31. Bhat, G. M., Craig, J., Hafiz, M., Hakhoo, N., Thurow, J. W., Thusu, B. and Cozzi, A., Geology and hydrocarbon potential of Neoproterozoic–Cambrian Basins in Asia: an introduction. *Geol. Soc. London*, *Spec. Publ.*, 2012, **366**, 1–17.
32. Ojha, P. S., Precambrian sedimentary basins of India: an appraisal of their petroleum potential. *Geol. Soc. London*, *Spec. Publ.*, 2012, **366**, pp. 69–74.
33. Vishnuvardhan, C., Panicker, C. K. and Kumar, B., Comparison of Proterozoic basins of India with similar basins of the world: implications to hydrocarbon resource prospects. In Proceedings of Petroleum Geochemistry and Exploration in the Afro-Asian Region (eds Digang Liang, Darui Wang and Zhenxili), 2008.
34. Kalpana, M. S., Patil, D. J., Dayal, A. M. and Raju, S. V., Near surface manifestations of hydrocarbons in Proterozoic Bhima and Kaladgi Basins: implications to hydrocarbon resource potential. *J. Geol. Soc. India*, 2010, **76**, 548–556.
35. Dayal, A. M. and Raju, S. V., Discovery of hydrocarbon in Proterozoic Vindhyan basin, East India, using geochemical signatures. In Proceedings of Goldschmidt Conference, Davos, Switzerland, 2010.
36. Kalpana, G., Madhavi, T., Patil, D. J., Dayal, A. M. and Raju, S. V., Light gaseous hydrocarbon anomalies in the near surface soils of Proterozoic Cuddapah basin: implications for hydrocarbon prospects. *J. Petrol. Sci. Eng.*, 2010, **73**(1), 161–170.

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Impact of rainfall variability on groundwater resources and opportunities of artificial recharge structure to reduce its exploitation in fresh groundwater zones of Haryana

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Climate change likely to impact rainfall patterns leading to higher uncertainty and difficulties in management of both water scarcity and flood events. Temporal trends of rainfall and its variability of Karnal district, representing fresh groundwater zones of Haryana, were analysed by non-parametric Mann–Kendall (MK) test and Sen's slope approaches. Analysis of long-term rainfall data (1972–2010) indicated that Karnal receives a mean annual rainfall of 757.6 mm with a high degree of variation (CV = 34.3%). Categorization of monsoon rainfall based on long-period average (LPA) and its CV indicates that during the last decade (2001–2010) Karnal received deficit rainfall in 6 years (18–57% lower than LPA), normal rainfall in 2 years and excess rainfall (9–70% higher than LPA) also for 2 years. The rainfall and rainy days during the last decade (2000–2010) decreased by 13% and 20% respectively, over long-term (1972–2010) averages. The MK and Sen's slope approach applied to pre- and post-monsoon groundwater levels indicated significant declining trend emphasizing the need to augment groundwater by artificial groundwater recharge (AGR) system. AGR through recharge wells installed by CSSRI at village Nabiabad in Karnal districts resulted in 2.32 m and 3.16 m rise in water table during 2009 and 2010 respectively. Installation of artificial groundwater recharge in low lying areas has proven highly effective in enhancing groundwater and improve its quality.

Keywords: Artificial groundwater recharge, Karnal, Mann–Kendall, rainfall.

SCIENTIFIC evidence has demonstrated that the Earth is moving towards a point of no return, where imbalances brought about by climate change will have serious ecological impacts. Climate change is no more an environmental concern. It has emerged as the biggest developmental challenge for the planet. Throughout the 21 century, India and other countries in southeast Asia are projected to experience warming above the global mean. India will also begin to experience greater seasonal variation in temperature, with more warming in winter than summer[1]. The longevity of heat waves across India has extended in recent years, leading to warmer temperatures at night and hotter days and this trend is set to continue[2]. These heat waves will lead to increased variability in summer monsoon precipitation, with drastic effects on the agricultural sector in India[3].

Rainfall is a climate parameter that affects the way and manner in which mankind survives. Apart from the beneficial aspects, rainfall can also be destructive by playing a major role in natural disasters such as floods and landslides. Long-term trends of Indian monsoon rainfall for the country as well as for smaller regions have been studied by several researchers. It has been reported that the monsoon rainfall is without any trend, being highly random in nature over a long period of time[4]. However, on a spatial scale, existence of trends was noticed[5,6]. Using the network of 306 stations and for the period 1871–1984, areas having increasing or decreasing trends of monsoon rainfall were identified[6].

Karnal district lies in the Upper Yamuna Basin and 70% of the net irrigated area is irrigated by groundwater. Despite greater use of new varieties and fertilizers, the current productivities of rice and wheat in Indo-Gangetic plains are showing stagnating trends[7]. Changes in the onset of monsoon and lack of contingency planning further complexes the farming process and ultimately affects its

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productivity. Overexploitation of groundwater resources and as a consequence decline in water table are causes of serious concern in certain parts of Haryana, Gujarat, Rajasthan, Tamil Nadu, Andhra Pradesh, Maharashtra and Punjab. The groundwater decline can be deferred to some extent by enhancing artificial recharge using rain and excess canal water through surface spreading and well injection recharging techniques. It helps in utilizing flood water that otherwise goes waste or causes damage to standing crops and also in improving groundwater quality[8]. Recharge through wells and tube wells is being considered due to failure or delay in arrival of natural or artificial recharge water to deeper aquifer zones with surface natural recharge methods.

Artificial groundwater recharge through wells and tube wells involves passing of excess rain and canal water under gravity through a borewell to subsurface sandy zones coupled to a recharge filter consisting of layers of coarse sand, small gravel and boulders in a small brick masonry chamber[9].

The main objective of this study is to assess the trends as well as variability of rainfall and groundwater levels to understand the response of groundwater systems to climatic stresses in Karnal district of Haryana and to study the scope of artificial groundwater recharge structures for mitigating the adverse impact of rainfall variability on groundwater.

Climatic data for 38 years (1972–2010) was collected from the agro-meteorological observatory located at Central Soil Salinity Research Institute (CSSRI), Karnal (29°43′N, 75°58′E, altitude of 245 m amsl) in the Indo-Gangetic alluvial plains. The climate of Karnal district is influenced in a major way by the southwest monsoon occurring during June to September. To study intra-annual variations in rainfall and rainy days, the year was divided into three different seasons: pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–February) months. Inter-annual and seasonal rainfall variations, deviations from long period average (LPA) and number of rainy days (>2.5 mm per day) were also worked out. Extreme rainfall events were considered when rainfall of more than 50 mm occurred in a single day (24 h). Monsoon rainfall was classified as deficient when the actual rainfall was less than the difference between long period average and its coefficient of variation (LPA – CV), normal when actual rainfall was within LPA ± CV and excess when actual rainfall was more than LPA + CV of the corresponding year[10].

The pre- and post-monsoon groundwater table depth data (1974–2010) were collected from the Central Ground Water Board (CGWB) to analyse seasonal variation in groundwater table and changes over last four decades for Karnal.

The Mann–Kendall (MK) test is a non-parametric method for identifying trends in time-series data. The MK test checks the null hypothesis of no trend versus the alternative hypothesis of the existence of increasing or decreasing trend.

The data values are evaluated as an ordered time series. Each data value is compared to all subsequent data values. The initial value of the MK statistic, τ (tau), is assumed to be 0 (i.e. no trend). If a data value at a later time is higher than a data value of an earlier time, τ is incremented by 1. On the other hand, if the data value at a later time is lower than a data value sampled earlier, τ is decremented by 1. The net result of all such increments and decrements yields the final value of τ.

Let $x_1, x_2, \ldots, x_n$ represent n data points, where x_j represents the data point at time j. Then, the MK (τ) is given by

$$\tau = \sum_{k-1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sign}(x_j - x_k)$$

$$\operatorname{sign}(x_j - x_k) = 1 \quad \text{if } x_j - x_k > 0,$$

$$= 0 \quad \text{if } x_j - x_k = 0,$$

$$= -1 \quad \text{if } x_j - x_k < 0.$$

A high positive value of τ is an indicator of an increasing trend, and a low negative value indicates a decreasing trend. The p-value for the MK test indicates the absence or presence of any statistically significant trends. If the computed value of $p > p_\alpha$, the null hypothesis (H_0) is rejected at α level of significance in a two-sided test. In this analysis, the null hypothesis was tested at 90% confidence level.

Sen's slope estimator provides an estimate of the magnitude of the detected trend and is calculated as

$$T_i = \frac{x_i - x_k}{j - k} \quad \text{for } i = 1, 2, \ldots, N, \tag{1}$$

where x_i and x_j are data values at time j and k ($j > k$) respectively. The median of (β) N values of T_i is the Sen's slope estimator.

$$\beta = T_{((N+1)/2)}, \quad \text{if } N \text{ is odd}$$

$$\beta = \frac{1}{2}(T_{N/2} + T_{(N+2)/2}), \quad \text{if } N \text{ is even}$$

Positive value of β indicates an increasing trend, and negative value indicates a decreasing trend in the time series.

Under a Ministry of Water Resources, Govt of India (GoI)-funded project at CSSRI and its regional research stations at Bharuch (Gujarat) and Lucknow (Uttar Pradesh) from 2008–2010, individual farmer-based groundwater recharge structures were implemented and evaluated in fields of 53 farmers. These included 33 sites in Haryana with a majority of them (25) in Karnal. Individual farmers can construct their recharge structures where runoff gets accumulated and adversely affects the production of rice during monsoon rains and wheat during occasional winter rains.

Groundwater recharge systems consisted of recharge tube wells that involved passing of excess rain and canal water to suitable aquifer zones after filtration under gravity. Mainly two types, i.e. recharge shaft and recharge cavity were used for recharging groundwater using excess storm runoff water.

Recharge shaft (Figure 1 *a*) consists of a bore hole of 45 cm filled with gravel to carry filtered water to subsurface sandy zones. The surface runoff was first passed through a designed recharge filter consisting of layer of coarse sand, small gravel and boulder in a small masonry chamber to safeguard against clogging. A high pressure PVC pipe of 12.5 cm slotted in the middle of the borehole was used for cleaning clogged sediments in the shaft with compressed air.

A recharge cavity (Figure 1 *b*) is similar to a cavity tube well coupled with a graded filter used in recharge shaft. It is constructed by drilling a bore hole until a sandy layer is found below a clay layer. A blind PVC pipe is drilled through the clay layer and sand is pumped out until a stable cavity is developed below the clay layer. A recharge cavity can also be used for occasional pumping.

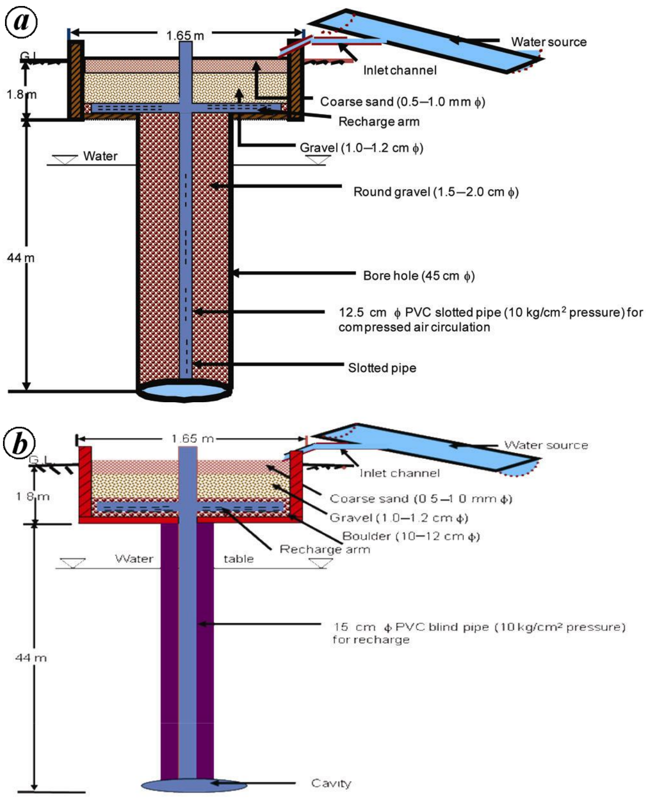

Figure 1. *a*, Schematic diagram of a recharge shaft. *b*, Schematic diagram of a recharge cavity.

Kamra and Sharma[8] reported that runoff water from 10–20 ha of surrounding fields was available at most selected sites during normal monsoon years for recharge through these structures. There have been very encouraging results in the effectiveness of recharge shaft and recharge cavities to replenish groundwater and improve its quality. Water table depth was periodically monitored and groundwater samples collected for chemical analysis to assess the impact of recharge structures. Results for four representing recharge sites of Karnal from 2008 to 2010 are discussed in this article. Groundwater samples were analysed for pH, electrical conductivity (EC), major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and major anions (CO_3^{-2}, HCO_3^{-1}, Cl^{-1}, SO_4^{-2}) using standard procedures[11]. Among variable parameters, pH and EC were measured by using pH meter and electrical conductivity meter respectively.

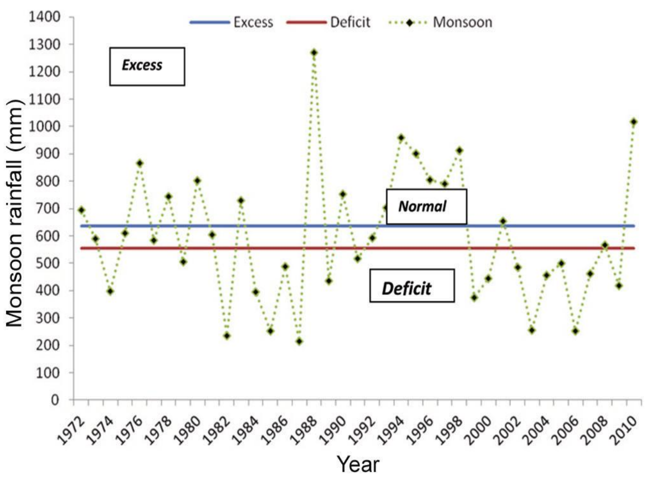

Figure 2. Monsoon rainfall categorization as deficient, normal and excess at Karnal, Haryana.

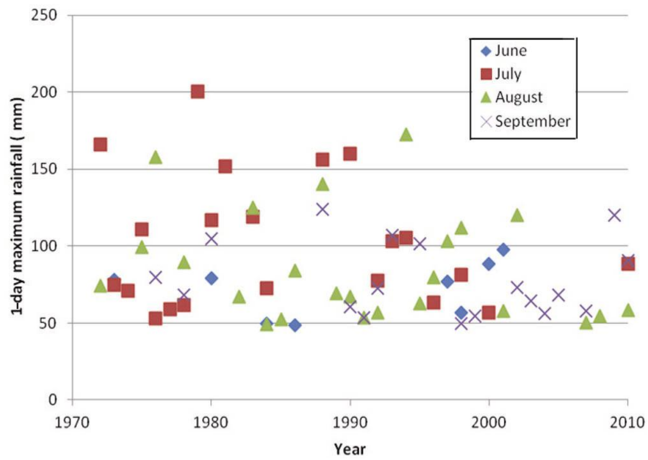

Figure 3. Frequency of one-day maximum rainfall in monsoon months at Karnal, Haryana.

Table 1. Statistical analysis of long period rainfall (mm) distribution and number of rainy days at Karnal (1972–2010)

	Total		Monsoon		Summer		Post-monsoon	
	Rainfall	Rainy days	Rainfall	Rainy days	Rainfall	Rainy days	Rainfall	Rainy days
Mean	757.6	47.6	595.9	32.0	67.7	6.9	94.0	8.7
Standard error	41.6	2.2	38.2	1.6	9.0	0.8	8.8	0.6
Median	706.3	45.0	585.1	29.0	55.0	5.0	84.5	9.0
Standard deviation	259.8	14.0	238.8	10.3	56.2	5.0	55.0	3.7
Minimum	340.7	24.0	215.3	11.0	0.2	0.0	14.9	1.0
Maximum	1399.9	81.0	1271.3	51.0	252.9	20.0	233.0	16.0
CV	34.3	29.5	40.1	32.1	83.0	72.3	58.5	42.4

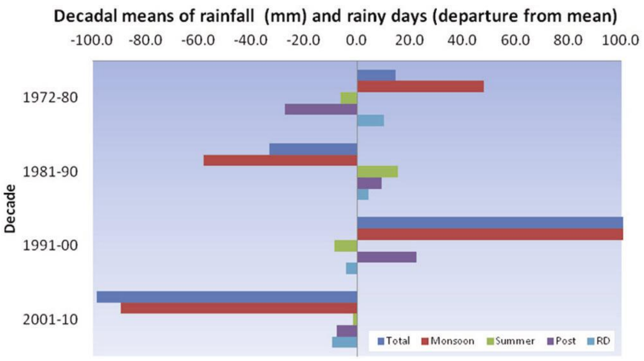

Figure 4. Decadal means of rainfall and rainy days.

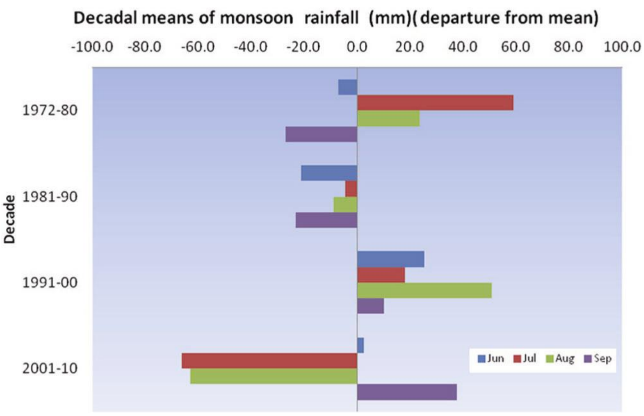

Figure 5. Decadal means of monsoon months rainfall.

Total hardness and calcium were determined by ethylenediaminetetraacetic acid titimetric method. Magnesium was estimated as difference in total hardness and calcium. Total alkalinity, carbonate and bicarbonate and chloride were estimated by using titimetric method. Sodium and potassium were estimated by flame photometer. Residual sodium carbonate (RSC) was calculated using equation

$$\text{RSC (meq/l)} = (CO_3^{-2} + HCO_3^{-1}) - (Ca^{2+} + Mg^{2+}).$$

Long-term analysis of rainfall data (1972–2010) (Table 1) indicates that Karnal receives a mean annual rainfall of 757.6 mm with a high degree of variation (CV = 34.3%), which is reflected by the range of minimum rainfall of 340.7 mm (during driest year 2006) and maximum rainfall of 1339.9 mm (during wettest year 1988). Monsoon rainfall contributed 79% of the total annual rainfall with high coefficient of variation (CV = 40.1). Categorization of monsoon rainfall based on LPA and CV indicates (Figure 2) that Karnal during the last decade (2001–2010) received deficient rainfall for 6 years (18–57% lower than LPA), 2 years normal rainfall and 2 years excess rainfall (9–70% higher than LPA). In the earlier two decades (1981–1990 and 1991–2000), one-day maximum rainfall (≥ 50 mm) was mainly confined to June and July months, but in recent decades (2001–2010), it has shifted to September (Figure 3). Change in frequency, magnitude (±) and direction of extreme rainfall events was also reported in other parts of India[12–14].

To understand the decadal behaviour of rainfall and rainy days, means of 38 years rainfall and rainy days were calculated and compared with the decadal means (Figure 4). It was observed that in the last decade (2001–2010), total rainfall reduced by 98 mm from average rainfall of 757 mm and number of rainy days decreased by 9 days from the average number of rainy days of 46. Categorization of rainfall and rainy days revealed that the total rainfall as well as monsoon and post-monsoon rainfall in the recent decade (2001–2010) are in negative phase.

Decrease in rainfall and rainy days of monsoon and post-monsoon months in the recent decades resulted in reduced availability of water during the active crop growth phases; and ultimately accelerated the process of groundwater extraction to irrigate the crops during those water-deficit periods.

To understand the epochal behaviour of rainfall series for different monsoon months, 38-year running means of each of the monsoon months was calculated and decadal means of each of the monsoon months was compared (Figure 5). It was observed that in the recent decade (2001–2010), epochal behaviour of July and August rainfall has changed from positive to negative phase by an amount of 66 and 63 mm rainfall from the average rainfall of 195 and 104 mm respectively. An opposite trend was observed in the September rainfall. During the two earlier decades, September rainfall was in negative phase, but it changed dramatically from negative to positive phase during the recent two decades with 36% excess rainfall as indicated by the long-term mean.

Trends in total, monsoon, post-monsoon, summer and winter rainfall and rainy days over the study period were analysed by MK trend test (Table 2). It was noticed that there is non-significant, nonlinear decreasing trend in total, monsoon, summer and post-monsoon rainfall at 10% significance level. High variability of total (CV = 34%) and monsoon rainfall (40%) over the study period (1972–2010) was responsible for this decreasing trend in rainfall. Rainy days revealed a significant negative trend for rainy days with Sen's slope parameter of –0.57. In the monsoon months (June–September), September's rainfall exhibited a positive trend with Sen's slope parameter of 2.5. Decline in number of rainy days at an annual rate of 0.5 days might be partially responsible for this decreasing trend in monsoon rainfall. The results of non-significant trends in rainfall at Karnal are similar to the reported non-significant trends in monsoon rainfall at 36 locations across India[12].

The changing patterns of rainfall are likely to hamper the sowing dates, reproductive and flowering stages, and consequently the productivity of *kharif* crops. Rice–wheat is the major cropping pattern of North India. In the *kharif* season, most of the rice transplanting operation is completed during June. The decrease in rainfall in that month may necessitate shifting of sowing/transplanting dates or may force enhanced dependence on groundwater for transplanting operations. The regression analysis between normalized yield and normalized rainfall during monsoon months indicates that rainfall in July and September is most significant to rice yield variability[15].

Canal water and groundwater respectively, accounts for 35% and 65% of the irrigated area of Karnal. From Figure 6, it can be observed that canal water irrigation is more or less stable during 1991–2005; while tube well irrigation increased by 16%. Unavailability of water during critical stages of the crops, particularly tail regions of the canal command areas, is forcing the farmer to use deep submersible tube well for groundwater extraction.

The depth of water table during the study period (1974–2010), presented in Figure 7, shows a declining trend of groundwater level. Groundwater levels in Karnal have declined from about 4 m in 1974 to deeper than 15 m in 2010. From the long-term water levels during pre- and post-monsoon periods, it was estimated that water level declined at an average rate of 0.24 m per year during 1974–2010. The decline was very deep @ 0.88 m per year during the recent decade of 2001–2010.

The MK trend test for pre- and post-monsoon water level depths and fluctuation (difference between pre- and post-monsoon months water table depth) during 1974–2010 also revealed a significant declining trend in water table depth in the Karnal region (Table 3). Further, monsoon rainfall and water table fluctuation revealed that the last decade (2001–2010) monsoon rainfall rarely contributed to groundwater recharge ($r^2 = 0.73$; Figure 8). Most of the negative fluctuation in water table depth occurred in the recent decade.

Groundwater is presently a vital source of irrigation in Karnal as most of the net irrigated area is covered by tube well irrigation. Groundwater contributes 70% of the total water needed for agriculture. Groundwater is being

Table 2. Mann–Kendall trend test for rainfall and rainy days

	Kendall's Tau	Sen's slope	*p*-value (two-tailed)	Alpha
January	0.07	0.17	0.53	0.10
February	0.10	0.26	0.37	0.10
March	–0.10	–0.11	0.40	0.10
April	0.01	0.00	0.96	0.10
May	0.09	0.21	0.44	0.10
June	0.09	0.70	0.43	0.10
July	–0.14	–2.08	0.21	0.10
August	–0.13	–2.33	0.27	0.10
September	0.20	2.50	0.07*	0.10
October	–0.21	0.00	0.08*	0.10
November	0.01	0.00	0.98	0.10
December	–0.11	–0.03	0.33	0.10
Total	–0.02	–0.33	0.89	0.10
Monsoon	–0.07	–2.02	0.56	0.10
Summer	0.01	0.02	0.95	0.10
Post	0.05	0.48	0.64	0.10
RD	–0.34	–0.57	0.00*	0.10

*Significant trend observed.

Table 3. Mann–Kendall trend test for groundwater table

	Kendall's tau	Sen's slope	*p*-value (two-tailed)	Alpha
June	0.779	0.228	0.000*	0.05
October	0.730	0.267	0.000*	0.05
Fluctuation	0.318	0.039	0.006*	0.05

*Significant trend observed.

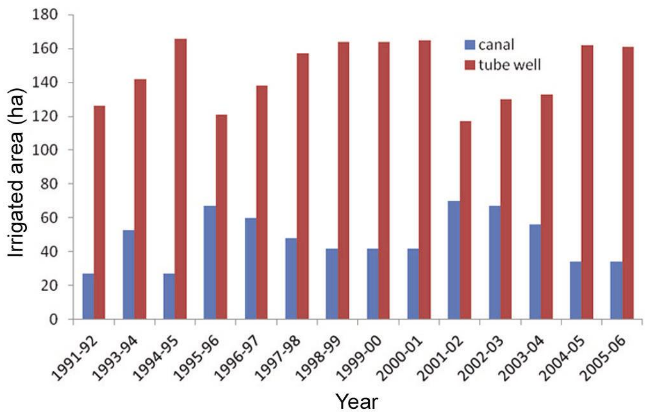

Figure 6. Net area irrigation by different irrigation systems in Karnal during 1991–2006.

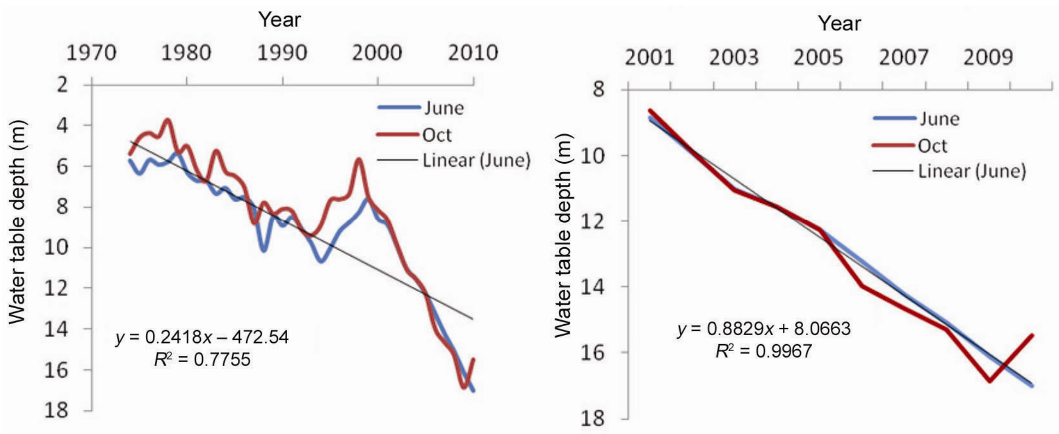

Figure 7. Trends of groundwater level in pre- and post-monsoon months.

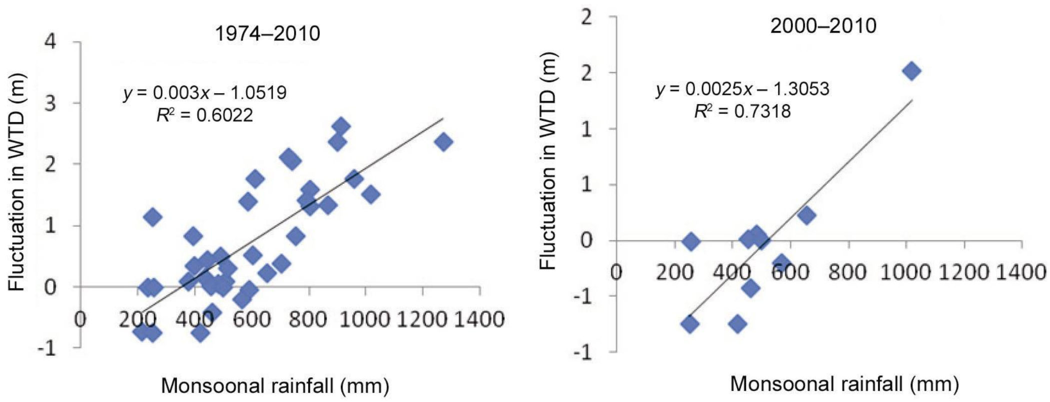

Figure 8. Relationship between fluctuation of water table depth and monsoon rainfall.

Table 4. Geographical location and type of artificial recharge structure installed at different locations in Karnal

	Geographical location		
Village	North	East	Type of artificial recharge structure
Nabiabad	29.5178	76.7692	Shaft
Bamberheri	29.6406	76.8825	Shaft
Yatriwala	29.7092	76.7394	Cavity
Sultanpur	29.9464	76.9225	Shaft

extracted through large number of shallow tube wells and dug cum bore holes which tap unconfined layers. As the major cropping pattern in Karnal is rice–wheat, farmers are more interested in extracting groundwater for irrigation of crops. The sharp decline in groundwater levels reflects the overexploitation of groundwater resources. Further, decline in rainfall and rainy days has accelerated the process of utilizing groundwater for irrigating crops.

Indiscriminate use of groundwater for irrigating rice crop coupled with decreasing trends in rainfall during transplanting season of rice has resulted in depletion of groundwater at an alarming rate. One of the ways to arrest and sustain the declining water table is by enhancing artificial recharge of groundwater using rain and excess canal water through well injection techniques. There are a number of pilot case studies on injection well type of groundwater recharge system, installed at farmers fields in different sites in fresh groundwater zones of Haryana, under a Ministry of Water Resources (GoI)-funded Farmers Participatory Action Research Project (FPARP). The locations of four representing sites are described in Table 4. The recharge structure was monitored extensively by recording its water-level data at monthly intervals for more than 2 years; and its water quality was analysed by standard procedure.

The temporal changes in water table depth, EC and RSC of groundwater at four representative sites in Karnal are presented in Figure 9. It is seen that recharge events (indicated by arrows), cause both a rise in water-table depth and reduction in EC and sometimes also of RSC of groundwater. The recharging of water resulted in 2.32 and 3.16 m rise in water table at Nabiabad village, Karnal, during rainy seasons of 2009 and 2010 respectively. The corresponding reduction in salinity and RSC of groundwater was 1.36 and 1.33 dS m^{-1} and 6.63 and 1.33 m eq/l respectively, during these 2 years. Similar cases of groundwater recharging with reduction in

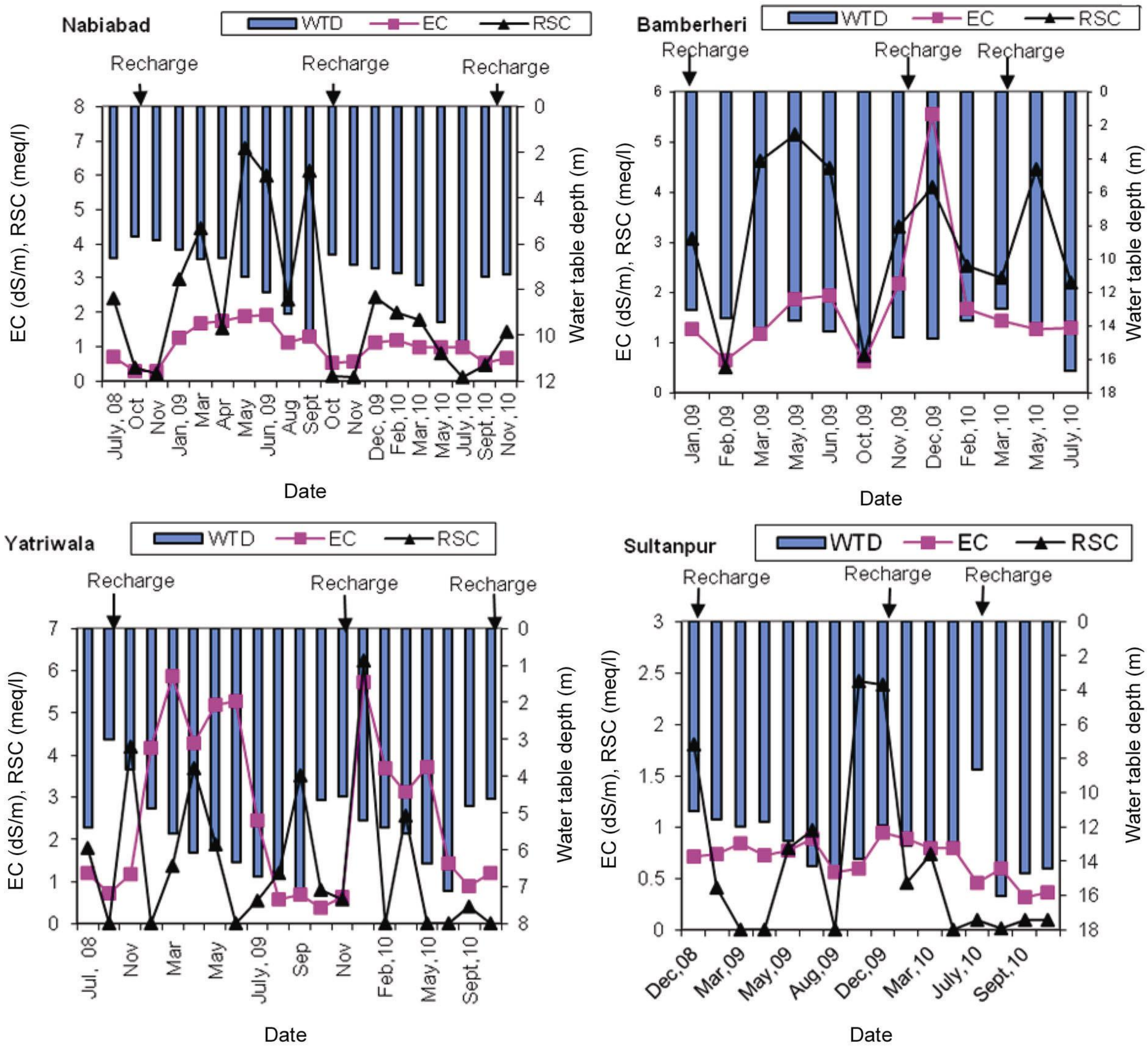

Figure 9. Artificial groundwater recharge system at different sites of Karnal.

salinity and alkalinity levels were observed in three other sites.

From Figure 8, it is clear that monsoon rainfall rarely contributes to groundwater recharge as fluctuation of groundwater level between monsoon months was 0.75 m in 2009 and 1.52 m in 2010 at Karnal. Deficit rainfall of 147 mm in 2009 resulted in 0.75 m decline in water table depth. Natural recharge of groundwater was noticed only in 2010, when 382 mm excess rainfall resulted in 1.52 m rise in water table. Formation of hardpan in subsurface layer and decrease in permeability of soil due to continuous transplanted rice–wheat cropping system resulted in retarding the process of natural recharge[16]. Simultaneously, excessive withdrawal of groundwater for irrigation purposes may also accelerate decline in water table depth. By installing these artificial groundwater recharge structures with intake rate of 8–10 $l\ s^{-1}$, we can effectively improve groundwater recharge and its quality (salinity and alkalinity) even in deficit rainfall years. Submerged crops can be saved by draining off excess water[17]; thus enhancing the farmer's income.

An understanding of temporal trends and changing patterns of rainfall is a basic and important requirement for planning and management of water resources to combat climate change. The MK test applied to the annual and seasonal rainfall time-series data showed statistically non-significant trends, but a significant decreasing trend was observed in the number of rainy days. Presence of significant negative change in the number of rainy days shows that at present there is indication of increase in rainfall intensities. The tendency of decreasing rainfall amount in June and July, and increase in September could indicate the shifting pattern of rainfall events in this area. Decrease in rainfall and rainy days will ultimately trigger greater extraction of groundwater for irrigating crops and results in decline of groundwater level. Decrease in rainfall pattern and its variability are likely to reduce soil moisture; while extreme rainfall events in the later monsoon months are likely to increase storm runoff. This accumulated runoff water from adjoining fields of higher elevation poses a serious threat to crops in the depression areas; sometimes it causes total yield losses. Groundwater recharge through artificial groundwater recharge structures installed in low-lying agricultural areas is one of the feasible solutions for controlling flood water damage. Installation of artificial groundwater recharge in these low-lying areas can effectively control excess flood water by draining off excess water into aquifers to improve groundwater recharge and its quality.

1. Christensen, J. H., Regional climate predictions. Climate Change 2007. The physical science basis. Contribution of Working Group 1 to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, Cambridge University Press, Cambridge, 2007.
2. Cruz, R. V., Asia. Climate Change 2007. Impacts, adaptation and vulnerability. Contribution of Working Group 2 to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 2007.
3. Bhadwal, S., Coping with global change: vulnerability and adaptation in Indian agriculture. TERI Report. Venema, IG Printers, New Delhi, 2003.
4. Mooley, D. A. and Parthasarathy, B., Fluctuations in All-India summer monsoon rainfall during 1871–1978. *Clim. Change*, 1984, **6**, 287–301.
5. Parthasarathy, B., Inter-annual and long term variability of Indian summer monsoon rainfall. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 1984, **93**, 371–385.
6. Rupa Kumar, K., Pant, G. B., Parthasarathy, B. and Sontakke, N. A., Spatial and sub-seasonal patterns of the long-term trends of Indian summer monsoon rainfall. *Int. J. Climatol.*, 1992, **12**, 257–268.
7. Ladha, J. K. *et al.*, How extensive are yield declines in long-term rice–wheat experiments in Asia? *Field Crops Res.*, 2003, **81**, 159–180.
8. Kamra, S. K. and Sharma, D. K., Groundwater recharge structures for small farmers in alluvial regions. Technical Papers, 3rd Ground Water Congress, Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, 22–23 March 2011, pp. 168–174.
9. Kumar, S., Kamra, S. K., Yadav, R. K. and Sharma, J. P., Evaluation of sand-based stormwater filtration system for groundwater recharge wells. *Curr. Sci.*, 2012, **103**, 395–404.
10. Choudhury, B. U., Das, A., Ngachan, S. V., Slong, A., Bordoloi, L. J. and Chowdhury, P., Trend analysis of long-term weather variables in mid altitude Meghalaya, North-East India. *J. Agric. Phys.*, 2012, **12**, 12–22.
11. American Public Health Association (APHA), Standard method for examination of water and wastewater, 2002.
12. Guhathakurta, P. and Rajeevan, M., Trends in the rainfall pattern over India, NCC Research Report No 2/2006, India Meteorological Department, Pune, 2006, p. 23.
13. Rupa Kumar, K. *et al.*, High resolution climate change scenarios for India for the 21st century. *Curr. Sci.*, 2006, **90**(3), 334–345.
14. Pattanaik, D. R. and Rajeevan, M., Variability of extreme rainfall events over India during southwest monsoon season. *Meteorol. Appl.*, 2010, **17**, 88–104.
15. Subash, N., Rammohan, H. S. and Sikka, A. K., Quantitative assessment of influence of monsoon rainfall variability on rice production over India. *J. Agrometeorol.*, 2009, **11**, 109–116.
16. Gathala, M. K., Ladha, J. K., Saharawat, Y. S. and Kumar, V., Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice–wheat rotation. *Soil Sci. Soc. Am. J.*, 2011, **75**, 1851–1862.
17. Kaledhonkar, M. J., Singh, O. P., Ambast, S. K., Tyagi, N. K. and Tyagi, K. C., Artificial groundwater recharge through recharge tube wells: a case study. *Inst. Eng. (I) J. – AG*, 2003, **84**, 28–32.

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Raindrop size distributions of southwest and northeast monsoon heavy precipitation observed over Kadapa (14°4′N, 78°82′E), a semi-arid region of India

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Raindrop size distributions (RSD) of southwest (SW – June to September) and northeast (NE – October to December) monsoon heavy precipitation are measured with PARticle SIze and VELocity (PARSIVEL) disdrometer and Micro Rain Radar (MRR) deployed at Kadapa (14.47°N; 78.82°E), a semi-arid continental site in Andhra Pradesh, India. RSD characteristics stratified on the basis of rainrate showed that the mean values of raindrop concentration of small (medium) drops are less (more) in SW when compared with NE monsoon heavy precipitation. Gamma function applied to heavy precipitation events showed that the mean value of mass weighted mean diameter, D_m (normalized intercept parameter $\log_{10} N_w$) is higher (lower) in SW monsoon than NE monsoon. Stratiform and convective precipitating cloud fraction observed during SW and NE monsoons revealed that contribution of stratiform precipitation is predominant for the seasonal variation in raindrop size distribution. The coefficient and exponent values of the *Z–R* relations are higher in SW than NE monsoon in both stratiform and convective precipitation.

Keywords: Raindrop size distribution, rainrate, mass weighted mean diameter.

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