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Regional teleconnections of ENSO, IOD events, and rainfall trends in Central India

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सार – इस अध्ययन में ENSO (एल नीनो दक्षिणी दोलन) और IOD (हिंद महासागर द्विध्रुव) घटनाओं के वर्षा के रुझानों से संबंध का विश्लेषण किया गया है। 50 वर्षों (1971-2020) के लिए स्थानिक-सामयिक वर्षा विश्लेषण किया गया है। मध्य भारत के नागपुर मंडल के छह जिलों के लिए, MK सांख्यिकी (Z मान) पर आधारित चार मैन-केंडल (MK) परीक्षणों का उपयोग करके 50 (1971-2020) और 30 (1991-2020) वर्षों के लिए रुझान विश्लेषण किया गया है। रुझान परिमाण की गणना के लिए थिल-सेन के ढलान अनुमानक का उपयोग किया गया है। चार परीक्षणों में से, यू और वांग संशोधित MK परीक्षण Z मानों में सबसे महत्वपूर्ण परिणाम प्रदान करता है। 50 वर्षों के रुझान विश्लेषण से पता चलता है कि जून में कोई रुझान नहीं था, जुलाई और सितंबर में वृद्धि का रुझान था, जबकि कुछ जिलों में अगस्त में गिरावट का रुझान था। स्थानिक-सामयिक भिन्नता, वर्षा की कमी और सहसंबंध विश्लेषण का उपयोग करते हुए, ENSO (अल नीनो और ला नीना) और IOD (सकारात्मक और नकारात्मक IOD) घटनाओं के ISMR (भारतीय ग्रीष्मकालीन मानसून वर्षा) पर प्रभाव का अध्ययन किया गया है। ENSO और IOD घटनाओं के प्रति वनस्पति की प्रतिक्रिया का उपयोग सत्यापन के लिए किया गया था। परिणामों से पता चलता है कि नागपुर डिवीजन में अल नीनो घटनाएं निम्न NDVI (सामान्यीकृत अंतर वनस्पति सूचकांक) वाले क्षेत्रों में शुष्क परिस्थितियों से जुड़ी हैं, जबकि सकारात्मक IOD घटनाएं उच्च NDVI वाले क्षेत्रों में अधिक नमी वाली परिस्थितियों से जुड़ी हैं। ला नीना और नकारात्मक घटनाएं शुष्क और अधिक नमी वाली दोनों परिस्थितियों (निम्न और उच्च NDVI) को दर्शाती हैं। अध्ययन क्षेत्र में ENSO घटनाओं की तुलना में IOD घटनाओं का ISMR के साथ महत्वपूर्ण सहसंबंध है।

ABSTRACT. The study investigates teleconnections of ENSO (El Niño Southern Oscillation), IOD (Indian Ocean Dipole) events to rainfall trends. Spatiotemporal rainfall analysis for 50 years (1971–2020) is carried out. Trend analysis for 50 (1971–2020) and 30 (1991–2020) years using four Mann-Kendall (MK) tests, based on MK statistics (Z value), is carried out for six districts of Nagpur division of central India. Theil-Sen's slope estimator is used to compute trend magnitudes. Out of four tests, the Yue and Wang Modified MK test provides the most significant result in Z values. Trend analysis of 50 years shows that June had no trend, July and September had an increasing trend, while August had a decreasing trend in some districts. The impact of ENSO (El Niño and La Niña) and IOD (positive and negative IOD) events on ISMR (Indian Summer Monsoon Rainfall) has been investigated using spatiotemporal variation, rainfall deficiency, and correlation analysis. The response of vegetation to ENSO and IOD events was used for validation purposes. Results indicate that El Niño events are associated with drier conditions in Low NDVI (Normalized Difference Vegetation Index) areas, whereas positive IOD events are associated with wetter conditions (High NDVI area) in Nagpur division. La Niña and negative events show both drier and wetter conditions (Low and high NDVI). The IOD events show a significant correlation with ISMR compared to ENSO events in the study area.

Key words – ISMR, Trend analysis, ENSO, IOD, Regional teleconnections, NDVI.

1. Introduction

Rainfall is an important hydroclimatic parameter that has received wide attention from the scientific community due to its varied spatial and temporal patterns. Climate change has an impact on global and local rainfall patterns, and it is observed that it affects various regions differently. Hence, it is necessary to keep an eye on the changing pattern of rainfall in a specific region. In agrarian countries like India, changes in rainfall patterns may have a significant influence on people's lives and means of livelihood. More so in regions that are not assured rainfall zones in central India. A significant portion of the Indian subcontinent receives the Indian Summer Monsoon Rainfall (ISMR) between June and September (Geethalakshmi *et al*., 2009; Pokhrel *et al*., 2012; Ashok *et al*., 2001; Preethi *et al*., 2017). Around 70% to 90% of the Indian subcontinent's yearly precipitation is contributed by ISMR (Prasanna, 2014; Shukla and Haung, 2016). For the same year, it has been noticed that some parts of India experience drought, while other parts experience flooding (Parthasarathy *et al*., 1994). The agriculture sector is directly affected by the ISMR pattern due to its high dependency on rainfed agriculture, which ultimately influences the Indian economy (Kripalani *et al*., 2003; Preethi and Revadekar, 2012; Prasanna, 2014; Gadgil and Gadgil, 2006). The spatiotemporal variation of rainfall over the region would also influence the distribution of soil moisture, runoff, and groundwater (Kumar and Jain, 2010) and is vital for sustainable use of water resources (Brunsell *et al*., 2010).

A trend analysis can be performed to know the changing pattern of rainfall due to global and regional climate change for better planning of water resources, irrigation practices, and construction of the water storage structures. A non-parametric test is selected over a parametric test due to its suitability for non-distributed (assumption of normality is not requisite), missing, and outlier data. The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is a nonparametric test used to analyze the consistently increasing or decreasing trends (monotonic trends) of time series data. The MK test works for all distributions. Many literatures widely use MK test as only test for trend analysis of rainfall (Martinez *et al*., 2012; Jain *et al*., 2013; Ramadan *et al*., 2013; Kumar *et al*., 2013; Asfaw *et al*., 2018; Ul Shafiq *et al*., 2018). Many researchers proposed the modified Mann-Kendall (MMK) tests to overcome the misinterpretation of significance levels (Z and P values etc.) that arises due to the serial correlation of data. In the MK test, variables such as Kendall's tau, S statistic, and Z statistic are taken into account to determine if climatic time series data showed an upward or downward trend (Asfaw *et al*., 2018). It has been discovered that the existence of serial correlation may produce an increase in the variance, particularly when applying the MK test, resulting in the true null hypothesis of no trends being rejected (e.g., Yue and Wang 2002). Recent research (e.g., Hamed and Rao, 1998; Yue *et al*., 2002; Yue and Wang, 2004) suggested trend-free pre-whitening and variance correction procedures before performing the MK test in order to avoid the influence of serial correlation on the test's performance. Very few literatures have discussed the different modified MK tests. Theil-sen’s slope test (Theil 1950 and Sen 1968) is used to estimate the magnitude of the increasing or decreasing trend. This test indicates a change in magnitude per unit of time. Various studies have been undertaken on spatiotemporal trends and their magnitude in rainfall time series data using parametric and non-parametric tests worldwide (Gajbhiye *et al*., 2016; Meshram *et al*., 2017; Chandniha *et al*., 2017; Bisht *et al*., 2018; Praveenkumar and Jothiprakash, 2018; Asfaw *et al*., (2018); Machiwal et al., 2019). The findings produced by the nonparametric technique seem more acceptable since the Mann-Kendall trend test has a 98% efficiency compared to the conventional least square method of testing $\beta = 0$ (Sneyer, 1990).

Malik *et al*. (2020) conducted a study on 13 districts of Uttarakhand state from 1901–2015. They utilized rainfall data to examine the spatiotemporal trend using MK, MMK, and Kendall Rank Correlation. They also detected the trend's magnitude using Theil-Sen's Slope (TSS) and Simple Linear Regression tests. They concluded that spatial maps can aid water management to avoid the risks and vulnerabilities associated with climate change. Adarsh *et al*. (2014) conducted spatio-temporal trend analysis on four meteorological subdivisions of southern India for the 1871–2011 period. They used linear regression, the Mann-Kendall test, Sen’s slope estimator, the sequential Mann-Kendall test, and the discrete wavelet transform. The results suggest that the frequency and fluctuation of rainfall patterns could be beneficial for hydrologists and irrigation planners to effectively utilize the water resources for farming. Tigabu *et al*. (2020) focused on the Lake Tana basin in Ethiopia for the period 1960 to 2015. They investigated the spatiotemporal variation (trends) of hydrometeorological data, including rainfall, lake water levels, and streamflow. Various statistical methods, including autocorrelation, cross-correlation, Mann-Kendall, and the Tukey mean comparison test, were used for analysis. The results highlighted the need for improved water management practices in agriculture to increase water efficiency and mitigate declining trends in water availability.

Zakwan *et al*. (2019) examined the rainfall data in Bihar from 1950 to 2016. Here, the monthly rainfall data was analyzed to explore spatiotemporal variation using different techniques, such as MK test, linear regression, the index of wetness, standardized rainfall anomaly, and the precipitation concentration index. The study observes a consistent decline in rainfall over the past thirty years, emphasizing the implementation of a comprehensive rainwater harvesting strategy to preserve freshwater and groundwater resources. Machiwal *et al.* (2019) studied the Kachchh district of Gujarat from 1979–2013 to investigate rainfall trends. They utilized eight statistical tests, including the Kendall rank correlation, Spearman rank

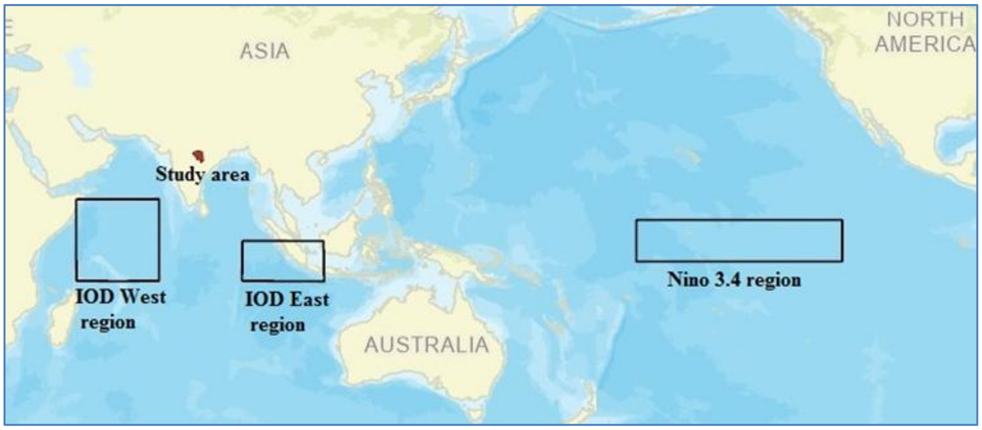


Fig. 1. IOD West and East boundary area of the Indian Ocean and ENSO 3.4 boundary area of the Pacific region, along with the Nagpur division of Central India as study area

order correlation, MK, and different modified MK tests, as well as the innovative trend analysis method. The authors emphasize the importance of considering serial correlation in hydrologic and climatological time series. They recommend using modified MK tests with variance correction methods to address this issue, as the original MK test's performance is poor (Machiwal *et al*., 2019). Three or more statistical tests should be used for trend identification (Machiwal and Jha, 2016; Sonali and Kumar, 2013; Machiwal and Jha, 2008). This form of research has been neglected in nearly all studies conducted in the Indian subcontinent (Sonali and Kumar, 2013).

ENSO and IOD are ocean-atmospheric phenomena occurring in the Pacific Ocean and Indian Ocean that influences the spatiotemporal rainfall variation around the world. Niño 3.4 is an index (currently Oceanic Niño Index–ONI), which represents the average sea surface temperature (SST) anomalies over a region of 5°S–5° N, 170°–120°W, used to track the ENSO phenomenon. The IOD phenomenon takes place in both the eastern (90°E–110°E and 10°S–0°N) and western (50°E–70°E and 10°S–10°N) pole regions. The anomalous SST gradient between the east and west pole regions is known as the Dipole Mode Index (DMI). The ENSO phenomenon affects the spatiotemporal variation of the ISMR (Kirtman and Shukla, 2000; Rasmusson and Carpenter, 1983; Kumar *et al*., 1999; Sikka and Ratna, 2011; Ratna *et al*., 2011; Ashok *et al*., 2019). Weak (strong) ISMR conditions are frequently linked with El Niño (La Niña) events over the Pacific Ocean (Walker 1925; Curtis *et al*., 2001; Hrudya *et al*., 2021). ISMR is highly variable in space and time affected by IOD phenomenon (Ashok *et al*., 2001, 2004; Anil *et al*., 2016). Positive IOD events strengthen the ISMR, while negative IOD events weaken the ISMR (Ashok *et al*., 2001), except during the commencement phase of ISMR (Sarkar *et al*., 2021). Ummenhofer *et al*., 2011 highlights that pure Positive IOD occurrences were often linked to anomalously wet circumstances, whereas most of the pure El Niño events were accompanied by significant deficits in ISMR. Some studies have been carried out near the present study area highlighting that rainfall deficits occurred during the El Niño years, and excess rainfall occurred during the La Niña years (Bothale and Katpatal 2016; Rishma and Katpatal 2016; Bothale and Katpatal 2014; Bothale and Katpatal 2017).

Finding the correlation between the ONI-ISMR and DMI-ISMR is very important to know the impact of the two on ISMR. The Pearson correlation coefficient (r) is one of the most widely used coefficients for identifying positive, negative, or no correlation. Geethalakshmi *et al*. (2009) and Ahmed *et al*. (2017) used correlation analysis to correlate the rainfall with the DMI and ONI indices. Saha *et al*. (2021) used regression analysis to correlate the rainfall with the DMI and ONI indices, considering pure events of ENSO and IOD. Sarkar *et al*. (2021) used correlation analysis to correlate the rainfall anomalies and DMI index. Decadal and yearly correlation of ONI-ISMR and DMI-ISMR doesn't produce a clear indication of impact on ISMR over the present study area (Jibhakate and Katpatal, 2024).

The present study is performed with two broad objectives; (*i*) To analyze the long-term spatial (six districts) and temporal rainfall trends [monthly, seasonal (monsoon season-June, July, August and September (JJAS), and annual] using different non-parametric Mann–Kendall (MK) tests-original MK, Hamed and Rao modified MK (HR-MMK), Yue and Wang modified MK (YW-MMK), and Pre-Whitening MK (PW-MMK); and to estimate the trend magnitude through Theil–Sen's Slope (TSS), (*ii*) To assess rainfall deviations during pure ENSO and IOD events; examine their spatiotemporal impacts on monthly, seasonal, and annual rainfall, and evaluate

TABLE 1

List of different pure events of ENSO (El Niño and La Niña) and IOD (Positive and Negative) years used in the present study (1971–2020)

Pure El Niño (ENSO) years	Pure La Niña (ENSO) years	Pure Positive IOD years	Pure Negative IOD years
1982	1971	1994	1990
1987	1973	2006	1992
1991	1988	2019	1996
2002	1999		1998
2004	2007		2014
2009	2011		2016
	2020		

correlations between ONI–ISMR and DMI–ISMR. The study further validates the teleconnections of ENSO and IOD with rainfall and vegetation (Rabi season) over central India for improved water resource planning. The study analyses the teleconnections of ENSO and IOD phenomena initiated from the regions (Fig. 1) with the ISMR validated for central India.

2. Data and methodology

2.1. *Study area*

The Maharashtra state of central India is divided into six administrative divisions, namely Aurangabad, Nashik, Amravati, Nagpur, Pune, and Konkan (https://dtp.maharashtra.gov.in/about-maharashtra/ administrative-structure/). Nagpur is the easternmost division of Maharashtra state with a total geographical area of 51,336 km^2, as shown in Fig. 2. The present study was conducted on Nagpur division comprising six districts, namely Wardha, Nagpur, Bhandara, Gondia, Gadchiroli, and Chandrapur. It is state division with abundant natural resources. The location of rainfall grid points and the land use/land cover (LULC) map of the study area are depicted in Fig. 3 (A) and (B) respectively.

Nagpur division had an average annual (yearly) rainfall of 1223.7 mm. Within Nagpur division, Gadchiroli district recorded the highest mean annual rainfall of 1438.7 mm, while Wardha district recorded the lowest mean annual rainfall of 988.3 mm. Nagpur, Bhandara, Gondia, and Chandrapur districts have mean annual rainfalls of 1101.6 mm, 1241.3 mm, 1328.2 mm, and 1244.2 mm, respectively. The maximum temperature observed in the region is approximately 46 °C, and the minimum temperature observed is around 5 °C.

2.2. *Data used*

The monthly rainfall (in mm) data of the Indian Meteorological Department (IMD) for Wardha, Nagpur, Bhandara, Gondia, Gadchiroli, and Chandrapur districts were obtained from the web portal of India Water Resources Information System (IWRIS) for the period 1971–2020. In the present study area, 73 IMD grid points are covered, where the grid size is 0.25 degrees x 0.25 degrees [Fig. 3 (A)]. The LULC map for 2020 was obtained from the Environmental Systems Research Institute, Inc. (ESRI), which was generated using European Space Agency (ESA) Sentinel-2 satellite images with 10 m spatial resolution.

2.3. *Methodology*

The present study considered 30-year and 50-year period for analysis. However, 30-year period offers very few pure ENSO and IOD event years, and also the results obtained for 30 years did not show significant trends. Hence, the long-term time series rainfall data, spanning over 50 years, have been considered for trend detection and to incorporate sufficient pure events of ENSO and IOD. ENSO and IOD years representing pure events are depicted in Table 1. Pure ENSO events (El Niño, pure La Niña) and pure IOD events (positive and negative) were considered, while neutral years were not considered. Niño 3.4 SST, i.e., ONI and DMI data, are collected from the Physical Sciences Laboratory (PSL) of the National Oceanic and Atmospheric Administration (NOAA). The Normalized Difference Vegetation Index (NDVI) is the index generated by taking the ratio of responses in red and infrared wavelengths to quantify the greenness of vegetation. The NDVI data were obtained from the MODIS Terra product (MOD13Q1 V6, 250 m resolution) through the ClimateEngine.org web portal. The platform provides 16-day maximum value composites (MVC) corrected for atmospheric effects and pre-processed to minimize cloud cover. For this study, the January NDVI layers of the Rabi season were directly downloaded for the study area.

Different Mann-Kendall tests and Theil-Sen’s slope tests were performed using the pyMannkendall library (Hussain *et al*., 2019) in the Google Colaboratory (i.e., Google Colab) web platform. Using Google Colab, anybody can write and run any Python code through a browser. It is particularly useful for data analysis and machine learning. pyMannkendall is a Python library that provides a complete tool for non-parametric MK trend analysis, covering several forms of MannKendall tests.

The number of events used for the present analysis is: pure positive (3), pure negative (6), pure El Niño (6), and pure La Niña (7). IOD years are referred to from BOM (Bureau of Meteorology), Australia, based on the DMI. Pure events have been sorted out by observing events in IOD and ENSO separately. ENSO years are

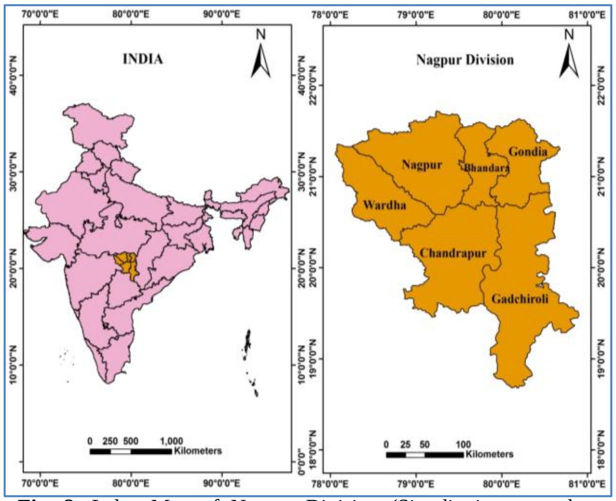


Fig. 2. Index Map of Nagpur Division (Six districts, namely Wardha, Nagpur, Bhandara, Gondia, Gadchiroli, and Chandrapur), Maharashtra (India)

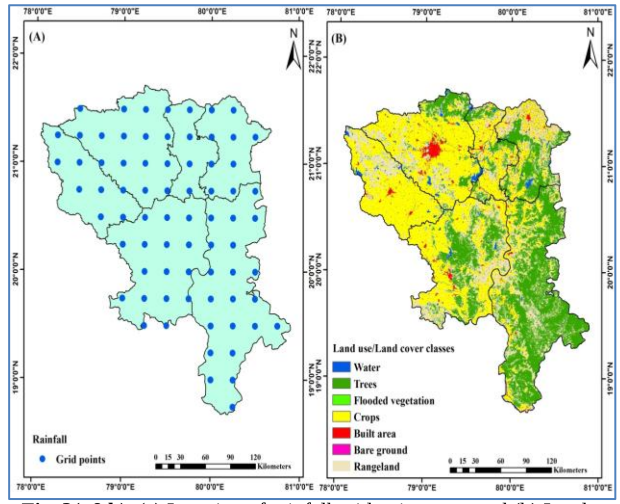


Fig. 3(a&b). (a) Location of rainfall grid points map and (b) Land use/Land cover map (2020) of the study area

referred to from NOAA (National Oceanic and Atmospheric Administration) climate prediction centre based on the Niño 3.4 index. A small attempt has been made to study the regional teleconnections of ISMR with pure events of ENSO and IOD phenomena.

2.3.1 *Mann-Kendall Methods*

In this, two hypotheses were considered: (i) the null hypothesis (Ho): No trend has been observed in the timeseries data. (ii) Alternative hypothesis (Ha): A trend has been observed in the timeseries data. The original MK test is a non-parametric test that does not take into account serial association or seasonal impact. The test provides information on the trend in the data, indicated by the variable h, which is either true (trend is observable) or false (trend is not observable). The significance test's p-value, denoted by p, measures the strength of the evidence against the null hypothesis. The z-score represents normalized test statistics, while tau represents Kendall Tau. The variable s is the Mann-Kendall's score, and var_s is the variance of the score. Theil-Sen's estimator/slope is denoted by the slope. Normalized test statistics (Z) have been considered to identify the trend in rainfall data. For an increasing trend, the Z value should be greater than or equal to 1.96, while for a decreasing trend, it should be less than or equal to -1.96. HR-MMK test was introduced by Hamed and Rao (1998) to overcome serial autocorrelation problems and suggested a variance correction method to improve trend analysis. YW-MMK test is a variance correction approach that addresses serial autocorrelation. It was proposed by Yue S. and Wang C. Y. in 2004. Yue and Wang (2002) recommended the PW-MMK method for pre-whitening the time series prior to the trend test.

2.3.2. *Theil Sen's slope Estimator*

It has been widely used for calculating the magnitude of trend analysis. The TSS test is not significantly affected by the large data errors and outliers, because of which it has the benefit over simple linear regression. A positive magnitude implies a rising value with time (an upward trend), whereas a negative magnitude shows a declining value with time (a downward trend). A complete methodology adopted during the research work is depicted in Fig. 4.

3. Results and discussion

Section-wise results have been discussed below, which try to incorporate the outcomes for the mentioned objectives. In all the analyses, the periods for which these calculations have been made are annual, monsoon season (JJAS), June, July, August, and September rainfall, except for rainfall deficiency (annual data) and correlation analysis (ISMR data) subsections.

3.1. *Descriptive statistics of rainfall*

Descriptive statistics is a basic and useful method for summarizing data in statistical analysis. Using descriptive statistics, we discuss the distribution of rainfall data for the study area. Nagpur division records around 1223.7 mm of mean annual rainfall, with a standard deviation of 228.5 mm. Wardha district records less mean annual rainfall, while Gadchiroli district records more. Gadchiroli has a higher standard deviation of rainfall, and Wardha has the least. Details of other districts regarding the mean, standard deviation, minimum value, and maximum value are listed in Table 2. Here, 25% (first quartile) means 25%

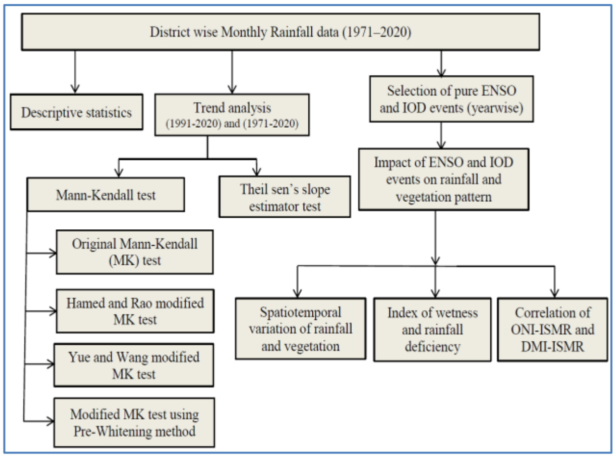


Fig. 4. Overall methodology adopted during research work

TABLE 2

Descriptive Statistics of annual rainfall (in mm) over six districts of Nagpur division including Nagpur division as well for the period of 50-year (1971–2020)

District	Mean	Std devi.	Min.	25%	50%	75%	Max.
Wardha	988.3	193.5	661.4	827.3	997.6	1079	1467.9
Nagpur	1101.6	206	664	954.7	1127.2	1198.4	1652.8
Bhandara	1241.3	258.5	818.1	1067	1221.2	1367.1	2029.3
Gondia	1328.2	273.1	887.4	1142.3	1246.8	1481	2244.5
Gadchiroli	1438.7	309.1	876.2	1190.2	1402.9	1699.1	2194.1
Chandrapur	1244.2	295	784.7	1070	1171.9	1423.9	2012.6
Nagpur division	1223.7	228.5	866.7	1050.2	1224.4	1350.4	1849.6

of the data is less than or equal to that value, and likewise for 50% (median) and 75% (third quartile).

3.2. *Trend analysis of rainfall*

3.2.1. *Mann-Kendall Tests*

The results of 30-years (1991-2020) and 50-years (1971-2020) of trends for the rainfall of June, July, August, September, seasonal (monsoon), and annual time series in the study area are shown in Figs. 5 and 6, respectively. The parameters in both figures, such as Zo (original MK), Zh (HR-MMK), Zy (YW-MMK), and Zp (PW-MMK), have been used to identify the Z values of respective districts and divisions. Statistically significant at $\alpha = 5\%$ (critical $Z = \pm 1.96$) has been shown with dotted red colour lines (Figs. 5 and 6). The value of Z greater than or equal to +1.96 indicates increasing trend while, less than or equal to −1.96 indicates decreasing trend. The original MK test and the Hamed and Rao modified MK tests exhibited similar trends but did not provide information on whether the trend was increasing or decreasing. In contrast, the Yue and Wang modified MK test showed statistically significant trends at a significance level of $\alpha = 0.05$. Out of these four methods, YW-MMK test provided the most significant results (Z values). The YW-MMK test results observed over here are consistent with the study carried out by Machiwal *et al.* (2019).

The comparison of these 30-year results with the 50-year results reveals the variation that occurs when the period of trend analysis is changed. In June, no trends are observed in either period. In July, the 30-year record shows no clear change, while the 50-year record indicates increase in rainfall trends in most districts except Bhandara. August declines are limited to Gondia in the 30-year record but extend to Wardha and Bhandara in the 50-year record. In September, increases expand from a few districts in the 30-year period to most districts in the 50 years. At the seasonal (JJAS) and annual scales, the 50-year record reveals broader increase (Nagpur, Gadchiroli, Chandrapur) and highlights Bhandara's annual decline, showing that longer records capture stronger and more widespread trends. Comparison of the 30-year and 50-year records demonstrates that trend detection is highly sensitive to dataset length. Short-term analyses capture only limited, localized changes, whereas longer records reveal robust, spatially consistent increases, especially in July and September, highlighting the risk of underestimating long-term variability when using shorter datasets.

3.2.2. *Estimating the Magnitude of trend using Theil–Sen's slope estimator method*

In the 30-year record, Gondia shows strong declining trends (≈ 8 mm/year for JJAS and annual, and 3.5–2.6 mm/year in July–August), while increases are limited mainly to September in Gadchiroli (4.5 mm/year), Chandrapur (3.5 mm/year), and Wardha (1.6 mm/year) (Fig. 7). Gadchiroli also shows an increasing trend with a magnitude of 2.5 mm/year in JJAS. A 50-year record reveals broader and more consistent increases across districts such as Gadchiroli, which exhibits robust gains (up to 4.3-4.26 mm/year in JJAS and annual, ≈ 215 mm increase over 50 years), with Chandrapur, Wardha, Gondia, and Nagpur also showing positive trends in July, September, and JJAS. Bhandara alone shows persistent declines (2.2 mm/year annual, 1.46 mm/year August).

3.3. *Impact of ENSO and IOD events on ISMR based on rainfall deficiency*

The index of wetness is the deviation of rainfall for a particular year and region. The index of wetness is

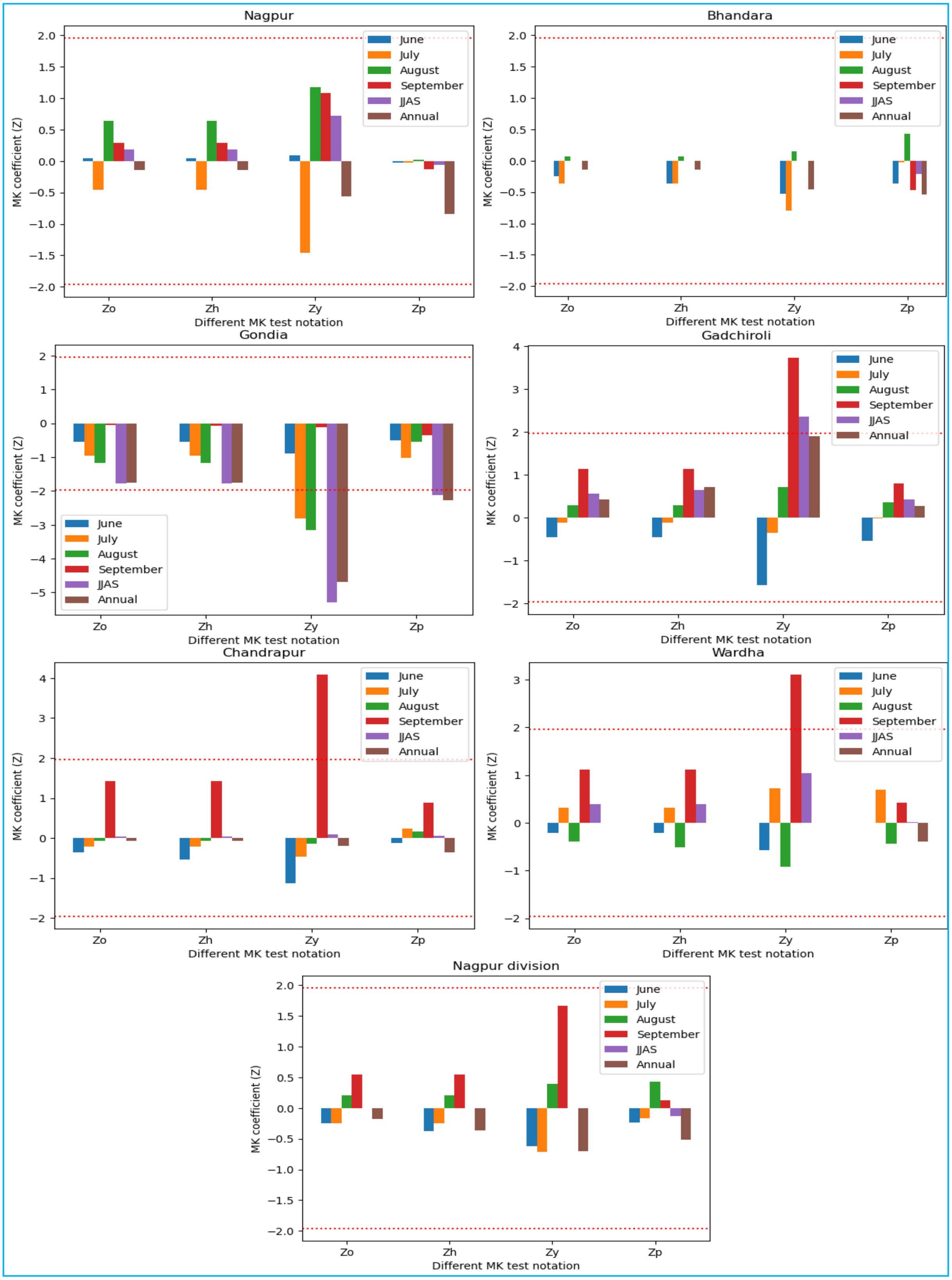


Fig. 5. Trend analysis over 30-year (1991-2020) of rainfall data using different Mann-Kendall methods (Zo-Original MK, Zh-Hamed and Rao MMK, Zy-Yue and Wang, and Zp-Pre-whitening) for various districts of Nagpur Division and for Nagpur Division

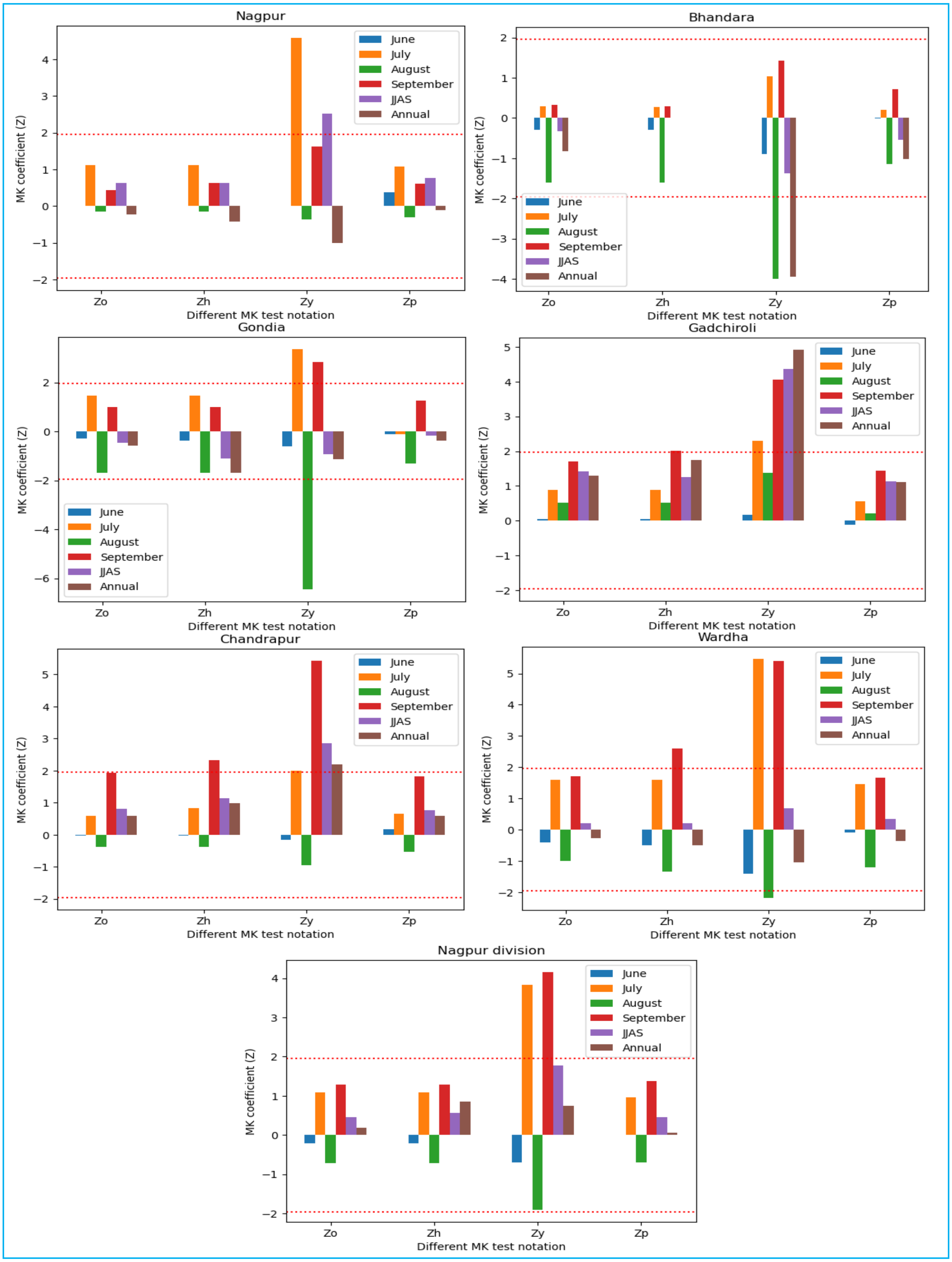


Fig. 6. Trend analysis over 50 years (1971-2020) of rainfall data using different Mann-Kendall methods (Zo-Original MK, Zh-Hamed and Rao MMK, Zy-Yue and Wang, and Zp-Pre-whitening) for various districts of Nagpur Division and for Nagpur Division

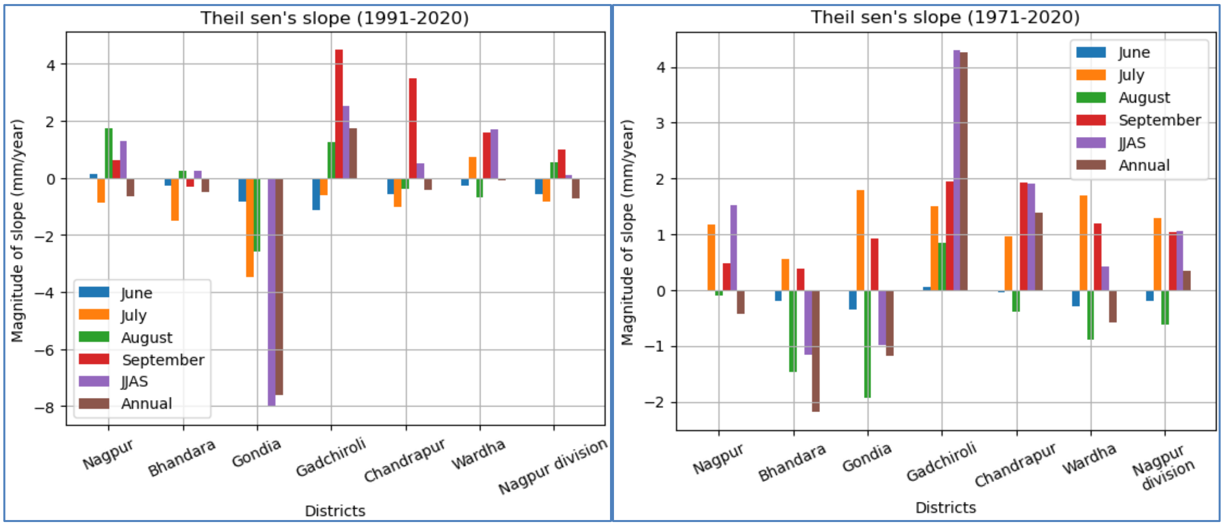


Fig. 7. Magnitude of slope (mm/year) for both the 30-year (1991-2020) and 50-year period (1971-2020) of time series estimated using Theil-Sen's slope method

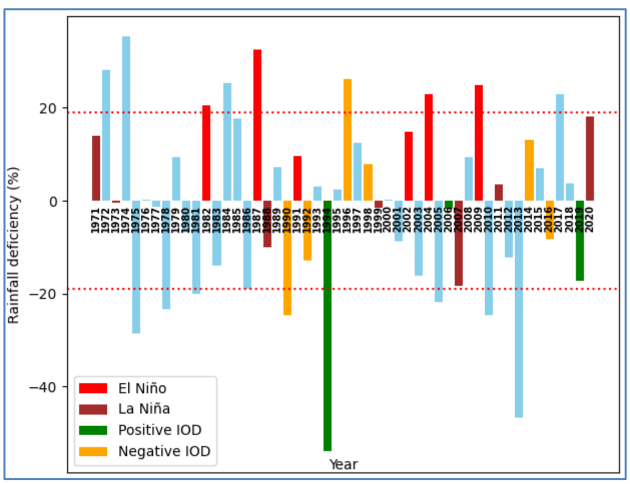


Fig. 8. Rainfall deficiency (%) during ISMR (JJAS) over Nagpur Division for pure events of Positive IOD, Negative IOD, El Niño, and La Niña from 1971–2020 (Threshold value: ±19% of normal rainfall considered to classify the years as deficit, normal, or surplus rainfall events)

represented in Eqn. (1), and rainfall deficiency is derived from the index of wetness and is represented in Eqn. (2).

$$\text{Index of wetness} = \frac{\text{Annual rainfall}}{\text{Average annual rainfall}} * 100 \qquad (1)$$

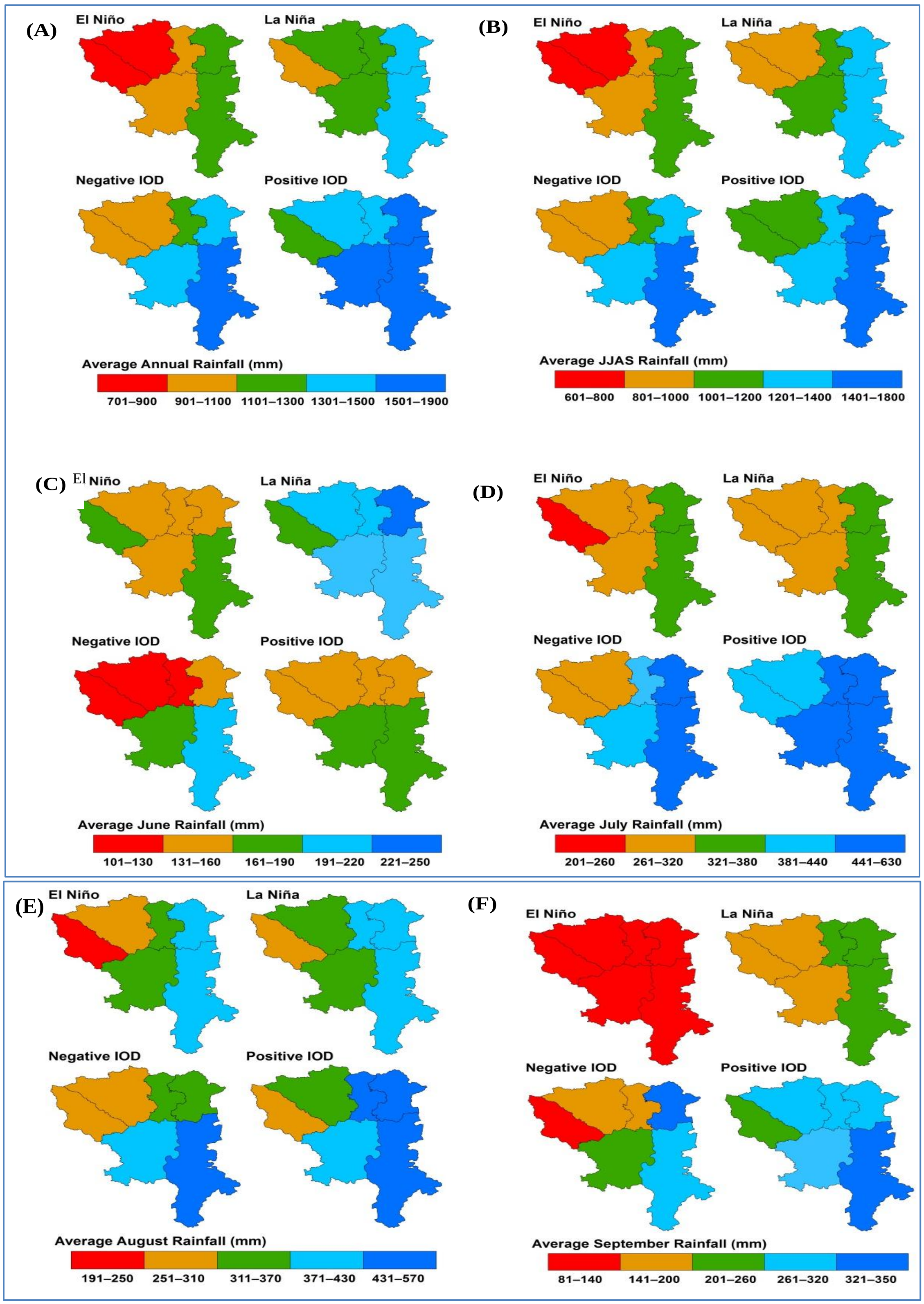
$$\text{Rainfall deficiency} = (100 - \text{Index of wetness}) \qquad (2)$$

Positive values of rainfall deficiency denote deficiency, and negative values denote surplus rainfall for that particular year. Rainfall deficiency was calculated based on the index of wetness to observe the scenarios of different events with respect to the rainfall.

For this analysis, we focused exclusively on the Nagpur division and analysed the monsoon season (JJAS). The plot in Fig. 8 illustrates the rainfall deficit, shown by different colour coding, and correlates it with specific occurrences of ENSO and IOD events.

The El Niño event of the ENSO phenomenon has a substantial influence on the rainfall pattern in the research area, as clearly demonstrated in Fig. 8. The IMD asserts that the ISMR is perceived as normal when the deviation of monsoon precipitation from its seasonal mean lies within the ±10% threshold on a national scale. In case of smaller geographic regions within the country for each meteorological sub-division and district, the following criteria are considered. Normal: ±19% of normal, Excess: +20% of normal or more, Deficient -20% to -59% of normal, Scanty: -60 % of normal or less (IMD chapter 34-Rainfall). This categorization is adopted for the analysis, which is crucial for understanding regional climate impacts.

Four out of six years of El Niño, have recorded significant rainfall deficits, corroborating the fact that El Niño events bring drier conditions to central India region (Bothale and Katpatal, 2014; Rishma and Katpatal, 2016; Bothale and Katpatal, 2016; Bothale and Katpatal, 2017). In 1994, a positive event of the IOD phenomenon recorded the highest rainfall over the study area. One positive IOD event (1994) observed surplus rainfall with respect to normal rainfall (Ashok *et al.*, 2001; Yamagata *et al.*, 2004; Hrudya *et al.*, 2021) while, two positive IOD events fall in normal rainfall category. Ummenhofer *et al.*, 2011 also presented a similar kind of interpretation with respect to El Niño and positive IOD events for the core



Figs. 9(A-F). Spatiotemporal variation of average rainfall considering pure events of ENSO and IOD phenomena (A) Average annual rainfall; (B) Average monsoon season (JJAS) rainfall; (C) Average June rainfall; (D) Average July rainfall; (E) Average August rainfall; (F) Average September rainfall to assess the response of rainfall pattern to these events

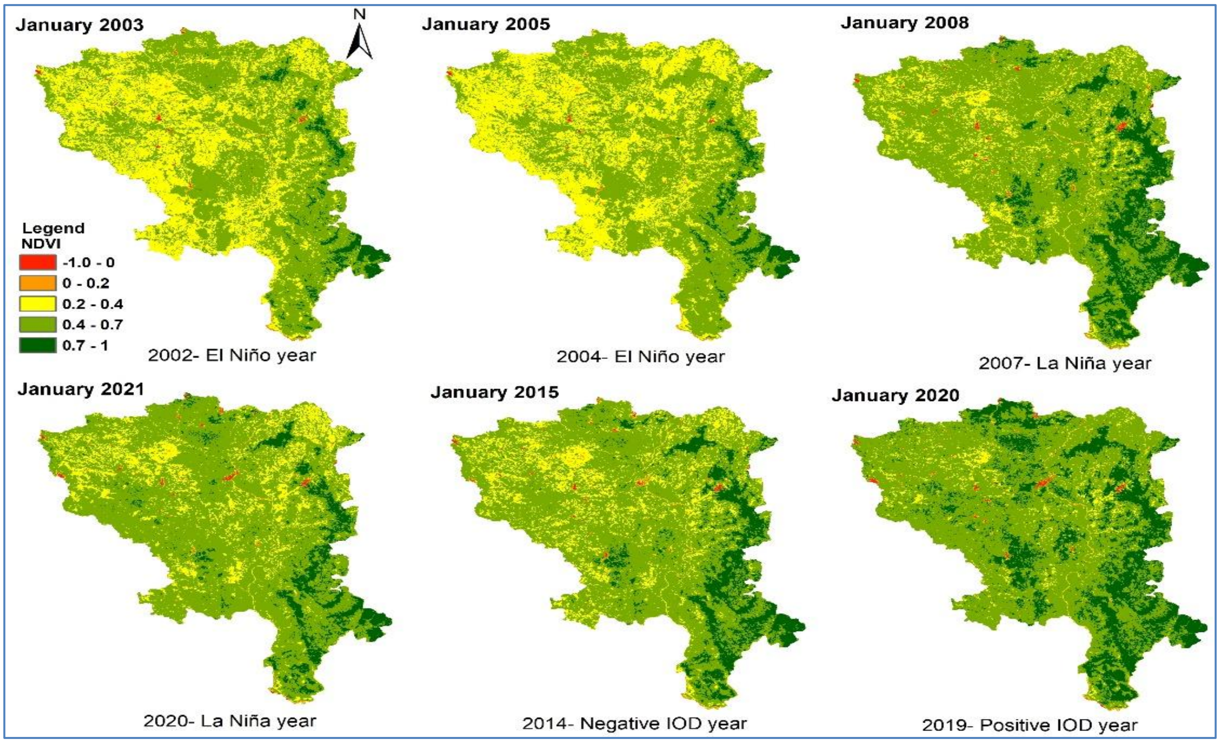


Fig. 10. Vegetation intensity (NDVI) response of the January month of the Rabi season to preceding pure events of ENSO (El Niño and La Niña) and IOD (Positive IOD and Negative IOD) for validating the impact of rainfall on vegetation dynamics

Indian monsoon region (central India). Ashok *et al*., 2001 observed that excess rainfall in the monsoon core zone is linked to positive IOD events, while negative IOD events result in a decrease in rainfall intensity. But here, La Niña events of the ENSO phenomenon and negative events of the IOD phenomenon show a mixed reaction of rainfall patterns, i.e., deficiency and surplus.

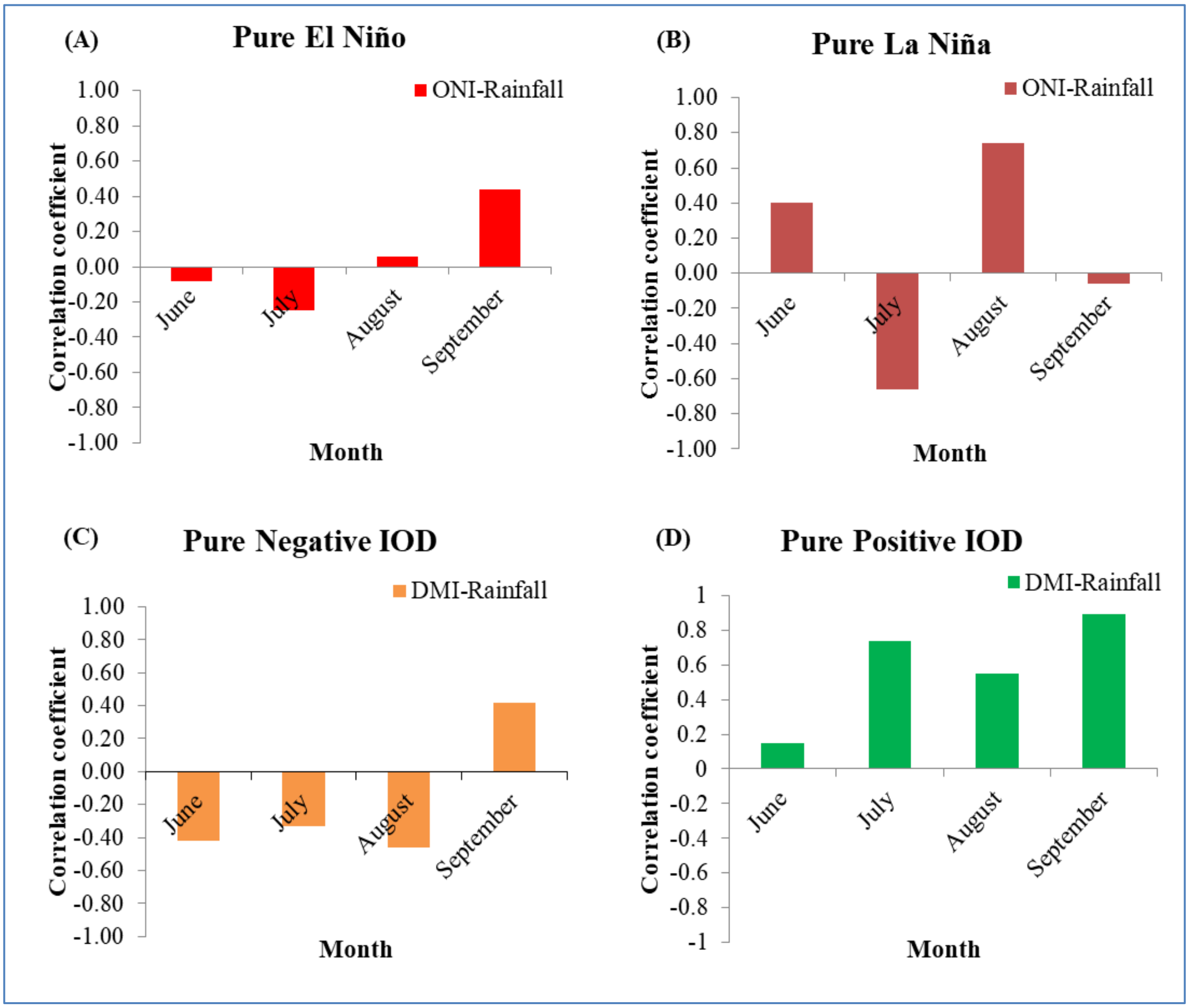
3.4. *Identifying impacts of IOD and ENSO events on spatiotemporal rainfall pattern*

Spatiotemporal maps of six districts of Nagpur division for the annual, JJAS, June, July, August, and September are shown in Fig. 9 (A) to (F), respectively. The impact has been analysed by averaging the rainfall data of respective years of pure events of ENSO and IOD. The results shows that June rainfall over the study area varies between 101 and 250 mm, and July rainfall varies between 201 and 630 mm. The July and August months observed the peak rainfall (around 200–600 mm) in the monsoon season. In September, average rainfall varies between 81 and 350 mm. It may be observed that during a positive IOD event, the average annual rainfall over the study area was higher than the other events [Fig. 9 (A)]. All the events, Gondia and Gadchiroli districts receive more rainfall. In all events, Nagpur and Wardha districts receive less rainfall [Fig. 9 (A) to 9 (F)]. It may be observed that the El Niño events are more prominent in September as it brings less rainfall to all districts compared to other events [Fig. 9 (F)]. The study area recorded less rainfall in all events of ENSO and IOD in June and September compared to July and August.

3.5. *Spatiotemporal variation of NDVI with respect to preceding IOD and ENSO events*

Variation in rainfall due to ENSO and IOD also affects the greenness in vegetation. Higher rainfall results in higher NDVI values and vice versa. In the present study, the impact of these events is assessed to validate by mapping spatiotemporal variation of NDVI for the January month (Rabi season) of successive years to the preceding pure events (Fig. 10).

The impact of ENSO and IOD events on vegetation was studied by using the 16-day MODIS Terra data (MOD13Q1 V6 product). A few events of the ENSO and IOD phenomena have been taken into account to highlight the response of vegetation over the study area. An area with low NDVI values is observed in Rabi crop of January



Figs. 11(A-D). Pearson correlation coefficient of ONI-ISMR and DMI-ISMR (June, July, August, and September) considering pure events of ENSO and IOD, viz., (A) Pure El Niño; (B) Pure La Niña; (C) Pure Negative IOD; (D) Pure Positive IOD

2003 and 2005 due to preceding pure El Niño events of 2002 and 2004 respectively. Whereas, La Niña events of 2007 and 2020 affected the NDVI of January 2008 and January 2021 with mixed higher and lower NDVI value areas compared to El Niño events. Response of vegetation in January 2020 due to Positive IOD years (2019) shows significantly high NDVI values over the study area compared to low NDVI values in Negative IOD year (2014).

3.6. *Assessing the correlation of ONI–ISMR and DMI–ISMR for monsoon season months*

An attempt has been made here to correlate the ENSO event (ONI values) and the IOD event (DMI values) with the rainfall in the study area using Pearson correlation coefficient. The correlation analysis of ENSO and IOD events with the monthly rainfall data for each month of the monsoon season (June, July, August, and September) is presented in Fig. 11. Monthly ONI and DMI values are available, therefore, we only used monsoon season months for correlation. Positive IOD event years show a significant positive correlation with the rainfall of all four months of ISMR. Negative IOD events show a significant negative correlation with ISMR, except for September. La Niña events show a positive correlation for June and August and a negative correlation for July and September. El Niño events show a negative correlation (weak) for June, July, and a positive correlation for August, while a significant positive correlation for September. Roy *et al*. (2019) examined the association between ENSO and ISMR by analysing CMIP5 models in central India and found a consistent negative correlation across all the models. It can be inferred that the relationship between the IOD and ISMR in the present research is more robust than the relationship between the ENSO and ISMR.

Findings of global teleconnections and the impacts of ENSO and IOD on ISMR are well known, but very few studies have been conducted for the regional (micro-level) teleconnections. Impact of ENSO and IOD on ISMR may vary region-wise and event-wise. For the first time, regional teleconnections of ENSO and IOD with ISMR have been analysed for the present study area. As both IOD and ENSO events have been included in the study, it would be tedious and complex if we considered years based on the intensity of the events (*i.e*., strong, moderate, and weak); thus, only pure events were investigated.

4. Conclusions

It is of the utmost importance to identify the trend and spatiotemporal variation of rainfall over a specific region, as such changes will impact surface water and groundwater availability. Four trend tests were applied to examine the trends, including original MK, HR-MMK, YW-MMK, and PW-MMK. Among these, Yue and Wang modified MK tests were found to be more significant than others in detecting trends in the rainfall time series data. The direction of the various MK trend tests varies depending on the annual, monsoon season, monthly rainfall, and number of years considered for trend detection. It indicated that the period of investigation is a significant factor. The 30-year record shows scattered and weaker trends, while the 50-year record captures broader and more consistent increasing trends, especially in July and September. The magnitude of rainfall change over time (mm per year) is largely statistically significant in the case of 50 years of trend detection, as observed by TSS. In June, no trend was observed in any district or division. In July, all districts and the division except for Bhandara observed an increasing trend. In August, Wardha, Bhandara, and Gondia observed a declining trend. In September, except for Bhandara and Nagpur, all other districts had a rising trend. In the monsoon season (JJAS), Nagpur, Gadchiroli, and Chandrapur had an increasing trend. In the annual period, Bhandara shows a decrease, while Gadchiroli and Chandrapur show an increase. The rainfall pattern in the Nagpur division is monomodal, typically peaking in July or August. This information can help the local community with effective planning of cropping patterns and water management.

It was observed that the impact of El Niño was prominent, resulting in a significant reduction in rainfall compared to other events, as validated by low NDVI values in successive years. The Index of Wetness (IOW) is utilized to determine the deficiency of rainfall in a particular year, and all pure El Niño events are correlated with a significant decline in monsoon season rainfall. These findings are consistent with previous studies on Indian summer monsoon failure during pure El Niño events (Ummenhofer *et al*., 2011; Kumar *et al*., 1999, 2006; Ashok *et al*., 2004). During the first decade of the 21st century, three El Niño events (2002, 2004, and 2009) were followed by significant disruptions to the Indian monsoon over the study area. Implementing strategies such as late-sowing variety seeds, water conservation and management, and monitoring monsoon patterns while preserving natural water reservoirs will enhance the agricultural sector's resilience to cope with challenges such as El Niño. In contrast, positive IOD events are associated with a considerable increase in rainfall and an expansion of areas with high NDVI values. In the case of La Niña events and negative IOD events, both reductions and increases in rainfall have been observed, validated by low and high NDVI values. The impact of the IOD phenomenon appears to be more significant than that of the ENSO phenomenon in terms of the correlation coefficient for the study area. Many parameters can impact the ISMR. The findings of this research can be utilized by both the local and national scientific communities. Based on the findings, effective strategies for mitigating the detrimental effects of climate change in the region may be devised by analyzing trends and understanding the impact of ENSO and IOD events on ISMR.

Data Availability

The datasets generated or analyzed during the current study are available from the corresponding author on reasonable request.

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Authors' Contributions

Tulshidas M. Jibhakate: Conceptualization, Methodology, Formal Analysis, Visualization, Validation, original draft, review & editing.
Yashwant B. Katpatal: Conceptualization, Methodology, Supervision, Visualization, review & editing. (email-ybkatpatal@rediffmail.com)

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