Heliyon 10 (2024) e24481

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Analyzing post-2000 groundwater level and rainfall changes in Rajasthan, India, using well observations and GRACE data

Md. Moniruzzaman Monir, Subaran Chandra Sarker *

Department of Geography and Environmental Science, Begum Rokeya University, Rangpur-5400, Bangladesh

ARTICLE INFO

Keywords:
Groundwater level
Rainfall
Trend
Correlation
GRACE
Rajasthan

ABSTRACT

Research on groundwater and water resources is essential for preserving viable environments. Although the arid area has been identified as a significant hotspot for groundwater depletion, the Indian desert region was not included in the initial analysis. This study intends to evaluate Rajasthan's groundwater level (GWL) and rainfall trends from 2000 to 2021 and how variations in GWLs are related to long-term rainfall. Annual GWL and rainfall data time series were collected from 921 monitoring stations for 33 districts of Rajasthan. The GWL trends and rainfall were identified using non-parametric modified Mann-Kendall test and Spearman rho techniques. Pearson's, Kendall's (tau b), and Spearman's analyses were used to determine the correlation between GWL and rainfall. The results from the modified Mann-Kendall and Spearman rho methods reveal that GWL has a significant declining trend in 38 % of districts, where 13 % have no trend, and the rest of 49 % have a rising trend. The yearly rainfall trend at 70 % and 30 % of the districts are rising and stable, respectively. A negative correlation between GWL depth and rainfall was discovered in each district, where 15 % are firm, 58 % are moderate, and 27 % are weak negative correlations. Also, the regression analysis estimates the effect of rainfall on GWL, which was observed: rainfall negatively influenced the depth of GWL at 58 % of the districts, had a positive impact at 33 %, and others had no effect. GRACE TWS anomaly shows a decreasing trend of −1.22 cm/yr, and GRACE and GWL anomalies have a positive relationship ($r = 0.471$). Results conclude that rainfall is the primary influencer on GWL in this semi-arid region vulnerable to drought.

1. Introduction

Groundwater, the primary source of fresh water, is highly vulnerable to depletion from both natural and human-made sources [1]. Extreme fluctuations in rainfall and temperature, evapotranspiration, a decline in snow packs, rising seas, and artificial aquifer exploitation all impact aquifer replenishment and outflow [2]. In arid and semi-arid parts worldwide, in contrast to geological and human influences, rainfall intensity determines changes in groundwater levels [3]. Rainfall is the primary input to the world's hydrological cycle and a vital indicator of the availability of groundwater resources [4]. Such fluctuations and changes in rainfall substantially impact the availability of water resources in aquifer systems that receive significant recharge from rainfall [5]. Around 37 % of the water utilized in homes and businesses comes from groundwater. Almost 42 % of the water used for irrigation is groundwater, while 90 % of the rural population receives drinking water from it [4]. India's high population density is increasing

* Corresponding author.
E-mail addresses: monirbrur83@gmail.com (Md.M. Monir), scsarker@brur.ac.bd (S.C. Sarker).

https://doi.org/10.1016/j.heliyon.2024.e24481
Received 11 June 2023; Received in revised form 9 January 2024; Accepted 9 January 2024
Available online 18 January 2024
2405-8440/

strain on the land and water resources. In both rural and urban regions, groundwater is the leading and preferred source of drinking water, providing 80 % of all drinking water needs and 50 % of all agricultural needs in rural India [6,7]. The thermodynamic properties of groundwater and rainfall demonstrate that rainfall is the primary source of groundwater replenishment in northwest India [8,9]. The greatest challenge is the failure to comprehend the relationship between rainfall and groundwater level. Hence, it is essential to ascertain how groundwater levels respond to rainfall.

Groundwater levels have fallen in many nations [10], and aquifers have been overused in arid and semi-arid regions because natural replenishments cannot keep up with groundwater withdrawals [11,12]. Total worldwide groundwater depletion has risen in sub-humid to dry places from 126 to 283 km^3/a from 1960 to 2000 [13]. Over 35 % of the global population (2 billion people) is projected to experience significant water stress [14], with the majority living in South Africa, the Central United States, Australia, western and southern parts of Asia, and North East China [15]. Various aquifers in India are under water stress [16]. Northwestern India's groundwater storage was drastically reduced from 2002 to 2010 by around 32 km^3 pre-monsoon and 25 km^3 post-monsoon periods [17]. The western portion of the Ganges-Brahmaputra aquifer systems also contains stressed groundwater aquifers [18]. The depletion of water storage in northern India is estimated by the *Gravity Recovery and Climate Experiment* satellite to be 19.2 ($\pm$1.1) km^3/yr [19]. In India, there is a much regional variation in groundwater depletion. Most CGWB (Central Ground Water Board) observation wells located above 23° north revealed a considerable reduction in groundwater level between 1996 and 2013 of around 15–25 cm per year [20]. In the six years from 2002 to 2008, groundwater storage in Northwest India decreased by over 109 km^3; this is more than four times larger than the largest artificial aquifers in the United States [21], with the water table dropping more than 1 m each year and exceeding 20 m [22,23]. Asoka et al. [20] found a negative trend of 2 cm/yr for groundwater anomalies in much of north India from 2002 to 2013. Meghwal et al. [24] examined Rajasthan's 4.17 km^3/y groundwater loss. One apparent measure of the impact of rainfall cycles is the long-term trend in groundwater level. It is anticipated that monsoon rainfall will rise by 10–15% in many parts of India. In contrast, precipitation will simultaneously decrease by 5–25% in drought-prone central and northern India [25]. In Rajasthan, India, the average annual rainfall has declined by 50 mm during the past 35 years (1973–2008) [26]. Even though the average rainfall in northwest India in 2010 was below the long-term average, it was insufficient to replenish the groundwater entirely [27].

Most of the researchers observed only the trend in groundwater levels over the world [13,28–33] and in different regions in India [21,29,34,35], especially in Gujarat [36], in Madhya Pradesh [37], in Tamil Nadu [38], in Jharkhand [31]. Numerous kinds of research have examined the consequences of changes in groundwater levels brought on by irrigation [39–42] in India [5,34,39]. Only a few studies have linked changes in rainfall to changes in groundwater levels globally [4,43] and in India [20,44–46]. Sing and Kumar [26] evaluated the relationship between climatic variability and groundwater. Nevertheless, the literature review reveals that no previous studies have been conducted on rainfall response to groundwater level trends in a desert area where less groundwater is extracted for anthropogenic purposes. Generally, it can be argued that little research has been done to evaluate the groundwater levels and rainfall trends in northwestern India. This present study observed short-term groundwater levels and rainfall changes in semi-desert Rajasthan in India. Also, some studies used GRACE products for water storage monitoring in western India [24,47,48]. Still, these studies never utilized the entire period due to the significant effort required for data collection and compilation. Otherwise, few researchers in Rajasthan used GRACE products along with in situ monitoring data, but they used fewer monitoring stations [24]. Together with in situ monitoring data, we used average data from several GRACE satellite data products to lower inter-product uncertainty and evaluate spatiotemporal fluctuations in TWSA and GWSA throughout the whole time (March 2002–October 2017).

Yue et al. [49] used Mann-Kendall (MK) and Spearman's rho tests to detect monotonic trends in Canada's hydrological series. However, the previous studies in this region used a single method to observe the trend in groundwater level or rainfall, either its Mann-Kendall test [30,35,37,38,45] or Spearman's rho test [50]. The present study first used the modified MK test and Spearman's rho test to detect the trend in the groundwater level and annual rainfall. The previous research on the relationship between groundwater level and rainfall used automated time-series approaches worldwide [51–53]. Nevertheless, the present study used several methods to observe the correlation between groundwater level and rainfall in Rajasthan, India. Applying different statistical approaches to detecting trends and understanding the responses of environmental variables is crucial [54]. Therefore, a thorough understanding of groundwater level trends with regard to rainfall variability and changes in terrestrial and groundwater storage is helpful in managing groundwater sustainably in semi-arid and arid locations. But the previous studies did not evaluate the GWL trend with rainfall variability and terrestrial and surface water changes variability. The present study attempts to fulfil this research gap. The novelty of this present work is that this study used a modified MK test with other non-parametric tests and innovative trend analysis to detect the GWL and rainfall trend using a large number of monitoring stations, used multiple models to evaluate the correlation between GWL and rainfall, and used the full period of GRACE products from several sources to assess spatial variation in water storage. The Generalized Three Concerned Hat (GTCH) technique was employed in this work to quantify the uncertainty related to various GRACE-derived TWSA datasets.

The objectives of this present study are: (a) to evaluate groundwater level and rainfall trends in Rajasthan from 2000 to 2021 by the modified MK test and Spearman rho approaches, (b) to determine the correlation between groundwater level and rainfall by Pearson's, Kendall's (tau b), and Spearman's methods, and (c) to assess the water storage anomalies using GTCH model. In this study, the Inverse distance weighting (IDW) interpolation was used to depict the spatial distribution of trend, TWS anomalies, and correlation between GWL and rainfall.

2. Sources of data and methods

2.1. Geological and hydrogeological summary of the area of study

The state of Rajasthan, which is the second-largest in India, is located at its southernmost point along the Tropic of Cancer, which runs between 23°30′ and 30°12′ N latitude and 69°30′ and 78°17′ E longitude (Fig. 1). With an average annual precipitation of 480.78 mm, the region has a predominantly arid and semi-arid continental climate. Monthly temperature fluctuations range from 23.0 to 30.8 °C [55]. Most of this region is covered by bare soils and deserts (Fig. 1), and nearly 58% of this area is occupied by the Thar Desert [26]. The Thar Desert and the Aravalli Range almost entirely cross the state from southwest to northeast, their two most notable geographical characteristics. The area's water balance exhibits a meager recharging rate throughout the rainy season. The region's soil contains a very high percentage of copper and fluoride, a total annual net recharge coefficient of just 0.04 %, high salinity, and high hardness [56]. The region is typified by an aquifer composed of hard rock beneath alluvium. There are areas of hydraulic continuity in both aquifer types. The Baswa-Bandikui watershed in the northwest Indian state of Rajasthan has "overexploited" its groundwater supplies, resulting in a steadily declining groundwater level [57].

This state includes 33 districts, i.e. *Ajmer, Alwar, Banswara, Baran, Barmer, Bharatpur, Bhilwara, Bikaner, Bundi, Chittaurgarh, Churu, Dausa, Dhaulpur, Dungarpur, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalor, Jhalawar, Jhunjhunun, Jodhpur, Karauli, Kota, Nagaur, Pali, Pratapgarh, Rajsamand, Sawai Madhopur, Sikar, Sirohi, Tonk,* and *Udaipur*.

Rajasthan's principal rivers include the Loni (which rises in the Nag Hills near Ajmer), the Ghagar (originates in Haryana), the

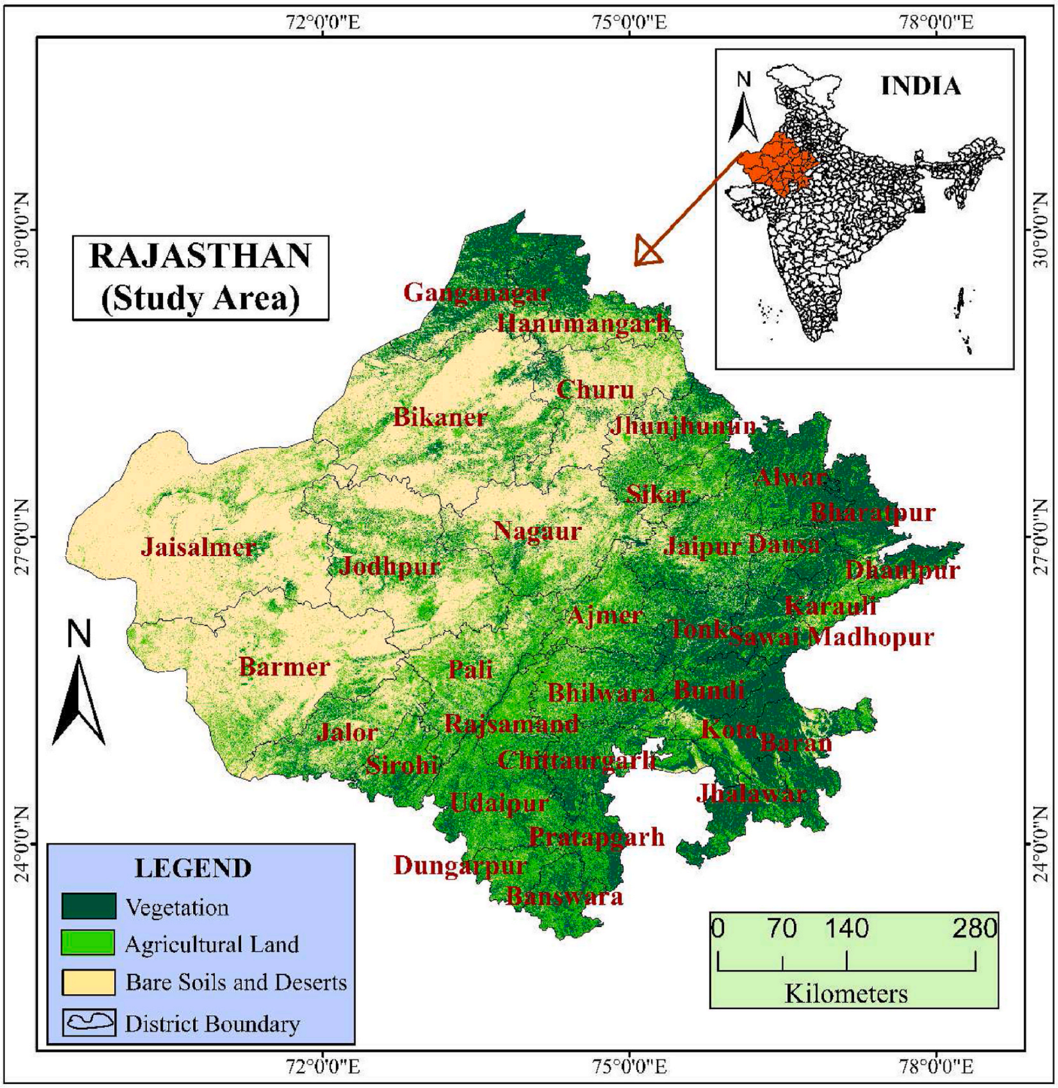

Fig. 1. Location and land cover of the study area.

Chambal, and its tributaries, including the Kali Sindh, Banas, and Parwati. The other rivers in the state are the Mahi and the Banganga.

2.2. Data sources

Annual time series (2000–2021) of groundwater level and rainfall data collected from the *National Water Informatics Centre (NWIC), Ministry of Water Resources, River Development & Ganga Rejuvenation, India*. This data was observed at a total of 921 monitoring stations. 28 stations located in Ajmer, 30 in Alwar, 34 in Banswara, 19 in Baran, 39 in Barmer, 29 in Bharatpur, 36 in Bhilwara, 41 in Bikaner, 12 in Bundi, 23 in Chittaurgarh, 24 in Churu, 16 in Dausa, 14 in Dhaulpur, 16 in Dungarpur, 39 in Ganganagar, 22 in Hanumangarh, 101 in Jaipur, 59 in Jaisalmer, 21 in Jalor, 25 in Jhalawar, 12 in Jhunjhunun, 45 in Jodhpur, 18 in Karauli, 16 in Kota, 18 in Nagaur, 24 in Pali, 27 in Pratapgarh, 9 in Rajsamand, 18 in Sawai Madhopur, 33 in Sikar, 15 in Sirohi, 20 in Tonk, and 38 in Udaipur.

Grubb's test [75] used to detect the outlier in well data. Then, outlier was removed and monitoring station-wise GWL data was compiled for each district.

3. Methods

The present study used *modified MK* and *Spearman's rho* test for GWL and rainfall trend detection. The MK test [58,59] has been frequently employed in water resources and climatic research to measure the trend in a time series of data [29]. The *Spearman partial rank correlation (SPRC)* test was devised by Helsel and Hirsch in 1992 as a trend test [60]. The Innovative Trend Analysis (ITA) was also used to assess the time series GWL data. The main advantage of the IAA over the MK test is that it doesn't depend on any assumptions about sample sizes, serial correlation, or non-linearity [62]. The correlation between GWL and rainfall was identified through *Pearson's correlation coefficient*, *Kendall's tau_b*, and *Spearman's (p)* models. The *Kendal rank correlation coefficient* assesses how similar two sets of rankings assigned to the same collection of objects are to one another, which is a valuable metric for determining the relationship between two variables [37]. To assess monotonic connections between causative variables and identify those that are highly linked with one another, *Spearman's rho* was utilized [28]. Pearson correlation coefficient techniques determine the relationship between various parameters [61]. Regression analysis, a statistical method used to investigate linear associations, was also used in this study to estimate the effect of rainfall on GWL. This present study used the GTCH approach [48] to compare several GRACE products (CSR, GFZ, JPL, CSR-M, and JPL-M) in order to assess the quality of the TWSA series. The spatial distribution of average GWL and rainfall and their trend and correlation behind them over the study area was mapped using a geostatistical *Inverse Distance Weighted (IDW)* interpolation in ArcGIS with a 1.5 × 1.5 km gridded spatial resolution. The root means square error (RMSE) is used to validate the models' performance.

3.1. Modified MK test

The non-parametric Mann-Kendall test is less sensitive to sudden pauses due to the homogeneous time series and does not need the data to be normally distributed [32,33]. *MK* trend test based on the *S* statistic [30] is given as (Eq. (1)):

$$\text{The S} = \sum_{b=1}^{n-1} \sum_{a=b+1}^{n} Sign(n_a - n_b) \tag{1}$$

The first step in the Mann-Kendall test for a time series $n_1, n_2, n_3, \ldots n_n$ of length n is to compute the indicator function Sign $(n_a - n_b)$ such that (Eq. (2)) [38]:

$$\text{Sign } (n_a - n_b) = \left\{ \begin{array}{ll} +1 & if(n_a - n_b) > 0 \\ 0 & if(n_a - n_b) = 0 \\ -1 & if(n_a - n_b) < 0 \end{array} \right\} \tag{2}$$

Next, we compute the variance of the above quantity (Eq. (3)) similarly to Patle et al. [29].

$$Var(S) = \frac{[(2n(n-1)n+5)] - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i - 5)}{18} \tag{3}$$

't', in this instance, stands for the range of any fictitious tie between sample locations. The total of all connections is shown by the $\sum t$. Consequently, the sample size exceeds 10, and the regular standard input 'Z' value is estimated by Eq. (4).

$$Z = \left\{ \begin{array}{ll} \dfrac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{array} \right\} \tag{4}$$

Eq. (5) is used to compute the modified variance [63].

$$Var\ (S)^* = \mathrm{Var}\ (\mathrm{S}) \times \frac{n}{n^*} \tag{5}$$

$\frac{n}{n^*}$ represents the modified coefficient of autocorrelated data (Eq. (6)), and r_k represents the autocorrelation coefficient of k_{th}.

The autocorrelation coefficient (Eq. (7)) of k_{th} is represented by r_k. In constant the modified coefficient of autocorrelated data is denoted by $\frac{n}{n^*}$ (Eq. (6)) [32].

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k-1}^{n-1} (n-k)(n-k-1)(n-k-2)r_k \tag{6}$$

$$r_k = \frac{\frac{1}{n-k}}{\frac{1}{n}} \times \frac{\sum_{i=1}^{n-k}(x_i - x^-)(x_i + k - x^-)}{\sum_{i=1}^{n}(x_i - x^-)^2} \tag{7}$$

According to Luo et al. [64], an upward trend is indicated by a positive value of (S*), whereas a negative value indicates a downward trend. With a 95 % confidence level, the current study's significance threshold was α = 0.05. If |S*| > 1.96, the null hypothesis of no trend is rejected at the 95 % significance level.

3.1.1. Kendall's tau_b

The *Kendall Tau-b* is more useful for assessing short-term trends in homogenous data [65]. The *Kendall Tau-b coefficient* is described as follows Eq. (8) [66]:

$$Tau\_b = \frac{n_c - n_d}{\sqrt{(n_0 - n_1) - (n_0 - n_2)}} \tag{8}$$

Here.

$n_0 = n(n-1)/2.$
$n_1 = \sum t_i(t_i - 1)/2.$
$n_2 = \sum_j^i u_j(u_j - 1)/2.$
n_c = concordant pairs present
n_d = discordant pairs present
t_i = in the ith group of ties for the initial quantity, the number of tied values
u_j = for the second quantity, the number of tied values in the j^{th} set of ties
Tau-b values vary from −1 (perfect inversion or 100 % negative association) to +1 (perfect agreement or 100 % positive association). The absence of connection is indicated by a zero-value [67].

3.1.2. Spearman's rank correlation

The degree of statistical reliance was determined using Spearman's rank, a non-parametric measure [68]. The formula for *Spearman's rank coefficient* is (Eq. (9)) [69].

$$Spearman's\ rank\ correlation\ coefficient\ (rho) = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{9}$$

d_i = variation between each observation's two rankings
n = total observations number

If there are tied values, Eq. (10) is used to detect trends [49].

$$rho_s = \frac{(n^3 - 3) - \sum_{i=1}^{n} d_i^2 - \sum T_x - \sum T_y}{\sqrt{\left[\left(\frac{n^3-3}{6}\right) - 2\sum T_x\right]\left[\left(\frac{n^3-3}{6}\right) - 2\sum T_y\right]}} \tag{10}$$

Where, $\sum T_x$ and $\sum T_y$ are calculated from Eq. (11) and Eq. (12).

$$\sum T_x = \frac{\sum_{j=1}^{g}\left(t_j^3 - t_j\right)}{12} \tag{11}$$

$$\sum T_y = \frac{\sum_{j=1}^{g}\left(t_j^3 - t_j\right)}{12} \tag{12}$$

The range of values for the *Spearman rank correlation* is +1 to −1 [50], where.

- A value of +1 indicates a perfect rank relationship
- If a value is 0, there is no correlation between rankings
- A complete negative rank correlation is represented by a value of −1.

In essence, it measures the monotonicity of the connection between two variables or the degree to which a monotonic function can adequately describe the relationship [69]—correlation between two variables also calculated by these equations (Eq. 9, Eq. (10)).

The calculated value exceeds the critical value at α = 0.05, so the trend is significant at the 95 % probability level.

3.1.3. Pearson's correlation coefficient

Pearson's Correlation Coefficient formula follows (Eq. (13)) [61].

$$\textit{Pearson's Correlation Coefficient}\ (\boldsymbol{r}) = \frac{\boldsymbol{n}(\sum \boldsymbol{ab}) - (\sum \boldsymbol{a})(\sum \boldsymbol{b})}{\sqrt{[\boldsymbol{n}\sum \boldsymbol{a}^2\ - (\sum \boldsymbol{a}^2]}\sqrt{[\boldsymbol{n}\sum \boldsymbol{b}^2\ - (\sum \boldsymbol{b}^2]}} \tag{13}$$

Here.

n = number of the pairs
$\sum ab$ = the sum of the paired stocks' products
$\sum a$ = the total a scores
$\sum b$ = the total b scores
$\sum a^2$ = the total of the a-squared scores
$\sum b^2$ = the total of the b-squared scores

r represents the strength of the connection and remains within the interval of −1.00 to 1.00. A value of 0.00 denotes no relationship, 1.00 suggests a strong positive, and −1.00 indicates a strong negative correlation [32].

3.1.4. Regression analysis

For correlation analysis across 20 years of data, regression analysis is frequently utilized [82,83], also correlation between GWL fluctuation and rainfall [46]. A straightforward linear regression equation can be expressed as (Eq. (14))

$$Z = a + bY \tag{14}$$

Here.

Z = Dependent variable
Y = Independent variable

The values of a and b are calculated from Eq. (15) and Eq. (16).

$$a = [(\sum z)\ (\sum y^2) - (\sum y)\ (\sum yz)]\ /\ [n(\sum y^2) - (\sum y)^2] \tag{15}$$

$$b = [n(\sum yz) - (\sum y)\ (\sum z)]\ /\ [n(\sum y^2) - (\sum y)^2] \tag{16}$$

Using a scale that ranges from +1 to −1 via 0, the effect is measured. As one variable rises along with the other, the impact is positive; however, when one falls as the other rises, the impact is negative. 0 describes the absence of correlation.

3.1.5. The Innovative Trend Analysis

Sen [70] suggested doing an innovative trend analysis. The processes we used are as follows:

The GWL data is divided into two time periods: (a)2000–2010 and (b) 2011–2021. The Xi (X-axis) represents the first period, while the Yi (Y-axis) represents the second. When the data is plotted along the 1:1 line, it displays a steady trend. A rising trend was seen when data was plotted above the 1:1 line, and when data was shown below the 1:1 line, a descending trend was seen. The formula underlying ITA [71] is (Eq. (17)):

$$S = \frac{1}{n}\sum_{i=1}^{n}\frac{10(\overline{y} - \overline{x})}{n} \tag{17}$$

The arithmetic average of the Yi and Xi series equals $\overline{x}$ and $\overline{y}$. n = the total findings. A positive s number indicates a rising trend, whereas a negative s value indicates a falling trend [72].

3.1.6. Generalized Three-Cornered hat method

Terrestrial water storage was calculated using Eq. (18) [27,48].

$$\Delta TWS = \Delta GWS + \Delta SMS + \Delta SWE + \Delta QS + \Delta CWS \tag{18}$$

Where, Δ represent the changes. The available time series of the TWSA products were considered, and it was assumed that each time series could be expressed by Eq. (19) to calculate the relative uncertainties among the GRACE-derived TWSA utilizing various GRACE products [48].

$$X_i = S + \epsilon_i \tag{19}$$

Where i corresponds to each TWSA product, S is the original signal, and ϵ_i is the measurement error in the equation $X_i = 1,2, \ldots, N$.

3.1.7. IDW interpolation

IDW is used for predicting unknown values in surrounding locations.

The equation behind the IDW is (Eq. (20)) [73].

$$w(x) = \frac{A}{B} \tag{20}$$

In Eq. (1), w = Predicted value.

Again, A and B are calculated from Eq. (21) and Eq. (22).

$$A = \sum_{i=1}^{n} \frac{1}{d(x1, x2)p} u_i \tag{21}$$

$$B = \sum_{i=1}^{n} \frac{1}{d(x1, x2)p} \tag{22}$$

Here, the distance is d; the unknown point is x, $x1$ is the n^{th} known point, the general point is u_i, and p means the power.

3.1.8. Accuracy measurement. RMSE

One of the most used error-index statistics is RMSE. It is well acknowledged that model efficiency increases with decreasing RMSE [74]. It uses Eq. (23) to get the standard deviation of the data's random components.

$$RMSE = \sqrt{\sum_{t=1}^{n} \frac{[y_t(obs) - y_t(pred)]^2}{n}} \tag{23}$$

This study used SPSS (https://www.ibm.com/products/spss-statistics) software to run the modified MK, Kendall's tau_b, Spearman's Rank Correlation, and Pearson's Correlation Coefficient analysis. Regression Analysis and The Innovative Trend Analysis conduct in Xlstat (https://www.xlstat.com) software. The RMSE was calculated by using R studio (https://www.rstudio.com/). IDW interpolation and different maps were produced using in ArcGIS platform (https://www.esri.com/en-us/arcgis).

Table 1
Rajasthan's average GWL depth and annual rainfall (2000–2021).

Districts	GWL depth (m)	Annual rainfall (mm)	Districts	GWL depth (m)	Annual rainfall (mm)
Ajmer	12.10	509.25	*Jaisalmer*	38.99	233.40
Alwar	25.82	562.65	*Jalor*	27.79	436.25
Banswara	7.43	946.75	*Jhalawar*	10.54	910.70
Baran	8.48	819.80	*Jhunjhunun*	48.93	474.90
Barmer	34.57	284.05	*Jodhpur*	34.25	353.25
Bharatpur	11.74	590.55	*Karauli*	16.21	672.20
Bhilwara	12.49	663.55	*Kota*	9.58	807.70
Bikaner	46.17	280.20	*Nagaur*	37.25	424.20
Bundi	9.36	720.60	*Pali*	13.33	535.85
Chittaurgarh	13.76	798.75	*Pratapgarh*	8.69	918.50
Churu	36.55	405.50	*Rajsamand*	12.35	617.10
Dausa	26.53	630.50	*Sawai Madhopur*	13.06	726.70
Dhaulpur	13.40	628.95	*Sikar*	41.66	514.35
Dungarpur	8.76	720.10	*Sirohi*	16.19	755.25
Ganganagar	14.20	241.40	*Tonk*	10.17	605.65
Hanumangarh	18.15	306.10	*Udaipur*	9.37	709.60
Jaipur	29.46	563.10			

4. Results

4.1. Spatial distribution of average groundwater level and annual rainfall

The average GWL depth and yearly rainfall throughout all districts from 2000 to 2021 show the average minimum groundwater level depth (8.69 m) and maximum annual rain (918.5 mm) found in Pratapgarh. On the contrary, the top maximum groundwater level (48.93 m) was found in Jhunjhunun, and the minimum rainfall (233.4 mm) was found in Jaisalmer (Table 1).

From Table 1, the average GWL depth of 18 (55 %) districts is less than 15 m, 3 (9 %) districts have 16–25 m, and 5 (15 %) districts have 26 to 35. The rest of the 7 (21 %) districts have more than 36 m. On the other hand, 5 (15 %) of districts found average annual rainfall above 800 m, 12 (37 %) districts had 601–800 mm, and 10 (30 %) districts had 401–600 mm. The remaining 6 (18 %) districts have less than 400 mm.

The spatial variation of average GWL depth and annual rainfall (2000–2021) is mapped in Fig. 2. Fig. 2a shows comparatively lower GWL depth was found in the southern portion of the study region (Fig. 2a), which area has more vegetation cover (Fig. 1).

Similarly, the average rainfall in this region decreased from the southern to the northern part (Fig. 2b). The southern part of Rajasthan has less GWL depth and more annual rainfall (Fig. 2a, b).

4.2. GWL trend and its spatial distribution

Fig. 3 shows that the northeastern part of the study area has a rapidly declining trend in GWL. Fig. 3A represents the GWL trend using the modified MK test and Fig. 3B uses the Spearman method. The western part has a moderate declining rate. In the middle portion of the study area, a very slow-rising trend in GWL was found. The remaining southern and northern part has a moderate to rapidly rising trend in GWL (Fig. 3). The values of the modified *MK* and *Spearman trend test* for GWL are presented in Table 2.

Modified *Mk* and *Spearman* trend tests provide similar results for GWL trends in this study area (Table 2). A declining groundwater level trend was found in 38 % of districts (S = 1+, and rho = 0.25+). A stable trend was observed in 13 % of districts (S = −1 to 1, and rho = −0.25 to 0.25). The remaining 49 % of districts provide a rising trend in groundwater level (S = less than −1, and rho = less than −0.25).

Innovative trend slope in GWL: The district-wise innovative trend in yearly GWL is depicted in Fig. 4. According to the yearly GWL innovation trend slopes, 12 (36.36 %) of the total districts have a rising trend in GWL depth, these are: Alwar, Bharatpur, Churu, Dausa, Dhaulpur, Jaipur, Jaisalmer, Jalor, Jhunjhunun, Karauli, Nagaur, and Sikar (Fig. 4 B, F, K, L, M, Q, R, S, U, W, Y, AD). 15 (45.45 %) of the total districts have a falling trend, these are Ajmer, Banswara, Baran, Bhilwara, Bundi, Chittaurgarh, Dungarpur, Ganganagar, Jhalawar, Kota, Pali, Rajsamand, Sawai Madhopur, Tonk, and Udaipur (Fig. 4 A, C, D, G, I, J, N, O, T, X, Z, AB, AC, AF, AG). The rest of the 6 (18.19 %) district has no significant trend in GWL depth, these are Barmer, Bikaner, Hanumangarh, Jodhpur, Pratapgarh, and Sirohi (Fig. 4 E, H, P, V, AA, AE).

4.3. Rainfall trend and its spatial distribution

Almost all of the study area has a rising trend in average annual rainfall (Fig. 5). According to the modified *Mk* trend test, the middle

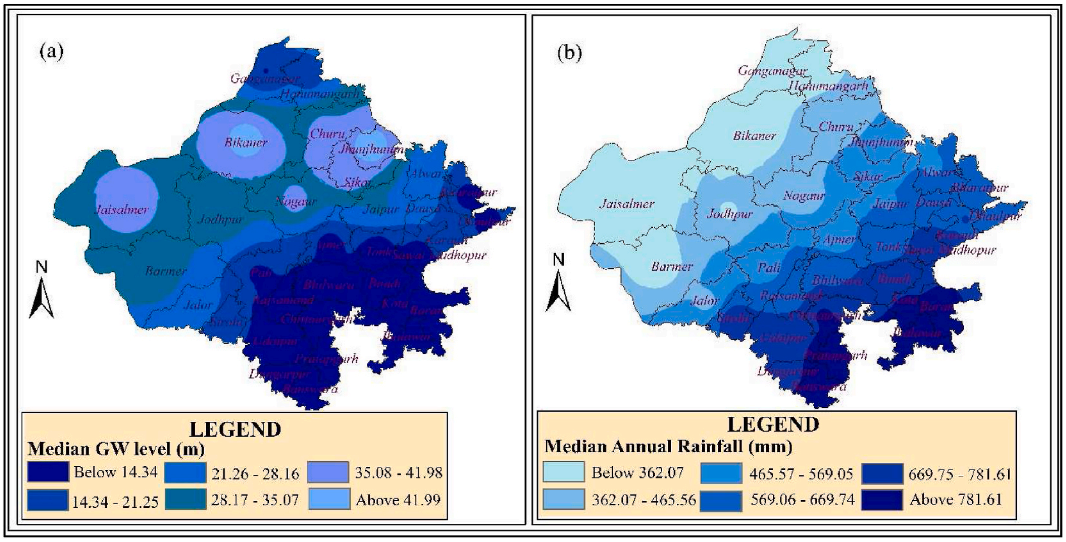

Fig. 2. Spatial distribution of average GWL depth and annual rainfall (2000–2021) in Rajasthan. (a) Median of GWL (mm), (b) Median of annual rainfall (mm).

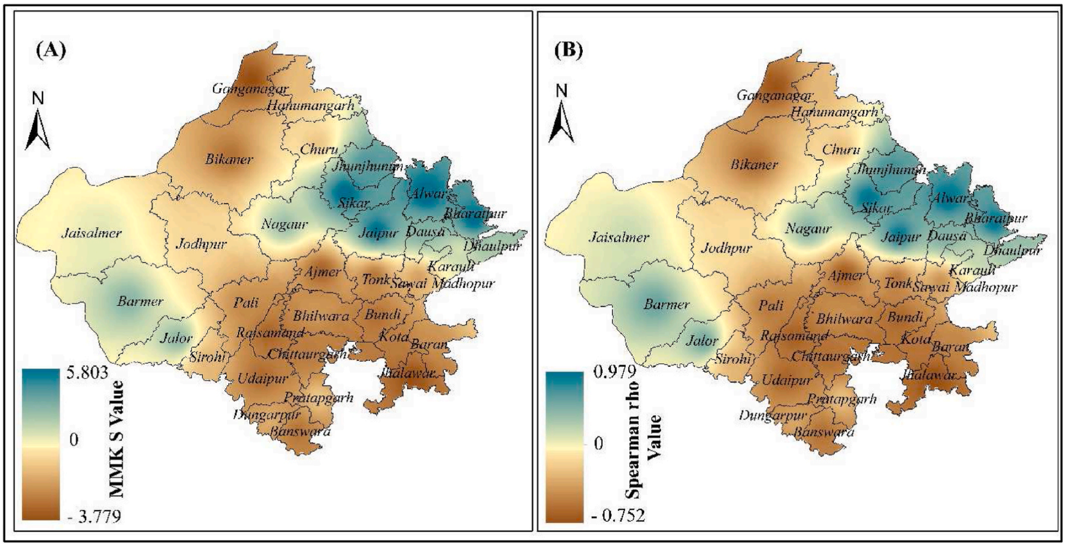

Fig. 3. Spatial distribution of GWL trend (2000–2021) in Rajasthan. (A) GWL trend using modified MK, (B) GWL trend using Spearman method.

Table 2
District-wise trend in GWL and annual rainfall and the correlation between GWL depth and rainfall.

Districts	GWL trend		Rainfall trend		Correlation		
	S	rho	S	rho	r	tau_b	p
Ajmer	−3.22	−0.669	1.69	0.436	−0.49	−0.3	−0.386
Alwar	5.81	0.980	−0.56	−0.105	−0.116	−0.091	−0.129
Banswara	−2.71	−0.558	1.35	0.293	−0.414	−0.335	−0.472
Baran	−1.98	−0.461	1.47	0.375	−0.312	−0.248	−0.321
Barmer	2.99	0.669	0.51	0.140	−0.388	−0.248	−0.337
Bharatpur	5.48	0.940	0.27	0.035	−0.036	−0.013	−0.016
Bhilwara	−1.81	−0.418	1.35	0.297	−0.647	−0.378	−0.511
Bikaner	−2.77	−0.597	1.47	0.342	−0.059	−0.048	−0.077
Bundi	−2.82	−0.627	1.52	0.33	−0.392	−0.23	−0.335
Chittaurgarh	−2.54	−0.574	1.47	0.295	−0.576	−0.3	−0.423
Churu	−0.62	−0.188	1.69	0.409	−0.415	−0.117	−0.171
Dausa	3.16	0.600	0.17	0.073	−0.135	−0.109	−0.15
Dhaulpur	2.37	0.467	0.06	0.045	−0.031	−0.204	−0.206
Dungarpur	−1.24	−0.302	1.53	0.352	−0.471	−0.361	−0.522
Ganganagar	−3.78	−0.717	1.07	0.2	−0.448	−0.309	−0.408
Hanumangarh	−0.9	−0.211	0.79	0.176	−0.367	−0.03	−0.084
Jaipur	5.31	0.941	1.13	0.29	−0.347	−0.204	−0.318
Jaisalmer	1.36	0.306	1.1	0.276	−0.491	−0.322	−0.426
Jalor	2.94	0.628	0.45	0.137	−0.209	−0.109	−0.158
Jhalawar	−3.73	−0.752	1.13	0.289	−0.519	−0.378	−0.545
Jhunjhunun	4.06	0.784	1.1	0.242	−0.215	−0.052	−0.123
Jodhpur	−0.17	−0.032	2.26	0.53	−0.264	−0.196	−0.313
Karauli	1.58	0.332	0.9	0.21	−0.261	−0.187	−0.258
Kota	−2.54	−0.547	0.85	0.2	−0.156	−0.1	−0.124
Nagaur	2.65	0.552	2.03	0.487	−0.46	−0.37	−0.534
Pali	−2.2	−0.522	1.58	0.417	−0.304	−0.17	−0.234
Pratapgarh	−0.56	−0.17	2.93	0.61	−0.463	−0.257	−0.321
Rajsamand	−3.16	−0.66	1.86	0.436	−0.756	−0.596	−0.745
Sawai Madhopur	−1.58	−0.398	1.47	0.317	−0.122	−0.048	−0.059
Sikar	5.53	0.9564	1.92	0.48	−0.401	−0.257	−0.38
Sirohi	−1.02	−0.241	0.68	0.188	−0.478	−0.283	−0.373
Tonk	−2.6	−0.545	2.43	0.51	−0.455	−0.335	−0.441
Udaipur	−2.99	−0.633	1.86	0.43	−0.645	−0.448	−0.612
RMSE	0.079	0.091	0.101	0.098	0.081	0.089	0.076

to the southern part of the study area has a moderate to rapidly rising trend for rainfall (Fig. 5A). Overall, some areas of eastern and the western part of the study area has a stable to very prolonged rising trend (Fig. 5A and B). The value of the modified *Mk* and *Spearman trend test* for rainfall are presented in Table 2.

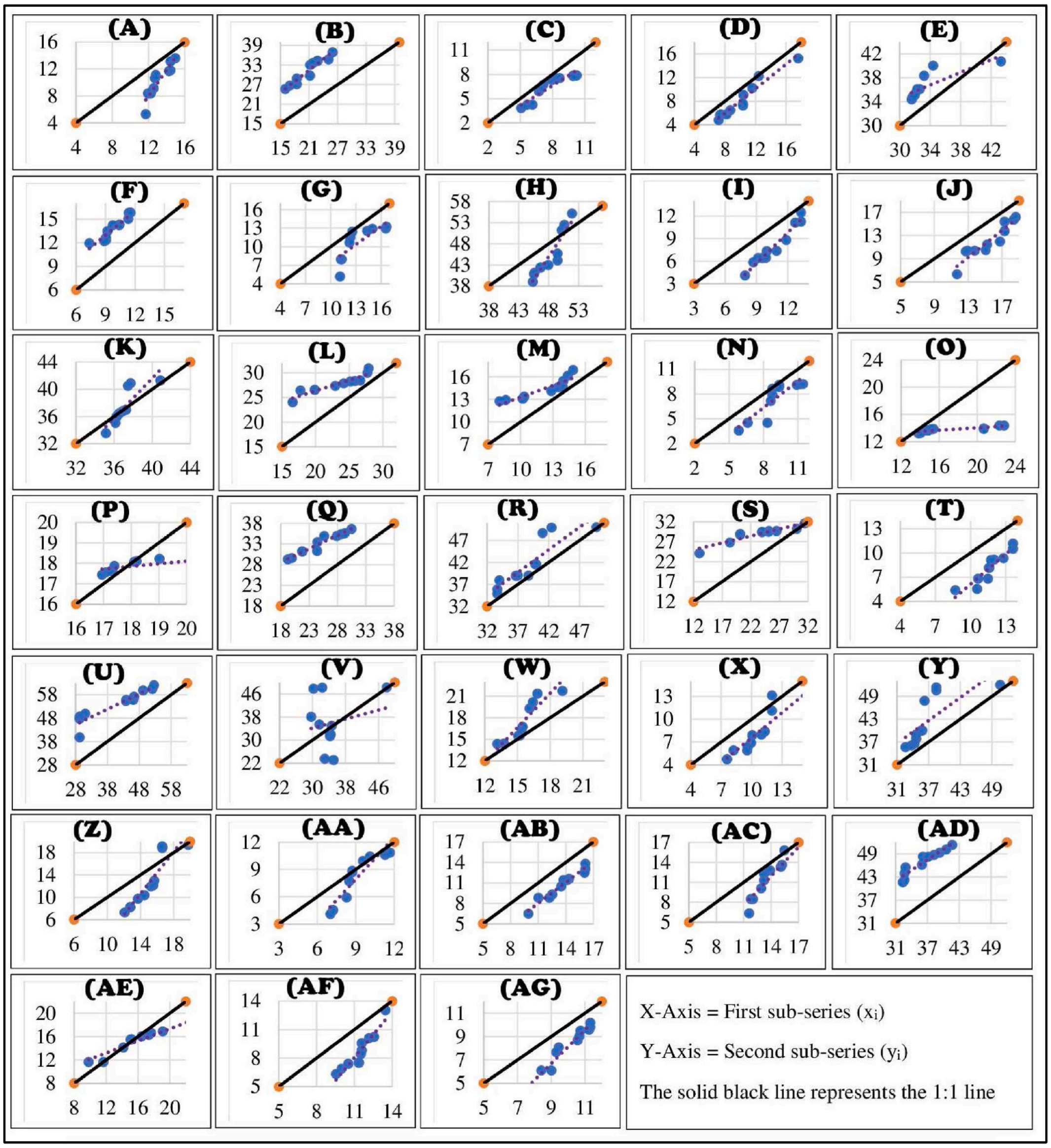

Fig. 4. The innovative trends in GWL depth for different districts in Rajasthan: (A) Ajmer; (B) Alwar; (C) Banswara; (D) Baran; (E) Barmer; (F) Bharatpur; (G) Bhilwara; (H) Bikaner; (I) Bundi; (J) Chittaurgarh; (K) Churu; (L) Dausa; (M) Dhaulpur; (N) Dungarpur; (O) Ganganagar; (P) Hanumangarh; (Q) Jaipur; (R) Jaisalmer; (S) Jalor; (T) Jhalawar; (U) Jhunjhunun; (V) Jodhpur; (W) Karauli; (X) Kota; (Y) Nagaur; (Z) Pali; (AA) Pratapgarh; (AB) Rajsamand; (AC) Sawai Madhopur; (AD) Sikar; (AE) Sirohi; (AF) Tonk; and (AG) Udaipur.

From the results of the modified Mk and Spearman trend test, 70 % of districts have a rising trend (S = 1+, and rho = 0.25+) in annual rainfall. The remaining 30 % of districts have a stable nature (S = −1 to 1, and rho = −0.25 to 0.25) in rainfall trend. Other hand 12 % of districts have a rapidly rising trend in annual rainfall (S = 2+) (Table 2).

4.4. Correlation between GWL depth and rainfall

There was a negative correlation between GWL depth and rainfall all over the study area. The depth of GWL decreases due to the rising amount of rainfall. A noticeable difference is present in the types of negative correlation. According to *Pearson's* correlation method, except eastern part, all area has a moderate negative correlation (Fig. 6A). Very weak negative correlation was found in maximum areas from the *Kendall tau_b* value (Fig. 6B). *Spearman's p*-value provides similar results to *Pearson's* (Fig. 6C). The value of *Kendall tau_b*, *Pearson's r*, and *Spearman's p* for historical correlation between groundwater level and rainfall are presented in Table 2.

15 % of districts have a strong negative correlation, where 58 % are moderate, and the remaining 27 % have a weak negative correlation between GWL depth and amount of rainfall (Table 2).

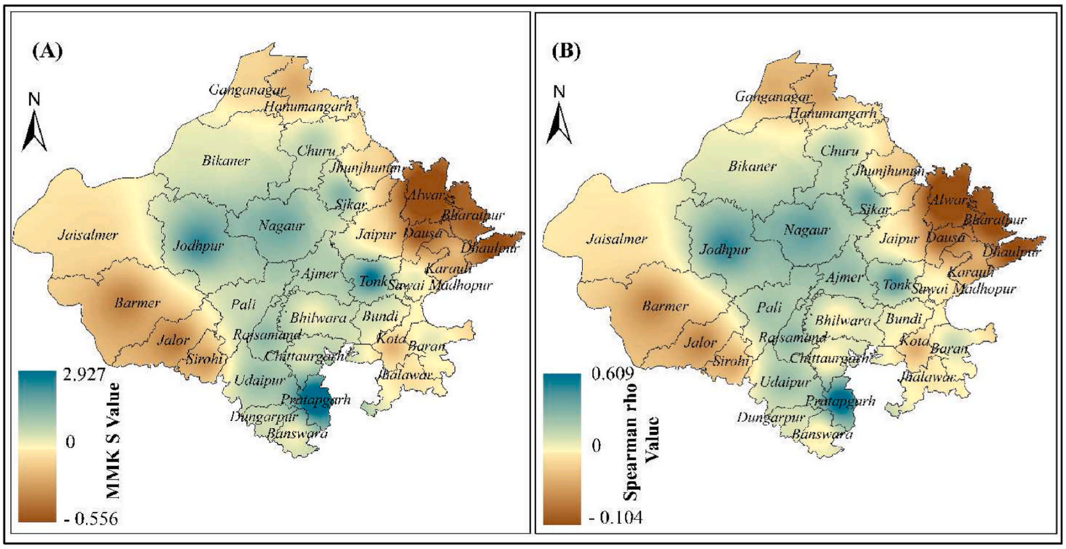

Fig. 5. Spatial distribution of rainfall trend (2000–2021) in Rajasthan. (A) Rainfall trend using modified MK, (B) Rainfall trend using Spearman method.

Regression analysis observed a positive impact of rainfall on GWL depth in only 11 (33 %) districts; these are Barmer, Churu, Dausa, Jaipur, Jaisalmer, Jalor, Jhunjhunun, Jodhpur, Karauli, Nagaur, and Sikar (Fig. 7 E, K, L, Q-S, U–W, Y, AD).

The negative impact was found in 19 (58 %) districts; these are Ajmer, Alwar, Banswara, Baran, Bhilwara, Bundi, Chittaurgarh, Dungarpur, Ganganagar, Hanumangarh, Jhalawar, Kota, Pali, Pratapgarh, Rajsamand, Sawai Madhopur, Sirohi, Tonk, and Udaipur (Fig. 7 A-D, G, I, J, N–P, T, X, Z, AA-AC, AE-AG). The rest 3 (9 %) districts: Bharatpur, Bikaner, and Dhaulpur, have no significant effect of rainfall on GWL depth (Fig. 7 F, H, M).

4.5. Terrestrial and groundwater storage changes

From March 2002 to October 2017, the GRACE-Terrestrial Water Storage (TWS) anomaly decreased by 1.22 cm/year (Fig. 8A). While certain locations in the south-eastern and south-western regions of Rajasthan have extremely minor positive anomalies, the eastern section of the state has a strong negative anomaly in TWS.

To investigate groundwater storage (GWS) variability in GRACE and in-situ wells, this work additionally assesses the association between GRACE GWS anomaly and standardized well anomaly (Fig. 8B). There is a positive correlation between GRACE and well groundwater anomalies ($r = 0.471$).

5. Discussion

In this study, the southeastern area of Rajasthan has a good GWL with more vegetation cover and healthy rainfall. On the other hand, the western part of the study area has deeper GWL with bare soils and desert areas and less annual rainfall. Also, GRACE-based TWS represents more negative anomalies in the northeastern part of the study area. It is understood that the northeastern portion of the study area has recently become severely affected, while the western section has historically been a severe GWL depletion area. Previous studies also found a significant correlation between GWL depth and vegetation in semi-arid [35] and arid regions [76], similar to Rajasthan. For some plant species, groundwater is a significant supply of water in many parts of the world [36]. The average GWL (2000–2021) was found in this study area from 8.69 m to 48.93 m from the surface (Table 1), which was almost close to Lapworth et al. [77], who observed shallow groundwater tables in 8–50 m depths in Norwest India.

This study observed that GWLs trend upward in 49 % of districts but downward in 38 % of stations (Table 2). However, Panda et al. [78] discovered contrasting outcomes in India's drought-prone western Gujrat region, where most monitoring wells (58 %) show a downward trend. Also, in Jharkhand, India, the groundwater level declined by 2–10 m from 1990 to 2008 [44]. In that research, the groundwater level in this area was detected ten years ago. Meghwal et al. [24] recently examined Rajasthan's 4.17 km^3/y groundwater loss. Similarly, this present study found a declining GWL trend in the semi-arid areas of Rajasthan (Fig. 3). The current study discovered that the yearly rainfall in the studied area is increasing at 70 % of districts (Table 2; Fig. 5). But at the end of the twentieth century (1973–2008), the average annual rainfall decreased by 50 mm in this area [26]. In contrast, Dey et al. [45] also found a decline in annual rainfall of 42 mm from 2003 to 2014 in Uttar Pradesh, near Rajasthan. The outcome indicates that Rajasthan has experienced an increase in yearly rainfall during the past 20 years. As a result, groundwater levels tend to be on the rise.

This study observed a negative correlation between GWL depth and rainfall for all districts (Table 2). However, according to the regression analysis, rainfall harmed GWL at 67 % of the districts and positively impacted 33 % (Fig. 6). This finding means that rainfall

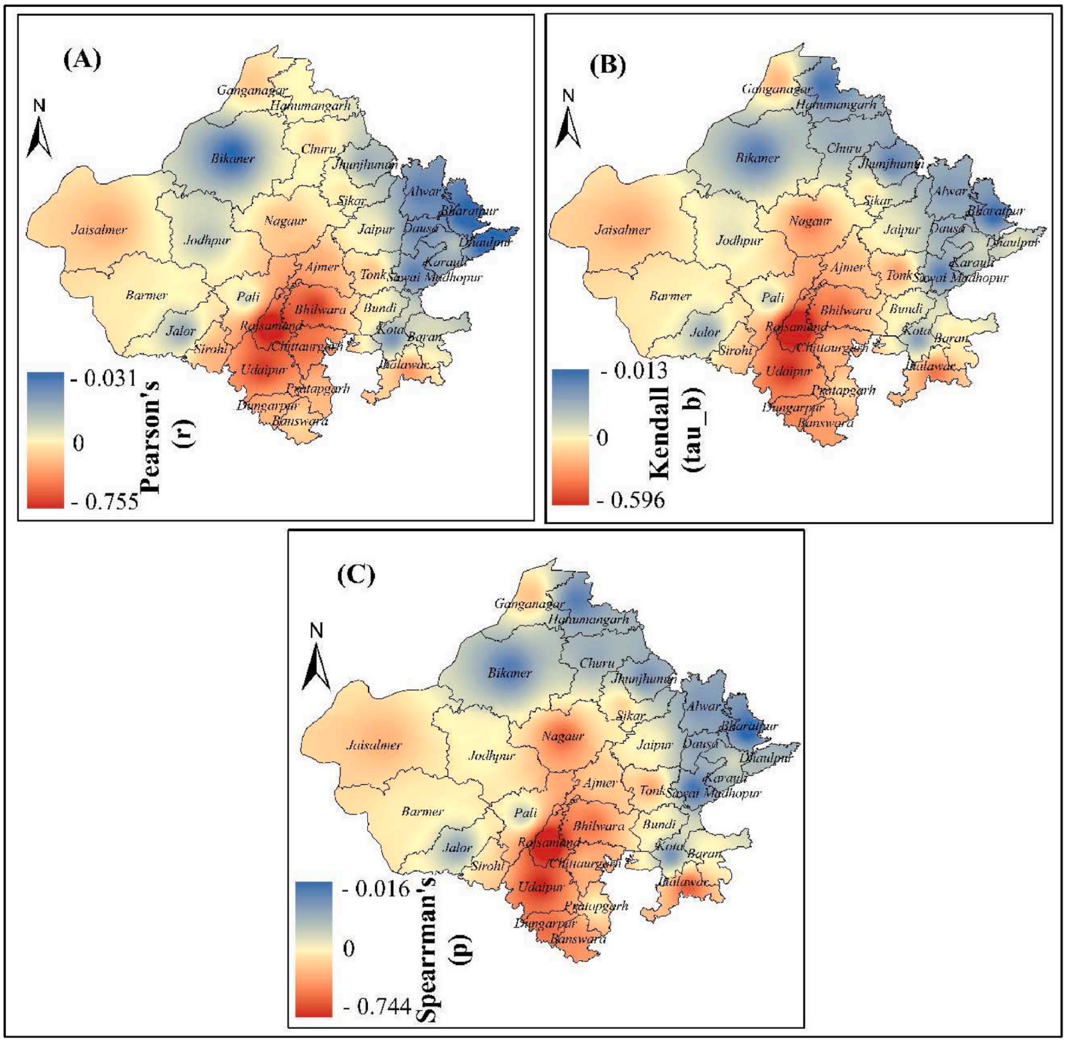

Fig. 6. Spatial distribution of the correlation coefficient between GWL depth and rainfall. (A) Correlation using Pearson Correlation Coefficient, (B) Correlation using Kendall tau_b value, (C) Correlation using Spearman method.

variability dominates the GWL over the study region. Similarly, most of the districts have a rising trend in GWL, and a significant number of districts have an increasing trend in annual rainfall (Table 2). Similar dependency has been found in different drought-prone areas in India, in Jharkhand [44], Gujarat [78], and Uttar Pradesh [45]. Precipitation is the primary source of groundwater recharge in western India [79,80]. According to Adham et al. [81], the tendency of decreasing rainfall, therefore, increases increased groundwater use, leading to a trend of depleting groundwater table levels. In western Rajasthan, Singh and Kumar [26] found a strong correlation between groundwater level and rainfall pattern. Rajasthan's western region is entirely desert, devoid of any flora cover and agricultural land (Fig. 1). This study looked at the relationship between groundwater levels and rainfall throughout Rajasthan, which has agricultural land in its eastern section and is covered in vegetation (Fig. 1). And this present study revealed some stations have a rising rainfall trend and a declining GWL trend through the regression analysis (Fig. 6). This heterogeneous result was observed in those stations, which located in the eastern part of the study area.

For the first time, this study used GRACE products from several sources with in situ GWL data for the whole period and observed that the TWS anomaly decreased by 1.22 cm/yr. A positive correlation exists between GRACE and well groundwater anomalies ($r = 0.471$). Previous studies also used GRACE products, but they are from one or two sources and not for the whole period of the GRACE mission [24,27,48]. The previous studies observed almost similar anomaly-decreasing rates and a relationship between GRACE and groundwater anomalies [24,27,48]. Based on well-observations and GRACE datasets in the study area, we uncover divergent trends in groundwater variability. For instance, groundwater storage in Rajasthan was trending downward according to GRACE data, but an almost 50 % upward trend was observed according to observation wells. Similar contrasting results were observed by Meghwal et al. [24] in western India. However, this present study found a more declining trend in GWL using well-observation data, compared with previous studies in this region [28,81]. The overall outcome indicates that Rajasthan has experienced an increase in yearly rainfall

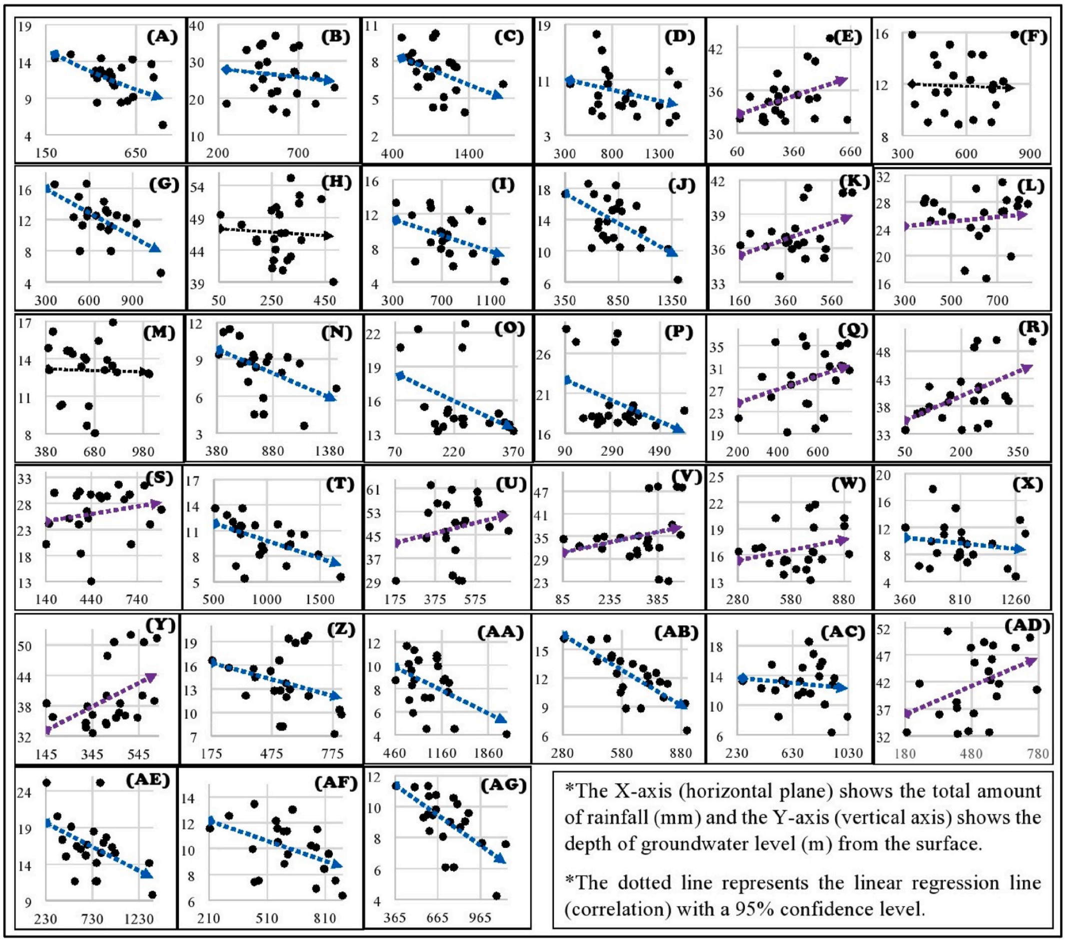

Fig. 7. Identifying the relationship between rainfall and GWL depth through Regression analysis for different districts: (A) Ajmer; (B) Alwar; (C) Banswara; (D) Baran; (E) Barmer; (F) Bharatpur; (G) Bhilwara; (H) Bikaner; (I) Bundi; (J) Chittaurgarh; (K) Churu; (L) Dausa; (M) Dhaulpur; (N) Dungarpur; (O) Ganganagar; (P) Hanumangarh; (Q) Jaipur; (R) Jaisalmer; (S) Jalor; (T) Jhalawar; (U) Jhunjhunun; (V) Jodhpur; (W) Karauli; (X) Kota; (Y) Nagaur; (Z) Pali; (AA) Pratapgarh; (AB) Rajsamand; (AC) Sawai Madhopur; (AD) Sikar; (AE) Sirohi; (AF) Tonk; and (AG) Udaipur.

during the past 15–20 years through a significant number of locations experiencing GWL depletion. This phenomenon happens when significant effects on groundwater sustainability are due to the overuse of abstraction through agricultural and industrial uses. Such GWL depletion may affect hydrothermal processes and water redistribution, which have a major impact on the water cycle and the long-term sustainability of the environment and economy [84].

6. Conclusion

This study used well observations and GRACE data to analyze GWL and rainfall trends and the relationship between GWL fluctuations and rainfall variability. This study used well observation for GWL from 921 monitoring stations for 33 districts of Rajasthan from 2000 to 2021 and GRACE data from March 2002 to October 2017. Modified MK, Spearman, Pearson, regression, and ITA methods were used for trend and relationship analysis, and the GTCH approach was used to assess the TWS and GWS anomaly. Model performance was evaluated using RMSE, and spatial visualization was done with IDW. These are the main findings from the present study.

- 45 % of districts have GWL above 15 m from the surface, and 48 % have less than 400 mm of annual rainfall.
- According to Modified *Mk* and *Spearman*, trend tests at a 95 % significant level represent a declining GWL trend found in 38 % of districts, and most of the districts (70 %) have a rising annual rainfall trend during the study period.
- Innovative trend slope in GWL represents 36.36 % of districts with a declining trend.
- The southern part of the study area is comparatively more vegetation-covered and has a rising trend for GWL and annual rainfall. The semi-arid middle to the northern part of this area has significantly less vegetation cover and annual rainfall, and this area has a declining trend in GWL.

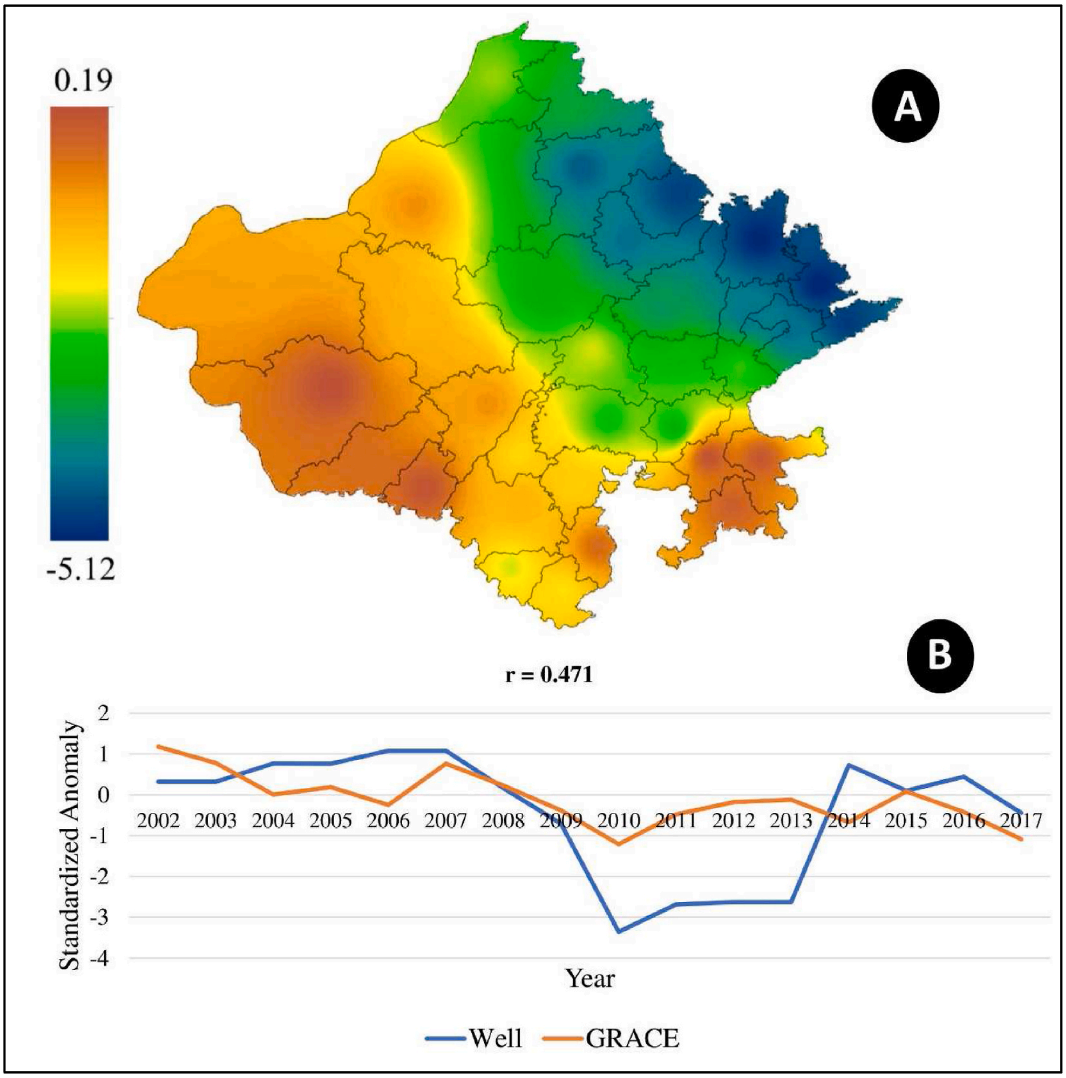

Fig. 8. Using GRACE (CSR + JPL) data and well data, TWS and GWS trends were examined in Rajasthan, India, from March 2002 to October 2017. (A) The mean monthly TWS anomaly is calculated using the long-term monthly anomaly (cm); (B) The standardized well level anomaly and the standardized GRACE GWS anomaly are compared. There has been mention of the correlation coefficient (r).

- The value of *Kendall tau_b*, *Pearson's r*, and *Spearman's p* for the relationship between GWL and rainfall variability shows all districts have a negative correlation, where 15 % are strong negative correlation, 58 % are moderate, and the remaining 27 % are weak negative correlation.
- The GRACE-based TWS anomaly decreased by 1.22 cm/year, and a positive correlation exists between GRACE and groundwater well anomalies (r = 0.471).

A more thorough understanding may be determined by analyzing the effect of rainfall on GWL at the seasonal scale. Further research should examine the changes in vegetation cover over time with the changes in GWL and rainfall. The policymakers' awareness of the groundwater possibilities in the research region will be aided by this annual study, which will help with their plans. As a result, it is crucial to implement water conservation strategies and water harvesting systems in the middle to the northern part of the study area to prevent further harm to the available water supply.

Ethics approval and consent to participate

National Water Informatics Centre, India has given ethical approval for the use of their in-situ GWL data in this work.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Md. Moniruzzaman Monir: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Subaran Chandra Sarker:** Writing – review & editing, Supervision, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The data used in the study was obtained from the National Water Informatics Centre (NWIC), Ministry of Water Resources, River Development & Ganga Rejuvenation, India is thankfully acknowledged.

References

[1] B. Nisi, A. Buccianti, B. Raco, R. Battaglini, Analysis of complex regional databases and their support in identifying background/baseline compositional facies in groundwater investigation: developments and application examples, J. Geochem. Explor. 164 (2016) 3–17, https://doi.org/10.1016/j.gexplo.2015.06.019.
[2] A. Rivera, D.M. Allen, H. Maathusi, Climate variability and change—groundwater, Chapter 10, in: Threats to the Availability of Water in Canada, National Water Research Institute, Environment Canada Report no. 3, Burlington, ON, 2004, pp. 89–95.
[3] O.A. Mohammed, K.N. Sayl, A GIS-based multicriteria Decision for groundwater potential zone in the west desert of Iraq, IOP Conf. Ser. Earth Environ. Sci. 856 (1) (2021), https://doi.org/10.1088/1755-1315/856/1/012049.
[4] C.S. Ngongondo, An analysis of long-term rainfall variability, trends and groundwater availability in the Mulunguzi river catchment area, Zomba mountain, Southern Malawi, Quat. Int. 148 (1) (2006) 45–50, https://doi.org/10.1016/j.quaint.2005.11.006.
[5] S. Dangar, A. Asoka, V. Mishra, Causes and implications of groundwater depletion in India: a review, J. Hydrol. 596 (February) (2021) 126103, https://doi.org/10.1016/j.jhydrol.2021.126103.
[6] R.C. Maheshwari Meenakshi, Fluoride in drinking water and its removal, J. Hazard Mater. 137 (1) (2006) 456–463, https://doi.org/10.1016/j.jhazmat.2006.02.024.
[7] G.H. Murhekar, Trace metals contamination of surface water samples in and around Akot city in Maharashtra, India, Res. J. Recent Sci. 1 (7) (2012) 5–9. http://www.isca.in/rjrs/archive/v1i7/1.ISCA-RJRS-2012-088Done.pdf.
[8] S.K. Joshi, S.P. Rai, R. Sinha, Understanding Groundwater Recharge Processes in the Sutlej-Yamuna Plain in NW India Using an Isotopic Approach, vol. 507, Geological Society, London, Special Publications, 2020, https://doi.org/10.1144/SP507-2020-174.
[9] P. Semwal, S. Khobragarde, S.K. Joshi, S. Kumar, Variation in δ18O and δ2 H rainfall values, surface water, and groundwater in the Sukhna Lake basin in northwest India, Environ. Earth Sci. 79 (24) (2020) 1–14, https://doi.org/10.1007/s12665-020-09285-9.
[10] L.F. Konikow, E. Kendy, Groundwater depletion: a global problem, Hydrogeol. J. 13 (1) (2005) 317–320, https://doi.org/10.1007/s10040-004-0411-8.
[11] C.J. Vörösmarty, D. Sahagian, Anthropogenic disturbance of the terrestrial water cycle, Bioscience 50 (9) (2000) 753–765, https://doi.org/10.1641/0006-3568(2000)050[0753:ADOTTW]2.0.CO;2.
[12] W.M. Alley, R.W. Healy, J.W. LaBaugh, T.E. Reilly, Flow and storage in groundwater systems, Science 296 (5575) (2002) 1985–1990, https://doi.org/10.1126/science.1067123.
[13] Y. Wada, L.P.H. Van Beek, C.M. Van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens, Global depletion of groundwater resources, Geophys. Res. Lett. 37 (20) (2010) 1–5, https://doi.org/10.1029/2010GL044571.
[14] J. Alcamo, P. Doll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, S. Siebert, Development and testing of the Water GAP 2 global model of water use and availability, Hydrol. Sci. J. 48 (3) (2003) 317–337, https://doi.org/10.1623/hysj.48.3.317.45290.
[15] N. Hanasaki, S. Kanae, T. Oki, et al., An integrated model for the assessment of global water resources - Part 2: applications and assessments, Hydrol. Earth Syst. Sci. 12 (4) (2008) 1027–1037, https://doi.org/10.5194/hess-12-1027-2008.
[16] T. Gleeson, Y. Wada, M.F.P. Bierkens, L.P.H. Van Beek, Water balance of global aquifers revealed by groundwater footprint, Nature 488 (7410) (2012) 197–200, https://doi.org/10.1038/nature11295.
[17] S.K. Joshi, S. Gupta, R. Sinha, et al., Strongly heterogeneous patterns of groundwater depletion in Northwestern India, J. Hydrol. 598 (April) (2021) 126492, https://doi.org/10.1016/j.jhydrol.2021.126492.
[18] T. Gleeson, Y. Wada, Assessing regional groundwater stress for nations using multiple data sources with the groundwater footprint, Environ. Res. Lett. 8 (4) (2013), https://doi.org/10.1088/1748-9326/8/4/044010.
[19] M. Rodell, J. Famiglietti, D. Wiese, et al., Emerging trends in global freshwater availability, Nature 557 (2018) 651–659, https://doi.org/10.1038/s41586-018-0123-1.
[20] A. Asoka, T. Gleeson, Y. Wada, V. Mishra, Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India, Nat. Geosci. 10 (2) (2017) 109–117, https://doi.org/10.1038/ngeo2869.
[21] M. Rodell, I. Velicogna, J.S. Famiglietti, Satellite-based estimates of groundwater depletion in India, Nature 460 (2009) 999–1002, https://doi.org/10.1038/nature08238.
[22] A.M. MacDonald, H.C. Bonsor, K.M. Ahmed, et al., Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations, Nat. Geosci. 9 (10) (2016) 762–766, https://doi.org/10.1038/ngeo2791.
[23] A.K. Mishra, V.P. Singh, A review of drought concepts, J. Hydrol. 391 (2010) 202–216, https://doi.org/10.1016/j.jhydrol.2010.07.012.
[24] R. Meghwal, D.N. Shah, V. Mishra, On the changes in groundwater storage variability in western India using GRACE and well observations, Remote Sens. Earth Syst. Sci. 2 (2019) 260–272, https://doi.org/10.1007/s41976-019-00026-6.
[25] R. Ramesh, M.G. Yadava, Climate and water resources of India, Current Science Association 89 (5) (2005) 818–824.
[26] R.B. Singh, A. Kumar, Climate variability and water resource scarcity in drylands of Rajasthan, India, Geoenviron. Disasters 2 (1) (2015), https://doi.org/10.1186/s40677-015-0018-5.
[27] D.K. Panda, J. Wahr, Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records, Water Resour. Res. 52 (1) (2016) 135–149, https://doi.org/10.1002/2015WR017797.

[28] D.A. Saad, Agriculture-related trends in groundwater quality of the glacial deposits aquifer, central Wisconsin, J. Environ. Qual. 37 (5) (2008) 209–225, https://doi.org/10.2134/jeq2007.0053.
[29] G.T. Patle, D.K. Singh, A. Sarangi, A. Rai, M. Khanna, R.N. Sahoo, Time series analysis of groundwater levels and projection of future trends, J. Geol. Soc. India 85 (2015) 232–242, https://doi.org/10.1007/s12594-015-0209-4.
[30] A.S. Rahman, M. Kamruzzama, C.S. Jahan, Q.H. Mazumder, Long-term trend analysis of water table using 'MAKESENS' model and sustainability of groundwater resources in drought-prone Barind area, NW Bangladesh, J. Geol. Soc. India 87 (2) (2016) 179–193, https://doi.org/10.1007/s12594-016-0386-9.
[31] S. Swain, S. Sahoo, A.K. Taloor, S.K. Mishra, A. Pandey, Exploring recent groundwater level changes using Innovative Trend Analysis (ITA) technique over three districts of Jharkhand, India, Groundw. Sustain. Dev. (2022), https://doi.org/10.1016/j.gsd.2022.100783.
[32] M.M. Monir, S.C. Sarker, S.K. Sarkar, et al., Groundwater level fluctuations and associated influencing factors in Rangpur District, Bangladesh, using modified Mann-Kendall and GIS-based AHP technique, Theor. Appl. Climatol. (2023), https://doi.org/10.1007/s00704-023-04541-x.
[33] M.M. Monir, S.C. Sarker, M.N. Islam, Assessing the changing trends of groundwater level with spatiotemporal scale at the northern part of Bangladesh integrating the MAKESENS and ARIMA models, Model. Earth Syst. Environ. (2023), https://doi.org/10.1007/s40808-023-01794-3.
[34] R.A. Kerr, Hydrology. Northern India's groundwater is going, going, going, Science 325 (2009) 798, https://doi.org/10.1126/science.325_798.
[35] E.V. Rathnam, Analysis and prediction of groundwater level trends using four variations of Mann Kendall tests and ARIMA modelling, J. Geol. Soc. India 94 (3) (2019) 281–289, https://doi.org/10.1007/s12594-019-1308-4. S.K. Kumar.
[36] P. Taylor, D.K. Panda, A. Mishra, A. Kumar, Quantification of trends in groundwater levels of Gujarat in western India, Hydrol. Sci. J. (2012), https://doi.org/10.1080/02626667.2012.705845.
[37] G.S. Thakur, T. Thomas, Analysis of groundwater levels for detection of trend in Sagar district, Madhya Pradesh, J. Geol. Soc. India 77 (4) (2011) 303–308, https://doi.org/10.1007/s12594-011-0038-z.
[38] B. Anand, D. Karunanidhi, T. Subramani, K. Srinivasamoorthy, M. Suresh, Long-term trend detection and spatiotemporal analysis of groundwater levels using GIS techniques in Lower Bhavani River basin, Tamil Nadu, India, J. Environ. Dev. Sustain. 22 (4) (2020) 2779–2800, https://doi.org/10.1007/s10668-019-00318-3.
[39] S. Siebert, J. Burke, J.M. Faures, et al., Groundwater use for irrigation – a global inventory, Hydrol. Earth Syst. Sci. 14 (2010) 1863–1880, https://doi.org/10.5194/hess-14-1863-2010.
[40] J.S. Famiglietti, The global groundwater crisis, Nat. Clim. Change 4 (2014) 945–948, https://doi.org/10.1038/nclimate2425.
[41] Z. Zhao, Z. Jia, Z. Guan, C. Xu, The effect of climatic and non-climatic factors on groundwater levels in the jinghuiqu irrigation district of the shaanxi province, China, Water 11 (2019) 956, https://doi.org/10.3390/w11050956.
[42] A. Razzaq, H. Liu, M. Xiao, et al., Analyzing past and future trends in Pakistan's groundwater irrigation development: implications for environmental sustainability and food security, Environ. Sci. Pollut. Res. 30 (2023), https://doi.org/10.1007/s11356-022-24736-5.
[43] S. Mancini, E. Egidio, D.A.D. Luca, M. Lasagna, Application and comparison of different statistical methods for the analysis of groundwater levels over time: response to rainfall and resource evolution in the Piedmont Plain (NW Italy), Sci. Total Environ. (2022), https://doi.org/10.1016/j.scitotenv.2022.157479.
[44] T.A. Shalini, A.C. Pandey, M.S. Nathawat, Groundwater level and rainfall variability trend analysis using GIS in parts of Jharkhand state (India) for sustainable management of water resources, Int. J. Res. Environ. Sci. 1 (4) (2012) 24–31.
[45] S. Dey, D. Bhatt, S. Haq, R.K. Mall, Potential impact of rainfall variability on groundwater resources: a case study in Uttar Pradesh, India, Arab, J. Geosci. 13 (3) (2020), https://doi.org/10.1007/s12517-020-5083-8.
[46] A. Natarajan, V. Tamizhazhagan, N. Tangudu, S. Kumar, Analysis of groundwater level fluctuations and its association with rainfall using statistical methods, J. Algebr. Stat. 13 (3) (2022) 1895–1904. https://www.publishoa.com/index.php/journal/article/view/828.
[47] P. Chinnasamy, B. Maheshwari, S. Prathapar, Understanding groundwater storage changes and recharge in Rajasthan, India through remote sensing, Water (Switzerland) 7 (10) (2015) 5547–5565, https://doi.org/10.3390/w7105547.
[48] S. Ali, Q. Wang, D. Liu, et al., Estimation of spatio-temporal groundwater storage variations in the Lower Transboundary Indus Basin using GRACE satellite, J. Hydrol. 605 (2022) 1–47, https://doi.org/10.1016/j.jhydrol.2021.127315.
[49] S. Yue, P. Pilon, G. Cavadias, Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series, J Hydrol 259 (2002) 254–271, https://doi.org/10.1016/S0022-1694(01)00594-7.
[50] T.D. Gauthier, Detecting trends using Spearman's rank correlation coefficient, Environ. Forensics 2 (4) (2001) 359–362, https://doi.org/10.1006/enfo.2001.0061.
[51] C.D. Jan, T.H. chen, W.C. Lo, Effect of rainfall intensity and distribution on groundwater level fluctuations, J Hydrol 332 (3–4) (2007) 348–360, https://doi.org/10.1016/j.jhydrol.2006.07.010.
[52] M.G. Abdullahi, I. Garba, Effect of rainfall on groundwater level fluctuation in terengganu, Malaysia, J. Remote Sensing & GIS 4 (2) (2016), https://doi.org/10.4172/2469-4134.1000142.
[53] Z. Cai, U. Ofterdinger, Analysis of groundwater-level response to rainfall and estimation of annual recharge in fractured hard rock aquifers, NW Ireland, J. Hydrol. 535 (2016) 71–84, https://doi.org/10.1016/j.jhydrol.2016.01.066.
[54] P.S. Porter, S.T. Rao, C. Hogrefe, Linear trend analysis: a comparison of methods, Atmos. Environ. 36 (18) (2002) 3055–3056, https://doi.org/10.1016/S1352-2310(02)00189-9.
[55] A. Rahman, K.K. Tiwari, N.C. Mondal, Assessment of hydro chemical backgrounds and threshold values of groundwater in a part of desert area, Rajasthan, India, Environ. Pollut. (2020), https://doi.org/10.1016/j.envpol.2020.115150.
[56] P.K. Gupta, D. Sharma, Assessment of hydrological and hydrochemical vulnerability of groundwater in semi-arid region of Rajasthan, India, Sustain. Water Resour. Manag. 5 (2019) 847–861, https://doi.org/10.1007/s40899-018-0260-6.
[57] R. Chatterjee, A.K. Jain, S. Chandra, et al., Mapping and management of aquifers suffering from over-exploitation of groundwater resources in Baswa-Bandikui watershed, Rajasthan, India, Environ. Earth Sci. 77 (2018) 157, https://doi.org/10.1007/s12665-018-7257-1.
[58] H.B. Mann, Nonparametric tests against trend, J. Econom. 13 (3) (1945) 245–259, https://doi.org/10.2307/1907187.
[59] M.G. Kendall, Rank Correlation Methods, Charles Griffin, London, 1955.
[60] D.R. Helsel, R.M. Hirsch, Statistical Methods in Water Resources, Elsevier, Amsterdam, 1992, 9780080875088.
[61] M. Mastrocicco, M.P. Gervasio, G. Busico, N. Colombani, Natural and anthropogenic factors driving groundwater resources salinization for agriculture use in the Campania plains (Southern Italy), Sci. Total Environ. (2020), https://doi.org/10.1016/j.scitotenv.2020.144033.
[62] F. Serinaldi, F. Chebana, C.G. Kilsby, Dissecting innovative trend analysis, Stoch. Environ. Res. Risk Assess. 34 (5) (2020) 733–754, https://doi.org/10.1007/s00477-020-01797-x.
[63] Z. Sa'adi, S. Shahid, T. Ismail, et al., Trends analysis of rainfall and rainfall extremes in Sarawak, Malaysia using modified Mann–Kendall test, Meteorol. Atmos. Phys. 131 (2019) 263–277, https://doi.org/10.1007/s00703-017-0564-3.
[64] Y. Luo, S. Liu, S.F. Fu, J. Liu, G. Wang, G. Zhou, Trends of precipitation in beijiang river basin, guangdong province, China, Hydrol. Processes 22 (2008) 2377–2386, https://doi.org/10.1002/hyp.6801.
[65] Z. Jia, J. Bian, Y. Wang, Impacts of urban land use on the spatial distribution of groundwater pollution, Harbin City, Northeast China, J. Contam. Hydrol. 215 (2018) 29–38, https://doi.org/10.1016/j.jconhyd.2018.06.005.
[66] G. Balacco, M.R. Alfio, M.D. Fidelibus, Groundwater drought analysis under data scarcity: the case of the salento aquifer (Italy), Sustainability 14 (2) (2022), https://doi.org/10.3390/su14020707.
[67] A. Agresti, Analysis of Ordinal Categorical Data, second ed., John Wiley & Sons, New York, 2010, 978-0-470-08289-8.
[68] K. Hamer, I. Gudenschwager, T. Pichler, Manganese (Mn) concentrations and the Mn-Fe relationship in shallow groundwater: implications for groundwater monitoring, Soil Systems 4 (3) (2020), https://doi.org/10.3390/soilsystems4030049.
[69] M. de Carvalho, F.J. Marques, Jackknife euclidean likelihood-based inference for Spearman's rho, N Am Actuar J 16 (4) (2012) 487–492, https://doi.org/10.1080/10920277.2012.10597644.

[70] Z. Şen, Innovative trend analysis methodology, J. Hydrol. Eng. 17 (9) (2012) 1042–1046, https://doi.org/10.1061/(ASCE)HE.1943-5584.

[71] M.M. Monir, M. Rokonuzzaman, S.C. Sarker, et al., Spatiotemporal analysis and predicting rainfall trends in a tropical monsoon-dominated country using MAKESENS and machine learning techniques, Sci. Rep. 13 (1) (2023) 13933, https://doi.org/10.1038/s41598-023-41132-2.

[72] H. Wu, H. Qian, Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s, Int. J. Climatol. 37 (5) (2017) 2582–2592, https://doi.org/10.1002/joc.4866.

[73] J. Chen, H. Zhang, H. Qian, J. Wu, X. Zhang, Selecting the proper method for groundwater interpolation based on spatial correlation, in: Proc. 4th International Conference on Digital Manufacturing & Automation., vol. 9, 2013, pp. 1192–1195, https://doi.org/10.1109/icdma.2013.282, 13.

[74] T.W. Chu, A. Shirmohammadi, Evaluation of the swat model's hydrology component in the piedmont physiographic region of Maryland, Trans. ASAE (Am. Soc. Agric. Eng.) 47 (2004) 1057–1073.

[75] D.S. Wilks, Statistical Methods in the Atmospheric Sciences, vol. 100, Academic Press, 2011.

[76] S. Danyar, S. Yudong, M. Jumakeld, Influence of groundwater level change on vegetation coverage and their spatial variation in arid regions, J. Geogr. Sci. 14 (2004) 323–329, https://doi.org/10.1007/BF02837413.

[77] D.J. Lapworth, A.M. Macdonald, G. Krishan, M.S. Rao, D.C. Gooddy, W.G. Darling, Groundwater recharge and age-depth profiles of intensively exploited groundwater resources in northwest India, Geophys. Res. Lett. 42 (18) (2015) 7554–7562, https://doi.org/10.1002/2015GL065798.

[78] D.K. Panda, A. Mishra, A. Kumar, Quantification des tendances du niveau des eaux souterraines du Gujerat (Inde occidentale), Hydrol. Sci. J. 57 (7) (2012) 1325–1336, https://doi.org/10.1080/02626667.2012.705845.

[79] A. Asoka, Y. Wada, R. Fishman, V. Mishra, Strong linkage between precipitation intensity and monsoon season groundwater recharge in India, Geophys. Res. Lett. 45 (11) (2018) 5536–5544, https://doi.org/10.1029/2018GL078466.

[80] S.N. Bhanja, A. Mukherjee, In situ and satellite-based estimates of useable groundwater storage across India: implications for drinking water supply and food security, Adv. Water Resour. 125 (2019) 15–23, https://doi.org/10.1016/j.advwatres.2019.02.001.

[81] M.I. Adham, C.S. Jahan, Q.H. Mazumder, M.M.A. Hossain, A.M. Haque, Study on groundwater recharge potentiality of barind tract, rajshahi district, Bangladesh using GIS and remote sensing technique, J. Geol. Soc. India 75 (2010), https://doi.org/10.1007/s12594-010-0039-3.

[82] P.J. Twomey, M.H. Kroll, How to use linear regression and correlation in quantitative method comparison studies, Int. J. Clin. Pract. 62 (4) (2008) 529–538, https://doi.org/10.1111/j.1742-1241.2008.01709.x.

[83] M. Pal, P. Bharati, Introduction to correlation and linear regression analysis, in: Applications of Regression Techniques, Springer, Singapore, 2019, https://doi.org/10.1007/978-981-13-9314-3_1.

[84] L. Wang, B. Jia, Z. Xie, et al., Impact of groundwater extraction on hydrological process over the Beijing-Tianjin-Hebei region, China, J. Hydrol. (2022), https://doi.org/10.1016/j.jhydrol.2022.127689.