002), which is based on the assumption that amount of water table rise (WTR) in an aquifer is proportionate to the amount of recharge the aquifer received (Schilling, 2009). Hence, when water enters the saturated zone of the aquifer, the water table rises and recharge occurs. However, the amount of WTR observed in an aquifer will greatly exceed the amount of actual groundwater recharge since the recharging water only fills void space between aquifer grains. Therefore, the concept of specific yield, S_y (Freeze and Cherry, 1979) is used to convert the WTR to groundwater recharge. The value of specific yield was taken as 0.0175 (GWD, 2005). The expression for actual groundwater recharge is given below:

$$R = 100 \times S_y \times \Delta WT \tag{1}$$

Where, R = groundwater recharge (cm); S_y = specific yield (dimensionless); and ΔWT = height of water table rise (m) between pre-monsoon and post-monsoon seasons.

RESULTS AND DISCUSSION

Temporal Characteristics of Groundwater

The groundwater hydrographs for all monitoring wells are shown in Fig. 3. The hydrographs showed similar patterns of groundwater fluctuation indicating all the wells tap the same aquifer and are hydraulically connected. The groundwater fluctuations are observed rising and declining in accordance of rainy and dry periods, respectively. The fair response of the groundwater to rainfall events further revealed unconfined nature of the underlying aquifer. Similar results have been reported for other hard-rock areas of Semi-arid Rajasthan (Machiwal et al., 2011; Machiwal et al., 2012).

Basic statistical properties of the groundwater levels for the ten monitoring wells are presented in Table 1. It is apparent from Table 1 that the mean values of the groundwater levels are the lowest (7.13 m bgs) for the well W10 and the highest (16.31 m bgs) for the well W6. Thus, the groundwater levels were shallow nearby the well W10 and relatively deeper at well W6. The large spatial variation in the average groundwater levels is most-likely due to topographical, physiographical and structural features present in the hard-rock geological formation, which control the groundwater occurrence in saturated zone of rock-formation (Machiwal and Jha, 2013). The standard deviation of the groundwater levels was the lowest for the well W10 and the highest for the well W6. This indicates relatively high groundwater fluctuations nearby the well W6 and relatively low fluctuation for the well W10 over three year period. Skewness values for the 10 sites range from -1.25 to 1.74, which may not be considered significant and it may be assumed that all the groundwater level time series follow a normal distribution curve. Similarly, the kurtosis values are also not significant for all the sites except sites W7 and W8 where the values exceed 3. The coefficient of variation values indicates significant temporal variation of the groundwater levels (CV>30%) at all the sites with the highest variation (CV>40%) at sites W5, W7 and W8.

Rainfall-Groundwater Dynamics

The groundwater fluctuations for monitoring wells along with rainfall during monsoon season for four years (2007-2010) are shown in Figs. 4(a-d). It is well discernible from Figs. 4(a-d) that the groundwater levels of almost all the monitoring wells responded well to the occurrence of the rainfall in all the four years. However, the extent of response is quite different in individual years. It can be seen that the amount of rainfall was low in the year 2009, moderate in the years 2007 and 2008, and high in the year 2010 in the study area. The groundwater levels reached to maximum during first/second week of September in 2007 and then started declining. In 2008, groundwater levels reached to maximum during second/third week of October due to rainfall occurrences and then started declining. During October 2008, the water harvesting structure existed in the area though meager amount of runoff water was harvested and stored. Due to scanty rainfall in 2009, groundwater levels started declining from last week of August. The water harvesting structure could not receive sufficient amount of the rainwater once again and there was no groundwater recharging from the WHS. In 2010, surplus amount of rainfall was received in the area and the WHS could store large quantities of the rainwater, which otherwise could have been lost as runoff. It can be seen from Fig. 4(d) that the groundwater levels were continuously rising even in the absence of rainfall events during September and October months in 2010. This clearly indicated that the groundwater was being augmented from some other source of surface water, which is most-likely the RWH structure constructed in the area. Furthermore, the time lag existing between rainfall occurrences and rising groundwater levels can be understood from the time taken by the harvested rainwater in reaching the underlying aquifer. Thus, it is apparent that the runoff water harvested within the RWH structure got effectively recharged, reached to underlying aquifer, and then augmented the groundwater levels.

Rainfall and Water Level in WHS

During monsoon season in 2010, sufficient amount of rainfall (1167 mm) was received in the study area, which generated abundant runoff in the catchment area of the WHS. The runoff water was harvested, stored and monitored in the WHS on daily basis during the entire monsoon season. Similar to groundwater levels, the water level of the stored runoff water was plotted over time scale along with rainfall (Fig. 5). It is clearly depicted by Fig. 5 that the water level of the WHS is affected by the occurrence of the rainfall events. There is a direct relationship between rainfall and amount of water stored in the WHS. After the cessation of monsoon season, the water stored in the WHS gets depleted through either evaporation and/or recharging of the groundwater.

During the study period, several small-scale water harvesting structures were constructed nearby the study area through Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) scheme. It was seen that those WHS also get filled up during monsoon season in 2010. Thus, groundwater recharge from all such WHS harvested large quantities of the rainwater, which raised the groundwater levels in the area.

Impact of Water Harvesting on Groundwater

The mean basic infiltration rate for all the ten infiltration test sites was observed to be 4.1 cm hr^{-1} with the maximum and minimum values of 14.4 and 0.6 cm hr^{-1}, respectively. The mean basic infiltration rate in the submergence area indicated the mean potential recharge rate of 1 m/day for the harvested rainwater in the WHS (Ojha *et al.*, 2013). The mean potential recharge rate is quite sufficient and proved adequacy of the constructed WHS in groundwater recharging.

Groundwater hydrographs of the ten observation wells and water level of the stored water in WHS for the year 2010 are shown in Fig. 6. It is seen that the water level of the WHS initially increased in response of runoff due to rainfall events and reached to its peak on 24th August and subsequently started declining. It was observed that a rainfall event of 8 cm and few shorter events after 24th August could not improve water level in the WHS, despite low declining rate. When dry spell started after 10th September, the water level in the WHS showed steep gradient of decline (Fig. 6). However, the groundwater levels at all the ten sites showed a continuous rise in the study area. It is worth to note that the groundwater levels are rising with higher rate till rainfall occurred up to 10th September (Fig. 4d) and later at relatively slower rate. This is most-likely due to occurrence of groundwater recharge from WHS's even after cessation of rainfall. A further study in this direction is required to achieve concrete results and confirm the findings.

Groundwater Quality

The summary of the water quality parameters for the pre- and post-monsoon seasons is given in Table 2. It is seen that pH of the groundwater varies from 6.8 to 7.8 during pre-monsoon season, which exceeds and ranges between 6.9 and 7.8 during post-monsoon season. This indicates that increased concentration of bases in the groundwater during the post-monsoon season recharge. On the contrary, range of electrical conductivity (EC) of the groundwater decreases from 1.0-3.0 dS/m to 1.0-2.8 dS/m from pre- to post-monsoon season. Likewise, ranges of total dissolved solids in pre-monsoon season (357 to 1040 ppm) reduces in post-monsoon season (332-965 ppm).The concentration of carbonate, bicarbonate and chloride ions also decreases from pre- to post-monsoon season. Moreover, all the groundwater quality parameters remain within their permissible limits prescribed by the US EPA and the Bureau of Indian Standards (BIS, 1991).

Estimation of Groundwater Recharge

The amount of water table rise, groundwater recharge estimated by using water table fluctuation technique and groundwater recharge computed as percentage of monsoon rainfall for ten sites are given in Table 3. It is seen that the water table rise and recharge varies from 2.4-17.4 m and from 4.3-30.4 cm, respectively over three-year period in the area, which is 8.3-26.1% of the monsoon rainfall. The groundwater recharge over the ten sites ranges from 6.4-11.7 cm, 4.3-5.9 cm, and 13.9-30.4 cm with mean values of 9.6, 5.3 and 23.4 cm for the years 2008, 2009, and 2010, respectively. It is apparent that the recharge amounts are influenced with the corresponding monsoon rainfall of 76.8, 25.5, and 116.7 cm during 2008, 2009 and 2010, respectively.

CONCLUSIONS

The paper presents a case study of rainwater harvesting for augmenting groundwater levels in a semi-arid region of Rajasthan. The uniform pattern of groundwater levels are found to be influenced by rainfall occurrences in the area and thus indicated unconfined nature of the underlying shallow aquifer. The impact of rainfall is seen on the runoff water stored in rainwater harvesting structure constructed in the study area. This study suggests that water harvesting structures would appropriately recharge adequate quantities of the harvested rainwater, which will help augmenting the groundwater levels in the area. The mean potential recharge rate is computed as 1 m/day from the water harvesting structure, which is quite satisfactory and proves efficacy of the structure in recharging the groundwater. The groundwater levels also seem to interact with surface water levels of the stored water in water harvesting structures. The pH of the groundwater increases from pre- to post-monsoon season. However, electrical conductivity, TDS, HCO_3, CO_3, and Cl are observed to be decreasing from pre- to post-monsoon season. Overall, the groundwater quality of the underlying aquifer is found to be satisfactory for drinking purposes as per guidelines provided by the World Health Organization. The actual recharge in the study area varied from 4.3 to 30.4 cm, which is 8.3-26.1% of the monsoon rainfall. The mean groundwater recharge for three-years is computed to be 9.6, 5.3 and 23.4 cm in response of 76.8, 25.5, and 116.7 cm of monsoon rainfall in the year 2008, 2009 and 2010, respectively. Finally, this study evidenced that rainwater harvesting structures are beneficial in recharging adequate quantities of the rainwater to augment the groundwater levels in semi-arid regions of Rajasthan.

ACKNOWLEDGEMENTS

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Table 1. Basic statistical properties of the groundwater levels of 10 sites

Statistics	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
Minimum (m bgs)	3.96	3.38	2.87	4.27	2.74	3.29	1.55	3.05	2.74	3.05
Maximum (m bgs)	17.68	21.03	16.15	21.03	18.90	25.91	18.90	17.98	15.54	12.19
Mean (m bgs)	9.90	14.79	7.87	14.86	8.03	16.31	7.48	7.63	7.23	7.13
Std Dev (m bgs)	3.00	4.67	3.02	4.64	3.58	5.50	3.46	3.28	2.31	2.30
Skewness	0.00	-1.25	0.90	-1.19	1.29	-0.92	1.59	1.74	0.25	-0.22
Kurtosis	0.04	0.49	0.85	0.34	2.04	-0.37	3.18	3.02	0.62	-0.91
CV (%)	30.29	31.55	38.36	31.21	44.61	33.74	46.24	43.03	31.96	32.29

Note: bgs = below ground surface; Std Dev = Standard Deviation; CV = coefficient of Variation

Table 2. Groundwater quality parameters during 2008 for ten sites

Parameter	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**
Pre-monsoon										
pH	6.8	7.1	7.3	7.2	7.4	7.7	7.1	7.8	7.1	7.3
EC (dS/m)	1.7	2.0	1.4	1.2	2.2	2.5	3.0	1.0	1.7	1.1
TDS (ppm)	542	672	470	433	716	853	1040	372	608	357
CO_3 (meq/l)	6	2	4	2	4	2	2	6	4	4
HCO_3 (meq/l)	10	12	3	4	6	6	8	3	4	6
Cl (meq/l)	16	12	10	9	12	17	16	13	12	9
Post-monsoon										
pH	6.9	7.2	7.3	7.3	7.5	7.7	7.2	7.8	7.1	7.4
EC (dS/m)	1.5	1.8	1.3	1.1	1.9	2.3	2.8	1.0	1.5	0.9
TDS (ppm)	489	599	432	380	635	782	965	340	492	332
CO_3 (meq/l)	4	0	4	0	2	0	0	4	4	2
HCO_3 (meq/l)	10	13	2	5	6	6	8	4	2	6
Cl (meq/l)	14	11	9	8	11	15	15	12	10	7

Table 3. Amount of groundwater recharge occurred at ten sites

Site		Year			Mean
		2008	2009	2010	
	Rainfall (cm)	76.8	25.5	116.7	72.9
W1	Water Table Rise (m)	6.40	3.05	13.72	7.72
	Monsoon Recharge (cm)	11.2	5.3	24.0	13.5
	Recharge as % of Rainfall	14.6	20.9	20.6	18.7
W2	Water Table Rise (m)	6.10	3.35	14.94	8.13
	Monsoon Recharge (cm)	10.7	5.9	26.1	14.2
	Recharge as % of Rainfall	13.9	23.0	22.4	19.8
W3	Water Table Rise (m)	6.71	3.05	12.80	7.52
	Monsoon Recharge (cm)	11.7	5.3	22.4	13.2
	Recharge as % of Rainfall	15.3	20.9	19.2	18.5
W4	Water Table Rise (m)	6.71	3.35	16.15	8.74
	Monsoon Recharge (cm)	11.7	5.9	28.3	15.3
	Recharge as % of Rainfall	15.3	23.0	24.2	20.8
W5	Water Table Rise (m)	6.40	3.35	14.63	8.13
	Monsoon Recharge (cm)	11.2	5.9	25.6	14.2
	Recharge as % of Rainfall	14.6	23.0	21.9	19.8
W6	Water Table Rise (m)	3.66	3.05	17.37	8.03
	Monsoon Recharge (cm)	6.4	5.3	30.4	14.0
	Recharge as % of Rainfall	8.3	20.9	26.1	18.4
W7	Water Table Rise (m)	4.57	2.44	14.02	7.01
	Monsoon Recharge (cm)	8.0	4.3	24.5	12.3
	Recharge as % of Rainfall	10.4	16.7	21.0	16.1
W8	Water Table Rise (m)	4.57	3.05	14.02	7.21
	Monsoon Recharge (cm)	8.0	5.3	24.5	12.6
	Recharge as % of Rainfall	10.4	20.9	21.0	17.5
W9	Water Table Rise (m)	4.88	2.74	8.23	5.28
	Monsoon Recharge (cm)	8.5	4.8	14.4	9.2
	Recharge as % of Rainfall	11.1	18.8	12.3	14.1
W10	Water Table Rise (m)	4.88	3.05	7.92	5.28
	Monsoon Recharge (cm)	8.5	5.3	13.9	9.2
	Recharge as % of Rainfall	11.1	20.9	11.9	14.6

Figure Captions

Fig. 1: Location map of the study area

Fig. 2: Earthen water harvesting structure constructed in the study area

Fig. 3: Groundwater hydrograph for ten observation wells

Fig. 4(a): Groundwater hydrographs and rainfall barcharts for year 2007

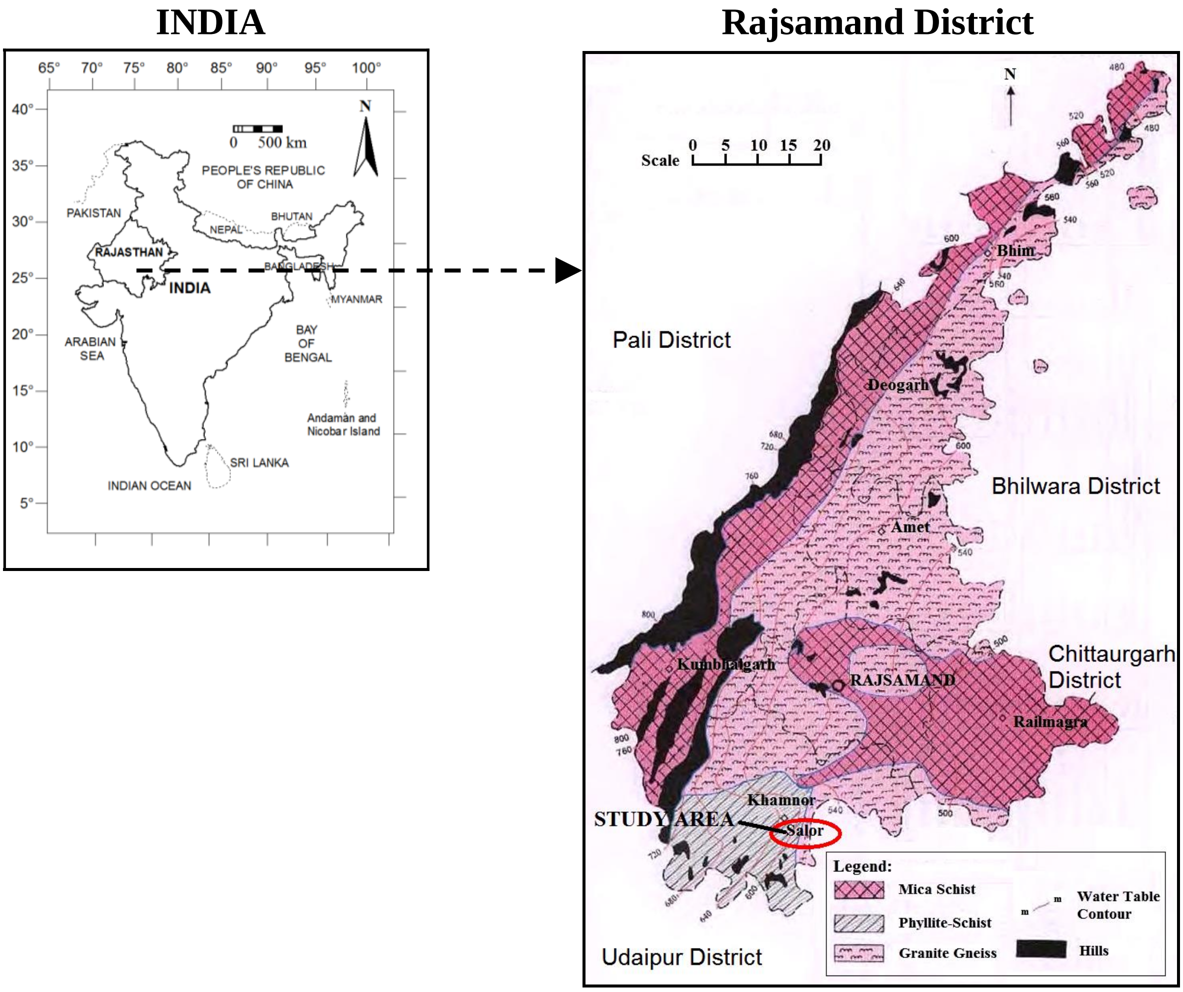
Fig. 4(b): Groundwater hydrograph and rainfall barcharts for year 2008

Fig. 4(c): Groundwater hydrograph and rainfall barcharts for year 2009

Fig. 4(d): Groundwater hydrograph and rainfall barcharts for year 2010

Fig. 5: Hydrograph of stored water in WHS and rainfall barcharts

Fig. 6: Groundwater levels and surface water level of WHS in 2010



Source: modified from CGWB (2009).

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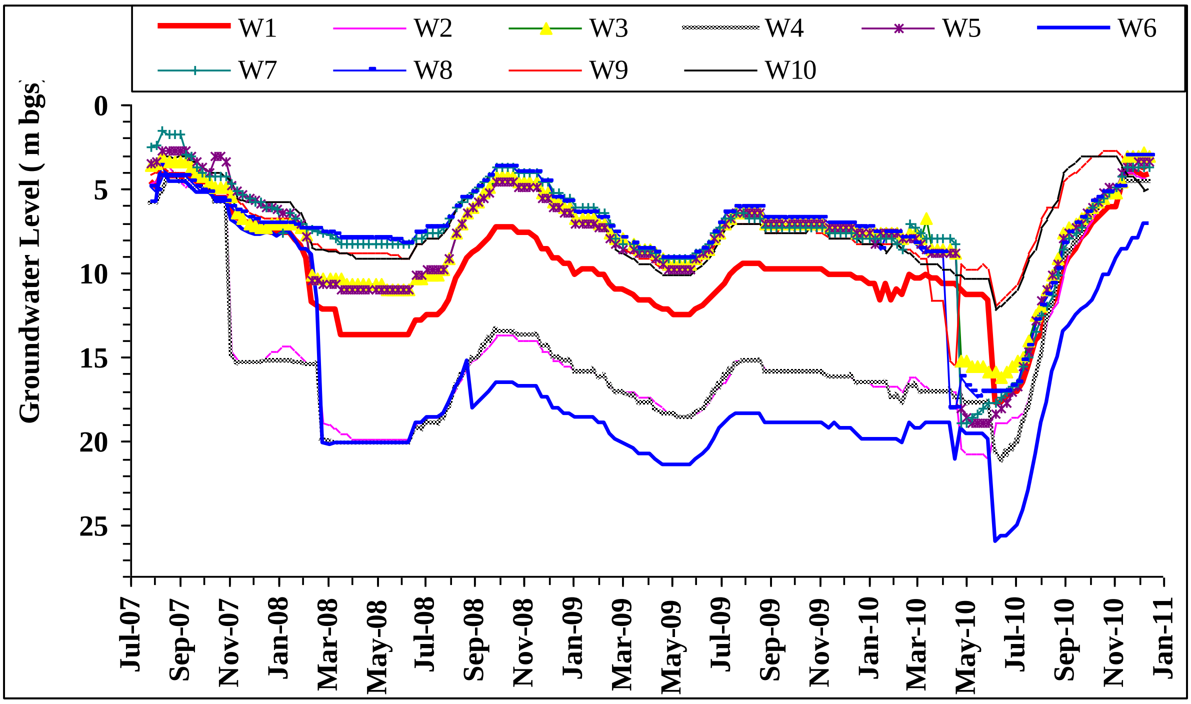

Fig. 3: Groundwater hydrograph for ten observation wells

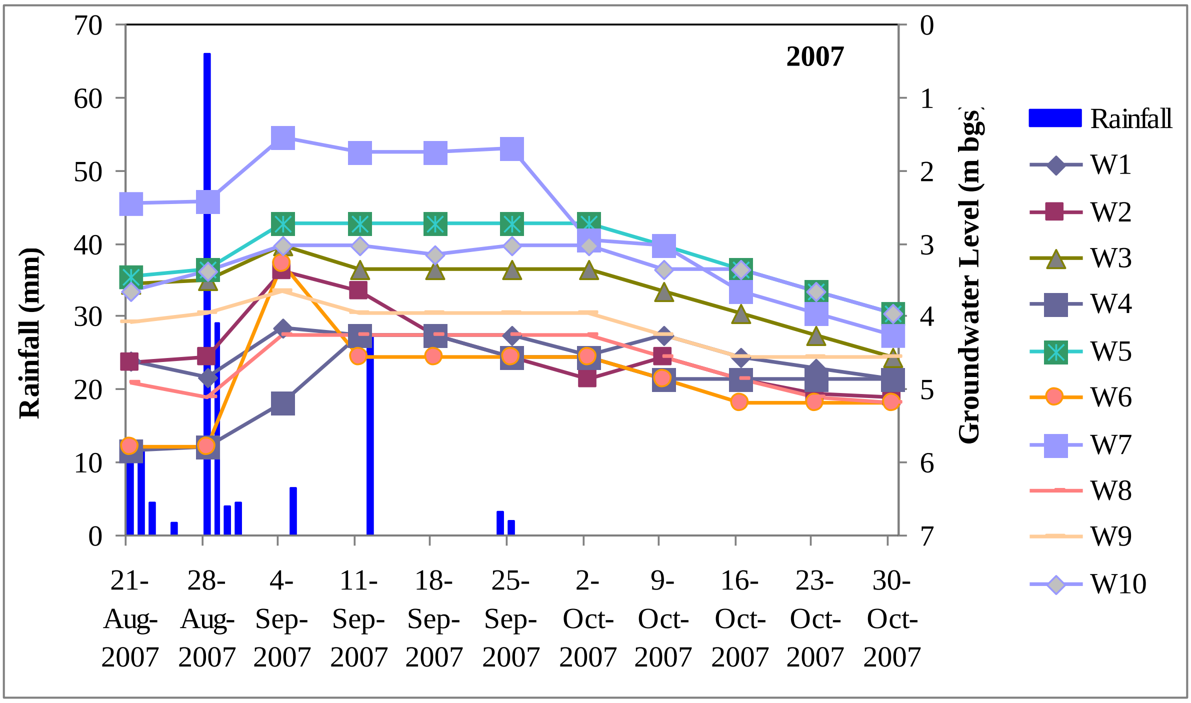

Fig. 4(a): Groundwater hydrographs and rainfall barcharts for year 2007

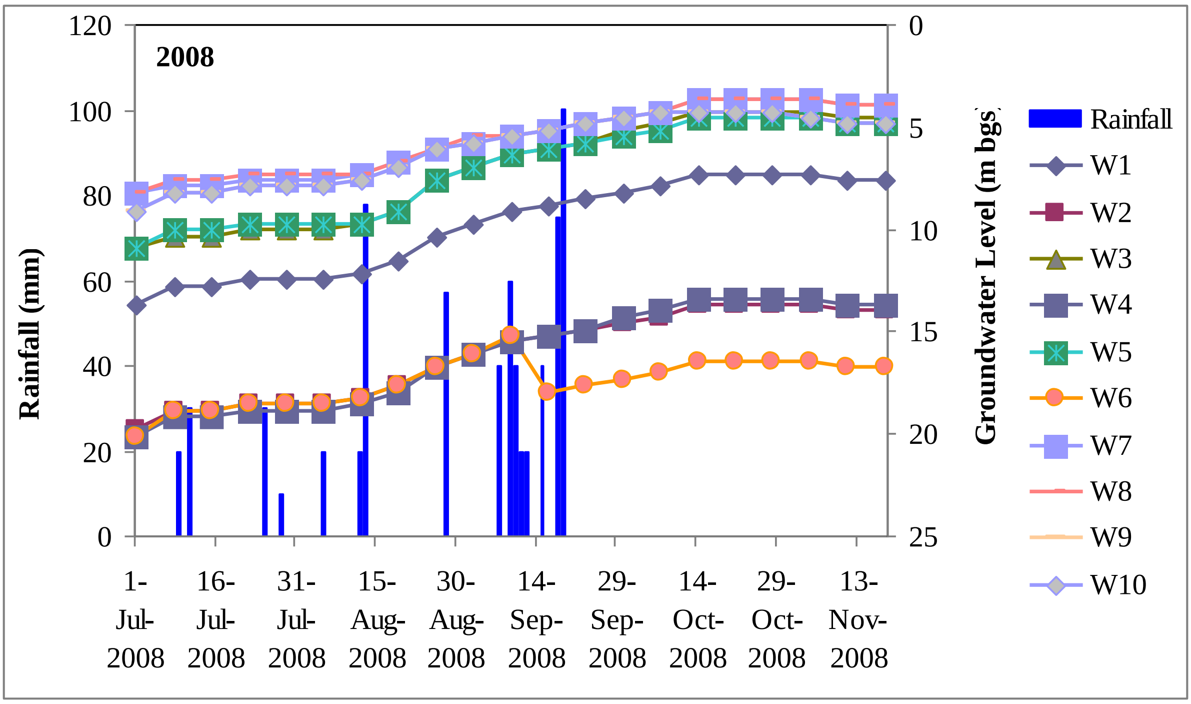

Fig. 4(b): Groundwater hydrograph and rainfall barcharts for year 2008

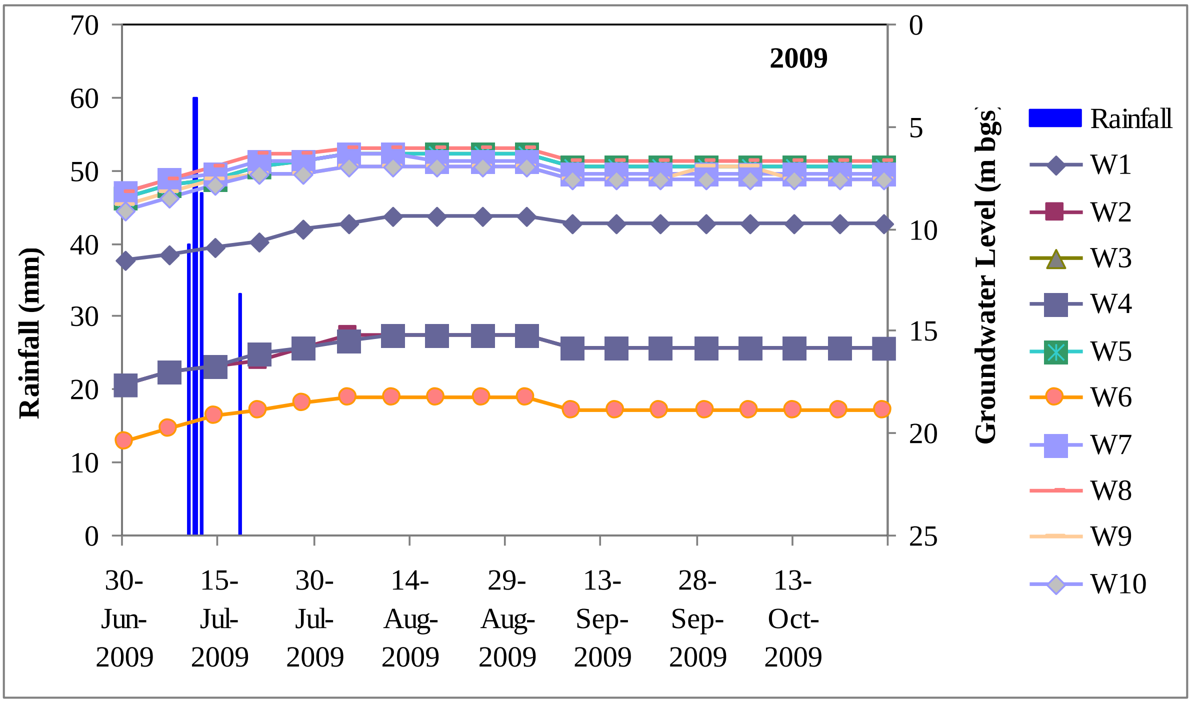

Fig. 4(c): Groundwater hydrograph and rainfall barcharts for year 2009

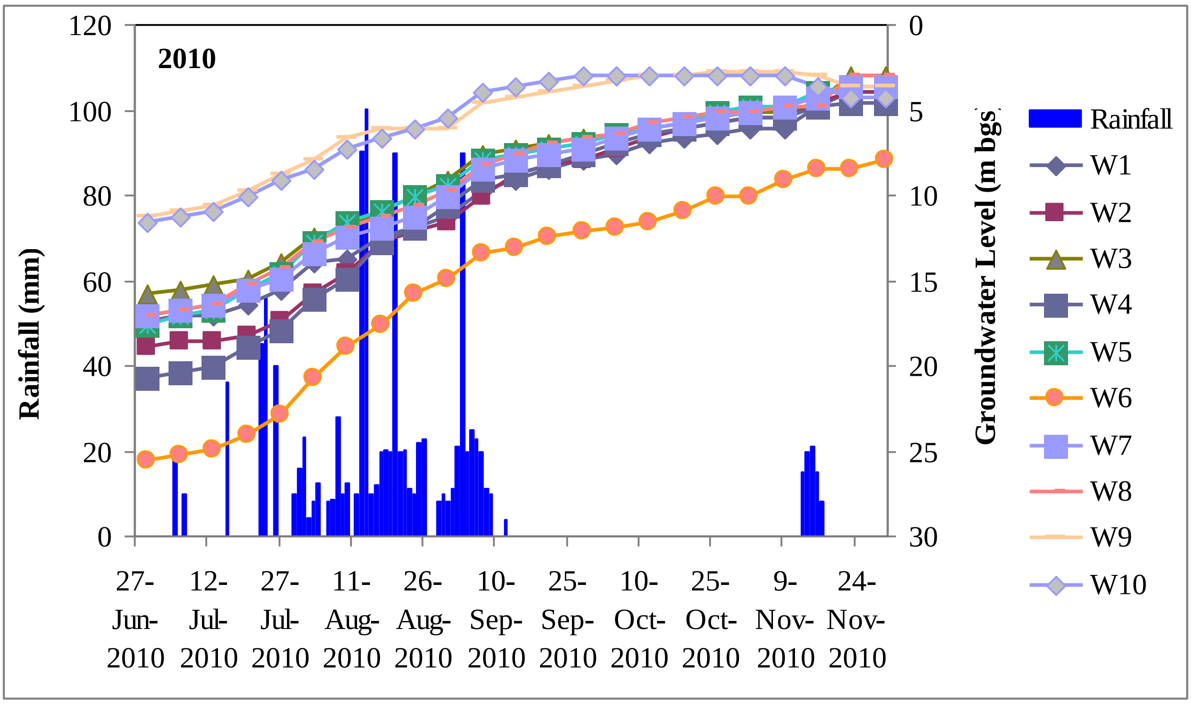

Fig. 4(d): Groundwater hydrograph and rainfall barcharts for year 2010

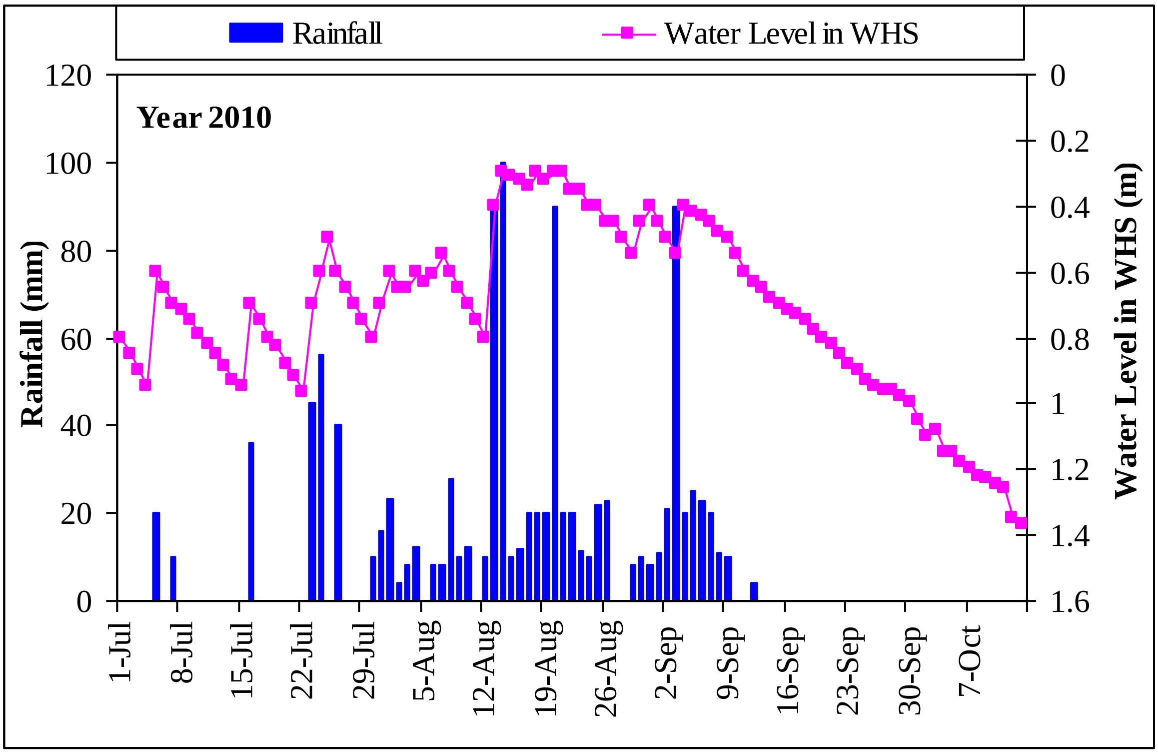

Fig. 5: Hydrograph of stored water in WHS and rainfall barcharts

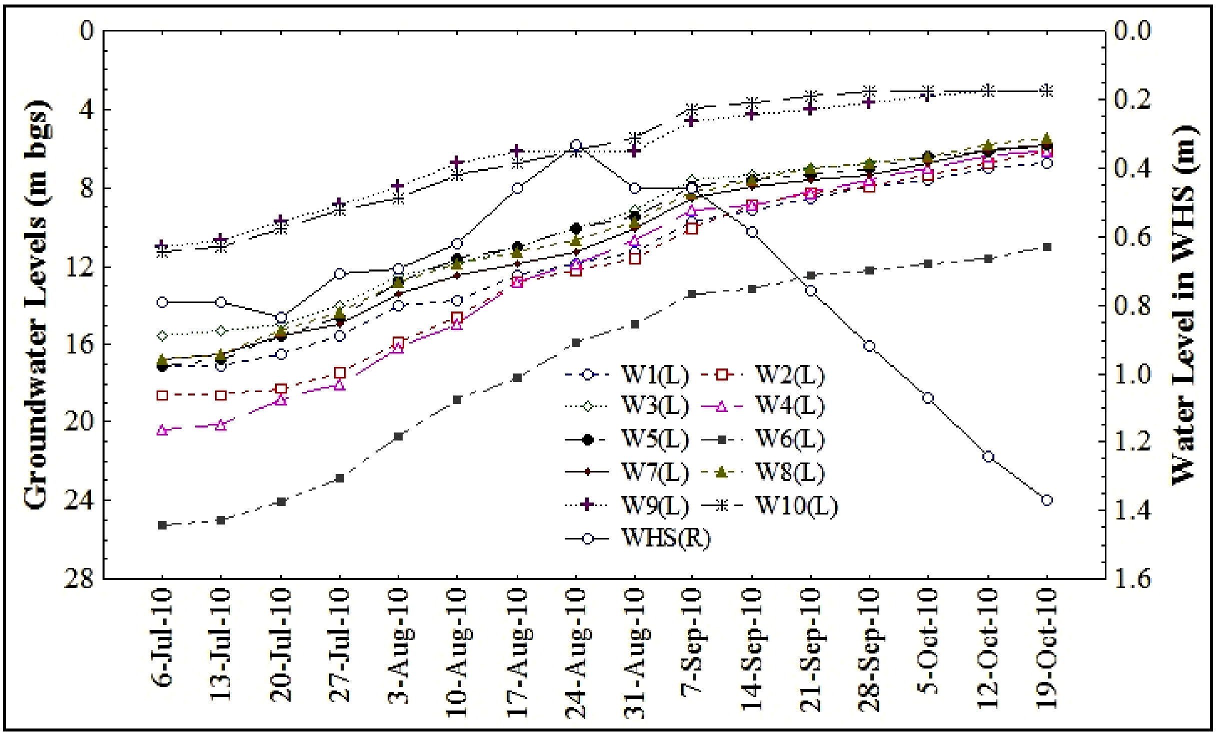

Fig. 6: Groundwater levels and surface water level of WHS in 2010