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ORIGINAL ARTICLE

Spatio-temporal analysis of precipitation dynamics and groundwater recharge trends in Jharkhand, india: implications for water resource management

Randhir Kumar[1] · Kiran Jalem[2] · Sagar Kumar Swain[3] · Shruti Kanga[4] · Suraj Kumar Singh[5] · Gowhar Meraj[6] · Pankaj Kumar[7] · Debdas Mandal[2]

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Abstract

Understanding regional hydroclimatic patterns is essential for managing water resources and ensuring agricultural sustainability in rain-fed areas under changing climate conditions. The intensifying effects of climate change on rain-fed agriculture in India necessitate a comprehensive understanding of the precipitation dynamics and groundwater recharge patterns. This study strives to evaluate the relationship in 11 districts of Jharkhand between 2001 and 2020 using rainfall and ground water level data collected from Indian Meteorological Department (IMD) and Central Ground Water Board (CGWB), Ranchi respectively. Rainfall data analysis reveals significantly positive and negative trends in pre-monsoon, monsoon, and post-monsoon across districts. Pre-monsoon rainfall ranged from 25 to 175 mm, monsoon from 650 to 1250 mm, and post-monsoon from 20 to 120 mm, with higher values in Simdega, Lohardaga, and Latehar, and lower values in Garhwa and Palamu. The Mann-Kendall test indicated negative rainfall trends in 7 out of 11 districts, with Sen's slope values declining up to −6.8 mm/year, especially in eastern and northern Jharkhand. Pre-monsoon groundwater levels varied between 2 and 18 m, with declining trends in Palamu, East Singhbhum, and Khunti, while positive trends (Sen's slope up to 0.21 m/year) were observed in Simdega and Ranchi. In the post-monsoon period, six districts such as Simdega, Latehar, Gumla, Ranchi, West Singhbhum, and Saraikela Kharsawan, exhibited positive trends, whereas Garhwa and East Singhbhum showed declines of −0.12 to −0.17 m/year. Addressing these hydroclimatic challenges in Jharkhand requires region-specific strategies, such as rainwater harvesting, efficient irrigation methods, and localized groundwater management to mitigate water stress, sustain agriculture, and enhance resilience to climate variability.

Keywords Climate change · Rainfall analysis · Trend analysis · Mann-Kendal test · Groundwater availability

✉ Pankaj Kumar
kumar@iges.or.jp

Randhir Kumar
randhirkumar1717@gmail.com

Kiran Jalem
jalemkiran@gmail.com

Sagar Kumar Swain
sagar.swain10@gmail.com

Shruti Kanga
shruti.kanga@cup.edu.in

Suraj Kumar Singh
suraj.kumar@mygyanvihar.com

Gowhar Meraj
gowharmeraj@gmail.com

Debdas Mandal
mandaldebdas1998@gmail.com

[1] ICAR-Indian Institute of Soil & water conservation, Research Center - Sunabeda, Koraput, Odisha 763003, India

[2] Department of Geoinformatics, Central University of Jharkhand, Ranchi, Jharkhand 835222, India

[3] Department of Geology, Central University of Jharkhand, Ranchi, Jharkhand 835222, India

[4] Department of Geography, School of Environment and Earth Sciences, Central University of Punjab, Bathinda, Punjab 151401, India

[5] Centre for Sustainable Development, Suresh Gyan Vihar University, Jaipur 302017, India

[6] Department of Biology, Chemistry and Environmental Sciences, College of Arts and Sciences, American University of Sharjah, Sharjah 26666, United Arab Emirates

[7] Institute for Global Environmental Strategies, Hayama, Kanagawa 240- 0115, Japan

Introduction

Climate variability is a widespread phenomenon globally, resulting in changes such as fluctuations in air temperature, humidity, precipitation, and solar radiation. These fluctuations have led to a continuous warming trend and an increased occurrence of extreme weather events such as floods, heat waves, and droughts (Tirkey et al. 2018). Precipitation plays a pivotal role in controlling various aspects including vegetation, hydrology, water quality, and agricultural production. Understanding the precipitation variability is crucial for systematic optimization of agricultural production (Chandniha et al. 2017; Meshram et al. 2020; Javadinejad et al. 2021; Adimalla And Qian 2021; Chauhan et al. 2022). Changes in rainfall patterns, temperature, and water availability significantly affect crop productivity and overall yield, particularly in rain-fed regions (Mall et al. 2006). Trend analysis of precipitation helps to explore the impacts of climate change, which include changes in intensity, frequency, and timing of precipitation, as well as variation in temperatures (Mo et al. 2019; Kumaraswamy 2022). By 2050, annual average runoff and water availability are projected to decrease in mid-latitude and dry tropical regions, while increasing in wet tropical areas (Bates et al. 2008). These changes will exacerbate crop water scarcity due to increased water requirements and reduced precipitation. Therefore, analysis of rainfall trends is critical for effective planning and management of water as well as groundwater recharge in parts of India impacted by the implementation of water policy changes (Bhanja et al. 2017).

The correlation between precipitation and groundwater recharge is crucial for efficient water resource management. Several researchers contribute valuable insights into the relationship between precipitation and groundwater recharge on various aspects such as temporal variations, regional differences, and the influence of land use on groundwater recharge processes (Lapworth et al. 2015; MacDonald et al. 2016; Bhanja et al. 2019).The spatial variation of the precipitation infiltration recharge coefficient and its associations with terrain characteristics and groundwater depth are studied by several researchers (Edmunds et al. 2002; Zomlot et al. 2015). These studies likely highlight how factors such as topography, soil type, and geology influence the rate at which precipitation infiltrates into the groundwater system. Understanding these spatial variations is crucial for accurately estimating the groundwater recharge rates and designing effective water resource management strategies tailored to specific geographic regions. The global synthesis offers valuable insights into the relationship between climatic aridity and groundwater recharge rates. By synthesizing field-estimated recharge data from six continents, the study revealed a simple function linking recharge rates to climatic aridity levels. Importantly, the study found that these observed recharge rates exceeded those predicted by artificial neural network (ANN) models. This discrepancy suggests that traditional methods of estimating recharge may underestimate its magnitude, highlighting the need for improved modelling approaches that consider the influence of climatic factors on groundwater recharge dynamics. Climate change significantly alters aquifer recharge dynamics, with projections indicating reduced recharge in arid and desert regions, while northern and high-altitude areas may experience increased recharge (Berghuijs et al. 2022). Understanding these projections is crucial for adapting water resource management strategies to changing climatic conditions. These findings highlight the importance of understanding the relationship between precipitation and groundwater recharge for effective water resource management (Thomas et al. 2016; Cárdenas Castillero et al. 2021).

The over-exploitation of groundwater in semi-arid regions has led to significant socio-economic repercussions, primarily due to declining groundwater tables caused by excessive extraction compared to recharge rates (Rai et al. 2006). This imbalance between extraction and recharge poses serious challenges to water resource sustainability in these regions. This issue is particularly evident in India, where groundwater levels have dropped by more than 2 m over the long term in various states including Delhi, Gujarat, Haryana, Karnataka, Punjab, Rajasthan, and Tamil Nadu (Mukherjee et al. 2015). Consequently, the phenomenon of groundwater recharge has become a focal point, with its correlation with rainfall being explored from an investigative perspective (Goswami And Sekhar 2022; Habib et al. 2023; Jiang et al. 2023). Groundwater recharge is influenced by a multitude of factors such as rainfall frequency and intensity, infiltration, soil type, and soil moisture content (Oke et al. 2014; Machiwal And Jha 2014). Understanding these factors and their interactions is essential for accurately assessing groundwater recharge processes. Anthropogenic activities, particularly climate change, play a significant role in shaping the long-term pattern of monsoon rainfall (Turner And Annamalai 2012). Understanding precipitation trends is crucial for countries like India, where agriculture is a significant contributor to the economy and sustenance (Kumar et al. 2022; Pastagia and Mehta 2022). By investigating how precipitation patterns change over time and how these changes impact groundwater recharge, aim to provide insights into the dynamics of groundwater resources in response to climate variability (Marchant et al. 2022; Londhe et al. 2023; Mohsine et al. 2023).

The impact of rainfall on groundwater recharge in India is a multifaceted interaction involving climatic factors, geological formations, and human activities. Northern regions like Punjab and Haryana, renowned as the country's breadbasket, heavily depend on groundwater for agriculture, especially during dry spells (Singh et al. 2020). In urban Delhi, researchers analyzed the correlation between rainfall patterns and groundwater levels (Roy et al. 2020). Conversely, western India, encompassing states such as Gujarat, Maharashtra, and the semi-arid state of Rajasthan, receives sufficient rainfall, but this variable distribution affects recharge rates and exacerbates water scarcity issues in certain areas (Yadav et al. 2023; Ansari et al. 2025). Southern states like Tamil Nadu and Kerala confront challenges of waterlogging and reduced infiltration during heavy rains, impacting recharge processes. In eastern India, states like West Bengal and Odisha rely on monsoon rains, contributing to groundwater recharge, albeit facing challenges of waterlogging and soil erosion. Central regions of India, including states like Madhya Pradesh and Chhattisgarh, exhibit diverse rainfall patterns, necessitating sustainable management practices to balance water demand and recharge rates. However, some areas within these states experience water scarcity, especially during prolonged dry periods. Variability in rainfall patterns directly affects groundwater recharge rates, thereby influencing the availability of water for both agricultural and domestic purposes (Muruganandham and Singh 2024).

In Jharkhand, the southwest monsoon significantly influences the climate, with the state receiving an average annual precipitation of 1400 mm, primarily during June to September. However, this concentrated rainfall distribution leads to water scarcity during non-monsoon periods, impacting agriculture, particularly in rain-fed areas (Todmal And Kale 2016; Ahammed et al. 2018). Understanding precipitation trends is vital for irrigation planning and determining crop water requirements given that Jharkhand's agriculture is predominantly rainfed (Petare et al. 2016). Detailed monitoring and assessment of climate trends in Jharkhand are necessary to analyze the long-term impacts of rainfall and temperature fluctuations and inform economic planning and decision-making processes. While several studies have examined rainfall variability or groundwater trends in other parts of India, there is a lack of integrated studies that simultaneously assess long-term rainfall and groundwater fluctuations at the district level in Jharkhand (Mall et al. 2006; Bhanja et al. 2017). Given the state's complex topography, diverse aquifer systems, and dependency on monsoon rainfall, localized analyses are essential for understanding spatial disparities in hydroclimatic trends.

With over 80% of the state's farmers dependent on monsoon rains for cultivation, any fluctuation in rainfall patterns or groundwater availability has a direct impact on food security and rural livelihoods in Jharkhand. The region's undulating terrain and shallow aquifers further increase its vulnerability to climate variability, making it crucial for studying rainfall and groundwater level trends. The objective of this study is to analyze long-term (2001–2020) spatio-temporal trends in seasonal rainfall and groundwater levels across 11 districts of Jharkhand, using non-parametric Mann-Kendall and Sen's slope estimators. By integrating seasonal precipitation data with groundwater depth observations, this research aims to identify statistically significant positive and negative trends, understand localized variability, and establish correlations between rainfall and groundwater recharge. The study also quantifies the magnitude of changes to develop a foundation for district-specific water resource planning. Ultimately, this work aims to contribute actionable insights for climate-resilient agriculture and sustainable groundwater management in rain-fed regions of Jharkhand.

Study area

The research area encompasses 11 districts within Jharkhand, including Garhwa, Palamu, Latehar, Lohardaga, Gumla, Ranchi, Simdega, Khunti, West Singhbhum, Saraikhela Kharsawan, and East Singhbhum. Geographically, this area is characterized by a humid subtropical climate in the north and a tropical wet and dry climate in the southeast. The monsoon typically extends from mid-June to mid-October annually, while the winter season spans from November to March. The region experiences heavy rainfall during the South-West monsoon season, which occurs between June and September. In contrast, the summer months, from March to May, offer pleasant weather with a maximum mean temperature of 36˚C. Winters, from November to February, are cooler with an average temperature of 7˚C, dipping further in January. The study area receives an annual rainfall of approximately 90%, with an average of around 1284 mm during the monsoon season (Fig. 1). Additionally, sporadic rainfall induced by Western disturbances affects the region during the winter months from January to March. Thunderstorms are prevalent in April and May. Among the monsoon months, July receives the highest rainfall, followed by August, June, and September in decreasing order. Topographically, the region consists of undulating terrain with scattered hills and plateau regions, primarily part of the Chotanagpur Plateau (Ghosh And Bera 2023). The predominant soil types include red sandy soils and lateritic soils, which influence infiltration and groundwater recharge (Kumar et al. 2022). Land use is dominated by agriculture and forests, with rice, maize, and pulses being the primary rain-fed crops (GoJ 2020). The population across these districts is largely rural and dependent on agriculture

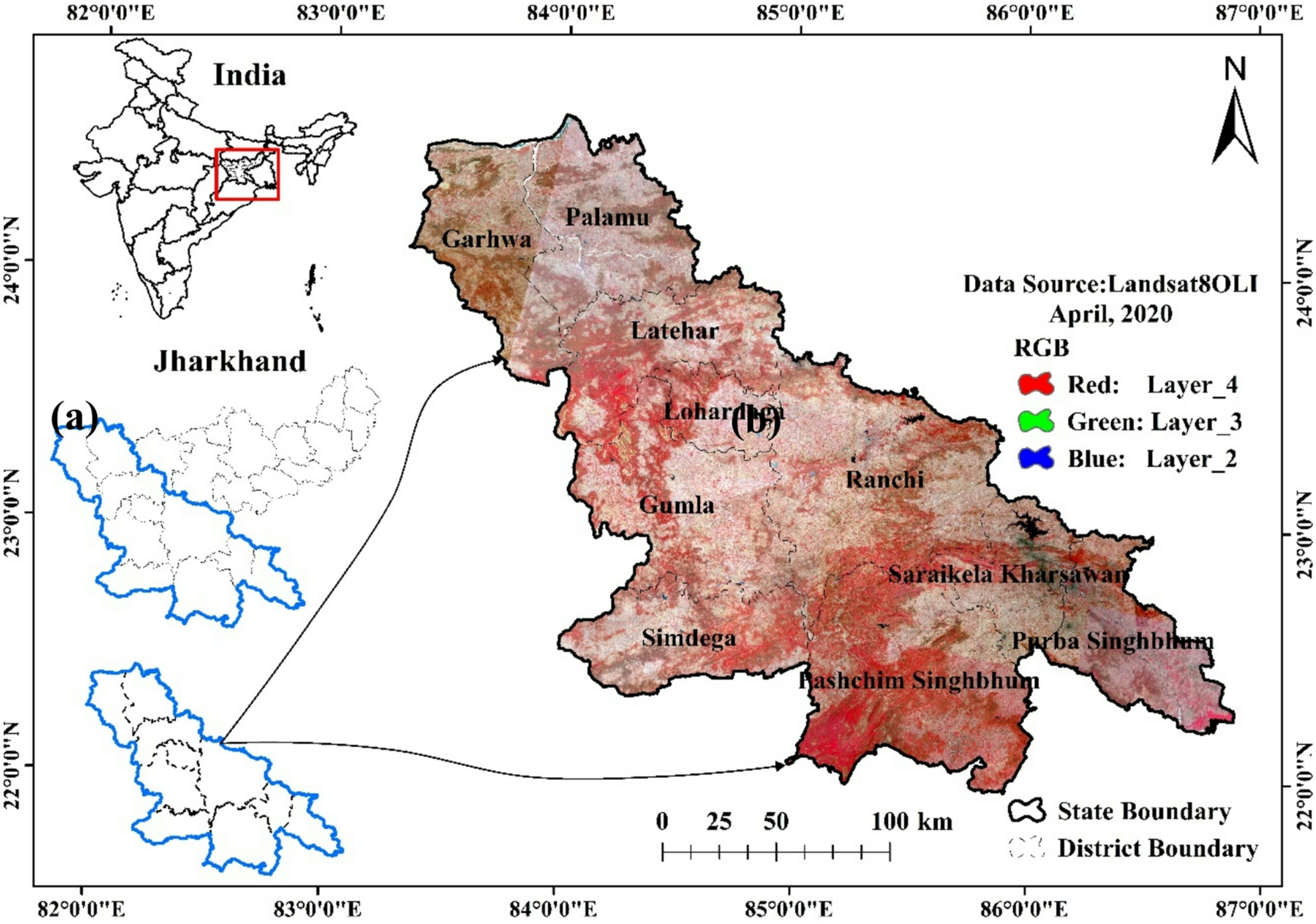


Fig. 1 Location map of the study area using Landsat8 OLI satellite imagery of the April, 2020

for livelihood, with over 75% of the working population engaged in farming and related activities (Census of India 2011) The Land Use Land Cover (LULC) map of the study area for the year 2022 is presented in Fig. 2, generated using Landsat-8 OLI satellite imagery from April 2020. The map illustrates the spatial distribution of six major land cover classes, including agriculture land, built-up area, barren land, dense forest, open forest, and waterbodies across different districts of Jharkhand. Table 1 provides the corresponding area statistics, showing that agricultural land covers the largest portion (40.2%) followed by dense forest (35.9%) and open forest (17.2%). Built-up areas account for 5.4% of the total, while barren land and waterbodies occupy less than 2% combined.

Methodology

Datasets

The study conducted in 11 districts of Jharkhand between 2001 and 2020. Rainfall data for 20 years were collected from Indian Meteorological Department (IMD), Ranchi, whereas, groundwater level data collected from Central Ground Water Board (CGWB), Ranchi. According to the IMD, the pre-monsoon season includes March to May, the monsoon season spans from June to September, and the post-monsoon season includes October to December. The purpose of using rainfall data from the IMD (2001–2020) is to map seasonal rainfall distribution, while the groundwater level data from the CGWB is utilized to assess temporal fluctuations in groundwater levels over the same period.

Percent departure of rainfall from normal

This method is widely used to quantify rainfall anomalies and assess spatial and temporal deviations from climatological normals, particularly in monsoon-dominated regions like India (Singh et al. 2015). The percentage of rainfall departure from normal is calculated using Eq. (1).

$$\text{Percentage Departure} = \frac{\text{Actual Rainfall} - \text{Normal Rainfall}}{\text{Normal Rainfall}} \times 100 \tag{1}$$

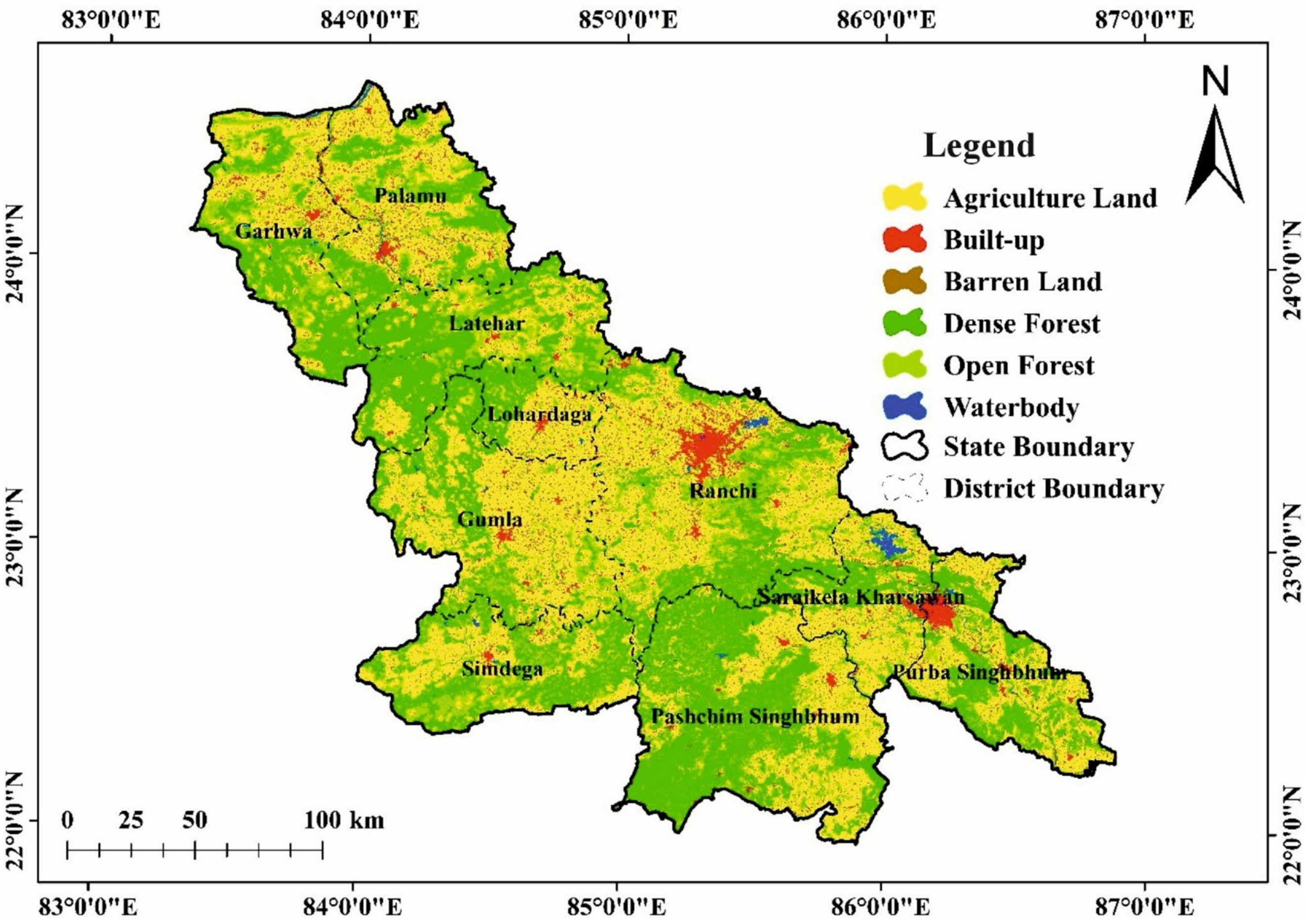


Fig. 2 Land Use Land Cover map of the study area using Landsat8 OLI satellite imagery of the year 2022

Table 1 Land use land cover area statics of the study from April, 2020

LULC Class	Area	
	Km2	%
Agriculture Land	17921.7	40.2
Built-up	2416.9	5.4
Barren Land	93.7	0.2
Dense Forest	16024.0	35.9
Open Forest	7652.6	17.2
Waterbody	484.9	1.1
Total Area	**44593.8**	**100.0**

Nonparametric Mann-Kendall technique with sen's slope prediction for determining trends

The non-parametric Mann-Kendall analysis is frequently applied in hydrology and meteorology to determine variables pattern (Wang et al. 2020; Monir et al. 2023). This non-parametric method utilizes the S statistic to assess the presence of monotonic trends in time-series data (Rahman et al. 2016) (Eq. 2). Prior to analysis, the data series was tested for missing values, and any inconsistencies was addressed. Additionally, serial correlation was checked and corrected where necessary to avoid bias in trend estimation, ensuring robustness in the application of the Mann-Kendall test and Sen's slope method.

$$S = \sum_{k=1}^{n-1} \sum_{\theta=\phi+1}^{n} sign\left(n\theta - n\phi\right) \tag{2}$$

$$sgn\left(n\theta - n\phi\right) = \left\{ \begin{array}{c} +1, if\ \left(n\theta - n\phi\right) > 0 \\ 0, if\ \left(n\theta - n\phi\right) = 0 \\ -1, if\ \left(n\theta - n\phi\right) < 0 \end{array} \right\} \tag{3}$$

When n denotes the sample length, $x\theta$ and $x\varphi$ comes from $\varphi=1, 2, \ldots$, n-1 and $\theta=\varphi+1, \ldots, n$. If $n>8$, statistics S approximates the normal distribution (Anand et al. 2020). The overall mean of S is 0, and the variability of S may calculate using the following method:

$$Var\left(S\right) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

The test statistic Z is represented by Eq. (5) (Patle et al. 2015).

$$Z = \left\{ \begin{array}{c} \frac{S-1}{\sqrt{Var(S)}}, ifS > 0 \\ 0,\ ifS = 0 \\ \frac{S-1}{\sqrt{Var(S)}}, ifS < 0 \end{array} \right\} \tag{5}$$

When Z > 0, it demonstrates an upward tendency, and inversely. For a certain confidence level α, the sequence of the data must demonstrate a trend with statistical significance if |Z|>Z(1-α/2), where Z(1-α/2) indicates the equivalent value of P = α/2 in a standard normal distribution. In this study, the Mann-Kendall trend analysis was applied at both 1% (α = 0.01) and 5% (α = 0.05) significance levels to identify trends with varying degrees of statistical confidence. The 5% significance level was used to detect moderate but statistically significant trends across seasonal and annual rainfall and groundwater datasets, while the 1% significance level was specifically applied to highlight highly significant trends, particularly in regions showing strong monotonic changes over time. This dual-level approach allowed us to differentiate between weaker and stronger trends and provide a more nuanced interpretation of spatial and seasonal variability.

Sen has proposed a straightforward non-parametric method for determining the size of a time series tendency Bates et al. (2008). The trend is computed as

$$\beta\ = Median\left(\frac{nk - ni}{k - i}\right),\ k > 1 \tag{6}$$

β represents Sen's slope prediction. β>0 shows a rising pattern in a time series. Alternatively, the data set indicates a negative tendency across the period.

In this study, Inverse Distance Weighting (IDW) interpolation method was used for generating spatial distribution maps of rainfall and groundwater levels. IDW was selected due to its simplicity, computational efficiency, and proven effectiveness in hydrological and meteorological studies where data points are irregularly distributed (Lu And Wong 2008). This method assumes that values closer to the prediction location have more influence than those farther away, which is particularly suitable for our dataset consisting of limited observation points spread across 11 districts.

The comprehensive flowchart of the methodology is shown in Fig. 3.

Results

Pre-monsoon rainfall map trends analysis

The analysis has revealed clear spatial distribution characteristics. The pre-monsoon rainfall maps from 2001 to 2020 were examined to identify the rainfall patterns across the study area (Fig. 4a). This line graph illustrates the trends in pre-monsoon rainfall from 2001 to 2020 in 11 selected districts in Jharkhand and provides insights into regional differences and long-term rainfall patterns (Fig. 4b).

Over these two decades, there's been a noticeable trend of higher rainfall from the southeast to the southwest, contrasting with lower rainfall observed from the northwest to the northeast. Specifically, during the years 2001–2005, 2007–2011, and 2016–2020, the southeastern and southwestern regions experienced higher rainfall ranging between 126 and 175 mm. Meanwhile, the central part of the study area received relatively normal rainfall, ranging from 76 to 125 mm throughout the entire period of 2001–2020. However, the northern districts like Garhwa and Palamu, along with the southwestern part of West Singhbhum, recorded lower rainfall ranging from 25 to 75 mm over the two-decade span from 2001 to 2020. The trend analysis of pre-monsoon rainfall (Fig. 4a & b) from 2001 to 2020 indicates a negative trend in the northern part of the study area, while a positive trend is evident in the southwestern part. This suggests potential shifts or variations in rainfall patterns across different regions within the study area over the given time period.

Monsoon seasonal rainfall map

The cumulative precipitation maps for the monsoon season over 20 years (2001–2020) reveal spatial precipitation distribution patterns in the study area (Fig. 5a). The line graph presented depicts the rainfall evolution during the monsoon season from 2001 to 2020 in 11 specifically specified districts of Jharkhand (Fig. 5b). This provides important insights into differences between regions as well as long-term precipitation trends.

Figure 5a illustrates the cumulative rainfall map of the monsoon season for 20 years (2001–2020), aiding better understanding of the monsoon seasonal rainfall. The observation revealed higher rainfall in the southeast to southwest regions (951–1250 mm) and minimum rainfall in the northwest to northeast regions (650–850 mm). It was also found that in the years 2004, 2005, 2007, 2008, 2009, 2013, 2014, 2015, and 2016, the south, southeastern part of the entire study area received maximum rainfall (951–1250 mm), while in 2001 and 2003, the north and northwestern part received maximum rainfall (1051–1250 mm). Further, the observation indicates that from 2002 and 2008–2020, the central part of the entire study area received normal rainfall (851–1050 mm). During the years 2001–2020 (except 2001 & 2003), the north, northeastern, and northwestern parts of the study area received low rainfall (651–850 mm) during the monsoon season. Additionally, Fig. 5b illustrates the trend of monsoonal seasonal rainfall during 2001–2020,

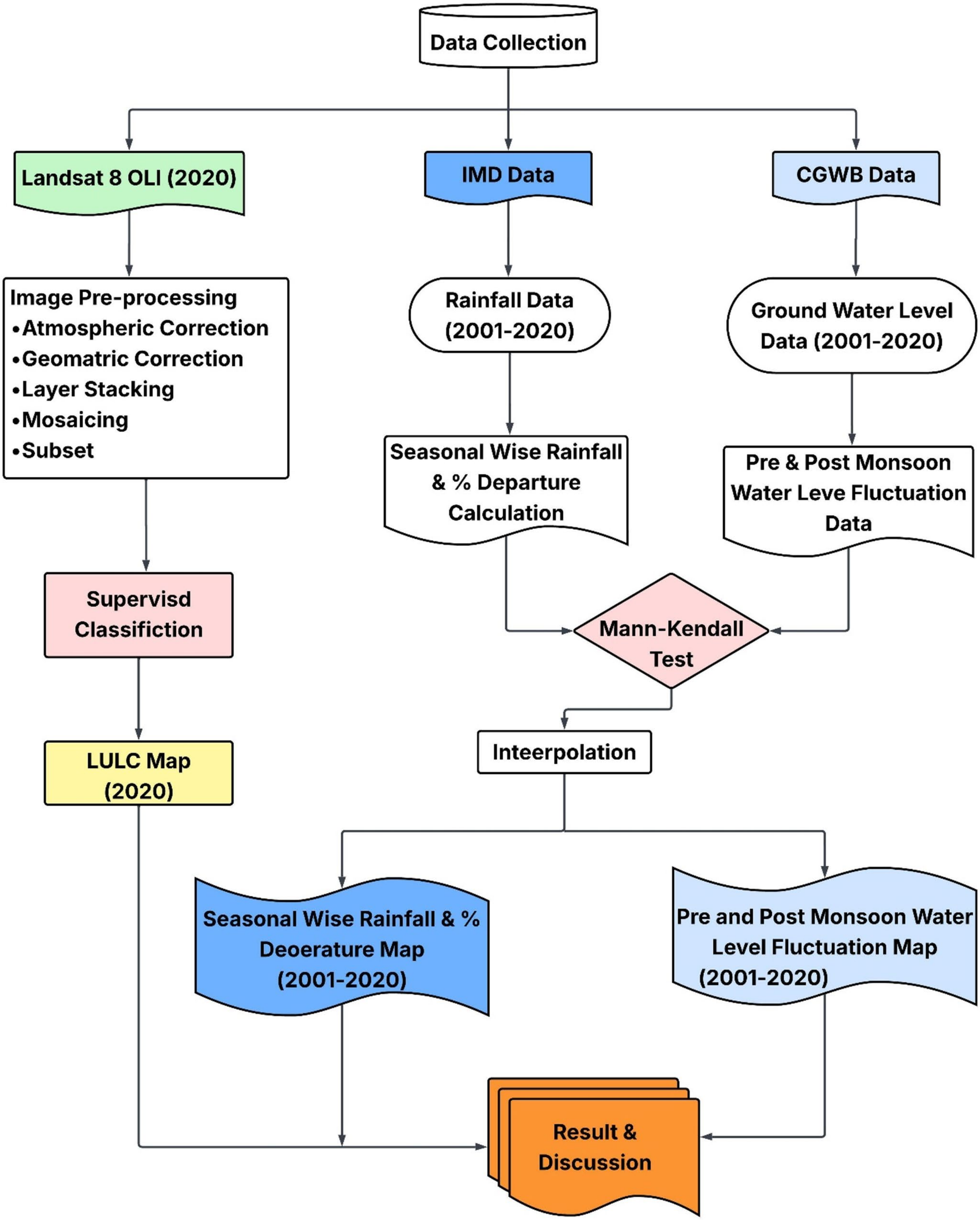


Fig. 3 Workflow of the present study

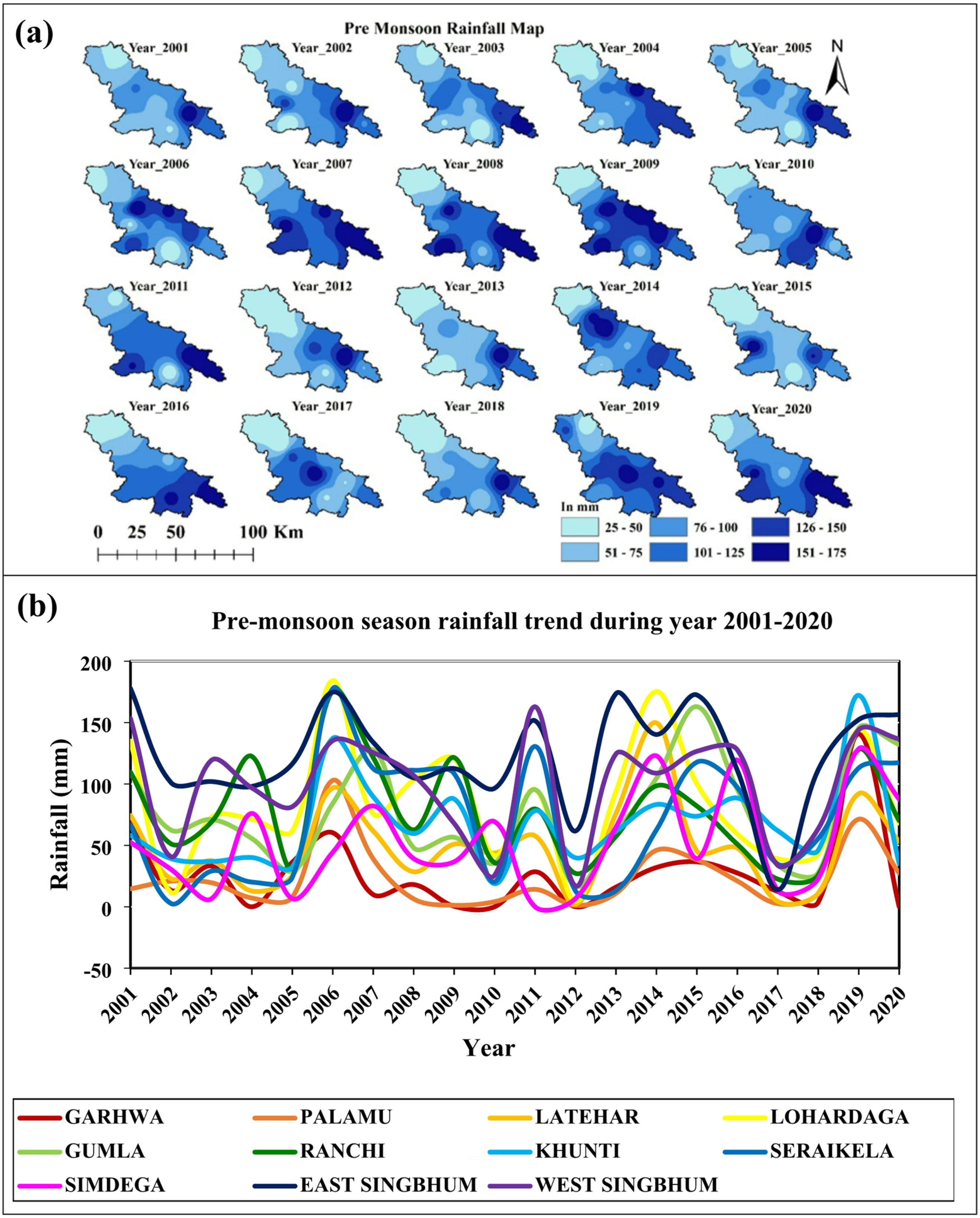


Fig. 4 Annual rainfall (**a**), and annual rainfall trend (**b**) during pre-monsoon season (2001-2020).

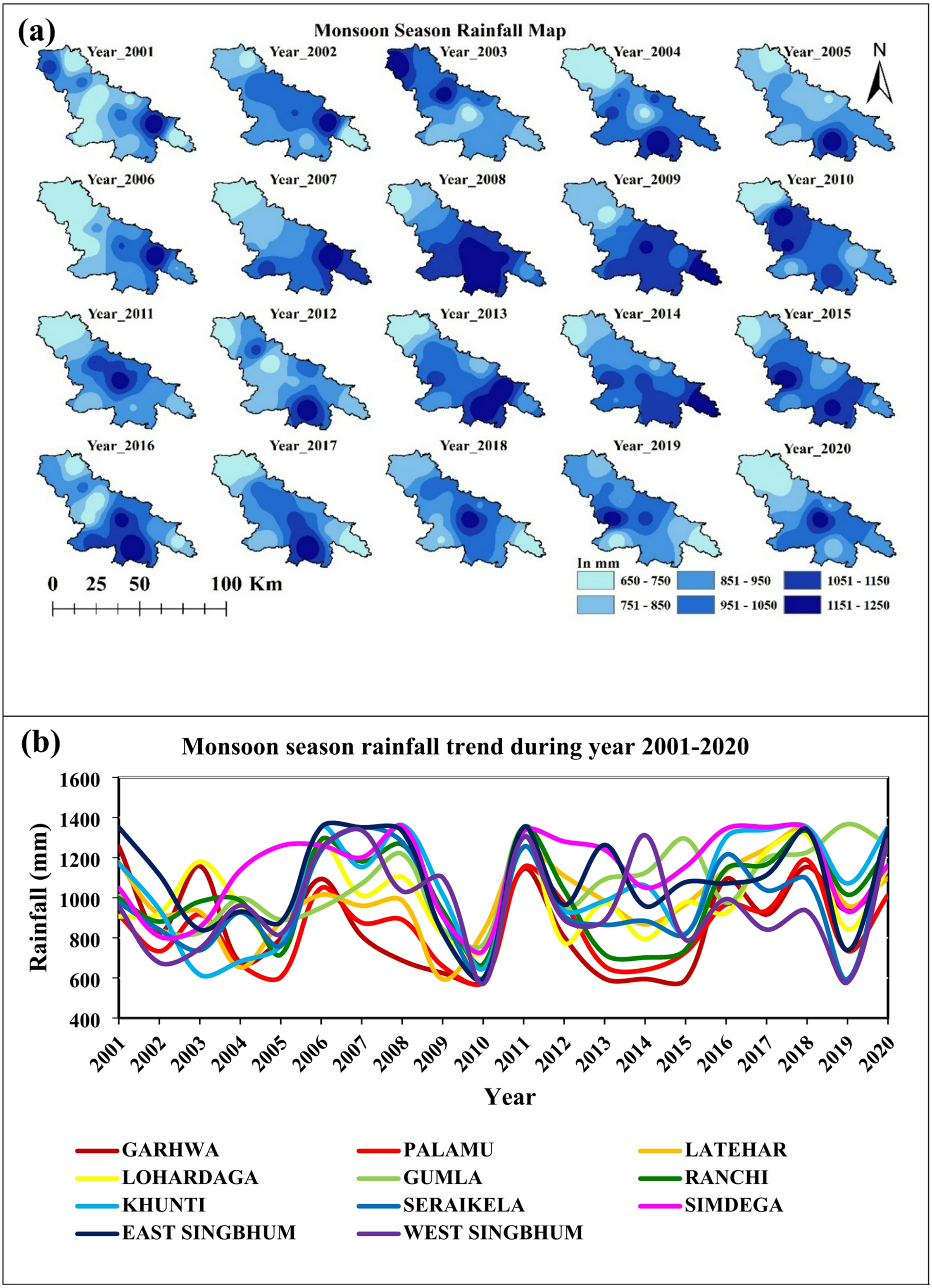


Fig. 5 Annual rainfall (**a**), and annual rainfall trend (**b**) during monsoon season (2001-2020)

showing a negative trend in the northern region of the entire study area and a positive trend in the southwestern part. Overall, we can conclude that during the monsoon season, the rainfall trend is positive.

Post-monsoon rainfall map

The spatio-temporal maps of post-monsoon rainfall over a period of 20 years (2001–2020) help to explain the seasonal variation throughout these years (Fig. 6a). The line graph provided represents the distribution of rainfall from 2001 to 2020 in 11 Jharkhand districts (Fig. 6b).

Rainfall distribution during the post-monsoon season exhibited a spatial pattern, with higher rainfall (101–120 mm) concentrated in the southeast to southwest regions, while minimum rainfall (20–40 mm) was recorded in the northwest to northeast parts of the study area. It was observed that in the years 2009, 2010, 2016, and 2020, rainfall (101–120 mm) occurred in the southeast and southwest parts of the entire study area. During 2001–2020, the central part of the study area experienced normal rainfall (81–100 mm). During 2001–2020, low rainfall (20–40 mm) occurred in the northern part of the study area of Garhwa and Palamu districts and in the southwestern part of East Singhbhum. The trend of post-monsoon rainfall (Fig. 6b) during 2001–2020 shows a negative trend (decreasing rainfall) in the northern region, and a positive trend (increasing rainfall) in the southeastern part of the study area.

Pre-monsoon water level

Pre-monsoon water level maps are used to assess groundwater conditions before the onset of the monsoon season. They assist in understanding groundwater availability, recharge potential, and predicting water availability. The spatial water level map was calculated from 2001 to 2020 using the pre-monsoon values shown in Fig. 7a. An analysis of groundwater status in the pre-monsoon season of the study area is undertaken. The spatio-temporal line chart is utilized to depict trends in water level changes over the 20 years. It is particularly effective in illustrating how water levels change in the pre-monsoon period across different study areas (Fig. 7b).

The pre-monsoon groundwater level (Fig. 7a) in the northeast region fluctuated between 2 and 4 m during the pre-monsoon seasons of 2001, 2003, 2004, 2008–2011, and 2013–2014. In 2002, 2005–2007, 2013, and 2014, the groundwater level in the northern part of the study area fluctuated between 4 and 11 m. Additionally, the groundwater level fluctuated between 12 and 18 m in the southeastern part of the study area in 2001, 2003, 2006, 2010, 2017, and 2020, and between 12 and 18 m in the southeastern part of the study area in 2002, 2003, 2006, 2013, and 2017. In the years 2001–2002, 2004–2006, 2008–2009, 2015, and 2018–2020, in the central part of the study area, the groundwater level fluctuates between 2 and 7 m. The trend of pre-monsoon water level in the study area, as shown in (Fig. 7b), exhibits mild values and drops to (4–16 m) during the pre-monsoon season in May.

Post-monsoon water level map

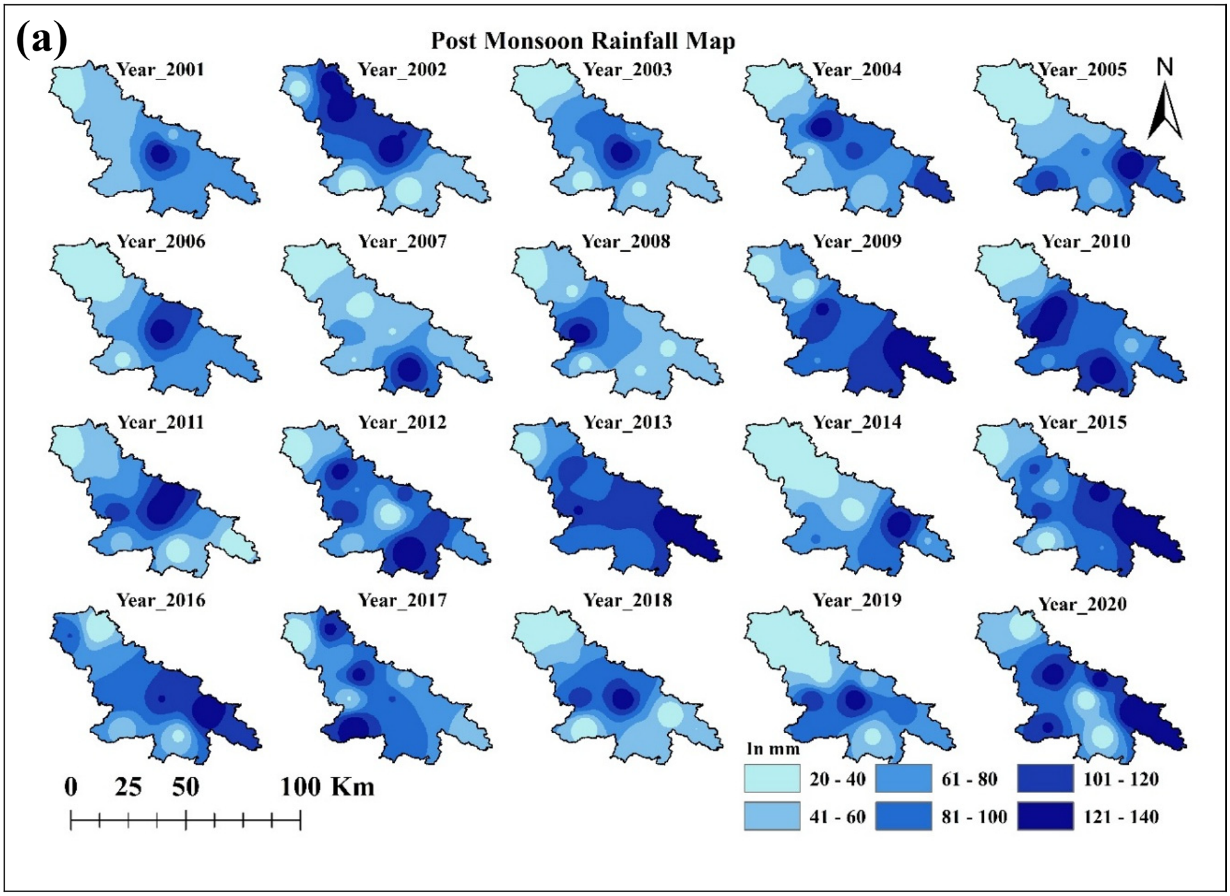
Spatiotemporal maps of post-monsoon water levels are used to assess changes in groundwater levels after the monsoon season. They help to understand recharge patterns, groundwater availability, and potential impacts on water resources and ecosystems. During the post-monsoon season from 2001 to 2020, the total water level of the study area increased compared to the pre-monsoon season, as shown in (Fig. 8a). The post-monsoon water level line graph illustrates changes in groundwater level after the monsoon season. Similarly, during the post-monsoon season from 2001 to 2020, the total water level of the study area increased compared to the pre-monsoon season, as shown in (Fig. 8b).

The water level increased from the northern to the central region, and there was also a rise in water levels in the southern region. After analyzing the map, it is evident that in the years 2003, 2004, 2010, 2014, 2016, and 2017, there was less groundwater recharge and thus less rainfall in the central area of the study area due to the strong urbanization of the region. The trend of positive rainfall during the post-monsoon period is shown in Fig. 8b. A study of groundwater table fluctuations reveals that this place experiences shallow water depths (2–9 m) during the post-monsoon period.

Pre-monsoon percent departure from normal

Pre-monsoon percentage departure from normal is used to assess deviations in rainfall from historical averages before the monsoon season. The pre-monsoon percentage departure from the normal spatio-temporal map displays the variation from 2001 to 2020 (Fig. 9).

The northern region of the study area, including Garhwa and Palamu, received no rainfall. Additionally, there was no rainfall in the Garhwa district in 2001, 2007, 2014, 2018, and 2020. In 2003, 2005, 2006, 2011, and 2015, some parts of the West Singhbhum district received no rainfall. The entire central, western, and eastern regions of the study area, including Latehar, Lohardaga, Gumla, and Khunti, experienced normal to heavy rainfall during 2001–2004, 2007–2009, 2011–2012, 2017, and 2020. The western and central parts of the study area experienced less than normal precipitation in 2002, 2003, 2006, 2010, 2013, and 2018, while the southern and southwestern parts of the study area



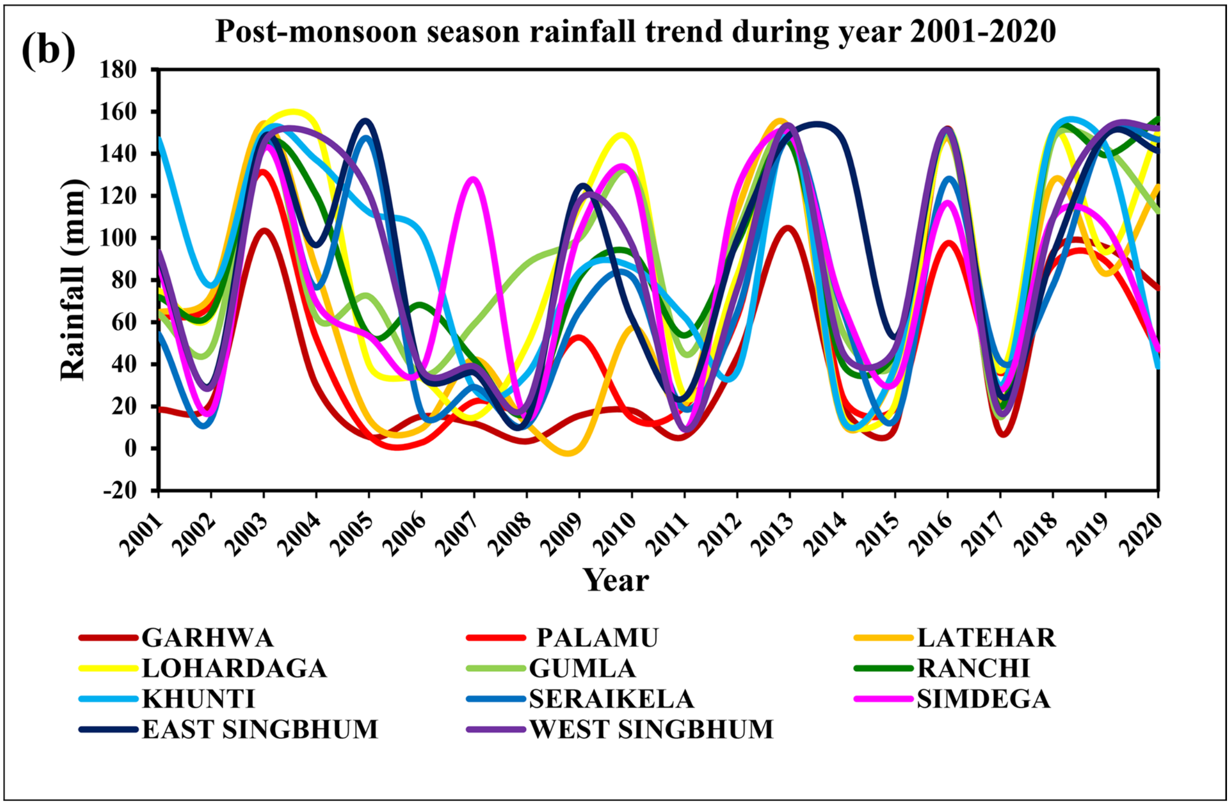


Fig. 6 Annual rainfall (**a**), and annual rainfall trend (**b**) during post-monsoon season (2001-2020)

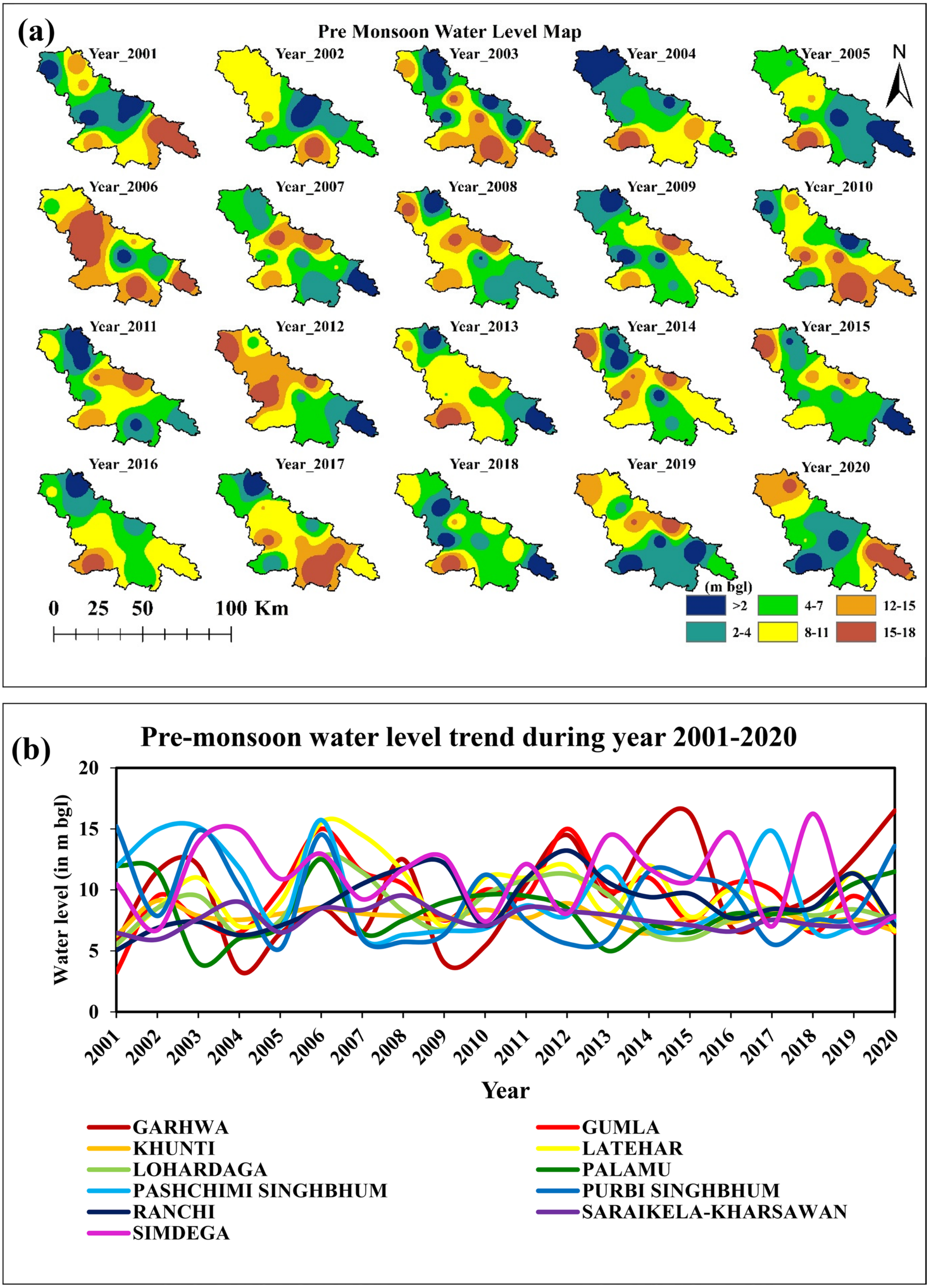


Fig. 7 Annual water level map (**a**), and annual trend of water level graph (**b**) during pre-monsoon season (2001-2020)

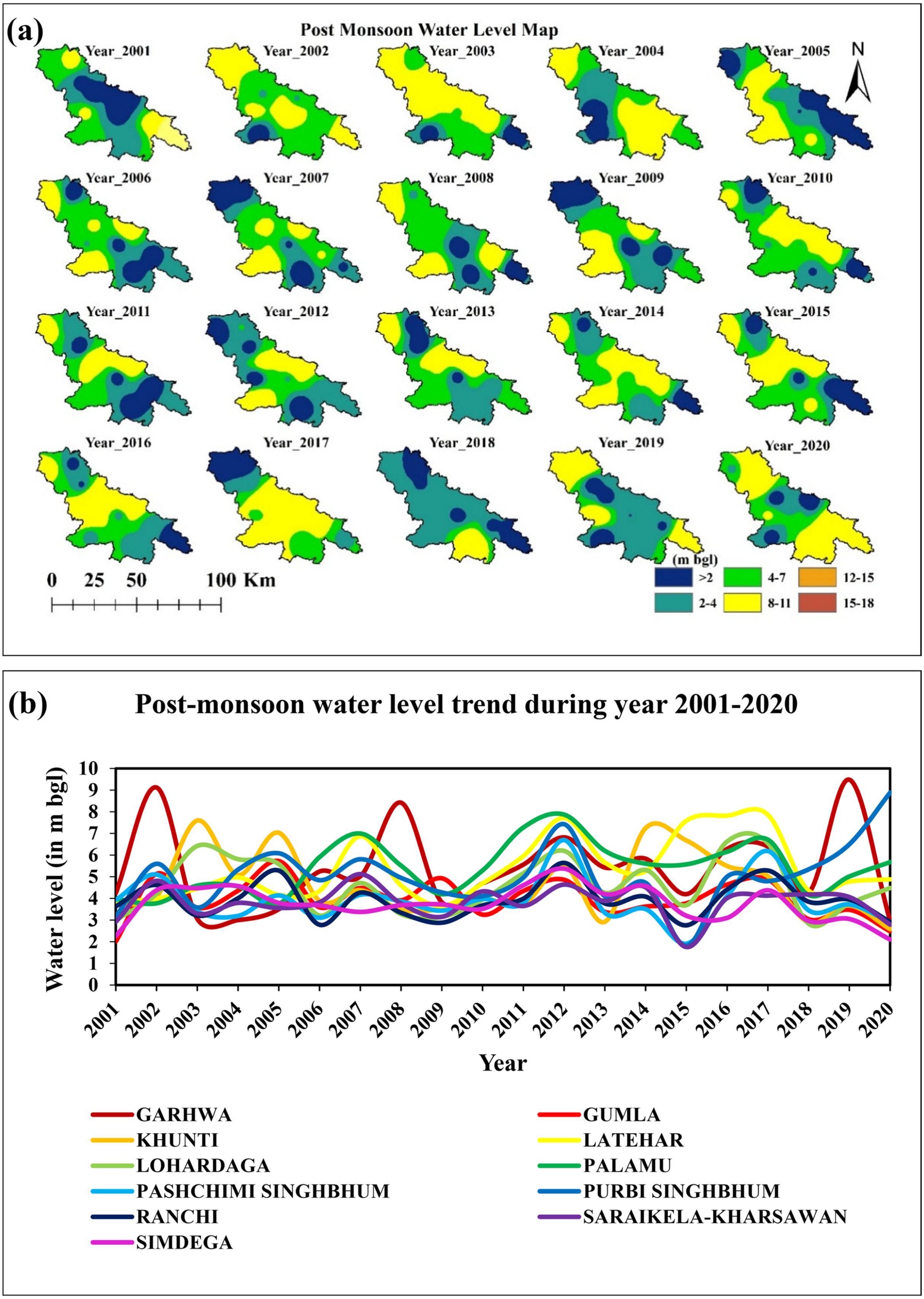


Fig. 8 Annual water level map (**a**), and annual trend of water level graph (**b**) during post-monsoon season (2001-2020)

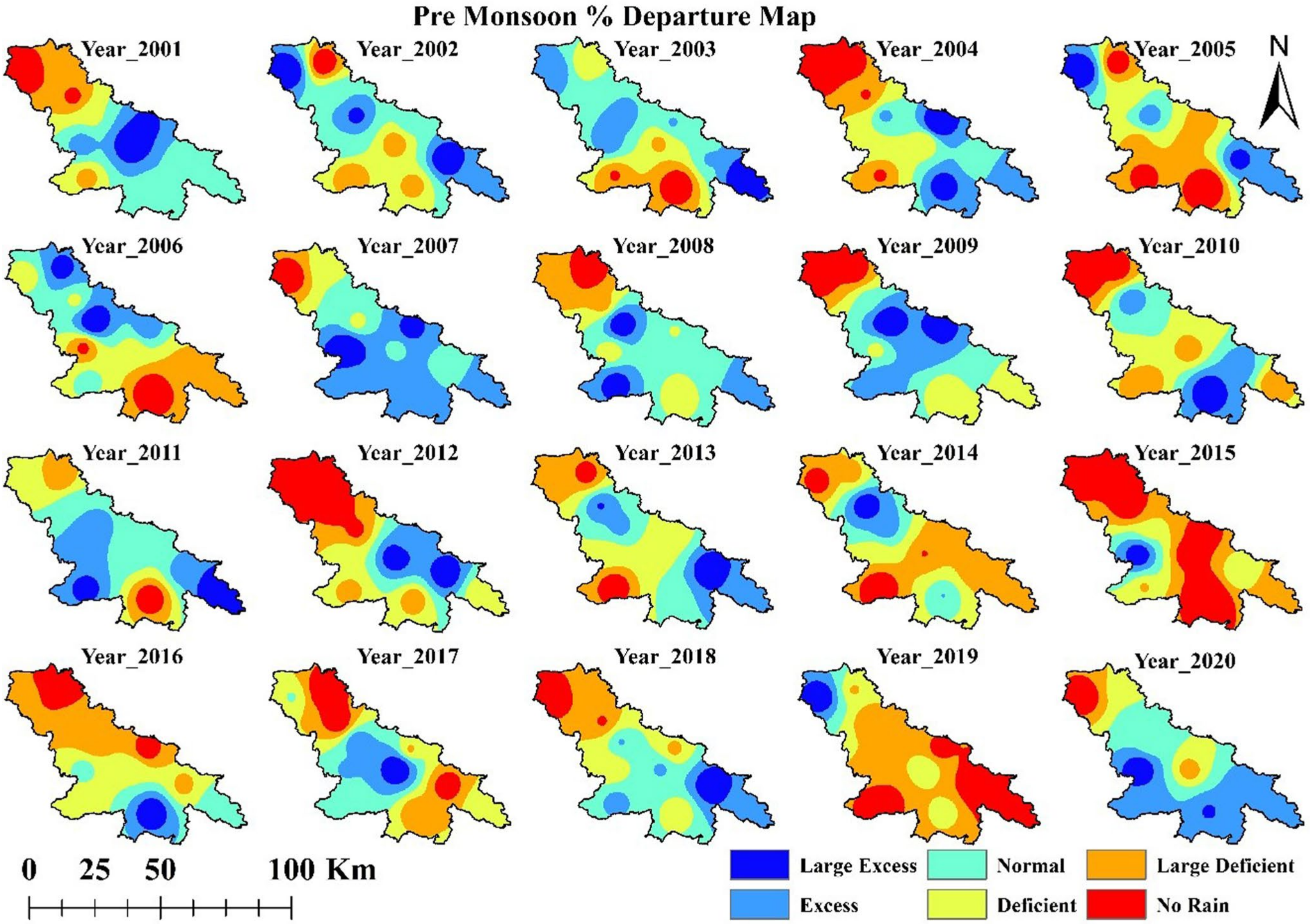


Fig. 9 Pre-monsoon percent departure map of the study area during the years 2001-2020

received less than normal precipitation in 2005, 2006, 2014, 2015, and 2019.

Monsoon season percent departure from normal

The monsoon seasonal percentage departure from normal maps are utilized to analyze deviations of rainfall during the monsoon season from historical averages. This assists in assessing drought or flood risk and in developing water resource management strategies. The spatiotemporal map displays the percentage departure of monsoon from normal patterns during 2001 to 2020 in 11 districts of Jharkhand (Fig. 10). This provides important information about regional differences.

The northern, north-western, southern, and south-western regions of the study area received excess to large excess rainfall, including Garhwa, East Singhbhum, West Singhbhum, and Simdega. Additionally, the central and western parts of the study area experienced inadequate to normal rainfall in 2002–2003, 2005–2006, 2009, 2013–2014, and 2017–2019. Furthermore, the northern part of the study area received significantly less rainfall in 2004, 2006, 2009, 2013–2015, 2017, and 2020, while the central part of the study area received significantly less rainfall in 2001, 2003, 2005, 2007, and 2012.

Post-monsoon percent departure from normal

The post-monsoon percent departure maps (Fig. 11) are used to assess variations in rainfall after the monsoon season compared to long-term climatic normal. This spatiotemporal map illustrates variations in post-monsoon rainfall over a 20-year period (2001–2020), which can be used to qualitatively infer potential groundwater recharge zones based on excess precipitation patterns.

The percentage departure from normal is mentioned in Table 2, with its different ranges mentioned in different categories.

The post-monsoon seasonal percentage departure map (Fig. 11) illustrates that the northern region of the study area, including Garhwa and Palamu, experienced little to no rainfall during 2001 and 2003–2020. Additionally, West Singhbhum and Simdega recorded little to no rainfall in 2002, 2003, 2006–2008, 2011, 2015, and 2016. Furthermore, the

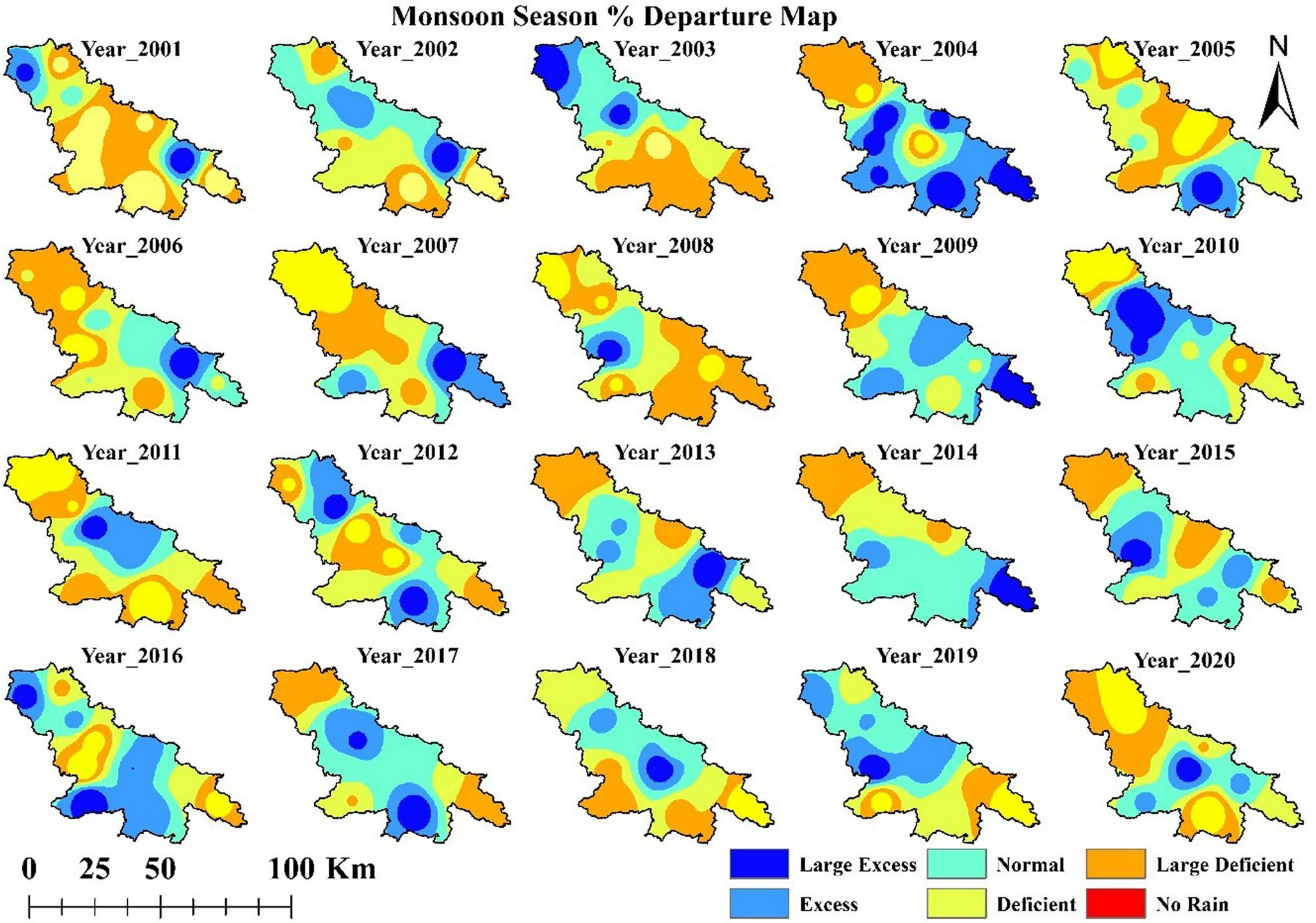


Fig. 10 Monsoonal season percent departure map of the study area during the years 2001-2020

central regions of the study area experienced moderate to excess precipitation in 2001–2003 and 2006, as well as 2009–2011 and 2019–2020. Moreover, the western and central parts of the study area witnessed deficient to severely deficient rainfall in 2001, 2005, 2007, 2008, 2013, and 2015–2018. This variation in rainfall may be attributed to shifts in monsoon withdrawal patterns, atmospheric disturbances, and the influence of large-scale climatic factors such as El Niño and La Niña events.

Rainfall trend using Mann-Kendal test

The Mann-Kendall test for rainfall trend or shifting is utilized to analyze temporal changes in precipitation patterns over time. It helps in identifying trends such as increasing, decreasing, or stable rainfall trends, facilitating climate change studies and water resource management. In this time series, the MK test is analyzed on a monthly, annual, and seasonal basis. The analysis includes pre-monsoon seasons (Fig. 12a), monsoon season (Fig. 12b), and post-monsoon season (Fig. 12c) for rainfall shifting trends.

In the pre-monsoon season (Fig. 12a), all eleven districts, including Garhwa, Palamu, Latehar, Lohardaga, Ranchi, Gumla, Simdega, Khunti, West Singhbhum, East Singhbhum, and Saraikela Kharsawan show negative rainfall trends, with eastern districts such as East Singhbhum and Saraikela Kharsawan showing stronger negative values (below -0.5). During the monsoon season (Fig. 12b), again, the entire study area shows a negative rainfall trend, particularly prominent in central and southern districts like Simdega, Khunti, and Ranchi, where values fall below -1.5. In the post-monsoon season (Fig. 12c), the rainfall trend is again consistently negative across all districts, with central and southern areas such as Simdega, West Singhbhum, and East Singhbhum showing marked declines (below -1), indicating a uniform drying trend.

Water level trend using Mann-Kendal test

The Mann-Kendall test for ground water level trend analysis is utilized to assess changes in groundwater levels over time. It aids in identifying trends such as rising, falling, or stable groundwater levels and thus helps in groundwater

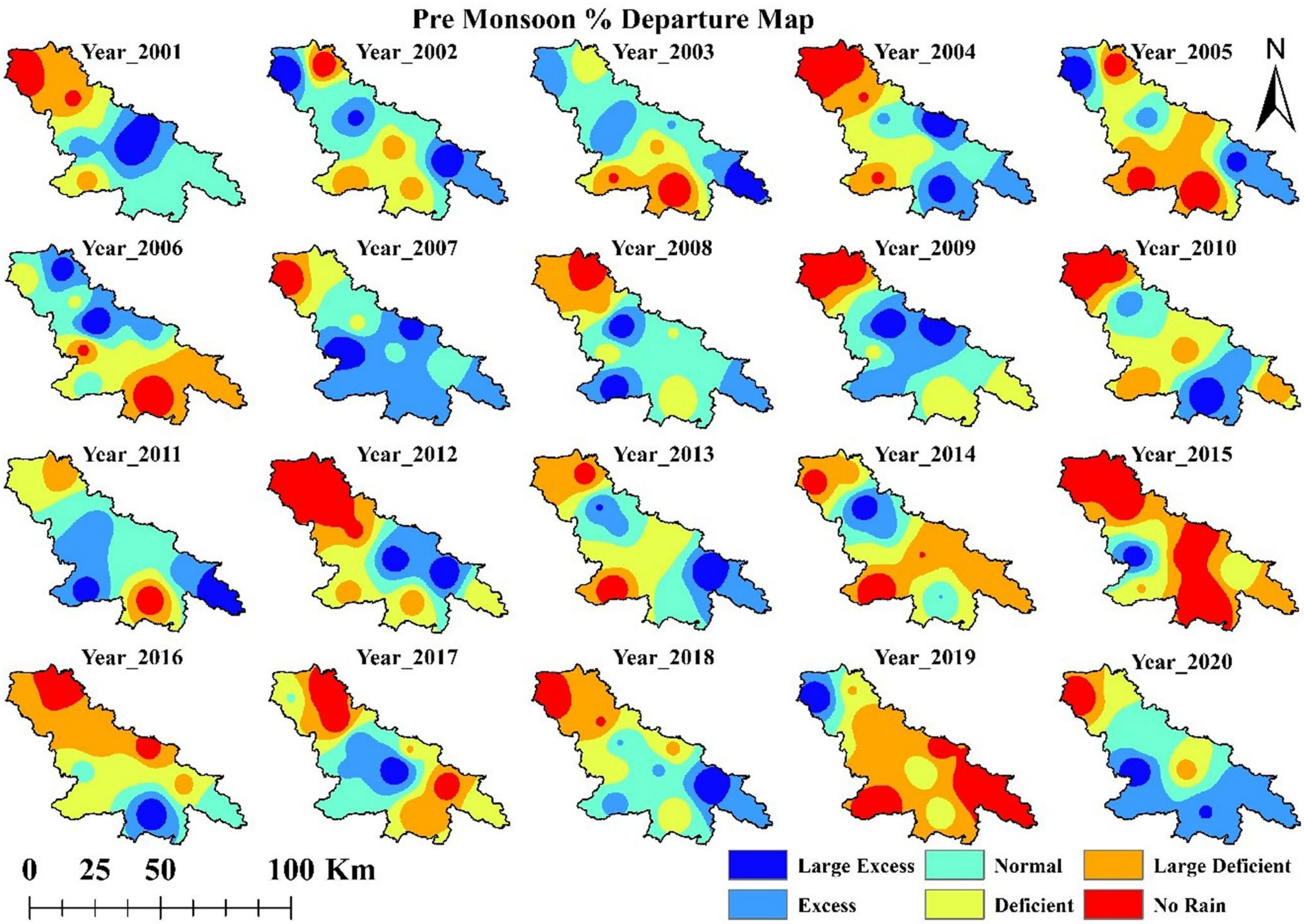


Fig. 11 Post-monsoonal season percent departure map of the study area during the years 2001-2020

Table 2 Different categories of percentage departure from normal

Category	Departure from Normal	Colour Code
Large Excess	60% or More	🟧
Excess	20% to 59%	🟦
Normal	-19% to 19%	🟩
Deficient	-20% to -59%	🟧
Large Deficient	-66% to -99%	🟨
No Rain	-100%	◼
No Data	Data Not Available	⬜

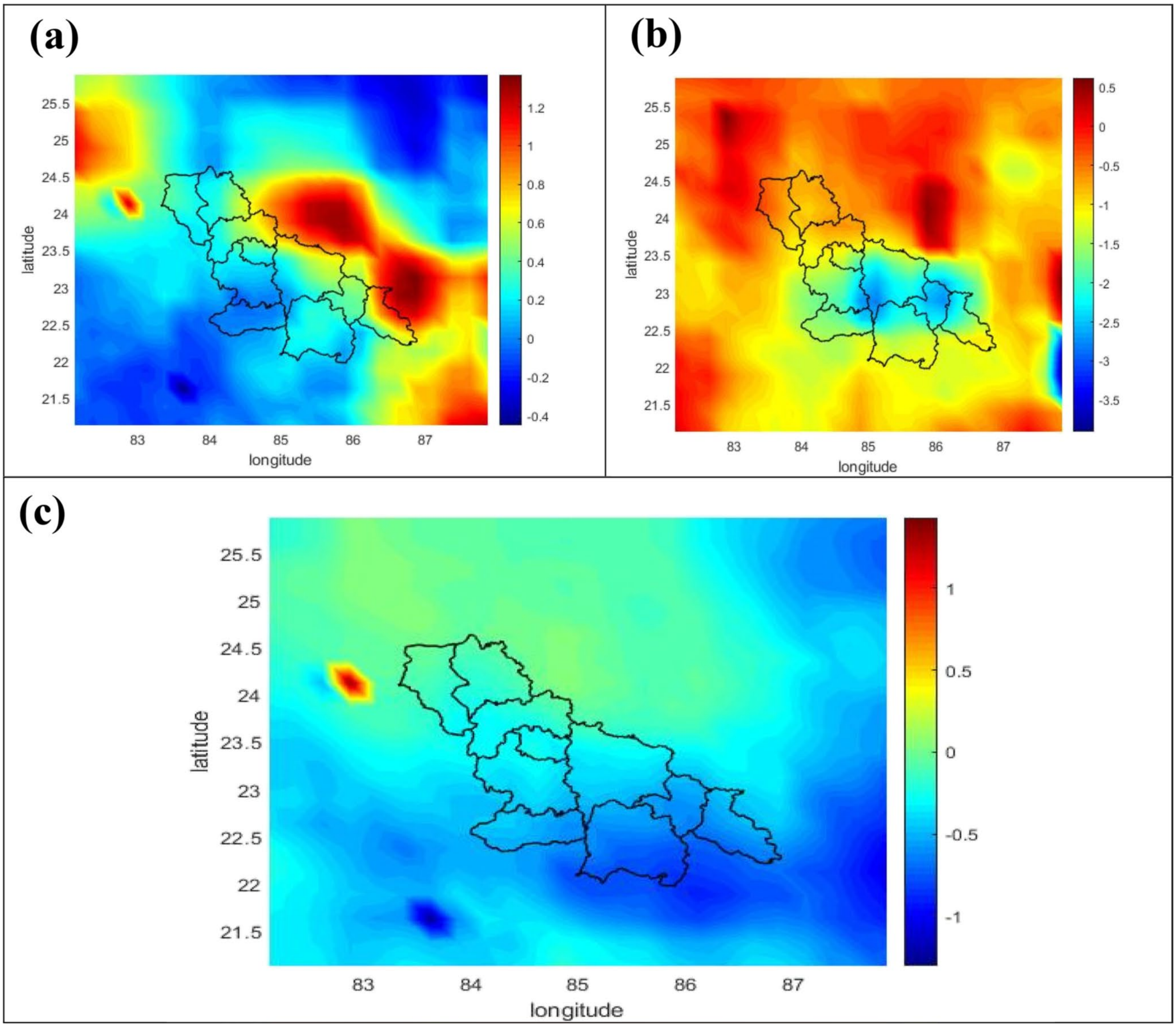


Fig. 12 Rainfall shifting trend of the pre-monsoon season (**a**), monsoon season (**b**), post-monsoon season (**c**) during the years 2001-2020

management. In this time series, the MK test is analyzed on a seasonal basis of water levels. The seasonal time series show the shift or trend of water level using the Mann-Kendall test in the pre-monsoon period (Fig. 13a) and the post-monsoon period (Fig. 13b).

In the seasonal time series (Fig. 13a) of eleven districts, five districts, including Simdega, Lohardaga, Garhwa, Latehar, and the western part of Ranchi, show positive trends, while the remaining districts such as Palamu, Khunti, Sarikhela Kharsawan, West Singhbhum, and East Singhbhum exhibit significant negative trends during the pre-monsoon seasons. During the post-monsoon period (Fig. 13b), six of the eleven districts, including Simdega, Latehar, Gumla, Ranchi, West Singhbhum, and Saraikela Kharsawa, show positive trends, whereas the remaining districts like Garhwa, Palamu, Khunti, and East Singhbhum display a negative trend. Overall, the northern and southwestern parts of the study area are affected by negative trends during the period 2001–2020. The positive groundwater trends observed may be attributed to higher monsoonal rainfall, greater forest cover, and lower groundwater extraction in these regions. In contrast, the negative trends identified in districts are likely due to a combination of low rainfall, over-extraction for irrigation and domestic use, and limited recharge potential due to hard rock terrain or urbanization.

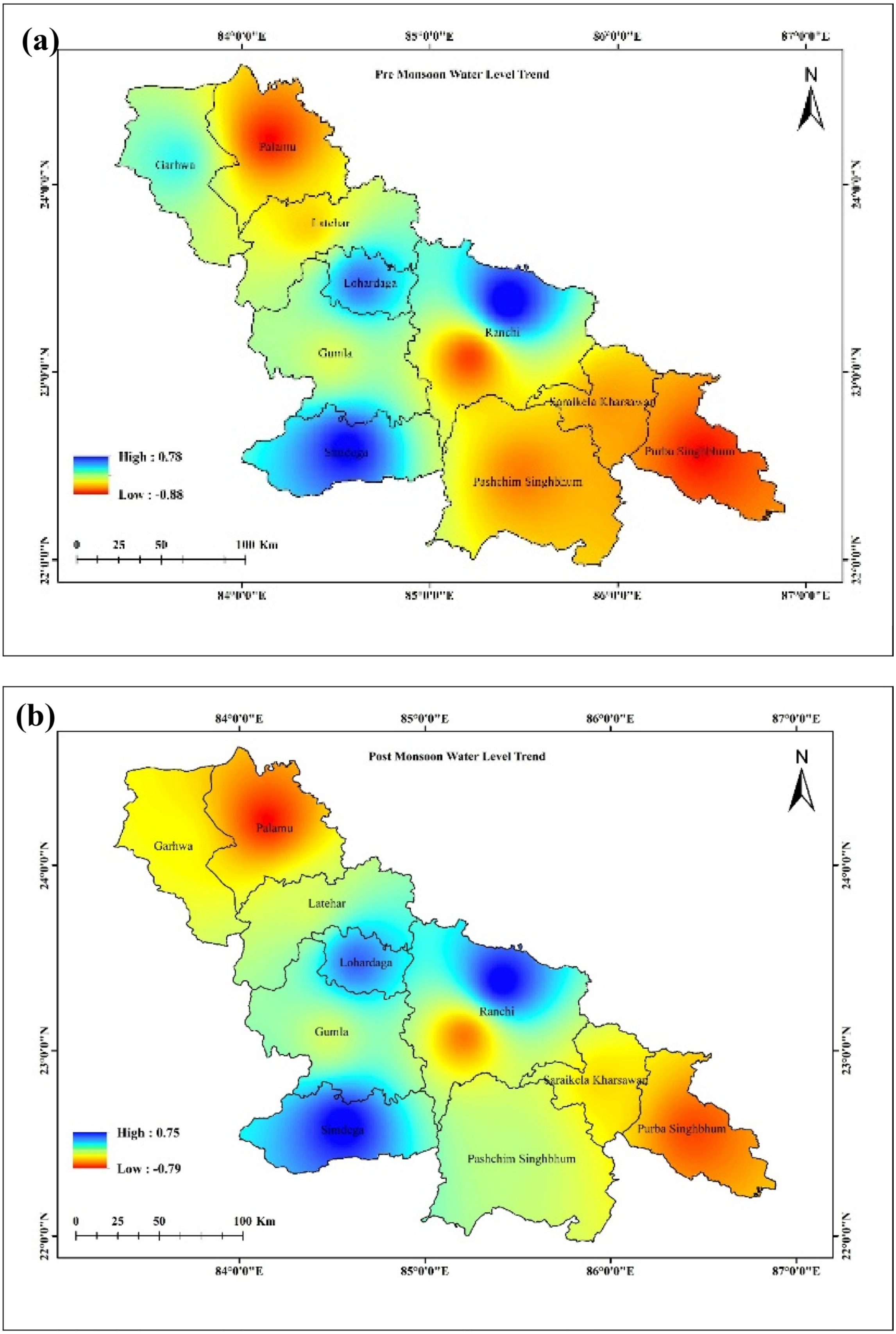


Fig. 13 Water level shifting or trend during the pre-monsoon (**a**), and post-monsoon (**b**) during the years 2001-2020

Discussion

The seasonal trend analysis of rainfall across the 11 districts of Jharkhand from 2001 to 2020 revealed substantial spatial and temporal variation. Negative trends were prevalent across all three seasons, pre-monsoon, monsoon, and post-monsoon, in more than half of the districts. Monsoon rainfall, the primary source of water in this rain-fed region, showed a decline in 7 out of 11 districts, with Sen's slope values decreasing up to −6.8 mm/year, particularly in the northern and eastern districts like Palamu, Garhwa, and East Singhbhum. This declining trend in rainfall is alarming, considering Jharkhand's reliance on seasonal rainfall for crop production and groundwater recharge. Districts such as Simdega, Lohardaga, and Latehar experienced comparatively higher rainfall (up to 1250 mm in the monsoon season), which explains their relative hydrological resilience. Conversely, Garhwa and Palamu experienced monsoon rainfall as low as 650 mm, exacerbating drought risks. These observations are consistent with regional studies that report diminishing monsoonal activity and increasing dry spells in eastern India due to shifts in atmospheric circulation and global warming (Tirkey et al. 2018; Mo et al. 2019). Rainfall during pre-monsoon and post-monsoon seasons also declined, with observed ranges of 25–175 mm and 20–120 mm, respectively. This reduced temporal spread of rainfall limits groundwater recharge and intensifies soil moisture stress. Since agricultural activity in Jharkhand is heavily dependent on these seasonal inputs, even minor deviations in rainfall timing and volume can affect sowing, crop maturity, and yield. The overall reduction in rainfall across all three seasons necessitates adaptive strategies focused on water retention and distribution. This also calls for better weather forecasting and climate-resilient cropping patterns. Thus, the rainfall trend analysis not only confirms ongoing climatic shifts but also establishes their critical role in shaping water resource vulnerability in Jharkhand.

Groundwater level trends exhibited mixed patterns during pre-monsoon and post-monsoon periods across districts. Pre-monsoon groundwater levels ranged from 2 to 18 m below ground level, with notable declines in Palamu, East Singhbhum, and Khunti districts. These negative trends may be attributed to high extraction rates for early-season irrigation coupled with insufficient recharge during the winter months. Conversely, Simdega and Ranchi showed improving trends, with Sen's slope values reaching up to +0.21 m/year, likely due to higher rainfall and possibly better water management practices. During the post-monsoon season, groundwater levels improved in six districts, such as Simdega, Latehar, Gumla, Ranchi, West Singhbhum, and Saraikela Kharsawan, suggesting seasonal recharge from monsoonal rainfall. However, continued depletion in Garhwa and East Singhbhum (–0.12 to −0.17 m/year) despite rainfall points to inefficient recharge, high withdrawal, or unfavourable hydrogeological conditions. Such groundwater trends mirror the concerns raised by earlier studies in India regarding the imbalance between recharge and over-extraction (Bhanja et al. 2017). Land use factors, such as increasing built-up areas, deforestation, and surface sealing, may be further restricting natural infiltration in certain districts. Soil texture, slope, and geology also influence recharge potential (Zomlot et al. 2015; Lapworth et al. 2015). Moreover, the reliance on shallow aquifers in rural areas also makes them more vulnerable to short-term climate fluctuations. This means that declining groundwater levels, especially in the pre-monsoon season, indicate less resilient water availability right before crop plantation. Effective monitoring and mapping of recharge zones can guide interventions like check dams and percolation tanks. However, disparities in groundwater trends across seasons highlight the need for district-specific assessment tools. These tools should integrate hydrological, meteorological, and land use datasets to enable evidence-based planning. The combined trend of decreasing rainfall and groundwater in northern and northeastern districts indicates a potential hydroclimatic hotspot needing immediate policy action.

It is crucial to emphasize that precipitation dynamics play a vital role in groundwater fluctuation (Bhanja et al. 2017). Rainfall serves as the primary natural recharge source for aquifers across the country, especially in hard rock terrains like Jharkhand, where groundwater storage is limited. Variability in monsoon intensity and distribution affects both surface runoff and infiltration potential. Lower rainfall reduces aquifer recharge, while erratic events lead to flash runoff rather than percolation. This linkage is particularly crucial in agriculturally dominant states like Jharkhand, where shallow aquifers support domestic and irrigation needs (Pastagia And Mehta 2022). Managing water resources under such fluctuating rainfall conditions requires integrating climate trend analysis with groundwater planning, using adaptive recharge methods, and regulating extraction, especially in vulnerable districts. Therefore, the insights from this study underscore the need to align groundwater management with precipitation patterns at the seasonal and regional scale.

These findings underline the importance of spatially targeted and season-specific water management strategies in Jharkhand. For instance, efficient irrigation methods can be promoted in Garhwa and Palamu, where groundwater depletion is most critical. In recharge-prone districts like Simdega and Ranchi, rainwater harvesting and aquifer recharge zones should be expanded. Linking rainfall–groundwater data with cropping patterns can also aid in formulating agro-climatic zoning for sustainable agricultural practices (Petare et al. 2016; Pastagia And Mehta 2022). Furthermore, the creation of district-level water resource action plans can guide local entities in addressing site-specific vulnerabilities. While this study focused on 20-year trends, future work should incorporate high-resolution climate models to project rainfall and groundwater patterns under various emission scenarios. These projections can inform early warning systems and climate-resilient agriculture programs. Integrating hydrological trends with socio-economic data such as population growth, irrigation demand, and land use changes will further strengthen policy relevance. This study thus provides a foundational dataset and methodological framework for future water resource planning and climate adaptation in Jharkhand.

Conclusions

A comprehensive analysis of meteorological and hydrological data spanning two decades (2001–2020) in Jharkhand provides valuable insights into the region's climatic patterns and groundwater trends. The rainfall analysis reveals that precipitation varied from 25 to 175 mm in pre-monsoon, 650–1250 mm in monsoon, and 20–120 mm in post-monsoon across different districts. Southern and southwestern regions, such as Simdega and Latehar, consistently receive higher rainfall, whereas northern and northeastern districts like Garhwa and Palamu experience lower precipitation levels. Groundwater levels during the pre-monsoon season ranged from 2 to 18 m below ground level, with deeper water tables in southeastern districts. Application of the Mann-Kendall trend test and Sen's slope estimator revealed that more than 50% of the districts show statistically significant negative trends in rainfall, particularly in monsoon and post-monsoon seasons, with Sen's slope values ranging from −5.4 to −2.1 mm/year. Similarly, pre-monsoon groundwater levels show declining trends in five out of eleven districts, most notably in Palamu, Khunti, and East Singhbhum, indicating reduced recharge potential. Conversely, positive trends were observed in districts like Simdega, Latehar, and Ranchi during the post-monsoon season, with a gradual rise in groundwater levels by up to 0.3 m/year. These findings underscore the importance of targeted and region-specific hydroclimatic analysis for effective water resource management. Identifying areas with significant negative trends supports prioritization for intervention, especially in agriculturally sensitive zones.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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