Characterizing Rainfall-Groundwater Dynamics in a Hard-Rock Aquifer System Using Time Series, GIS and Geostatistical Modeling

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ABSTRACT

The aim of this study was to investigate rainfall-groundwater dynamics over space and annual time scales in a hard-rock aquifer system of India by employing time series, GIS and geostatistical modeling techniques. Trends in 43-year (1965-2007) annual rainfall time series of ten rainfall stations and 16-year (1991-2006) pre- and post-monsoon groundwater levels of 140 sites were identified by using Mann-Kendall, Spearman rank order correlation, and Kendall rank correlation tests. Trends were quantified by Kendall slope method. Furthermore, the study involves novelty of examining homogeneity of pre- and post-monsoon groundwater levels, for the first time, by applying seven tests. Regression analysis between rainfall and post-monsoon groundwater levels was performed. The pre- and post-monsoon groundwater levels for four periods: (a) 1991-1994, (b) 1995-1998, (c) 1999-2002, and (d) 2003-2006 were subjected to GIS-based geostatistical modeling. The rainfall showed considerable saptio-temporal variations, with a declining trend at the Mavli rainfall station ($p\text{-value}<0.05$). The Levene's tests revealed spatial homogeneity of rainfall at $\alpha = 0.05$. Regression analyses indicated significant relationships ($r^2>0.5$) between groundwater level and rainfall for eight rainfall stations. Non-homogeneity and declining trends in the groundwater level, attributed to anthropogenic and hydrologic factors, were found at 5 to 61 more sites in pre-monsoon compared to post-monsoon season. The groundwater declining rates in phyllite-schist, gneiss, schist and granite formations were found to be 0.18, 0.26, 0.21 and 0.14 m year^{-1} and 0.13, 0.19, 0.16 and 0.02 m year^{-1} during the pre- and post-monsoon seasons, respectively. The geostatistical analyses for four time periods revealed linkages between the rainfall and groundwater levels.

Keywords: Groundwater dynamics, GIS, homogeneity, trend, geostatistical modeling, Udaipur district.

1. INTRODUCTION

Groundwater is one of the most valuable natural resources, which supports human health, economic development, and ecological diversity (e.g., Zektser, 2000; Humphreys, 2009; Steube et al., 2009). The occurrence of drought and heavy rainfall are the most important climatic extremes having both short- and long-term impacts on the groundwater availability. Besides the natural forces creating pressure on water resources, ever-increasing human activities have become the primary drivers of the pressure affecting our planet's water systems. On top of it, freshwater resources are highly vulnerable to climate change, with wide-ranging consequences for human life and ecosystems (Bates et al., 2008).

India is on the brink of a severe water crisis (Briscoe, 2005). The country's average annual rainfall (about 120 cm yr^{-1}) is more than that of any other country of comparable size (Kumar et al., 2005), but the rainfall is unevenly distributed both in space and time. In India, groundwater accounts for about 50-80% of domestic water use and 45-50% of irrigation (Kumar et al. 2005; Mall et al., 2006) and groundwater lowering due to its overexploitation is prevalent in several parts of the country (CGWB, 2011). For instance, a recent study reported that groundwater reserves are depleting at a rate of 4.0 ± 1.0 cm yr^{-1} in the Indian states of Rajasthan, Haryana and Punjab (Rodell et al., 2009). It was also found that between August 2002 and December 2008, these states lost 109 km^3 of groundwater which is double the capacity of India's largest reservoir Wainganga and almost triple the capacity of 'Lake Mead', the largest man-made reservoir in the United States (Rodell et al., 2009). The detrimental impacts of climate change on declining water resources availability are posing a serious threat for India (Barnett et al., 2005; Kumar et al., 2005; Amarasinghe et al., 2007; Tiwari et al., 2009). For the arid zone of Rajasthan, it is reported that even 1% increase in temperature from the base data could result in an increase in evapotranspiration by 15 mm, which means an additional water requirement of 34.275 million cubic metres (MCM) for Jodhpur district alone and 313.12 MCM for entire Rajasthan (Goyal, 2004).

Udaipur district (study area of this study), situated in the hard-rock hilly terrains of Rajasthan, suffers from frequent droughts due to poor and delayed monsoon, low rainfall, abnormally high summer temperature and inadequate water resources (Bhuiyan et al., 2006). Occurrence of droughts is a common phenomenon in Rajasthan and the 2002 drought was one of the severest droughts not only in Rajasthan but also in the history of India, which affected 56% of the geographical area and the livelihoods of 300 million people in 18 states (Samra, 2004). In 2002, the deviation from the normal rainfall was as high as -49% in Rajsamand, -67% in Sirohi, and -33% in Udaipur districts of Rajasthan (UNDP, 2002). Consequently, the groundwater levels declined considerably in Udaipur district as well as in many other semi-arid and arid regions of the country. Therefore, it is necessary to understand the groundwater dynamics and to quantitatively estimate the temporal and spatial variability of groundwater in the study area, which is a first step towards management of sustainable water resources under changing climate.

There are several analytical techniques to study the sensitivity of aquifer water levels to climate variability, e.g. crossing theory approach (Eltahir and Yeh, 1999), general circulation models (Loaiciga et al., 2000; Allen et al., 2004; Gunawardhana and Kazama, 2012), hydrologic models (Eltahir and Yeh, 1999), cross-correlation analysis (Chen et al., 2004; Lee et al., 2006), singular spectrum analysis (Venencio and Garcia, 2011), among others. Besides, Moukana and Koike (2008) employed geostatistical modeling to correlate declining groundwater levels with changes in land cover in Kumamoto plain, southwest Japan. Park and Parker (2008) developed and applied one physically-based semi-analytical model to predict water table fluctuations based on discrete record of rainfall such as daily or monthly rainfall data in South Korea. Tremblay et al. (2011) used correlation and wavelet analyses to understand inter-annual dynamics of groundwater levels in three Canadian regions. They found evidence of linkages between groundwater levels and climatic data. Leung et al. (2011) used regional climate model with and without surface water-groundwater interactions for the conterminous United States to assess the effects of climate, soil, and vegetation on the water table dynamics. Time series modeling is another useful tool for detecting trends, developing hydrologic or climatic models, forecasting of hydrologic time series and prediction of future climate scenarios (Salas, 1993). The application of time series modeling in groundwater hydrology has been limited to the detection of trends in groundwater quality and groundwater levels (Machiwal and Jha, 2006). The application of time series analysis techniques to groundwater level time series is very few (Panda et al., 2007; Shamsudduha et al., 2009). In such studies, trends in the groundwater levels are detected by applying single test, e.g., linear regression test, Mann-Kendall test. Moreover, none of the studies addressed the presence of homogeneity in the groundwater-level time series, which is one of the important time series characteristics. The term ‘homogeneity’ implies that the data in the series belong to one population, and hence have a time-invariant mean and variance. Non-homogeneity arises due to the changes in the method of data collection and/or the environment in which it is carried out (Fernando and Jayawardena, 1994). For groundwater systems, non-homogeneity of groundwater levels may suggest changes occurring in aquifer stresses.

The objectives of this study were: (i) to explore the dynamics of groundwater levels on temporal and spatial scales; (ii) to identify the trends and homogeneity, and quantify trend magnitudes in the pre-monsoon and post-monsoon groundwater-level time series; and (iii) to understand the influence of spatio-temporal distribution of rainfall on the groundwater levels using GIS-based geostatistical modeling. The novelty of the study lies in the GIS-based geographical delineation of sites having homogeneous/non-homogeneous groundwater levels during both pre- and post-monsoon seasons. In addition, it is very common to use only one or two tests for time series analysis, which facilitates easy decision-making. However, Machiwal and Jha (2008) recommended that an adequate number of statistical tests must be applied for detecting a particular time series characteristic and the results should be analyzed critically to arrive at a reliable decision. Hence, unlike the customary approach in time series modeling, adequate/multiple statistical tests have been applied in this study so as to make realistic decisions based on time series modeling. Since the spatio-temporal groundwater-level data were available only for the pre-monsoon and post-monsoon seasons, it was not possible in this study to characterize the dynamics of rainfall-groundwater on shorter time scales (i.e., daily or weekly).

2. DESCRIPTION OF STUDY AREA

2.1 Location and Climate

The study area, Udaipur district (Fig. 1) is situated in the southern part of Rajasthan which is the driest state of India. It lies between 23°45′ and 25°10′ N latitude and 73°0′ and 74°35′ E longitude and has a geographical area of about 12698 km^2. There are 11 blocks in Udaipur district namely, Badgaon, Bhinder, Dhariawad, Girwa, Gogunda, Jhadol, Kherwara, Kotra, Mavli, Salumber, and Sarada. From the administration purpose, a state in India consists of several districts, districts of many blocks and blocks consist of *Gram Panchayats* which govern a group of villages.

The study area has a tropical and semi-arid climate. The average annual rainfall of the area is 675 mm, precipitating more than 80% during June through September. The rainy (wet) season starts from mid-June and lasts up to the end of October. November to May months usually remain dry. The mean temperature ranges between 42.3 and 28.8 °C during summers through the maximum daily temperature reaches up to 44.5 °C, while the winters are cold with the lowest temperature of 2.5 °C. January is the coldest month and May is the hottest month.

2.2 Geology and Groundwater Occurrence

Geologic lithology of the study area consists of phyllite-schist, gneiss, schist, granite, quartzite and hillocks (Fig. 2). Phyllite-schist and gneiss types of geologic formations dominates in Udaipur district which encompass 3567 and 3157 km^2 area, respectively, while the areas under schist, granite and quartzite formations are 808, 418 and 174 km^2, respectively (Machiwal et al., 2011). The phyllite-schist lithologic formations are relatively soft and friable compared to the gneiss formation. The phyllite-schist geologic formations occur in central half and southern portions of the district. The gneiss comprises porphyritic gneissic complex associated with aplite, amphibolite, schist and augen gneiss, and exists in eastern portion of the area. The schist formation occurs in the northeast and southeast portions and the granite lithologic formation exists in the western portion. The quartzite formation is located in a small elongated strip in the western portion. Hillocks, present in the study area, generally have negligible potential for the occurrence of groundwater resources. The phyllite-schist and gneiss, which are the major water-bearing formations in the study area, have little primary porosity and serve as groundwater reservoirs because of secondary porosity (fissures/fractures or joints). Thus, the groundwater through the rocky aquifers mainly moves through fissures/fractures or joints. These rocky geological formations are generally known as ‘hard-rock formations’ or specifically as ‘hard-rock aquifer systems’ if they have significant secondary porosity (CGWB, 1997). The groundwater occurs in the district mainly under unconfined to semi-confined conditions in saturated zone of the rock formation and the groundwater occurrence is controlled by the topographical, physiographical and structural features present in geological formations (CGWB, 2010).

3. METHODOLOGY

3.1 Database Preparation

This study utilized daily rainfall data for a period of 43 years (1965-2007) of ten rainfall gauging stations namely, Bhinder, Dhariawad, Girwa, Gogunda, Jhadol, Kherwara, Kotra, Mavli, Salumber, and Sarada located in Udaipur district (study area); location of the rainfall stations is shown in Fig. 1. The monthly rainfall data were collected from the Land Record Section, Collectorate, Udaipur, Rajasthan and were summed up for individual years to compute annual rainfall amounts.

Groundwater level data of pre- and post-monsoon seasons for 19-year (1988-2006) period were collected for a total of 251 sites over the study area from the Ground Water Department, Udaipur. All the collected groundwater-level records were processed and checked for the consistence and continuity. Finally, a total of 140 consistent and regular groundwater-level time series for 16 years (1991-2006) were selected for time series modeling; location of the consistent groundwater monitoring sites is shown in Fig. 2 (phyllite-schist formation 64 sites; gneiss formation 58 sites; schist formation 10 sites; granite formation 8 sites). The rainfall stations and the groundwater monitoring sites were registered into geographic information system (GIS) through UTM projection of longitude and latitude to facilitate spatial analyses be performed.

3.2 Analysis of Spatial and Temporal Variations of Rainfall

Box and whisker plots of annual rainfall series were drawn for the ten rainfall stations and for 43 years (1965-2007). These plots provide a summary of five important statistical properties viz., mean/median, 25 and 75 percentiles, maximum and minimum values along with outliers/extremes, and thereby reveal useful information about spatial and temporal variations of time series (USEPA, 2006). In addition, annual rainfall time series of individual rainfall stations were analyzed for detecting trends by applying three most powerful statistical tests, viz., Mann-Kendall test, Spearman Rank Order Correlation (SROC) test and Kendall Rank Correlation test. Spatial homogeneity of the annual rainfall time series was also examined by applying Levene’s Analysis of Variance (ANOVA) Test and Levene’s Median tests. To accomplish the above-mentioned time series analyses, spreadsheet programs were developed using MS-Excel software.

3.3 Regression and Correlation Analysis between Groundwater Level and Rainfall

Response of the groundwater levels to rainfall was investigated by plotting 16-year (1991-2006) mean pre- and post-monsoon groundwater levels (groundwater depth below the ground surface) in the eleven blocks of the study area along with bargraphs of monthly rainfalls in pre- and post-monsoon seasons. The mean groundwater level in a block refers to the mean of groundwater depths measured in the monitoring wells present in that block. The representative groundwater-monitoring wells for each block were identified based on Theissen polygons drawn for the rainfall station network using ILWIS software.

Relationship between rainfall and groundwater levels in the study area was investigated by performing regression analysis between annual rainfall and post-monsoon groundwater levels (groundwater depth below the ground surface). Similar and dissimilar response of groundwater levels at two or more sites indicates extent of hydraulic connectivity in the aquifer system underlying the observed sites. Such information is important for efficient groundwater management. In the monsoon-dominated climatic region, the groundwater characteristics are well distinct during pre- and post-monsoon seasons. Therefore, the correlation analyses were performed using three types of groundwater-level datasets of 16-year period (1991-2006): (i) only pre-monsoon data, (ii) only post-monsoon data, and (iii) combined pre- and post-monsoon data so that the hydraulic connectivity among 140 sites could be evaluated properly.

3.4 Time Series Modeling of Groundwater Levels

Homogeneity of the groundwater level time series was tested by applying seven statistical tests, viz., Hartley test, Link-Wallace test, Bartlett test, Tukey test, von Neumann test, Cumulative Deviation test, and Bayesian test. The major limitation with all the multiple comparison tests of homogeneity (i.e., Tukey, Link-Wallace, Bartlett and Hartley tests) is the requirement that populations should be normally distributed with equal variances, which makes the tests parametric in nature. Although the Link-Wallace test and the Hartley test can be employed for the same purpose as the Tukey’s test, the former three tests can be applied only when the sample size of all populations is equal, though methodology of the Hartley test can still be followed in case sample size of all the populations are more or less similar.

The most commonly used approach for trend detection is to formulate a linear model between the data and time. The main problem with the above approach is that it does not distinguish between the trend and the persistence (Hameed et al., 1997). This test can be misleading if seasonal cycles are present, the data are not normally distributed, and/or the data are serially correlated (Gilbert, 1987). To overcome the problem associated with the linear model for trend detection, the Spearman rank order correlation (SROC) nonparametric test (McGhee, 1985) is used to check the existence of long-term trend. Among the available nonparametric trend tests, the World Meteorological Organization (WMO, 1988) recommends the SROC test for detecting trend in flow volumes. Other excellent non-parametric tests mostly preferred for trend detection tests in hydrologic time series are Kendall's Rank Correlation test and Mann-Kendall test (Hirsch et al., 1982; Jayawardena and Lai, 1989; Gan, 1992; Zipper et al., 1998; Kumar, 2003; Machiwal and Jha, 2008). The Mann-Kendall test is a nonparametric test for exploring a trend in a time series without specifying the type of trend (i.e., linear or nonlinear). Therefore, trend in the groundwater level time series was detected by applying three statistical tests, viz., Mann-Kendall test, Spearman Rank Order Correlation test and Kendall Rank Correlation test. Theoretical backgrounds of these statistical tests are available in the books on statistical hydrology (e.g., Shahin et al., 1993; Kanji, 2001; Machiwal and Jha, 2012), and hence the theoretical details of these tests are omitted here in order to avoid excessive length of the paper. The homogeneity and trend tests were applied separately for pre- and post-monsoon seasons using 16 years (1991-2006) groundwater-level time series data of 140 sites. Thus, in total, ten statistical tests were applied to 280 individual groundwater-level time series. Time series modeling was performed using MS-Excel spreadsheet programs developed in this study.

3.5 Geostatistical Modeling of Groundwater Levels

To estimate spatial distribution of the groundwater levels during pre- and post-monsoon seasons, geostatistical modeling was performed in three steps: firstly, experimental semivariogram was computed, secondly four geostatistical models were fitted, and finally, spatial maps of groundwater level were prepared. For geostatistical modeling, the 16-year (1991-2006) groundwater-level data of 140 consistent monitoring sites were grouped into four periods: 1991-1994, 1995-1998, 1999-2002, and 2003-2006 by taking mean over the 4-year periods. Thereafter, the time series of groundwater levels were examined for the presence of spatial trends because it is a pre-requisite for geostatistical modeling.

3.5.1 Spatial Estimation by Kriging Technique

In geostatistics, if Z(x) represents any random function with groundwater levels measured at n locations in space z(x_i), i = 1, 2, … n and if the groundwater level of the function Z has to be estimated at the point x_0, which has not been measured, the kriging estimate is defined as (Journel and Hujibregts, 1978; Kitanidis, 1997):

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i \, z(x_i) \tag{1}$$

Where, $Z^*(x_0)$ = estimation of function $Z(x)$ at point x_0 and λ_i = weighting factors that minimize the variance of the estimation error (ordinary kriging weights).

Now two conditions are imposed to Eqn. (1), i.e., the unbiased condition and the condition of optimality. The unbiased condition means that the expected value of estimation error or the mean difference between the estimated $z^*(x_0)$ and the true (unknown) $z(x_0)$ value of the groundwater level should be zero. The condition of optimality means the variance of the estimation error should be minimum.

The spatial structure defined by theoretical variogram, a kriging system of linear equations combining neighbouring information can be defined as

$$\sum_{j=1}^{n} \lambda_j \, C(x_i, x_j) - \mu = C(x_i, x_0) \qquad i = 1, 2, \ldots n \tag{2}$$

subjected to constraint on weights:

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{3}$$

Where, μ = Lagrangian multiplier and $C(x_i, x_j)$ = value of covariance between two points x_i and x_j.

When we deal with an intrinsic case, i.e., working with variogram, the kriging Eqns. (2) and (3) are simply modified as follows (Marsily, 1986; Ahmed, 2006):

$$C(x_i, x_j) = C(0) - \gamma(x_i, x_j) \tag{4}$$

$$C(x_i, x_0) = C(0) - \gamma(x_i, x_0) \tag{5}$$

Eqns. (4) and (5) hold good only when both the covariance and the variogram exist, i.e., variables are stationary.

3.5.2 Fitting of Geostatistical Models

A total of four most-widely used geostatistical models, viz., spherical, circular, Gaussian, and exponential were fitted to the experimental variograms of groundwater levels separately for pre- and post-monsoon seasons by adjusting the parameters of the geostatistical models (i.e., nugget, sill and range). Description along with mathematical expressions of the geostatistical models is available in literature (Isaaks and Srivastava, 1989; Kitanidis, 1997).

3.5.3 Selection of the Best-Fit Model

Finally, the best-fit geostatistical model was selected based on seven goodness-of-fit criteria namely, mean error (ME), root mean squared error (RMSE), correlation coefficient (r), mean standard error (MSE), mean reduced error (MRE), reduced variance ($S^2_{R_e}$), and coefficient of determination (r^2). The details about these goodness-of-fit criteria are given in Table 1. The best-fit geostatistical model thus obtained was used to generate spatial maps of pre- and post-monsoon groundwater levels by using ILWIS 3.2 GIS software (ILWIS, 2001).

4. RESULTS AND DISCUSSION

4.1 Long-Term Spatiotemporal Variation of Rainfall

The variation of annual rainfalls over the study area along with the 43-year mean annual rainfall is shown in Fig. 3 using box and whisker plots. It is evident from this figure that the temporal variation of annual rainfall is the highest for Kotra rainfall station and the median rainfalls of Dhariawad (81 cm) and Kotra (78 cm) stations are more than the 43-year mean annual rainfall (66.2 cm) in the area. Some outliers and/or extreme rainfall events occurred during the 43-year period at almost all the ten rainfall stations (Fig. 3). The outliers/extremes were detected by the STATISTICA software, which considers a data point to be an outlier if the data point is outside the 1.5 times box length range from the upper and lower values of the box. On the other hand, an extreme value is that which is outside the 3 times box length range from the upper and lower values of the box (Tukey, 1977).

Moreover, long-term temporal variation of the annual rainfall for the 43-year period is shown in Fig. 4. Clearly, no overall trend in the annual rainfall is discernible, but the presence of outliers indicates that the annual rainfalls in some of the years at Dhariawad and Kotra stations are substantially higher than the rainfalls at other stations. Of the total 43-year period, the annual rainfalls at all the rainfall stations exceeded the mean annual rainfall in five years (1973, 1983, 1990, 1994, and 2006), whereas they were below the mean annual rainfall in eleven years (1966, 1972, 1974, 1982, 1986, 1987, 1988, 1995, 1999, 2000, and 2002). Thus, it can be inferred that the rainfall of the study area exhibits considerable variations with space and time.

4.2 Trend and Homogeneity in the Rainfall Time Series

Results of the Mann-Kendall, SROC, and Kendall Rank Correlation tests are summarized in Table 2. It can be seen from this table that the calculated test-statistic values of all three trend tests is more than their critical values at 5% level of significance (p-value<0.05) for Mavli rainfall station, which indicates presence of trend in the annual rainfall time series of Mavli station. However, there is no trend in the rainfall series of the remaining nine rainfall stations (p-value>0.05). Negative test-statistic value of the Mann-Kendall test suggests declining trend in the annual rainfall time series of Mavli rainfall station.

The results of the Levene's ANOVA test (Table 3) revealed that the calculated test-statistic value (0.014) is less than its critical value (≈1.96 for 9 degrees of freedom in the numerator and 420 degrees of freedom in the denominator). Hence, the annual rainfalls at the ten rainfall stations do not have significant variance at $\alpha = 0.05$. It is apparent from Table 2 that the calculated test-statistic values of the Levene's median test do not vary significantly for the ten rainfall stations. Thus, the results of the Levene's median test are in agreement with those of the Levene's ANOVA test. This finding suggests that the annual rainfalls over the area are spatially homogeneous.

4.3 Groundwater Dynamics and Hydraulic Connectivity in the Aquifer

The mean groundwater levels for the representative Theissen polygons of ten individual rainfall stations are shown in Fig. 5 along with rainfall bargraphs of the corresponding rainfall station. Fig. 5 reveals that the rainfalls of Kotra and Dhariawad stations are fairly large compared to that at other stations in almost all the years. The groundwater levels at Kotra and Dhariawad stations barely fall below 10 m depth from the ground surface. This suggests that the groundwater levels at both the stations are influenced by large amounts of annual rainfall, among other factors. There was a continuous drought over 5-year period (1998-2002), among which the drought in year 2002 was the severest in the history of India. A considerable decline in the groundwater levels can be seen for the continuous drought period in all the blocks. Both the pre- and post-monsoon groundwater levels were the deepest over the entire 16-year period at Mavli station situated in gneiss geologic formations where relatively high population density extract the groundwater for domestic purposes. The relatively low amounts of the annual rainfall at Mavli station is also one of the major factors responsible for the lowest groundwater levels. The groundwater levels in two of the rainfall stations (i.e., Kherwara and Sarada) remain the shallowest (9.80 and 6.78 m below ground surface in pre-monsoon season and 4.78 and 4.71 m below ground surface in post-monsoon season) despite the fact that the mean annual rainfall at these stations is quite low (589 and 561 mm). Both the stations are bestowed with phyllite-schist geologic formation, relatively flat topography with lesser slopes, and existence of surface water bodies (lakes and rivers) nearby the wells, which indicate greater possibility of groundwater recharge.

The results of regression analyses between annual rainfalls and post-monsoon groundwater levels for the 16-year period (1991-2006) are depicted in Figs. 6(a-j) for the ten locations. It is apparent that the r^2 values for the eight rainfall stations (Bhinder, Girwa, Gogunda, Jhadol, Kotra, Mavli, Salumber, and Sarada) are more than 0.5, which suggest that the groundwater levels are significantly influenced by rainfall at these locations. However, the groundwater response to rainfall is very poor ($r^2 = 0.25$ and 0.33) at Dhariawad and Kherwara locations [Figs. 6(e,f)].

The correlation analyses demonstrate the hydraulic connectivity among the sites over the study area or similarity in the response of groundwater among the sites due to hydrological and anthropogenic factors. Results of the correlation analyses of groundwater levels (groundwater elevations) at 140 sites for pre-monsoon, post-monsoon, and combined pre- and post-monsoon data are illustrated in Fig. 7. Total pairs of sites (9730) in the correlation matrices were grouped into following four classes based on the values of correlation coefficient (r): highly significant ($r \geq 0.7$), moderately significant ($0.7 > r \geq 0.5$), less significant ($0.5 > r \geq 0.166$), and insignificant ($r < 0.166$). Here, the value 0.166 is the critical limit of r for 140 sites at 5% significance level ($\alpha = 0.05$). It is apparent from Fig. 7 that the percentage pairs of sites showing ‘moderate’ and ‘high’ correlation coefficients are the highest for combined pre- and post-monsoon groundwater level data and the lowest for the pre-monsoon data. On the contrary, large pairs of sites showed ‘insignificant’ correlations during pre-monsoon season as compared to the post-monsoon season and/or combined pre- and post-monsoon data. Therefore, it was inferred that strong hydraulic connectivity exists in the aquifer system during post-monsoon season. It is recommended that the post-monsoon or combined pre- and post-monsoon data should be used for exploring the hydraulic connectivity among the sites.

4.4 Homogeneity and Trends in Groundwater Level

Results of the seven homogeneity tests indicating sites with presence/absence of homogeneity in the time series of pre- and post-monsoon groundwater levels are shown in Figs. 8 and 9, respectively. According to the Hartley test, the pre-monsoon groundwater levels at about 96% of the sites are homogeneous, while the von Neumann test indicates that only 11% of the sites have homogeneity in pre-monsoon groundwater levels (Fig. 8). The results of the Tukey and Link-Wallace tests suggest that homogeneity is associated with 31% of the sites in pre-monsoon groundwater levels. On the other hand, three test-statistics (Q of Cumulative Deviations test and U and A of Bayesian test) indicate that 47, 44, and 46% of the sites have homogeneity in pre-monsoon groundwater level time series, respectively, whereas the R test-statistics of Cumulative Deviation test reveals that 78% of the sites have homogeneity (Fig. 8). As far as the post-monsoon groundwater level time series is concerned, the results of the Hartley test (Fig. 9) suggest presence of homogeneity in all 140 post-monsoon groundwater level time series. The Tukey, Bartlett and the Link-Wallace tests suggest that 66, 66, and 59% of the sites have homogeneous post-monsoon groundwater level time series. Three test-statistics (i.e., Q, U, and A) of the Cumulative Deviations and the Bayesian tests indicate that 79, 82, and 88% of the sites have homogeneity in post-monsoon groundwater level time series, respectively, but the R-statistic of the Cumulative Deviations test shows that homogeneity is present in 97% of the post-monsoon groundwater level time series. It is clearly revealed from the above discussion that the number of sites showing homogeneity and non-homogeneity differs for both the pre-monsoon and post-monsoon groundwater-level time series according to the homogeneity tests applied in this study. This finding justifies the use of multiple statistical tests (more than one) to detect time series characteristics.

It can be seen from Figs. 8 and 9 that out of nine test-statistics of seven tests used, eight test-statistics (Hartley, Link-Wallace, Tukey, von Neumann, Q and R of Cumulative Deviations, and U and A of Bayesian) indicate 4, 27, 34, 4, 31, 19, 39 and 41% more sites with homogeneous groundwater levels during post-monsoon season than during pre-monsoon season. The large homogeneity in the post-monsoon groundwater levels seems to be logical because of limited human stress on the aquifer during monsoon/post monsoon season. The homogeneity tests (Fig. 8) suggest that non-homogeneous sites appear in three major clusters over the study area during the pre-monsoon season: (i) in northeast portion, (ii) in southwest portion, and (iii) in south portion of the area. Of the three clusters, the first cluster falls in the residential area, second in hillocks, and the third cluster falls in the cultivated command area. Based on the type of land use/land cover in non-homogeneity clusters, the non-homogeneity in the pre- and post-monsoon groundwater levels of the first cluster may be due to unsystematic and uncontrolled seasonal groundwater withdrawals for domestic uses. Similarly, the non-homogeneity of the third cluster may be attributed to the uncontrolled and frequent groundwater withdrawals for irrigation during pre-monsoon season when irrigation water demand is fairly high and surface water supply is not adequate to meet crop water requirements in the command areas. Thus, the non-homogeneity in pre- and post-monsoon groundwater levels in the first and third clusters are due to anthropogenic factors. However, the non-homogeneity in the second cluster could be attributed to the hydrologic factors (i.e., natural hydrologic processes). Almost similar types of three non-homogeneity clusters are also discernible in the post-monsoon groundwater levels (Fig. 9) for the Link-Wallace test, Tukey test, Cumulative Deviations (Q-statistic) test, and Bayesian test (both U and A test-statistics). However, these clusters are relatively less dense for the post-monsoon groundwater levels compared to the pre-monsoon groundwater levels. The lesser number of non-homogeneous groundwater level sites in post-monsoon season is reasonable due to the fact that sufficient surface water is available for meeting domestic and agricultural water demands, and that groundwater supply is augmented due to natural recharge, and hence the aquifer system is almost free from artificial stress.

Results of the three trend tests indicating number of sites with presence/absence of the trends in pre- and post-monsoon groundwater levels are shown in Figs. 10 and 11. It is apparent that the number of sites with significant trends of increasing groundwater level at 5% significance level ($p\text{-value} < 0.05$) is approximately same for the Mann-Kendall test (49% and 7% of the sites in pre- and post-monsoon seasons, respectively) and the Kendall Rank Correlation test (51% and 8% of the sites in pre- and post-monsoon seasons, respectively). However, the Spearman Rank Order Correlation test does not indicate nature of trend (i.e., increasing/decreasing) and results in relatively large number of sites with significant trends (i.e., 61% in pre-monsoon and 20% in post-monsoon) at $\alpha = 0.05$ compared to two earlier trend tests.

Furthermore, Figs. 10 and 11 reveal that significant increasing trends of groundwater levels (at $\alpha = 0.05$) are at relatively more number of sites in the pre-monsoon season in comparison to that in the post-monsoon season, which is due to the rise in groundwater levels in post-monsoon season and increased hydraulic connectivity among the sites. It is also apparent from Figs. 10 and 11 that sites having significant declining groundwater-level trends ($p\text{-value} < 0.05$) appear in three major clusters, which are in agreement with the findings of the homogeneity tests discussed earlier. The first cluster is in the northeast portion, second in southwest portion, and third in south portion of the area. The factors responsible for significant increasing trends ($p < 0.05$) in these clusters could be explained based on the type of land use/land cover in the area as discussed in the previous section. Moreover, it is revealed that significant trends in the first and third clusters are due to non-systematic variation of groundwater withdrawals for domestic and irrigation purposes, respectively (or anthropogenic sources) since the clusters exist at the same location where the clusters of non-homogeneity exist. However, significant trends in the second cluster could be attributed to hydrological factors.

4.5 Groundwater Dynamics vis-à-vis Geology

As a matter of fact, recharge, aquifer storage and aquifer transmissivity, which play a central role in the dynamics of a groundwater system, are heavily dependent on geology, among other factors. Thus, geology plays a significant role in groundwater dynamics, which can't be ignored. The results of the Mann-Kendall test identified nature of trends, i.e., increasing/decreasing, in major geological formations of the area. Since the groundwater levels are recorded in m bgs (meters below ground surface), positive test-statistic values indicate declining groundwater levels and negative test-statistics indicate rising water levels. Fig. 12 shows percentage of sites having positive, negative and neutral trends for the pre- and post-monsoon seasons under different geological formations, while Table 4 shows number of sites having significant positive and negative trends at $\alpha = 0.01$, 0.05 and 0.10.

In the phyllite-schist formation, positive trend indicating decline in pre-monsoon groundwater levels was observed in 53 (83%) sites of the total of 64 sites. Out of these positive trends, 12 (23%), 39 (74%) and 44 (83%) sites experienced significant groundwater level decline at $\alpha = 0.01$, 0.05 and 0.10, respectively. On the contrary, 11 (17%) sites exhibited negative trends or rise in the pre-monsoon groundwater levels and out of these negative trends, 2 (18%), 2 (18%) and 3 (27%) sites showed significant rise of the groundwater levels at $\alpha = 0.01$, 0.05 and 0.10, respectively. In the post-monsoon season, 47 (73%) of the total 64 sites exhibited groundwater level decline and 25% of the sites experienced rise in groundwater level. However, the significant groundwater level decline was observed at 1 (2%), 5 (11%) and 9 (19%) sites showing positive trends at $\alpha = 0.01$, 0.05 and 0.10, respectively but the significant groundwater level rise was found only at one site at $\alpha = 0.10$.

In the gneiss formation, the decline in the pre-monsoon groundwater levels was revealed at 48 (83%) sites of the total 58 sites in this formation. However, the significant groundwater decline was observed at 16 (33%), 31 (65%) and 37 (77%) sites at the significance levels $\alpha = 0.01$, 0.05 and 0.10, respectively. In contrast, the rise in the pre-monsoon groundwater levels was observed at 9 (16%) of the sites only. In the post-monsoon season, the declining trend of the groundwater levels was detected at 45 (78%) sites, of which only 1 (2%), 4 (9%) and 8 (18%) sites showed the significant trend at the significance levels $\alpha = 0.01$, 0.05 and 0.10, respectively. Furthermore, around 12 (21%) of the sites experienced rising trends, however, the significant trends were found to be present at only one site at the significance level $\alpha = 0.10$.

In the schist formation, declining pre-monsoon groundwater levels were observed at 9 (90%) sites of the total 10 sites. The decline was found to be the significant at 4 (44%), 7 (78%) and 7 (78%) sites at the significance levels α = 0.01, 0.05 and 0.10, respectively. On the other hand, rising pre-monsoon groundwater levels were detected only at a single site. In the post-monsoon season, declining groundwater level was apparent at 8 (80%) sites, of which one (13%) and 4 (50%) sites showed the significant trends at the significance levels α = 0.05 and 0.10, respectively. Only one site showed rising trend, which was not the significant. On the other hand, in the granite formation, the pre-monsoon groundwater levels showed decline at all the 8 (100%) sites. However, the decline was the significant at 1 (13%), 2 (25%) and 4 (50%) sites only. In the post-monsoon groundwater levels, decline and rise was observed at 3 (38%) sites each though both the decline and rise was not found to be the significant at any significance levels.

Based on the above discussion, trends in the groundwater monitoring sites are apparent both during pre- and post-monsoon seasons in all the geologic formations of the study area. It was found that the declining trends are multi-fold than the rising trends indicating an overall drop in the groundwater levels in all the geologic formations. However, the percentage sites showing declining groundwater levels are 17 and 7% more during pre-monsoon season in the granite and schist formations, respectively, and 6 and 4% more during post-monsoon season in the schist and gneiss formations, respectively than those in the phyllite-schist formation. This may be attributed, among other factors, to the fact that the phyllite-schist formation has relatively high specific yield compared to the other geologic formations in the area, and hence, this portion of the study area induces more recharge to the aquifer and hence enhanced groundwater storage.

4.6 Quantification of Trend Magnitude

The trends of pre- and post-monsoon groundwater levels were quantified by the Kendall slope method for all the four geologic formations. The box and whisker plots of the trend magnitudes are depicted in Fig. 13. The square within the box represents median value of trend magnitude, the length of the box indicates interquartile range, and upper and lower whiskers are at 1.5 times of the box length. The '+' symbol shows outlier values. The median of the trend magnitudes are above zero, except for granite formation in the post-monsoon season, which mean an overall decline in the pre- and post-monsoon groundwater levels (Fig. 13). In pre-monsoon season, the groundwater levels decline at a mean rate of 0.18, 0.26, 0.21 and 0.14 m year^{-1} in the phyllite-schist, gneiss, schist and granite geologic formations, respectively. In the post-monsoon season, the groundwater levels recede at a mean rate of 0.13, 0.19, 0.16 and 0.02 m year^{-1} in the phyllite-schist, gneiss, schist and granite geologic formations, respectively.

The significant differences in the interquartile range of the trend magnitudes between seasons for all the geologic formations indicate variability of trend magnitudes. The interquartile range of the trend magnitudes is quite high for the gneiss formation and the least for granite formation irrespective of the seasons.

4.7 Influence of Rainfall Variation on Spatial and Temporal Distribution of Groundwater

Regression analysis between pre-monsoon and post-monsoon groundwater levels and geographical coordinates (i.e., latitude and longitude) revealed that no spatial trends exist in groundwater levels over the study area and stationarity was present in the groundwater levels. Thus, the trend-free groundwater levels were adequately fitted to four geostatistical models by adjusting the model parameters (nugget, sill and range). The best chosen parameter values for the four geostatistical models are given in Table 5. The values of goodness-of-fit criteria (Table 6) indicated that the spherical, Gaussian, and exponential geostatistical models are best-fit models for estimating areal distribution of groundwater levels in both pre- and post-monsoon seasons. However, the exponential model was selected as the best-fit model for this study based on RMSE, r and r^2, which are relatively more powerful than the other criteria. The experimental and exponentially-modeled variograms of the pre- and post-monsoon groundwater levels for four periods are shown in Figs. 14(a-h). The values of the nugget and sill parameters of the geostatistical model are quite low for the post-monsoon season compared to that for the pre-monsoon season. This indicates that the groundwater levels are less variable over the study area during the post-monsoon season than in the pre-monsoon season.

The classified Theissen polygons of the mean annual rainfall along with the kriged pre- and post-monsoon groundwater levels for the four periods, 1991-1994, 1995-1998, 1999-2002, and 2003-2006 are shown in Fig. 15. There are apparent temporal differences that reflect the dominant influence of the rainfall forcing on the groundwater levels. The impact of drought period 1999-2002 is depicted from the mean annual rainfall and its influence on the corresponding groundwater levels is clearly distinguished (Fig. 15). It is seen that the mean groundwater levels increases (i.e., becomes deeper) sharply with decreasing rainfall, and hence, the rainfall has a certain degree of control over the groundwater levels. The weighted mean annual rainfall during the period 1999-2002 (46.58 cm) was less than the long-term weighted mean annual rainfall (67.50 cm) of the study area. During the drought period (1999-2002), the groundwater levels were relatively deeper (more than 9 m bgs) in 9748 (77%) and 5894 (46%) km^2 areas during pre- and post-monsoon seasons, respectively, compared to those during rest of the periods. During the periods, 1991-94, 1995-99, and 2003-06, more than 9 m bgs deep pre-monsoon groundwater levels occurred in 44, 44, and 71% and the post-monsoon groundwater levels occurred in 7, 15, and 13% of the total study area, respectively. Relatively deeper groundwater levels mostly occurred in the northeast portion of the area, where the mean annual rainfall is also relatively low (less than 60 cm) during the drought period. Fig. 15 depicts resemblance in spatial distribution of the rainfall and pre- and post-monsoon groundwater levels over the study area. A comparison of Figs. 15(a-d) for four time periods reveals linkage of the rainfall and groundwater levels in the study area. Thus, the rainfall has direct impact on the behavior of groundwater levels. The distribution of the groundwater levels over time and space is vital from the viewpoint of groundwater potential in the region.

5. CONCLUSIONS

Present study aimed at investigating groundwater dynamics in a hard-rock aquifer system of India by using time series, GIS and geostatistical modeling techniques. Trends in the 43-year annual rainfall time series of ten rainfall stations and in the 16-year pre-and post-monsoon groundwater level time series are identified for 140 sites by using Mann-Kendall, Kendall Rank Correlation, and Spearman Rank Order Correlation tests, and quantified by using Kendall slope test and box-whisker plots. Spatial homogeneity of the annual rainfall is tested by applying two Levene's statistical tests. The study involves novel work of identifying the sites having homogeneous/non-homogeneous groundwater level time series by using seven homogeneity tests within GIS environment. Further, the impact of rainfall and geology on the groundwater levels are explored.

The box-whisker plots of rainfall in the study area revealed considerable temporal and spatial variations. However, no significant trend in the rainfall time series is detected ($p\text{-value}>0.05$) at any rainfall stations, except at the Mavli rainfall station where a declining trend is found to be present ($p\text{-value}<0.05$). The mean annual rainfall is considerably higher for Dhariawad (84±33 cm) and Kotra (82±26 cm) rainfall stations compared to that (54-70 cm) at other stations. Regression analyses indicated that there exist significant relationships ($r^2>0.5$) between the mean post-monsoon groundwater levels and the annual rainfalls of eight rainfall stations. The groundwater levels are found to be influenced by rainfall. Of the total 9730 pairs of the sites, correlation analyses indicated that the percentage sites with 'high' ($r\geq0.7$) and 'moderate' ($0.7>r\geq0.5$) correlation coefficients are the highest (81%) for combined pre- and post-monsoon groundwater levels, 62% for post-monsoon groundwater levels, and the lowest (50%) for the pre-monsoon groundwater levels. Thus, it is recommended that the groundwater level data for post-monsoon seasons and/or for combined pre- and post-monsoon seasons should be used for exploring hydraulic connectivity in the study area. Non-homogeneity and declining trends in the groundwater level time series are found at relatively large number of sites (ranging from 5 to 61) in the pre-monsoon season compared to the post-monsoon season. Non-homogeneous groundwater monitoring sites appeared in three major clusters in the study area, which is attributed to the anthropogenic and hydrologic factors. The percentage sites showing declining groundwater level trends in gneiss, schist and granite geologic formations were 6 to 17% higher than those in phyllite-schist formation. The mean groundwater declining rates as indicated by the Kendall slope method for the phyllite-schist, gneiss, schist and granite geologic formations are 0.18, 0.26, 0.21 and 0.14 m year^{-1}, respectively during the pre-monsoon and 0.13, 0.19, 0.16 and 0.02 m year^{-1}, respectively during the post-monsoon season. The geostatistical analyses revealed that both the pre-monsoon and post-monsoon groundwater levels almost follow the rainfall distribution pattern in the area and are largely controlled by the distribution of the rainfall over space and time.

Overall, the results of this study demonstrate that time series modeling, geostatistical modeling, and GIS techniques are powerful and very useful tools for investigating dynamics of groundwater and developing an efficient groundwater utilization plan. The findings obtained in this study are useful for the planners and decision-makers to formulate groundwater utilization and management policies/strategies for hard-rock aquifer systems of other regions or parts of the world in order to ensure sustainable water supply and livelihoods. Finally, it is recommended that the short-term rainfall-groundwater dynamics could be investigated in the future when required groundwater-level data are made available.

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REFERENCES

Ahmed, S. (2006). Application of geostatistics in hydrosciences. In: M. Thangarajan (editor), Groundwater Resource Evaluation, Augmentation, Contamination, Restoration, Modeling and Management, Capital Publishing Company, New Delhi, India, pp. 78-111.

Allen, D.M., Mackie, D.C. and Wei, M. (2004). Groundwater and climate change: A sensitivity analysis for the grand forks aquifer, southern British Columbia, Canada. Hydrogeology Journal, 12(3): 270-290.

Amarasinghe, U.A., Shah, T., Turral, H. and Anand, B.K. (2007): India's water future to 2025 - 2050: Business-as-usual scenario and deviations. IWMI Research Report 123, International Water Management Institute, Colombo, Sri Lanka.

Barnett, T. P., Adam, J. C. and Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438: 303-309.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P. (editors) (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Bhuiyan, C., Singh, R.P. and Kogan, F.N. (2006). Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. International Journal of Applied Earth Observation and Geoinformation, 8(4): 289-302.

Briscoe, J. (2005). India's Water Economy: Bracing for a Turbulent Future. World Bank Report No. 34750-IN, viii–xi.

CGWB (1997). Ground Water Resource Estimation Methodology - 1997. Report of the Ground Water Resource Estimation Committee, Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India, New Delhi, India, 107 pp.

CGWB (2010). Groundwater Scenario: Udaipur District, Rajasthan. District Groundwater Brochure, Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India, Western Region, Jaipur, 15p.

CGWB (2011). Dynamic Ground Water Resources of India (as on 31 March 2009). Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India, New Delhi, 243 pp.

Chen, Z., Grasby, S. and Osadetz, K.G. (2004). Relation between climate variability and groundwater levels in the upper carbonate aquifer, south Manitoba, Canada. Journal of Hydrology, 290: 43-62.

Eltahir, E.A.B. and Yeh, P.J.F. (1999). On the asymmetric response of aquifer water level to floods and droughts in Illinois. Water Resources Research, 35(4): 1199-1217.

Fernando, D.A.K. and Jayawardena, A.W. (1994). Generation and forecasting of monsoon rainfall data. Proceedings of the 20th WEDC Conference on Affordable Water Supply and Sanitation, Colombo, Sri Lanka, pp. 310-313.

Goyal, R.K. (2004). Sensitivity of evapotranspiration to global warming: A case study of arid zone of Rajasthan (India). Agricultural Water Management, 69(1): 1-11.

Gunawardhana, L.N. and Kazama, S. (2012). Statistical and numerical analyses of the influence of climate variability on aquifer water levels and groundwater temperatures: The impacts of climate change on aquifer thermal regimes. Global and Planetary Change, 86-87: 66-78.

Humphreys, W.F. (2009). Hydrogeology and groundwater ecology: Does each inform the other? Hydrogeology Journal, 17(1): 5-21.

ILWIS (2001). Integrated Land and Water Information System, 3.2 Academic, User’s Guide. International Institute for Aerospace Survey and Earth Sciences (ITC), The Netherlands, pp. 428-456.

Journal, A.G. and Huijbregts, C.J. (1978). Mining Geostatistics. Academic Press, London.

Kanji, G.K. (2001). 100 Statistical Tests. Sage Publication, New Delhi, 111 pp.

Kitanidis, P.K. (1997). Introduction to Geostatistics: Applications in Hydrogeology. Cambridge University Press, New York, 249 pp.

Kumar R., Singh, R.D. and Sharma, K.D. (2005). Water resources of India. Current Science, 89(5): 794-811.

Lee, L.J.E., Lawrence, D.S.L. and Price, M. (2006). Analysis of water-level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England. Journal of Hydrology, 330: 604-620.

Leung, L.R., Huang, M., Qian, Y. and Liang, X. (2011). Climate-soil-vegetation control on groundwater table dynamics and its feedbacks in a climate model. Climate Dynamics, 36(1-2): 57-81.

Loaiciga, H.A., Maidment, D.R. and Valdes, J.B. (2000). Climate change impacts in a regional karst aquifer, TX, USA. Journal of Hydrology, 227: 173-194.

Machiwal, D. and Jha, M.K. (2006). Time series analysis of hydrologic data for water resources planning and management: A review. Journal of Hydrology and Hydromechanics, 54(3): 237-257.

Machiwal, D. and Jha, M.K. (2008). Comparative evaluation of statistical tests for time series analysis: Application to hydrological time series. Hydrological Sciences Journal, 53(2): 353-366.

Machiwal, D. and Jha, M.K. (2012). Hydrologic Time Series Analysis: Theory and Practice. Springer, Germany and Capital Publishing Company, New Delhi, India, 303 p.

Machiwal, D., Jha, M.K. and Mal, B.C. (2011). Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. Water Resources Management, 25(3), 1359-1386.

Mall, R.K., Gupta, A., Singh, R., Singh, R.S. and Rathore, L.S. (2006). Water resources and climatic change: An Indian perspective. Current Science, 90(12): 1610-1626.

Marsily, G. de (1986). Quantitative Hydrogeology: Groundwater Hydrology for Engineers. Academic Press, CA, 440 pp.

Moukana, J.A. and Koike, K. (2008). Geostatistical model for correlating declining groundwater levels with changes in land cover detected from analyses of satellite images. Computers and Geosciences, 34: 1527-1540.

Panda, D.K., Mishra, A., Jena, S.K., James, B.K. and Kumar, A. (2007). The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. Journal of Hydrology, 343: 140-153.

Park, E. and Parker, J.C. (2008). A simple model for water table fluctuations in response to precipitation. Journal of Hydrology, 356: 344-349.

Rodell, M., Velicogna, I. and Famiglietti, J.S. (2009). Satellite-based estimates of groundwater depletion in India. Nature, 460: 999-1003.

Salas, J.D. (1993). Analysis and Modeling of Hydrologic Time Series. In: D.R. Maidment (editor-in-chief), Handbook of Hydrology, McGraw-Hill, Inc., USA, pp. 19.1-19.72.

Samra, J.S. (2004). Review and Analysis of Drought Monitoring, Declaration and Management in India. Working Paper 84, International Water Management Institute (IWMI), Colombo, Sri Lanka, 31 pp.

Shahin, M., Van Oorschot, H.J.L., and De Lange, S.J. (1993). Statistical Analysis in Water Resources Engineering. A. A. Balkema, Rotterdam, the Netherlands, 394 pp.

Shamsudduha, M., Chandler, R.E., Taylor, R.G. and Ahmed, K.M. (2009). Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrology and Earth System Sciences Discussions, 6, 4125-4154.

Steube, C., Richter, S. and Griebler, C. (2009). First attempts towards an integrative concept for the ecological assessment of groundwater ecosystems. Hydrogeology Journal, 17(1): 23-35.

Tiwari, V.M., Wahr, J. and Swenson, S. (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. Geophysical Research Letters, 36, L18401, doi:10.1029/2009GL039401.

Tremblay, L., Larocque, M., Anctil, F. and Rivard, C. (2011). Teleconnections and interannual variability in Canadian groundwater levels. Journal of Hydrology, 410(3-4): 178-188.

Tukey, J.W. (1977). Exploratory Data Analysis. Addison-Wesley, MA.

UNDP (2002). Mission Report on Drought Damage Assessment and Agricultural Rehabilitation for Drought Affected Districts of Rajasthan Draft 2, United Nations Development Programme (UNDP), pp. 1-20, http://www.undp.org.in/dmweb/RAJASTHAN%20DROUGHT.pdf (accessed on 30 March 2009).

USEPA (2006). Data Quality Assessment: Statistical Methods for Practitioners. Guidance Document EPA QA/G-9S, US Environmental Protection Agency (USEPA), Office of Environmental Information, Washington D.C.

Venencio, M.V. and Garcia, N.O. (2011). Interannual variability and predictability of water table levels at Santa Fe Province (Argentina) within the climatic change context. Journal of Hydrology, 409(1-2): 62-70.

Zektser, I.S. (2000). Groundwater and the Environment: Applications for the Global Community. Lewis Publishers, Boca Raton, Florida, 175 pp.

Table 1. Summary of the goodness-of-fit criteria used in the study

Sl. No.	Goodness-of-fit Criteria	Mathematical Expression
1	Mean Error (ME)	$ME = \frac{1}{n}\sum_{i=1}^{n}\left[z(x_i) - z^*(x_i)\right]$ Where, $z(x_i)$ and $z^*(x_i)$ = observed and estimated values of variable z at the location x_i, and n = number of data points.
2	Root Mean Squared Error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left[z(x_i) - z^*(x_i)\right]^2}{n}}$
3	Correlation Coefficient (r) (Rodgers and Nicewander, 1988)	$r = \frac{n\sum_{i=1}^{n}\left[z(x_i)\cdot z^*(x_i)\right] - \left[\sum_{i=1}^{n} z(x_i)\cdot\sum_{i=1}^{n} z^*(x_i)\right]}{\left[\sqrt{n\left\{\sum_{i=1}^{n}\left[z(x_i)^2\right]\right\} - \left\{z(x_i)\right\}^2}\right]\cdot\left[\sqrt{n\left\{\sum_{i=1}^{n}\left[z^*(x_i)^2\right]\right\} - \left\{z^*(x_i)\right\}^2}\right]}$
4	Mean Standard Error (MSE)	$MSE = \frac{1}{n}\sigma_k(x_i)$ Where, $\sigma_k(x_i)$ = estimation variance at the location x_i.
5	Mean Reduced Error (MRE) (Vauclin et al., 1983)	$MRE = \frac{1}{n}\sum_{i=1}^{n}\left[z(x_i) - z^*(x_i)\right]/\sigma_k(x_i)$
6	Reduced Variance ($S^2_{R_e}$) (Vauclin et al., 1983)	$S^2_{R_e} = \frac{1}{n}\sum_{i=1}^{n}\left[\left\{z(x_i) - z^*(x_i)\right\}/\sigma_k(x_i)\right]^2$
7	Coefficient of Determination (r^2) (Draper and Smith, 1998)	$r^2 = 1 - \frac{SSE}{(SSR + SSE)}$; Where, $SSE = \sum_{i=1}^{n}\left[z(x_i) - z^*(x_i)\right]^2$ and $SSR + SSE = \sum_{i=1}^{n}\left[z(x_i) - \bar{z}(x_i)\right]^2$ Where, $\bar{z}(x_i)$ = mean of $z(x_i)$.

Table 2. Calculated and critical test-statistic values of trend and homogeneity tests for the annual rainfall time series

Rainfall Station	**Levene's Median Test**	**Mann-Kendall Test**		**Spearman Rank Order Correlation Test**		**Kendall Rank Correlation Test**	
		Calculated	**Critical**[a]	**Calculated**	**Critical**[a]	**Calculated**	**Critical**[a]
Bhinder	0.11	0.10	±1.96	0.06	1.683	-0.115	±1.96
Dhariawad	0.11	0.36	±1.96	0.40	1.683	-0.366	±1.96
Girwa	0.11	0.44	±1.96	0.47	1.683	-0.450	±1.96
Gogunda	0.12	-0.04	±1.96	0.05	1.683	0.052	±1.96
Jhadol	0.12	-0.38	±1.96	0.57	1.683	0.387	±1.96
Kherwara	0.13	-0.48	±1.96	0.46	1.683	0.492	±1.96
Kotra	0.15	-0.17	±1.96	0.16	1.683	0.178	±1.96
Mavli	0.12	-2.09^{*}	±1.96	2.25^{*}	1.683	2.104^{*}	±1.96
Salumber	0.12	-0.77	±1.96	0.78	1.683	0.785	±1.96
Sarada	0.12	-0.36	±1.96	0.45	1.683	0.366	±1.96

Note: * $p < 0.05$; [a] Critical values are at $\alpha = 0.05$.

Table 3. Results of the Levene's analysis of variance test

Source	Sum of Squares (SS)	Degree of Freedom	F-ratio
SS between Rainfall Stations	26866147	9	0.014
Residual SS	26858056	420	–

Table 4. Cases of significant Mann-Kendall trends for different geological formations

Season	**Nature of Trend**	**Number of Cases with Significant Trends at Three Significance Levels**											
		Phyllite-Schist			**Gneiss**			**Schist**			**Granite**		
		0.01	**0.05**	**0.1**	**0.01**	**0.05**	**0.1**	**0.01**	**0.05**	**0.1**	**0.01**	**0.05**	**0.1**
Pre-monsoon	Positive	12	29	34	16	31	37	4	7	7	1	2	4
	Negative	2	2	3	0	1	3	0	0	0	0	0	0
Post-monsoon	Positive	1	5	9	1	4	8	0	1	4	0	0	0
	Negative	0	0	1	0	0	1	0	0	0	0	0	0

Table 5. Parameters of four geostatistical models for pre- and post-monsoon groundwater levels of four periods

Period	**Season**	**Model Parameters**	**Spherical**	**Circular**	**Gaussian**	**Exponential**
1991-1994	Pre-monsoon	Nugget (m^2)	9	9	14	9
		Sill (m^2)	41	41	42	48
		Range (m)	120000	100000	60000	70000
	Post-monsoon	Nugget (m^2)	7	7	7.5	6
		Sill (m^2)	20	20	20	22
		Range (m)	120000	110000	55000	63000
1995-1998	Pre-monsoon	Nugget (m^2)	9	9	13	9
		Sill (m^2)	42	42	43	47
		Range (m)	120000	110000	60000	70000
	Post-monsoon	Nugget (m^2)	7	8	10	4
		Sill (m^2)	27	27	28	32
		Range (m)	110000	105000	62000	60000
1999-2002	Pre-monsoon	Nugget (m^2)	12	12	18	12
		Sill (m^2)	45	45	45	49
		Range (m)	115000	100000	60000	60000
	Post-monsoon	Nugget (m^2)	12	12	15	12
		Sill (m^2)	36	36	36	40
		Range (m)	100000	90000	50000	55000
2003-2006	Pre-monsoon	Nugget (m^2)	12	12	17	12
		Sill (m^2)	43	42	43	50
		Range (m)	110000	95000	55000	65000
	Post-monsoon	Nugget (m^2)	9.5	10	12	9
		Sill (m^2)	24.5	25	25	25
		Range (m)	100000	100000	55000	45000

Table 6. Comparative performance of geostatistical models for groundwater levels

Period	**Goodness-of-fit Criteria**	**Geostatistical Model**							
		Pre-monsoon				**Post-monsoon**			
		Spherical	**Circular**	**Gaussian**	**Exponential**	**Spherical**	**Circular**	**Gaussian**	**Exponential**
1991-1994	Mean Error (cm)	-0.55	-0.55	**-0.53**	-0.55	0.002	0.002	-0.004	**-0.0004**
	Root Mean Squared Error (cm)	2.94	2.94	3.67	**2.78**	2.41	2.44	2.84	**2.18**
	Correlation Coefficient	0.83	0.83	0.71	**0.86**	0.79	0.78	0.67	**0.84**
	Mean Standard Error (cm)	**3.44**	**3.44**	3.93	3.50	2.93	2.92	2.88	**2.79**
	Mean Reduced Error	-0.16	-0.16	**-0.14**	-0.16	-0.0003	**0.00003**	-0.003	-0.001
	Reduced Variance	0.73	0.73	**0.88**	0.63	0.68	0.70	**0.97**	0.61
	Coefficient of Determination	0.70	0.70	0.51	**0.73**	0.62	0.61	0.45	**0.70**
1995-1998	Mean Error (cm)	**0.01**	**0.01**	0.03	**0.01**	**0.001**	0.01	0.02	-0.002
	Root Mean Squared Error (cm)	2.81	2.86	3.69	**2.65**	2.43	2.57	3.11	**1.86**
	Correlation Coefficient	0.86	0.85	0.72	**0.88**	0.85	0.82	0.71	**0.92**
	Mean Standard Error (cm)	3.44	**3.43**	3.79	3.50	3.01	3.17	3.31	**2.43**
	Mean Reduced Error	0.001	0.001	0.01	**0.001**	**-0.001**	**0.001**	0.003	-0.002
	Reduced Variance	0.67	0.69	**0.95**	0.57	0.66	0.66	**0.88**	0.59
	Coefficient of Determination	0.74	0.73	0.52	**0.77**	0.71	0.68	0.51	**0.84**
1999-2002	Mean Error (cm)	0.014	0.014	**0.012**	0.013	**0.001**	**0.001**	-0.01	0.003
	Root Mean Squared Error (cm)	3.34	3.35	4.17	**3.11**	3.22	3.25	3.89	**3.04**
	Correlation Coefficient	0.82	0.82	0.68	**0.85**	0.81	0.80	0.68	**0.83**
	Mean Standard Error (cm)	**3.92**	**3.92**	4.44	4.00	3.89	**3.87**	4.07	3.95
	Mean Reduced Error	0.002	0.002	**0.001**	0.002	-0.001	-0.001	-0.003	**-0.0002**
	Reduced Variance	0.72	0.73	**0.88**	0.61	0.69	0.71	**0.91**	0.59
	Coefficient of Determination	0.68	0.67	0.47	**0.72**	0.65	0.64	0.46	**0.70**
2003-2006	Mean Error (cm)	0.014	0.014	0.021	**0.013**	-0.01	-0.01	-0.03	**-0.004**
	Root Mean Squared Error (cm)	3.33	3.37	4.15	**3.14**	2.82	2.91	3.36	**2.60**
	Correlation Coefficient	0.82	0.82	0.68	**0.85**	0.78	0.76	0.65	**0.82**
	Mean Standard Error (cm)	3.92	**3.91**	4.33	3.98	3.42	3.47	3.62	**3.41**
	Mean Reduced Error	0.003	0.003	0.003	**0.002**	-0.004	-0.004	-0.01	**-0.002**
	Reduced Variance	0.72	0.74	**0.92**	0.62	0.68	0.70	**0.86**	0.58
	Coefficient of Determination	0.68	0.67	0.47	**0.72**	0.61	0.58	0.42	**0.68**

Note: Figures in boldface indicate relatively high values of goodness-of-fit criteria.

Figure Caption

Fig. 1. Location map of the study area.

Fig. 2. Geology map of the study area.

Fig. 3. Box-whisker plots of 43-year annual rainfalls at the ten rainfall stations.

Fig. 4. Spatial variation of 43-year mean annual rainfall.

Fig. 5. Theissen polygons, rainfall bargraphs and mean pre- and post-monsoon groundwater levels for the ten rainfall stations.

Figs. 6. Linear regression between annual rainfall and post-monsoon groundwater levels.

Fig. 7. Pairs of groundwater-monitoring sites under different categories of correlation coefficients.

Fig. 8. Distribution of sites having homogeneous and non-homogeneous pre-monsoon groundwater levels over the study area based on the seven homogeneity tests.

Fig. 9. Distribution of sites having homogeneous and non-homogeneous post-monsoon groundwater levels based on the seven homogeneity tests.

Fig. 10. Trends in the pre-monsoon groundwater-level time series based on the three trend tests.

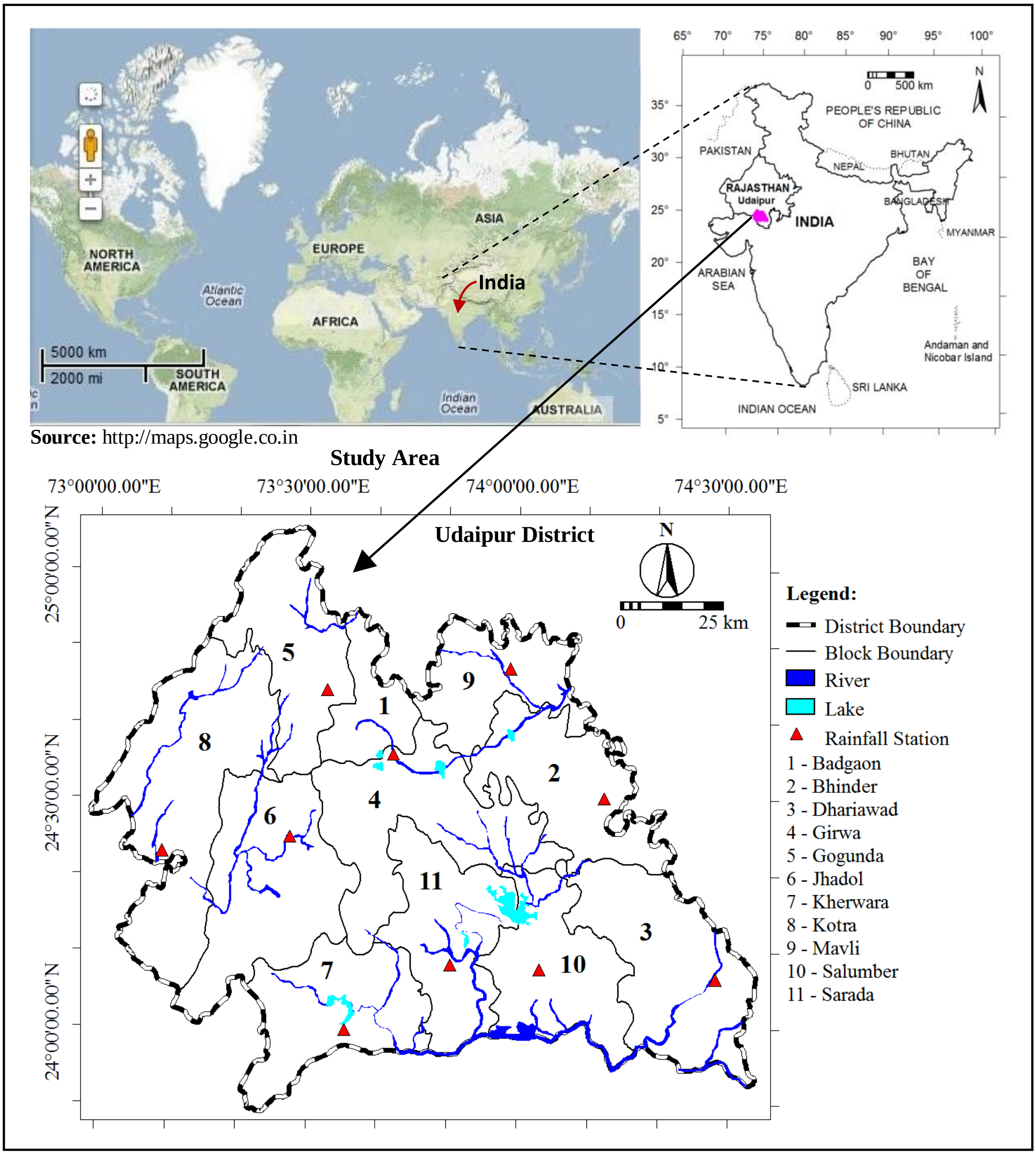
Fig. 11. Trends in the post-monsoon groundwater-level time series based on the three trend tests.

Fig. 12. Percentage of positive, negative and neutral trends in pre- and post-monsoon seasons.

Fig. 13. Box-whisker plots of Sen’s slope estimates for the pre- and post-monsoon groundwater levels under different geologic formations.

Fig. 14. Experimental and the best-fit modeled variograms of the pre- and post-monsoon groundwater levels for the four periods: (a,b) 1991-1994, (c,d) 1995-1998, (e,f) 1999-2002, and (g,h) 2003-2006.

Fig. 15. Spatial distribution of mean annual rainfall and groundwater levels of pre-monsoon and post-monsoon seasons for the four periods: (a) 1991-1994, (b) 1995-1998, (c) 1999-2002, and (d) 2003-2006.



Source: http://maps.google.co.in

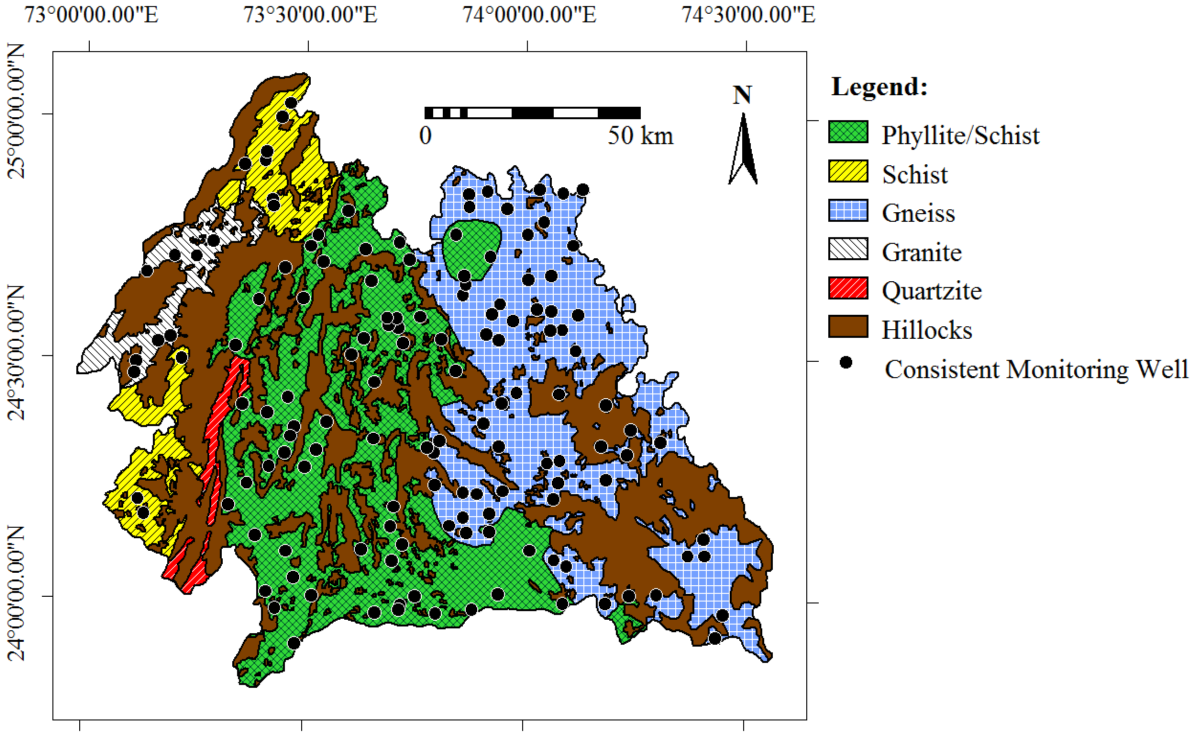

73°00'00.00"E
73°30'00.00"E
74°00'00.00"E
74°30'00.00"E
25°00'00.00"N
24°30'00.00"N
24°00'00.00"N
0
50 km
N
Legend:
Phyllite/Schist
Schist
Gneiss
Granite
Quartzite
Hillocks
Consistent Monitoring Well

Fig. 2

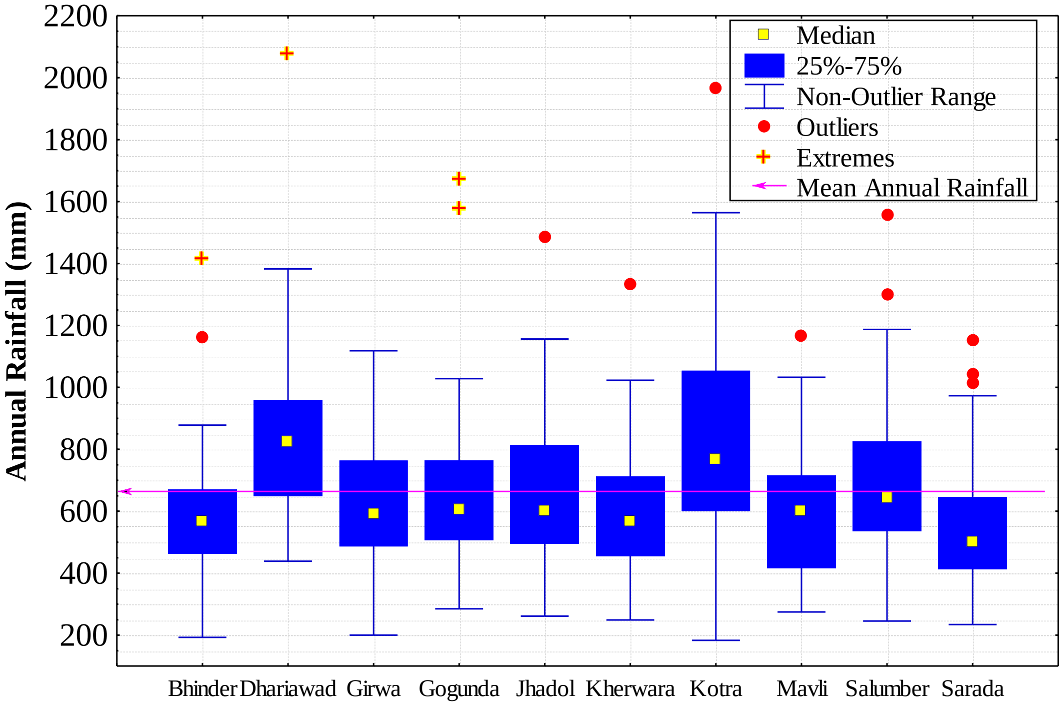

2200
2000
1800
1600
1400
1200
1000
800
600
400
200
Annual Rainfall (mm)
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Mean Annual Rainfall
Bhinder
Dhariawad
Girwa
Gogunda
Jhadol
Kherwara
Kotra
Mavli
Salumber
Sarada

Fig. 3

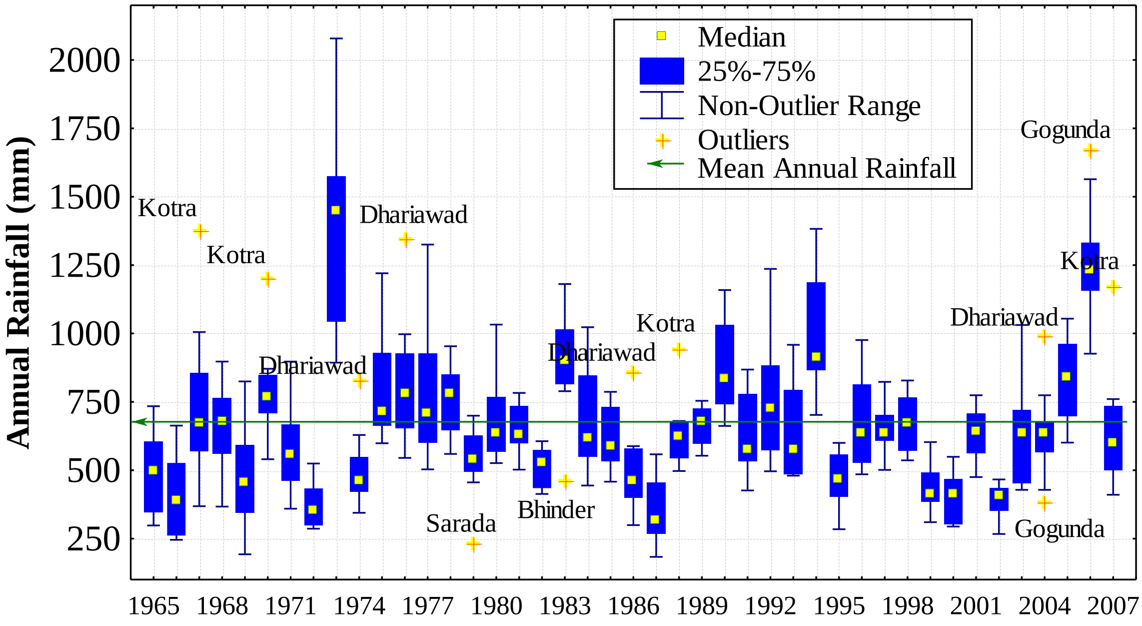
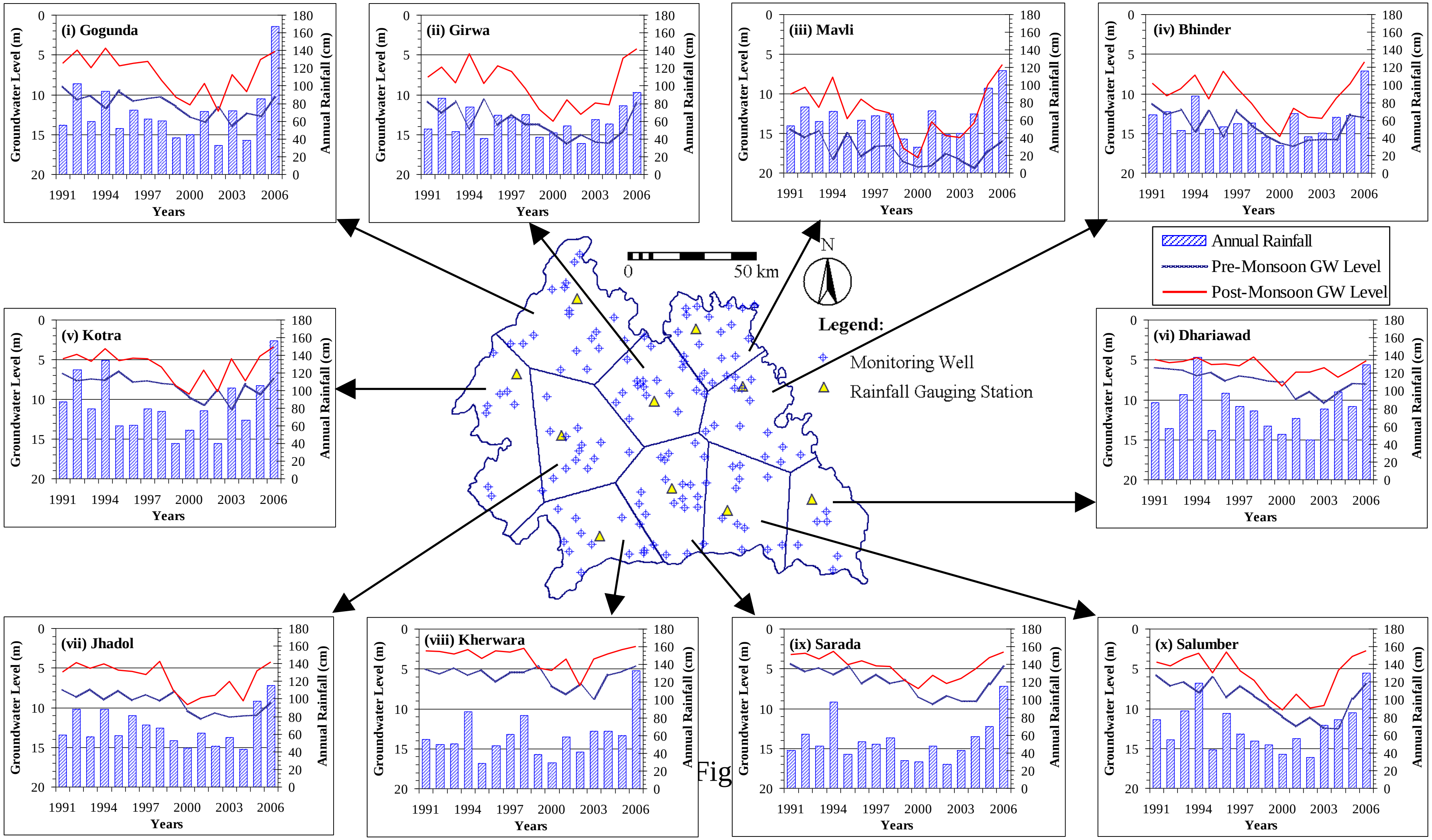
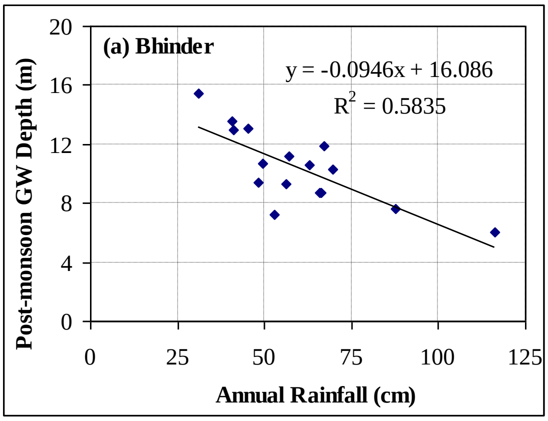
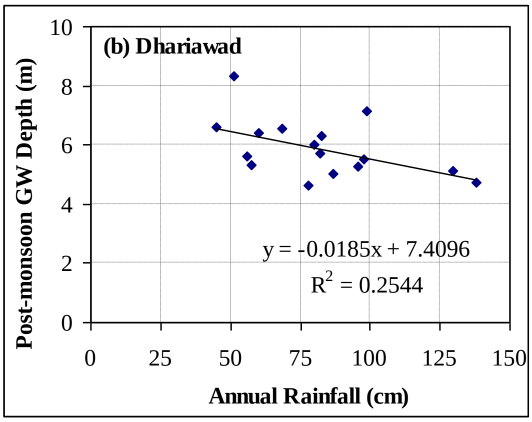

Annual Rainfall (mm)
2000
1750
1500
1250
1000
750
500
250
1965
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
Median
25%-75%
Non-Outlier Range
Outliers
Mean Annual Rainfall
Kotra
Kotra
Dhariawad
Dhariawad
Sarada
Bhinder
Dhariawad
Kotra
Gogunda
Kotra
Dhariawad
Gogunda

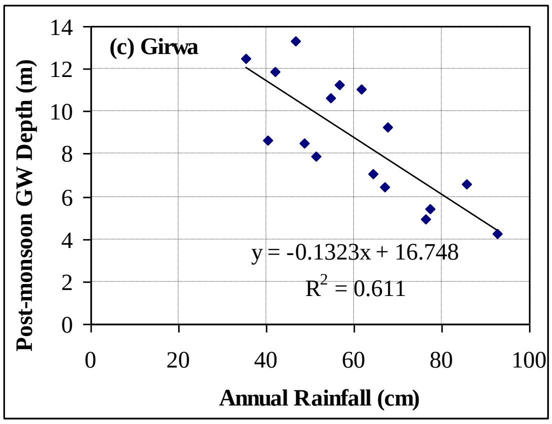
Fig. 4

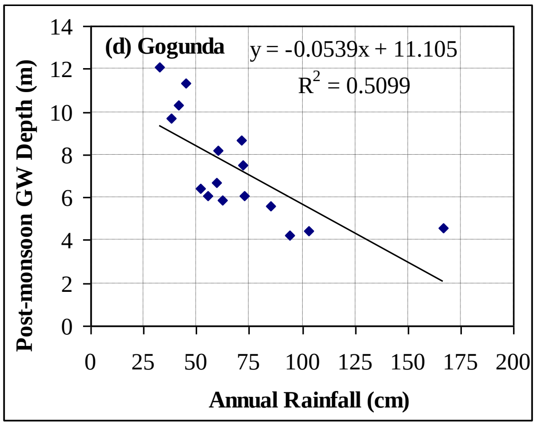

(i) Gogunda
(ii) Girwa
(iii) Mavli
(iv) Bhinder
(v) Kotra
(vi) Dhariawad
(vii) Jhadol
(viii) Kherwara
(ix) Sarada
(x) Salumber
Groundwater Level (m)
0
5
10
15
20
Annual Rainfall (cm)
180
160
140
120
100
80
60
40
20
0
1991
1994
1997
2000
2003
2006
Years
▨ Annual Rainfall
Pre-Monsoon GW Level
Post-Monsoon GW Level
0
50 km
N
Legend:
Monitoring Well
Rainfall Gauging Station

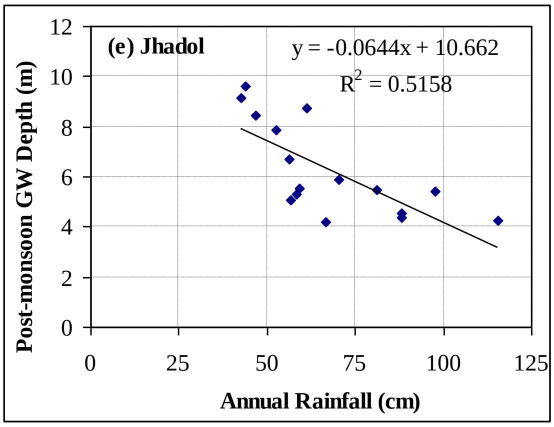
Fig

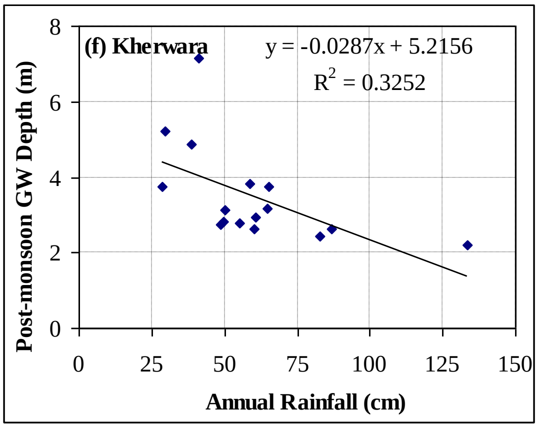

(a) Bhinder
y = -0.0946x + 16.086
R² = 0.5835
Post-monsoon GW Depth (m)
20
16
12
8
4
0
0
25
50
75
100
125
Annual Rainfall (cm)

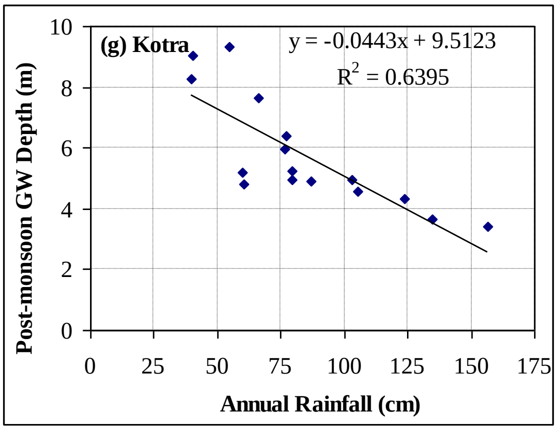

(b) Dhariawad
y = -0.0185x + 7.4096
R² = 0.2544
Post-monsoon GW Depth (m)
10
8
6
4
2
0
0
25
50
75
100
125
150
Annual Rainfall (cm)

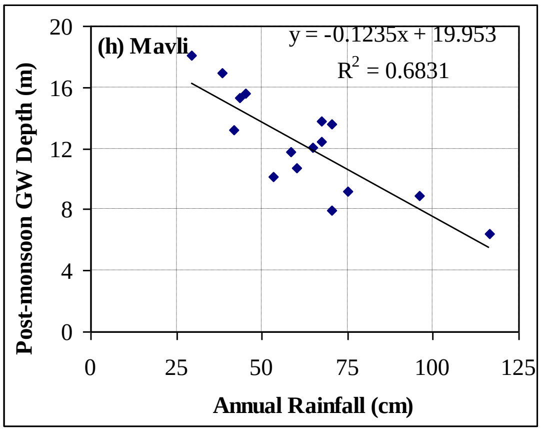

(c) Girwa
y = -0.1323x + 16.748
R² = 0.611
Post-monsoon GW Depth (m)
14
12
10
8
6
4
2
0
0
20
40
60
80
100
Annual Rainfall (cm)


(d) Gogunda
y = -0.0539x + 11.105
R² = 0.5099
Post-monsoon GW Depth (m)
14
12
10
8
6
4
2
0
0
25
50
75
100
125
150
175
200
Annual Rainfall (cm)


(e) Jhadol
y = -0.0644x + 10.662
R² = 0.5158
Post-monsoon GW Depth (m)
12
10
8
6
4
2
0
0
25
50
75
100
125
Annual Rainfall (cm)


(f) Kherwara
y = -0.0287x + 5.2156
R² = 0.3252
Post-monsoon GW Depth (m)
8
6
4
2
0
0
25
50
75
100
125
150
Annual Rainfall (cm)


(g) Kotra
y = -0.0443x + 9.5123
R² = 0.6395
Post-monsoon GW Depth (m)
10
8
6
4
2
0
0
25
50
75
100
125
150
175
Annual Rainfall (cm)


(h) Mavli
y = -0.1235x + 19.953
R² = 0.6831
Post-monsoon GW Depth (m)
20
16
12
8
4
0
0
25
50
75
100
125
Annual Rainfall (cm)

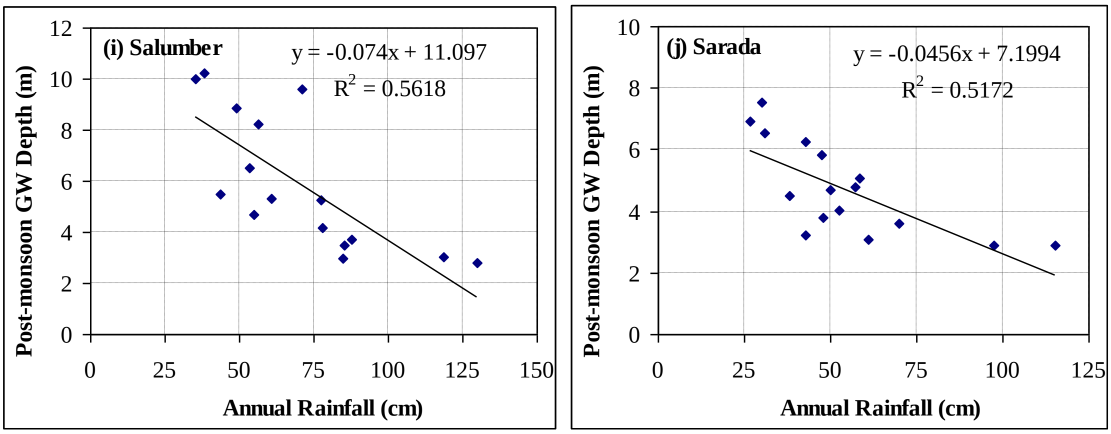

(i) Salumber
y = -0.074x + 11.097
R2 = 0.5618
Post-monsoon GW Depth (m)
12
10
8
6
4
2
0
0
25
50
75
100
125
150
Annual Rainfall (cm)
(j) Sarada
y = -0.0456x + 7.1994
R2 = 0.5172
Post-monsoon GW Depth (m)
10
8
6
4
2
0
0
25
50
75
100
125
Annual Rainfall (cm)

Fig. 6

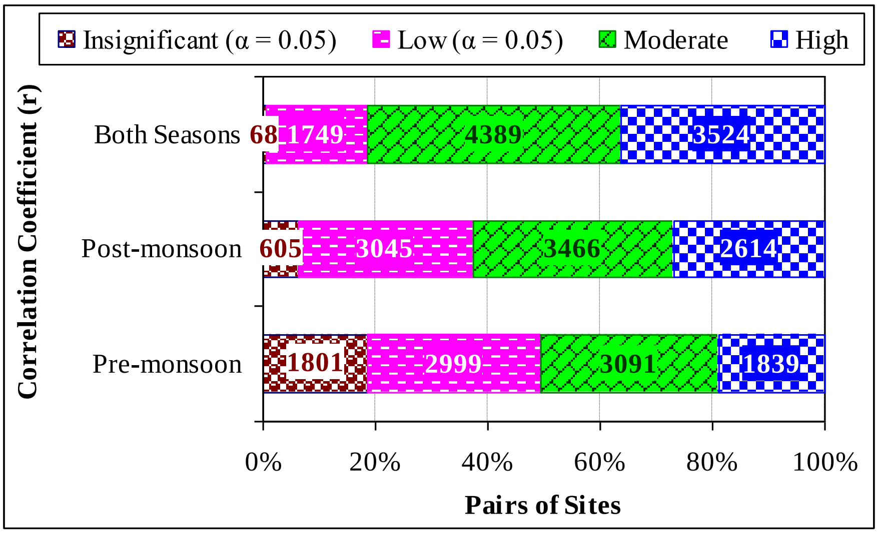

Insignificant (α = 0.05)
Low (α = 0.05)
Moderate
High
Correlation Coefficient (r)
Both Seasons
68
1749
4389
3524
Post-monsoon
605
3045
3466
2614
Pre-monsoon
1801
2999
3091
1839
0%
20%
40%
60%
80%
100%
Pairs of Sites

Fig. 7

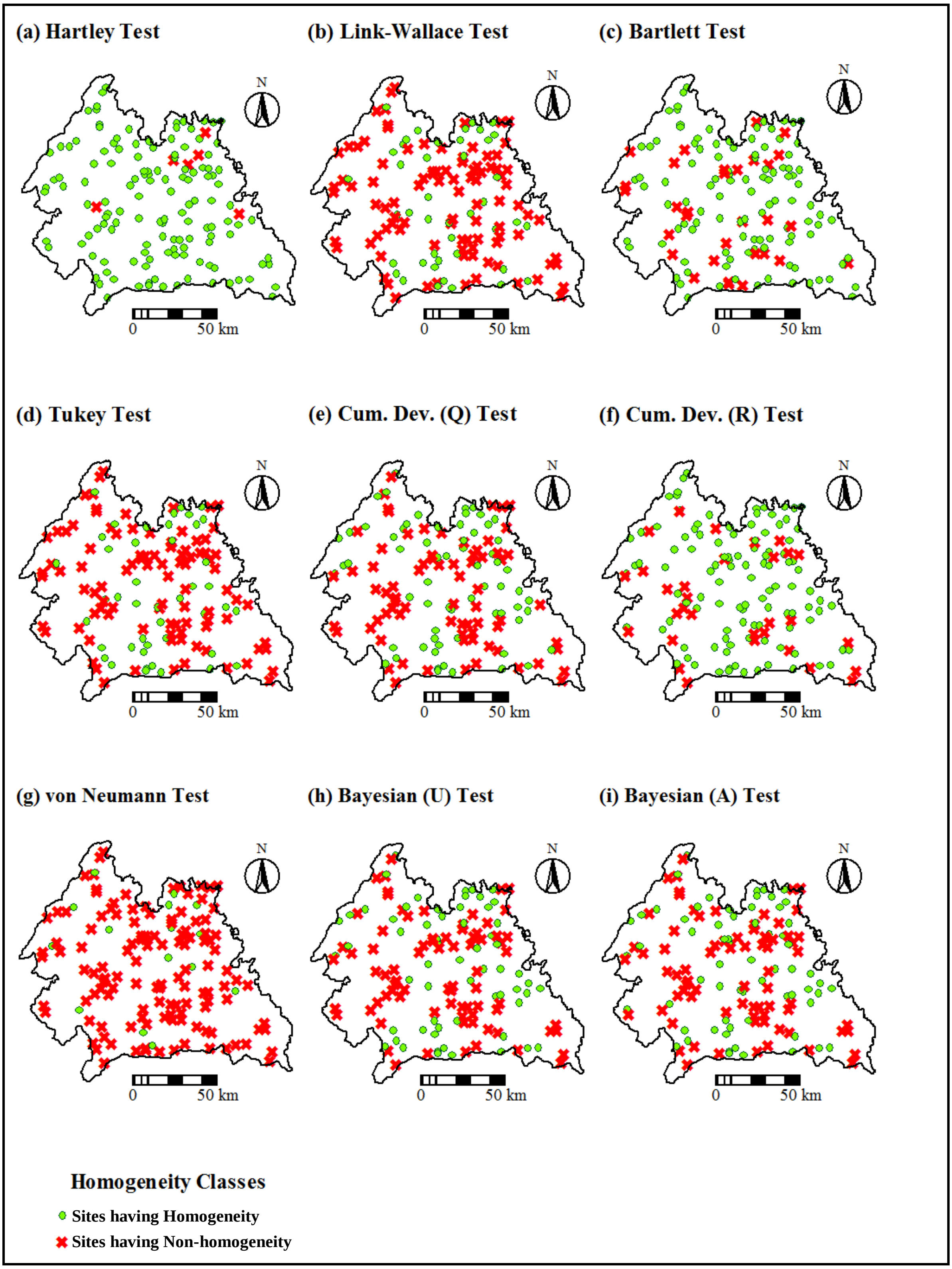

(a) Hartley Test
(b) Link-Wallace Test
(c) Bartlett Test
(d) Tukey Test
(e) Cum. Dev. (Q) Test
(f) Cum. Dev. (R) Test
(g) von Neumann Test
(h) Bayesian (U) Test
(i) Bayesian (A) Test
N
0
50 km
Homogeneity Classes
● Sites having Homogeneity
✖ Sites having Non-homogeneity

Fig. 8

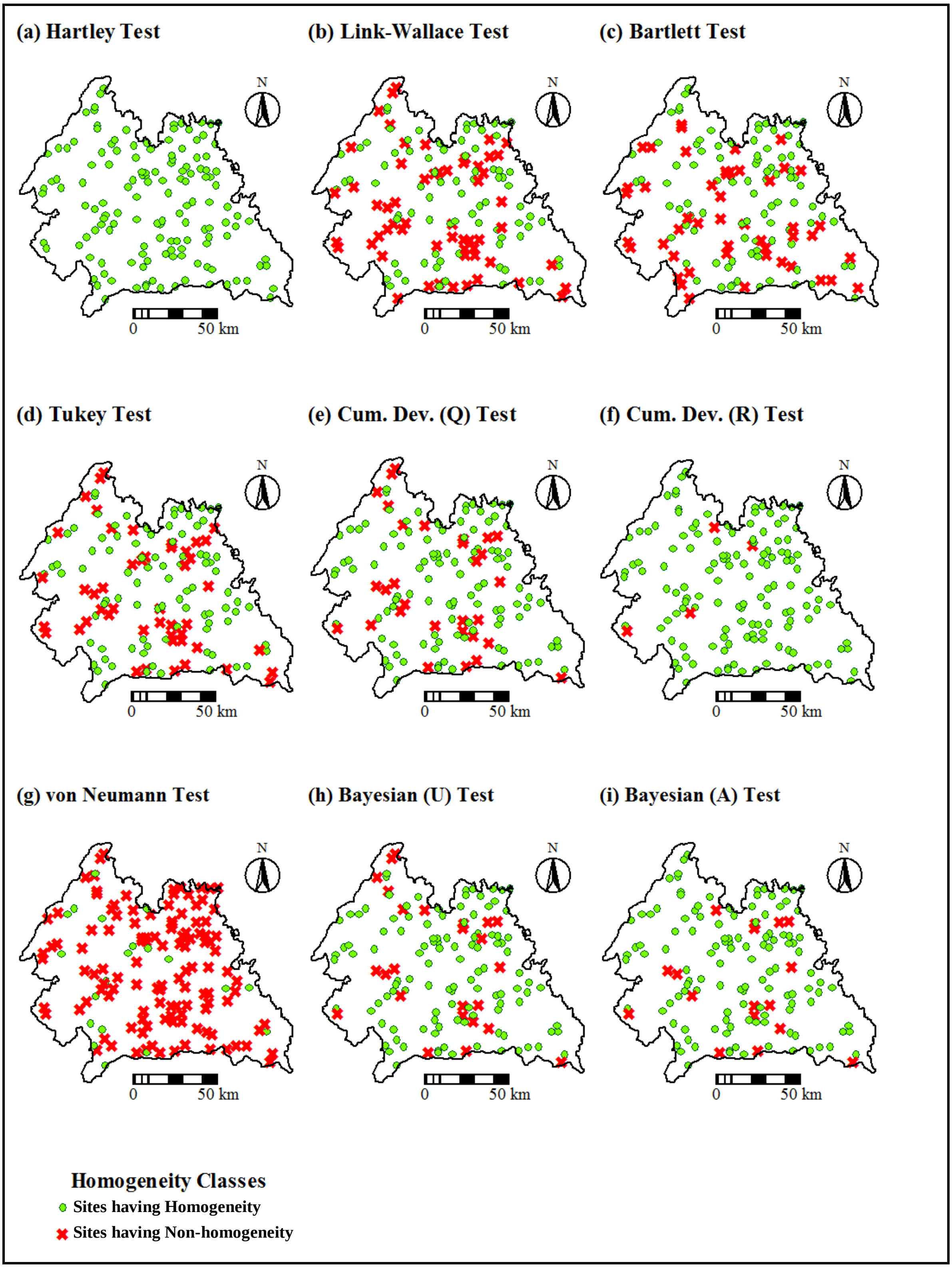

(a) Hartley Test
(b) Link-Wallace Test
(c) Bartlett Test
(d) Tukey Test
(e) Cum. Dev. (Q) Test
(f) Cum. Dev. (R) Test
(g) von Neumann Test
(h) Bayesian (U) Test
(i) Bayesian (A) Test
N
0
50 km
Homogeneity Classes
Sites having Homogeneity
Sites having Non-homogeneity

Fig. 9

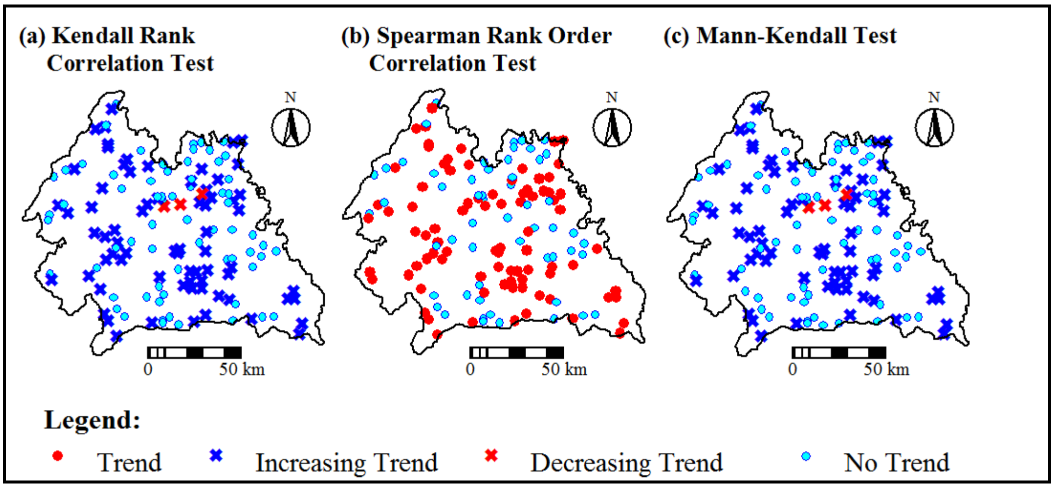

(a) Kendall Rank Correlation Test
(b) Spearman Rank Order Correlation Test
(c) Mann-Kendall Test
N
0
50 km
Legend:
● Trend
✖ Increasing Trend
✖ Decreasing Trend
● No Trend

Fig. 10

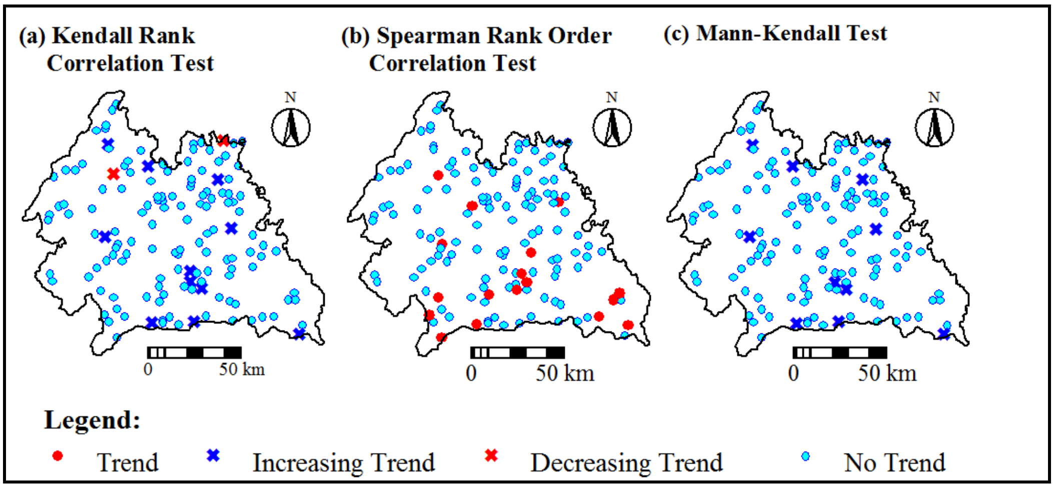

(a) Kendall Rank Correlation Test
(b) Spearman Rank Order Correlation Test
(c) Mann-Kendall Test
N
N
N
0
50 km
0
50 km
0
50 km
Legend:
● Trend
✖ Increasing Trend
✖ Decreasing Trend
● No Trend

Fig. 11

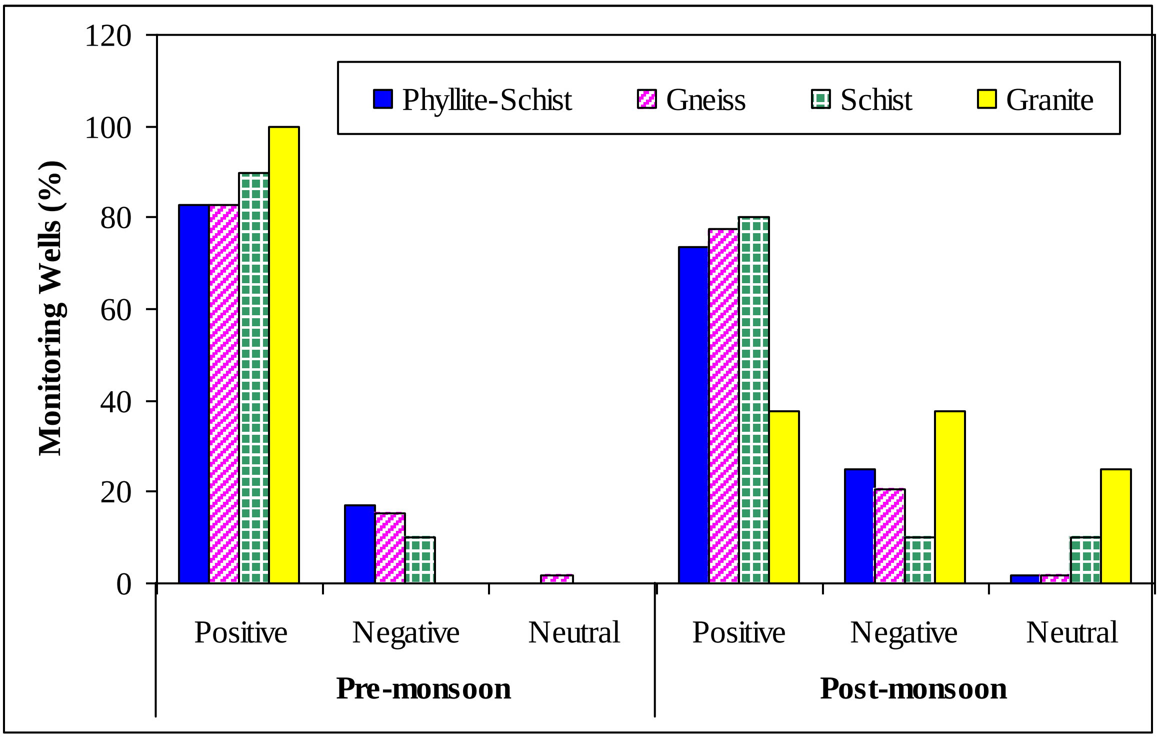

120
100
80
60
40
20
0
Monitoring Wells (%)
Phyllite-Schist
Gneiss
Schist
Granite
Positive
Negative
Neutral
Positive
Negative
Neutral
Pre-monsoon
Post-monsoon

Fig. 12

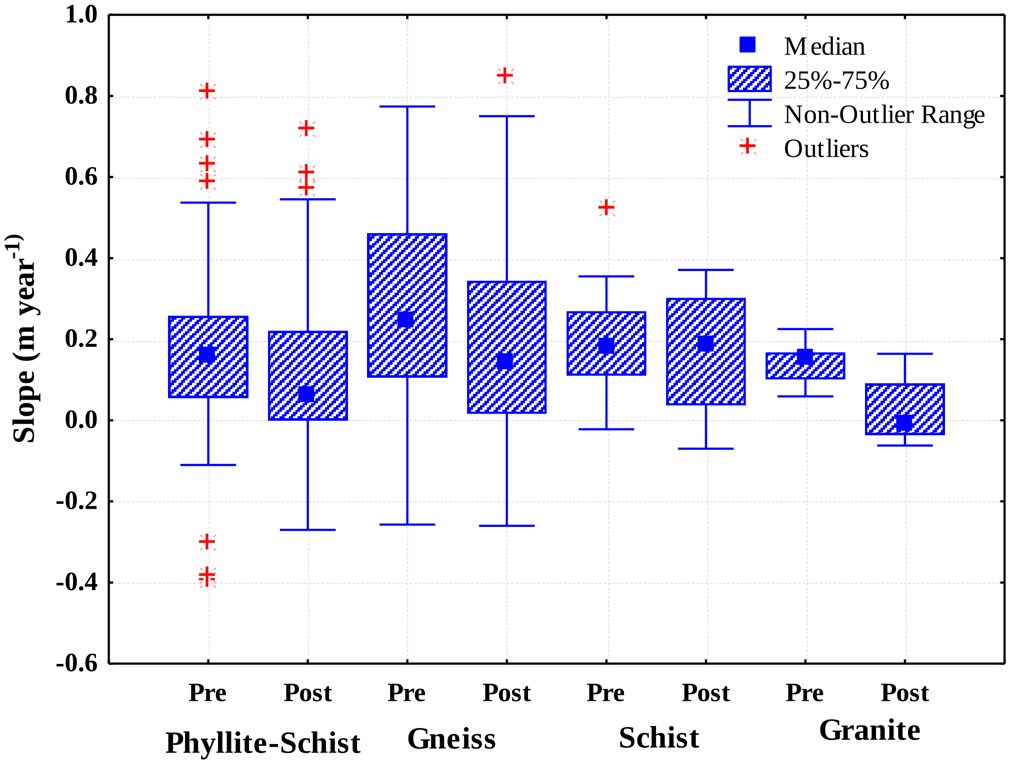

1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Slope (m year^{-1})
Median
25%-75%
Non-Outlier Range
Outliers
Pre
Post
Pre
Post
Pre
Post
Pre
Post
Phyllite-Schist
Gneiss
Schist
Granite

Fig. 13

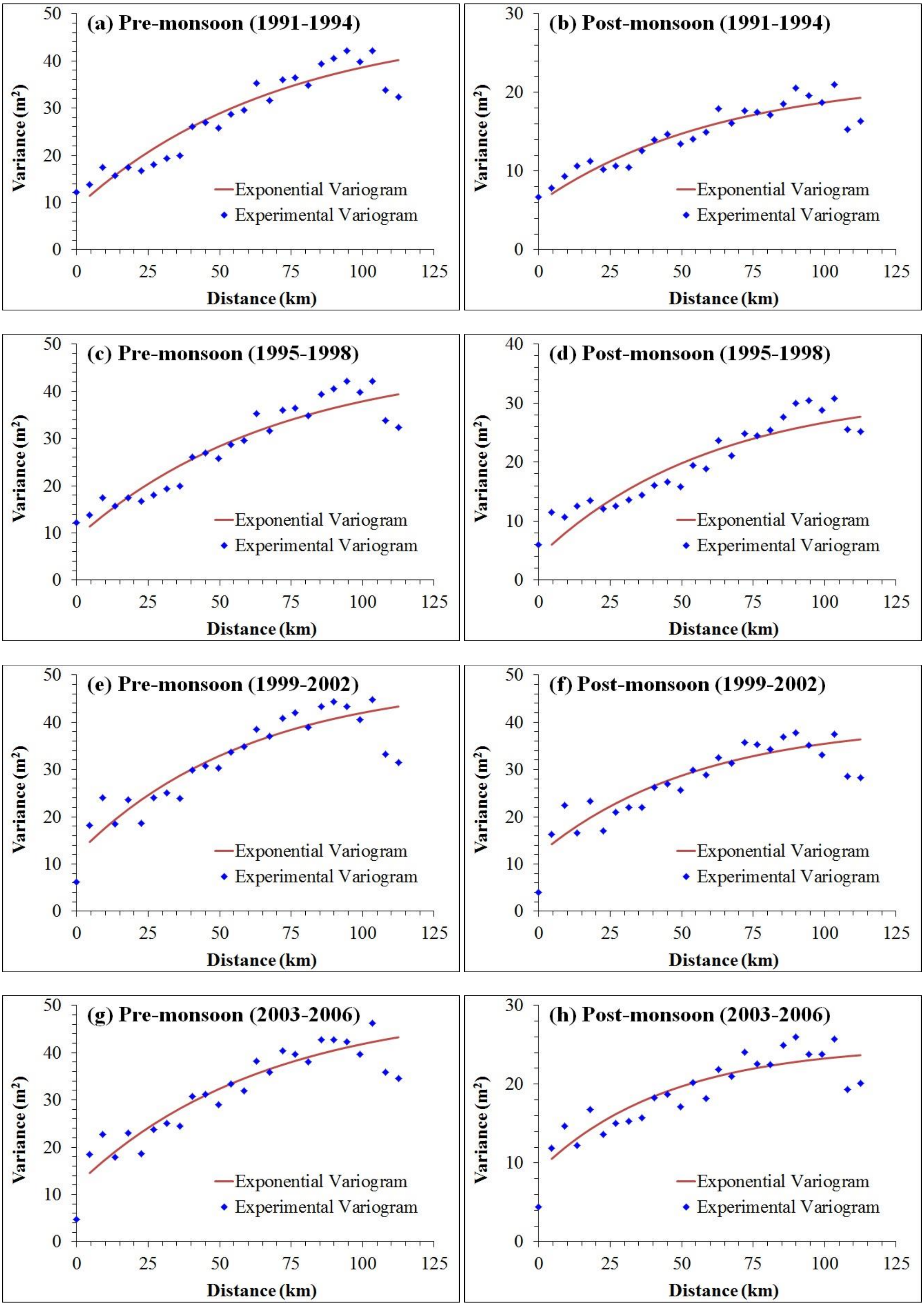

(a) Pre-monsoon (1991-1994)
(b) Post-monsoon (1991-1994)
(c) Pre-monsoon (1995-1998)
(d) Post-monsoon (1995-1998)
(e) Pre-monsoon (1999-2002)
(f) Post-monsoon (1999-2002)
(g) Pre-monsoon (2003-2006)
(h) Post-monsoon (2003-2006)
Variance (m²)
Distance (km)
Exponential Variogram
Experimental Variogram
0
10
20
30
40
50
25
75
100
125

Fig. 14

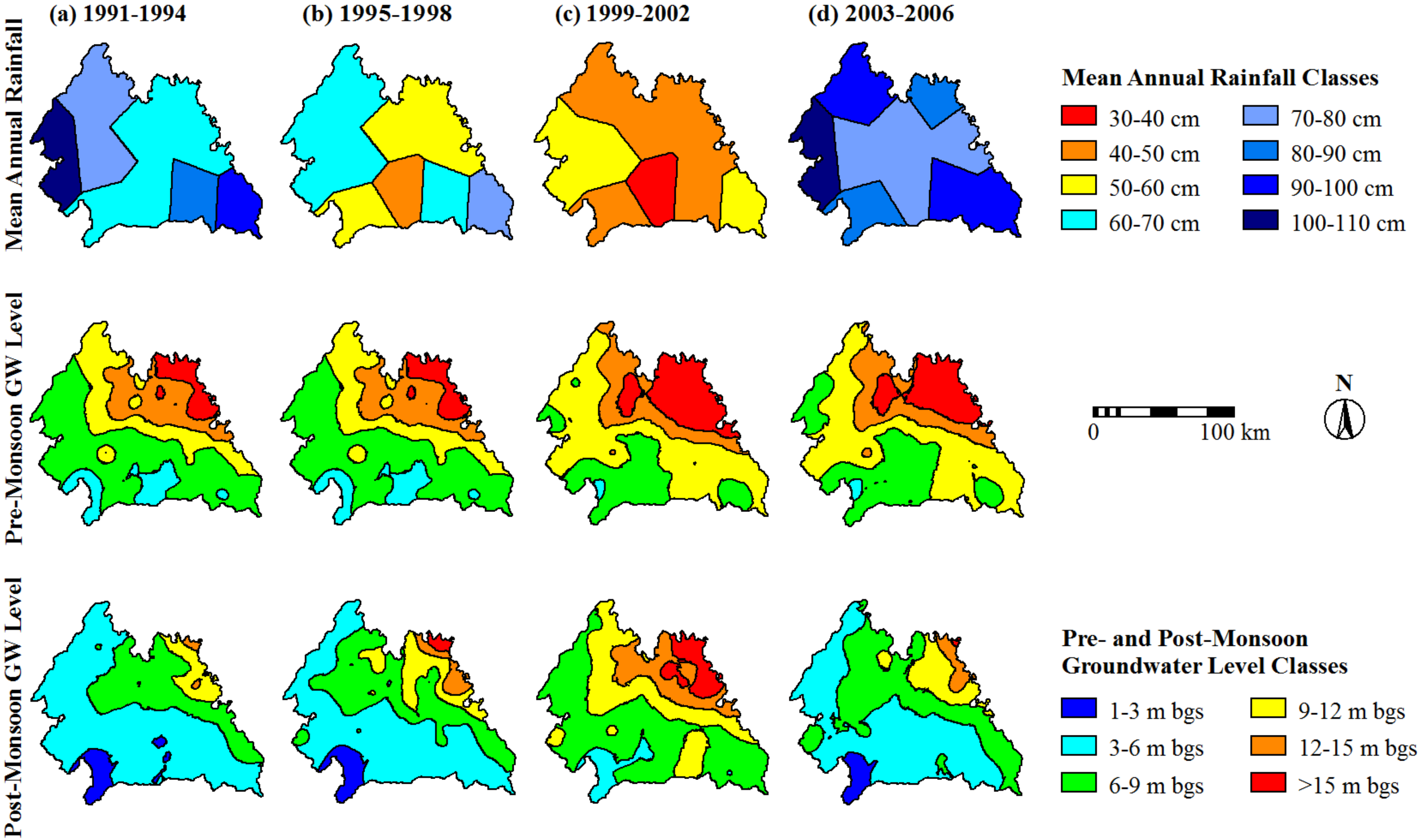

(a) 1991-1994
(b) 1995-1998
(c) 1999-2002
(d) 2003-2006
Mean Annual Rainfall
Pre-Monsoon GW Level
Post-Monsoon GW Level
Mean Annual Rainfall Classes
30-40 cm
40-50 cm
50-60 cm
60-70 cm
70-80 cm
80-90 cm
90-100 cm
100-110 cm
0
100 km
N
Pre- and Post-Monsoon Groundwater Level Classes
1-3 m bgs
3-6 m bgs
6-9 m bgs
9-12 m bgs
12-15 m bgs
>15 m bgs

Fig. 15