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RESEARCH ARTICLE

# Assessment of spatio-temporal trend in hydro-climatic variables and their agricultural implications in the Mahanadi River Basin using innovative trend analysis technique

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## Abstract

Climate change and its effects on hydro-climatic parameters have become a major concern for water resource management in India. This study provides a comprehensive assessment of long-term (1980-2024) hydro-climatic variability in the Mahanadi River Basin (MRB) using the robust Innovative Trend Analysis (ITA) technique. Trends in rainfall, streamflow, maximum temperature ($T_{max}$) and minimum temperature ($T_{min}$) were analyzed on season-wise (summer, monsoon, post-monsoon and winter) and annually for the entire basin as well as for its upper, middle and lower sub-basins. The results revealed a complex trend: annually, 48.3 % of stations showed increasing rainfall with significant spatial divergence. The upper sub-basin experienced a clear wetting trend (66.7 % of stations showing increase), while the middle sub-basin faced a significant declining trend of rainfall (57.3 % of stations showing decrease). However, streamflow exhibited a consistent decreasing trend at 60 % of gauging stations throughout the basin and at more than 80 % of stations in the upper and middle sub-basins, even having positive rainfall trend. $T_{max}$ showed a uniform increasing trend at all of the stations, while $T_{min}$ trends varied, leading to a widening diurnal temperature range. These findings confirm that increasing evapotranspiration, driven by global warming, has become a key factor influencing water availability in the basin. Hence, site specific water conservation measures are urgently required particularly in the upper and middle sub-basins to build resilience against growing climatic stress. The observed hydro-climatic shifts have already begun to affect the soil moisture dynamics and crop yields across the basin. Therefore, climate-resilient agricultural planning, adoption of drought-tolerant crop varieties, micro-irrigation and rainwater harvesting are essential to sustain agricultural productivity in the Mahanadi basin.

**Keywords:** climate change; hydro-climatic variability; innovative trend analysis; Mahanadi River Basin; rainfall; streamflow

## Introduction

Climate change has emerged as a critical driver influencing temperature and precipitation patterns across the globe. According to the Intergovernmental Panel on Climate Change (1), the global surface temperature has increased by approximately 1.1 °C above pre-industrial levels and extreme weather events such as heavy rainfall, droughts and heat waves have become more frequent and intense. These global shifts are profoundly impacting regional climates. In India, a continental-scale warming trend has been firmly established, accompanied by significant regional shifts in monsoon rainfall intensity and frequency (2, 3). Studies have indicated that central India has experienced up to 10 % decline in rainfall since the 1950s, while there has been a threefold increase in widespread extreme rain events across the country (4), posing complex challenges for water resource management. Such variability in rainfall and temperature directly influences crop growth cycles, soil moisture availability and irrigation demands, thereby threatening agricultural productivity and food security in many rainfed regions.

These large-scale climatic trends are mirrored at the regional level, particularly in major river basins, which are the primary conduits of freshwater for agriculture, industry and human consumption. The Mahanadi river basin is one of the most important east-flowing river systems in India which is highly sensitive to hydro-climatic variability due to its diverse physiography and agro-ecological settings. The basin is mainly spread in the states of Odisha and Chhattisgarh and hydrology of the basin is mainly governed by the variables like rainfall and temperature. Recent evidence suggests that these parameters are already undergoing significant spatial and temporal shifts (5). Therefore, a long-term analysis of these hydro-climatic fluxes is crucial to identify the magnitude of change and formulate effective, basin-wide adaptive strategies. Understanding these trends is vital for designing climate-resilient agricultural systems, promoting efficient water management and ensuring sustainable livelihoods for farming communities of the basin (6).

Historically, researchers have largely employed non-parametric methods like the Mann-Kendall test and Sen's slope estimator to detect trends in climatic time series (7, 8). These conventional methods are primarily designed to identify monotonic trends and can be constrained by data characteristics such as serial correlation, seasonality and non-normality. To overcome these limitations, the Innovative Trend Analysis (ITA) technique (9), offers a more robust graphical approach. As a non-parametric method, ITA is capable of detecting complex and sub-period trends within a time series without being bound by strict statistical assumptions of distribution or serial independence (10).

The present study employed ITA to analyze long-term trends in four key hydro-climatic parameters such as rainfall, streamflow, maximum temperature ($T_{max}$) and minimum temperature ($T_{min}$). The analysis is performed on both annual and seasonal scales for the entire MRB as well as for its distinct upper, middle and lower sub-basins. By providing a detailed, spatially disaggregated assessment of climatic trends, this study will generate critical scientific evidence of climate-induced hydrological changes. The findings are intended to support policymakers, water managers and agricultural planners in identifying the most vulnerable regions within the basin and designing targeted, sub-basin-specific interventions to build resilience against future climate variability. Ultimately, this research aims to contribute towards adaptive agricultural planning and climate-smart river basin management to safeguard regional food and water security.

## Materials and Methods

### Study area description

The Mahanadi River Basin is a major peninsular river system of eastern India which is located between latitudes 19°08′ N to 23°32′ N and longitudes 80°28′ E to 86°43′ E. The geographical extent of the basin is 141589 km$^2$ which constitutes about 4.3 % of India's total area (Fig. 1). The basin stretches across Chhattisgarh (52 % area) and Odisha (47 % area) with marginal areas in Maharashtra, Jharkhand and Madhya Pradesh. The Mahanadi River originates from the Sihawa Hills in Chhattisgarh at an elevation of 442 m above mean sea level and traverses 851 km before draining into the Bay of Bengal at Paradeep of Odisha. For hydrological analysis, the basin is broadly divided into 3 sub-basins: the Upper Mahanadi River Basin (UMRB), Middle Mahanadi River Basin (MMRB) and Lower Mahanadi River Basin (LMRB). A number of tributaries including Seonath, Hasdeo, Mand, Ib, Ong, Tel etc. are carrying water to the main river system of the basin. The UMRB covers 21.79 % of the total basin area, which includes 21.62 % in Chhattisgarh and 0.17 % in Maharashtra. The MMRB accounts for 41.24 % of the basin, comprising 31.03 % in Chhattisgarh, 9.76 % in Odisha and 0.45 % in Jharkhand. The LMRB occupies the remaining 36.97 %, with 36.55 % in Odisha and 0.42 % in Chhattisgarh.

The basin experiences a tropical monsoon climate characterized by 4 distinct seasons, like hot summer (March-May), wet southwest monsoon (June-September), post-monsoon (October-December) and mild winter (January-February). The average annual rainfall ranges from 1360 to 1463 mm, with 85 % to 90 % concentrated during the monsoon season. The average annual maximum temperature varies from 32 °C to 40 °C, while the minimum temperature ranges from 8 °C to 22 °C. Agriculture is the dominant land use, covering about 54 % of the area followed by forest covers of approximately 30–32 % while wastelands and fallow lands constitute about 6-8 %. Water bodies and natural wetlands occupy around 4.5-5 % basin area. Soils of the basin are predominantly inceptisols and alfisols, with textures ranging from clay to loam. These soils support variety of crops like rice, pulses, oilseeds and horticultural crops.

### Data collection and preparation

A 45-year hydro-climatic dataset, spanning from 1980 to 2024 was utilized for this study. Daily gridded rainfall data (0.25° × 0.25° resolution) (11) and temperature data ($T_{max}$ and $T_{min}$, at 1° × 1° resolution) (12) were availed from the India Meteorological

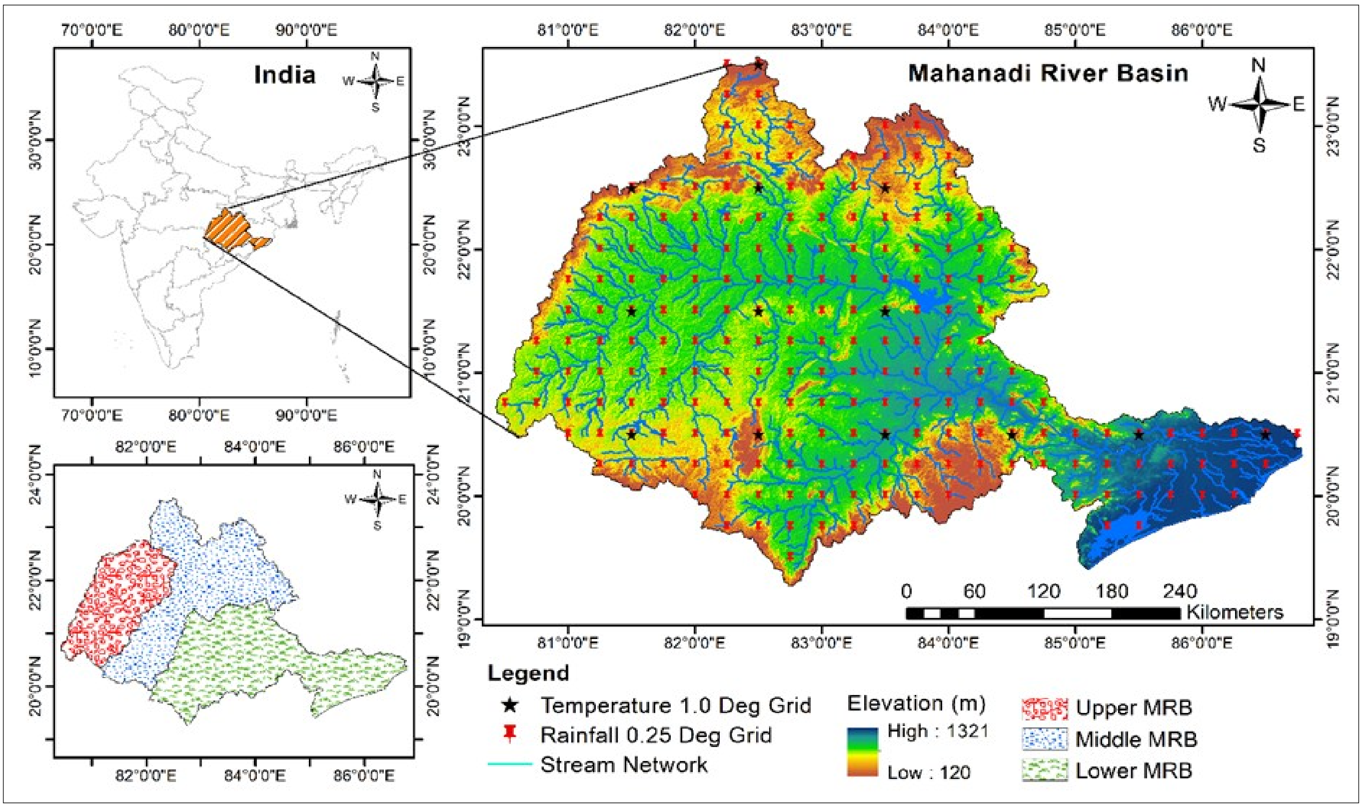

**Fig. 1.** Location map of the Mahanadi River Basin.

Department (IMD), Pune. The dataset comprised of 201 rainfall grid points and 13 temperature grid points distributed across the basin. For sub-basin analysis, the data were segregated in UMRB (42 rainfall, 2 temperature grids), MMRB (75 rainfall, 5 temperature grids) and LMRB (84 rainfall, 6 temperature grids). IMD gridded data is generated by statistical interpolation technique from recording stations data and is less accurate in areas with sparse stations. It useful for broad, regional-level or basin scale studies but less reliable for highly localized studies (12). Daily streamflow data for 15 gauging stations were obtained from the Central Water Commission (CWC), Bhubaneswar. All daily data were aggregated into seasonal and annual time series for trend analysis, corresponding to the 4 seasons.

### Innovative trend analysis (ITA)

The Innovative trend analysis method offers a graphical non-parametric approach for detecting both monotonic and sub-trends within time series data (13). The core concept of ITA is data splitting and pairwise comparison of sub-series to assess how the values change over time. The technique doesn't rely on assumptions such as normality, homoscedasticity or linearity, which makes it especially useful for hydrological and climatic data that often violate these conditions.

The application of ITA involves the following steps: (i) The complete time series (1980-2024) for each variable is divided into 2 equal sub-periods: the first half (1980-2002) and the second half (2003-2024), (ii) The data within each sub-period are sorted independently in ascending order, (iii) The sorted data from the first half are plotted on the X-axis and the sorted data from the second half are plotted on the Y-axis. A 1:1 (45°) reference line is drawn on the plot, (iv) Data points falling above the 1:1 line indicates an increasing trend, while points below the line indicate a decreasing trend. Points clustered along the line suggest no significant trend.

As shown in Fig. 2, the scatter plot compares sorted data from the first half of the time series (X-axis) with the second half (Y-axis). The solid black line represents the 1:1 (no trend) line. Data points (red circles) falling predominantly above this line indicate an increasing trend, while the dashed lines represent the 95 % confidence interval for significance of trend.

To quantify the trend, the ITA slope (S) is calculated using Eqn. 1:

$$S = \frac{2(\bar{y} - \bar{x})}{n} \qquad (1)$$

Where, n is the data length, $\bar{x}$ and $\bar{y}$ are the means of the first and second halves of the time series, respectively.

A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend. In this study, a trend was considered statistically significant if its slope value fell outside the 95 % confidence interval (α = 0.05), which was determined using the probability distribution function of the trend slope.

The ITA method, while effective for detecting non-linear and non-parametric trends, has certain limitations for hydro-climatic studies at the basin scale. It does not account for serial autocorrelation and spatial heterogeneity, which may lead to overestimation or masking of localized trends. Additionally, short or discontinuous datasets can introduce bias in trend interpretation, limiting the robustness of basin-wide hydro-climatic assessments (13).

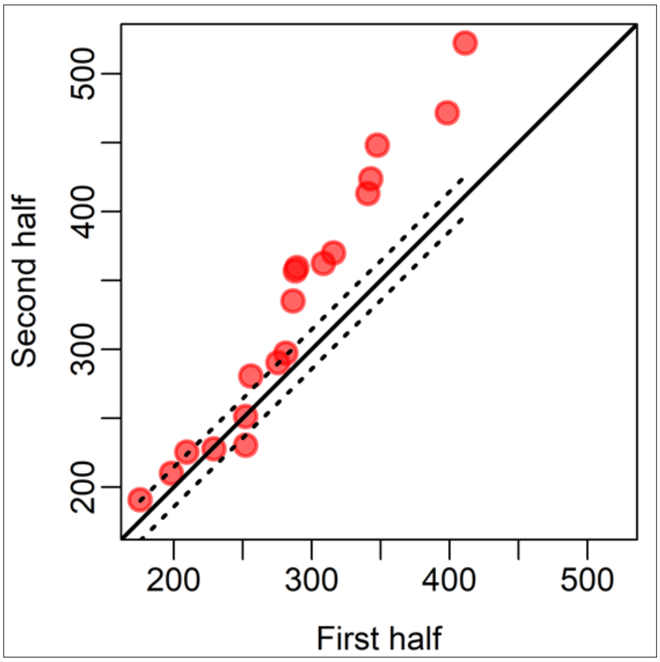

**Fig. 2.** A graphical representation of the ITA method.

## Results and Discussion

### Trend in rainfall

The spatio-temporal rainfall trend analysis based on the ITA method revealed a highly variable pattern across the Mahanadi as presented in Fig. 3. At the annual scale over the entire basin, 48.3 % of the stations exhibited a significant increasing (SI) trend in rainfall, while 36.8 % showed a significant decreasing (SD) trend and the remaining 14.9 % indicated no significant (NS) change. The spatial segregation of annual rainfall has shown that the UMRB experienced a predominantly positive trend with 66.7 % of grid stations of the sub-basin showing an increasing trend. In contrast, the MMRB faced considerable rainfall depletion, with 57.3 % of stations showing a decreasing trend and only 37.3 % showing an increase. In LMRB, 48.8 % of grid stations have shown SI and 27.4 % SD trend in rainfall which represents higher localized variabilities in rainfall across the basin. Seasonal assessments further clarified that during summer, the UMRB and MMRB have shown a strong SI trend (85.7 % and 50.7 %, respectively), but the LMRB has shown significant decline in rainfall at 75.0 % of grid stations of the sub-basins. In the monsoon, SI trends are witnessed in the upper and lower sub-basins covering 61.9 % of the grid stations, while the middle sub-basin continued to show rainfall decline (57.3 % SD). Post-monsoon trends were again positive in the middle (80.0 % SI) and lower (64.3 % SI) sub-basins. However, winter rainfall has shown remarkable decreases, especially in the lower sub-basin (78.5 % SD) and middle sub-basin (46.6 % SD), potentially impacting winter irrigation and soil moisture recharge. This aligns perfectly with more localized research in the middle catchment which also confirmed significant rainfall variability. This may be due to a large-scale shift in the core monsoon circulation which is weakening moisture transport to the middle sub -basin, leading decline in rainfall. The MMRB is the agricultural heartland of the basin. The measured decline in monsoon rainfall directly threatens the viability of the primary rainfed *Kharif* rice crop. A reduction in water availability during critical growth phases, such as panicle initiation and flowering, can lead to severe moisture stress, resulting in significant yield losses and threatening the food and livelihoods security of the millions farm families of the basin (14).

This quantitative finding of a declining precipitation trend in the MMRB is not an isolated observation but is strongly corroborated by recent, independent studies. In a detailed analysis of the basin, identified a statistically significant drying trend specifically in the MMRB, calculating a precipitation decline of -2.185 mm/year (16). This aligns perfectly with more localized research in the middle catchment which also confirmed significant rainfall variability (15). It was compellingly argued that the South Asian Summer Monsoon Index (SASMI) now exerts a more dominant influence on the basin's precipitation than the traditional Indian Summer Monsoon Index (ISMI) (16). This suggests a large-scale shift in the core monsoon circulation is disproportionately weakening moisture transport to the middle sub-basin, leading to the observed, quantified decline in rainfall. Such persistent drying trends are likely to delay the onset of monsoon-dependent sowing operations, reduce the effective crop growing period and necessitate shifts toward short-duration or drought-tolerant varieties. In the long term, farmers may be compelled to diversify cropping patterns and adopt water-efficient management practices to sustain agricultural productivity under the emerging climatic variability (16).

## Trend in streamflow

The streamflow trend was studied at 15 gauging stations spread across the basin. Out of the 15 stations, 5 stations namely, Kotni, Simga, Andhiyarkhore, Jondhra and Ghatora are present in UMRB, six stations namely Rajim, Baronda, Rampur, Basantpur, Bamnidhi and Kurubhata are present in the MMRB and 4 stations namely Kesinga, Kantamal, Salebhata and Tikarpara are present in the LMRB. The spatial and seasonal trend of streamflow is presented in Fig. 4. The study revealed that the streamflow trend departed sharply from the rainfall trend of the basin indicating an increased influence of evapotranspiration, land use changes, watershed activities, construction of dams and base flow variation on river discharge. At the annual time step, only 20.0 % of gauging stations of the whole basin showed an increasing streamflow trend, while 60.0 % recorded a significant decrease and 20.0 % showed no trend. The contradiction of rainfall-streamflow relationship was most pronounced in the UMRB, where rainfall increased at 66.7 % of grid stations, but streamflow decreased at 80.0 % of gauging stations of the upper sub-basin. The MMRB, which already had declining rainfall at 57.3 % of stations, also showed 83.3 % SD in streamflow. Even in the lower sub-basin, where rainfall trends were mostly positive at maximum grid points and 50.0 % of gauging stations recorded significant increase in flow.

In seasonal terms, summer streamflow showed a widespread decline across all basins, with 60 % of stations showing SD. The UMRB has shown decline in streamflow at 80 % of its stations whereas the MMRB and LMRB have shown increase in flow at 66.7 % and 75 % of stations present in the respective sub-basins during summer. The monsoon season which typically contributes most of the annual flow, also showed SD at 60 % of gauging stations of the basin. Both upper and middle sub-basins have experienced significant decline in streamflow at 80 % and 80.3 % of the stations respectively, while the lower sub-basin has shown significant increase in flow at 50 % of its gauging stations. This may be caused due to the gradual increase in dam construction in the upper and middle sub-basins which are storing the monsoon flow for irrigation and hydro-electric generation. A significant increase in streamflow was observed at 33.3 % stations of the entire basin while only 13.3 % stations showed SD during post-monsoon season. The post-monsoon flow has shown SD at 40 %, SI at 16.7 % and SI at 75 % of the stations of UMRB, MMRB and LMRB respectively. Winter streamflow, which is mostly contributed by base flow and source of rabi season irrigation has shown significant decline at 60 % stations across basin. The winter streamflow has shown SD at 100 %, SD at 50.0 % and SI at 75 % of the stations of UMRB, MMRB and LMRB respectively. The base flow is mostly decreasing at UMRB and MMRB due to the decline of groundwater sources either due to intensive withdrawal or less recharge in monsoon (17).

Rate of change in streamflow at 15 gauging stations of the basin at annual and seasonal time scale is presented in Fig. 4. Kantamal and Kesinga gauging stations which are located at the southern part of the LMRB have shown the highest rate of increase in streamflow throughout all the seasons while the rainfall trend is not consistent. This may be caused either due to high intensity of rainfall or deforestation in the catchments. Similarly, Tikarpara station which is present at the extreme downstream of the river has shown

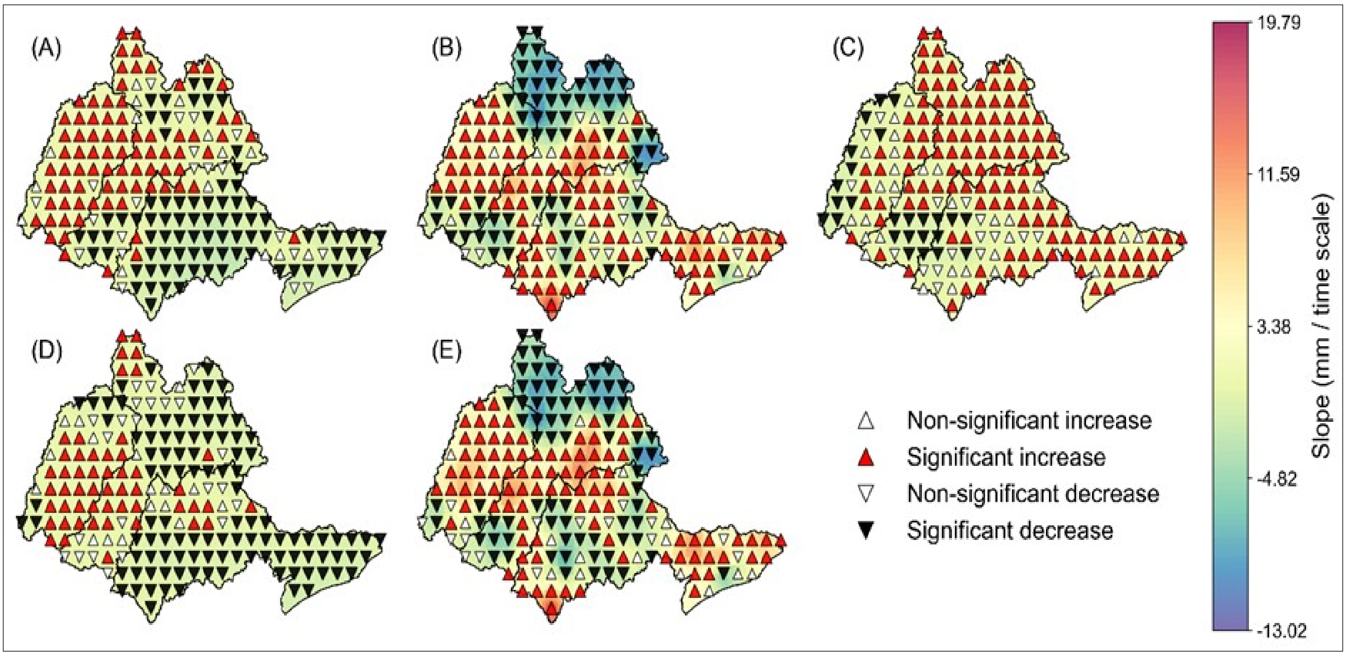

**Fig. 3**. Spatio-temporal trend analysis of rainfall across the MRB from 1980-2024. The maps illustrate the magnitude and statistical significance of trends for (A) summer, (B) monsoon, (C) post-monsoon, (D) winter and (E) annual rainfall.

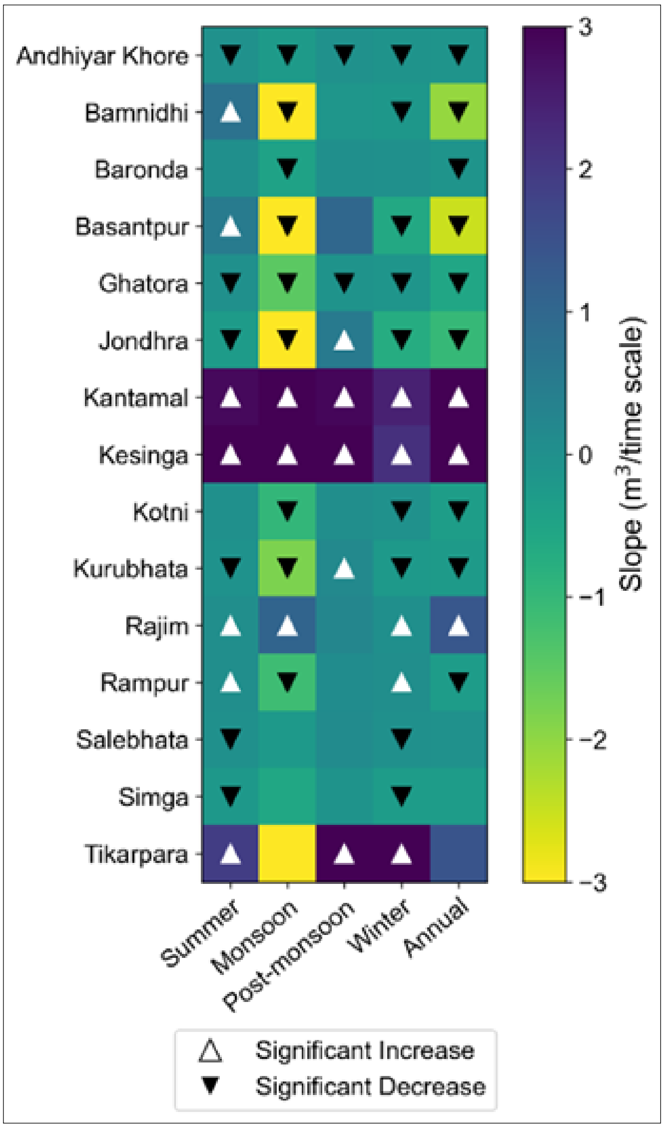

**Fig. 4.** Heatmap illustrating the seasonal and annual streamflow trend slope at 15 gauging stations within the MRB.

the highest rate of increase in streamflow during post monsoon and winter, which may be caused due to increased release of water from Hirakud dam for irrigation purpose or flow accumulation from the upper catchment of the basin. Decline in streamflow is observed at majority of the stations but the rate of decrease is not much higher except few stations like Bamnindi, Basantapur and Jondhra during monsoon.

## Correlation of rainfall and streamflow

The time series analysis indicated a positive linear relationship between rainfall and streamflow across all regions of the Mahanadi River Basin (MRB) as depicted in Fig. 5. The basin-wide average correlation coefficient between rainfall and streamflow was estimated at $r = 0.78$, reflecting that variations in rainfall have a direct and significant influence on river discharge. Sub-basin-wise analysis further revealed that the upper, middle and lower Mahanadi sub-basins exhibit high rainfall-streamflow coupling with average correlation coefficients of $r = 0.75$, $r = 0.77$ and $r = 0.83$ respectively. The UMRB includes the stations Kotni, Simga, Andhiyarkhore, Jondhra and Ghatora; the MMRB comprises Rajim, Baronda, Rampur, Basantpur, Bamnidhi and Kurubhata; while the LMRB consists of Kesinga, Kantamal, Salebhata and Tikarpara stations. At the individual station level, the correlation values ranged between 0.56 and 0.92, indicating spatial variability influenced by local hydrological and land use conditions. Stations such as Kesinga ($r = 0.92$) and Kantamal ($r = 0.91$) in the lower sub-basin exhibited the strongest correlation, suggesting a more direct rainfall-runoff response, whereas stations like Andhiyarkhore and Ghatora ($r = 0.56$ each) in the upper sub-basin showed relatively weaker relationships, possibly due to increasing trend of rainfall and declining streamflow influenced by temperature driven higher rate of evapotranspiration. All correlation coefficients were found statistically significant at $p < 0.01$, confirming a robust and coherent rainfall-streamflow relationship across the basin.

## Trend in temperature

### Maximum temperature

Across the MRB, maximum temperature ($T_{max}$) exhibited a consistent and statistically significant rise at all grid points between 1980 and 2024. As shown in Fig. 6, the basin-wide $T_{max}$ increased at an average rate of approximately 0.21 °C - 0.28 °C per decade, with slightly higher rates during the summer and monsoon seasons. This persistent warming pattern establishes $T_{max}$ as the most uniformly changing hydro-climatic variable in the basin. The rise in $T_{max}$ directly enhances potential evapotranspiration and reduces effective water availability, contributing to declining streamflow even in areas with increasing rainfall. This warming also elevates crop water demand, intensifies heat stress during critical crop growth stages and accelerates soil moisture depletion, thereby adversely affecting water-intensive crops such as rice and wheat (18).

The increasing $T_{max}$ during monsoon and post-monsoon seasons may adversely affect flowering in *Kharif* crops and may shift sowing time of *Rabi* crops, while the summer $T_{max}$surge could lead to extreme heat waves. Rice (*Oryza sativa*) is highly susceptible to high-temperature stress throughout its growth cycle (18). High temperatures exceeding 35 °C during reproductive stages and 33 °C during vegetative stages can impair seed germination, reduce tillering, disrupt pollination and diminish grain quality (19, 20). The yield of wheat is decreased by 0.45 t/ha due to 0.5 °C rise in winter temperature (21). Rising $T_{max}$ also contributes significantly to streamflow decline, by accelerating surface water and soil moisture evaporation.

### Minimum temperature

The minimum temperature ($T_{min}$) showed more spatial and temporal variability than $T_{max}$, as depicted in Fig. 7. At the annual scale, 53.8 % of stations of the entire basin have shown a significant increase, while 38.5 % witnessed a significant decrease in minimum temperature. The upper (100 % SI) and middle (60.0 % SI) sub-basins mostly perceived increasing trend of minimum temperature annually, while lower sub-basin has shown significant decline at 66.7 % of grid stations. In the winter, $T_{min}$ showed significant declining trend at all stations of UMRB and LMRB while 80 % grid stations of MMRB have shown significant decrease, indicating colder nights, which may lead to cold stress in sensitive *Rabi* crops like mustard and pulses. In contrast, monsoon $T_{min}$ showed an increasing trend in the upper (100.0 % SI) and middle (80.0 % SI) sub-basins, potentially resulting in higher nighttime respiration losses in rice and other crops. During post-monsoon season all grid stations have shown significant increase in $T_{min}$and the rate of increase is highest during this period across entire MRB. Summer $T_{min}$ showed a significant decrease at 50 %-66 % stations of the three sub-basins.

These decreasing $T_{min}$ trends, when combined with the consistently rising $T_{max}$, lead to a widening diurnal temperature range (DTR), particularly during summer and winter seasons. Such an increase in DTR can affect crop phenology, flowering and grain filling

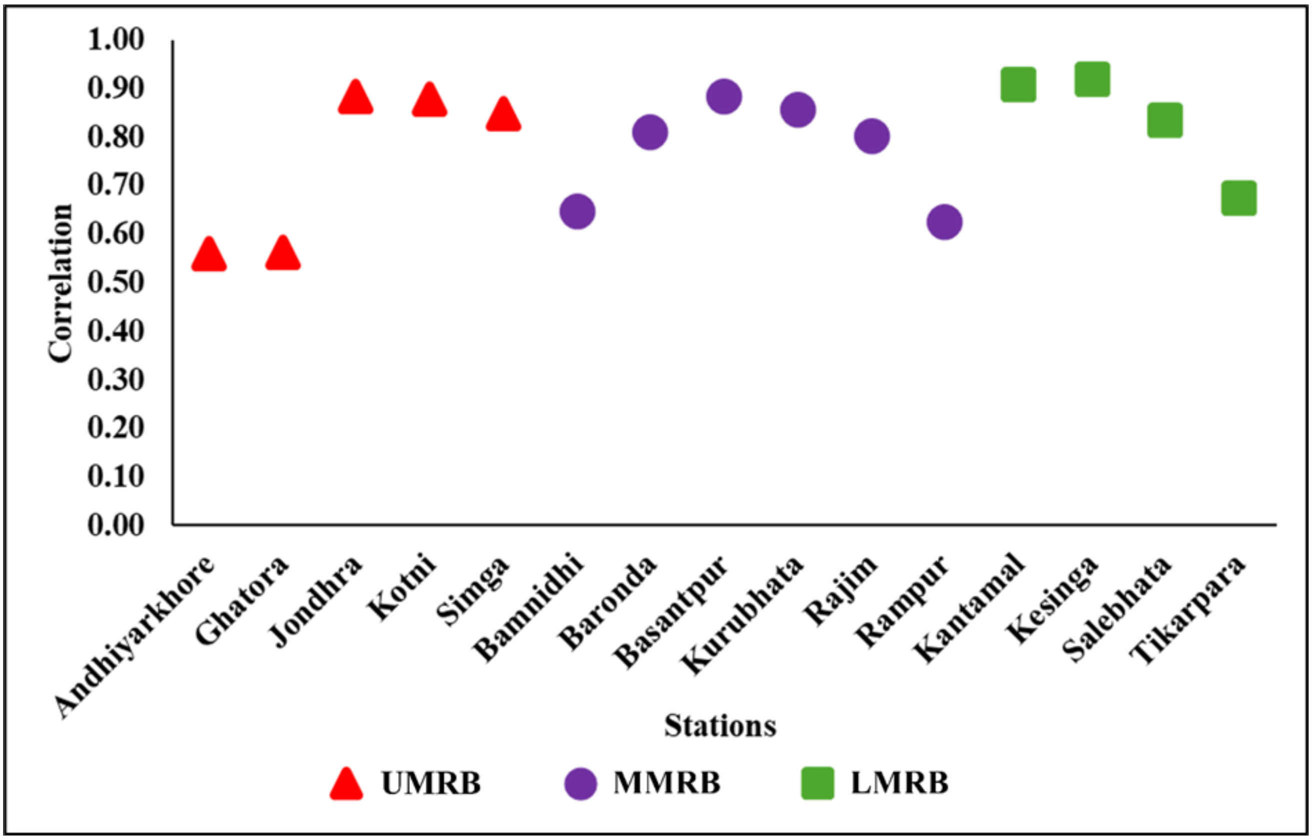

**Fig. 5.** Rainfall-streamflow correlation.

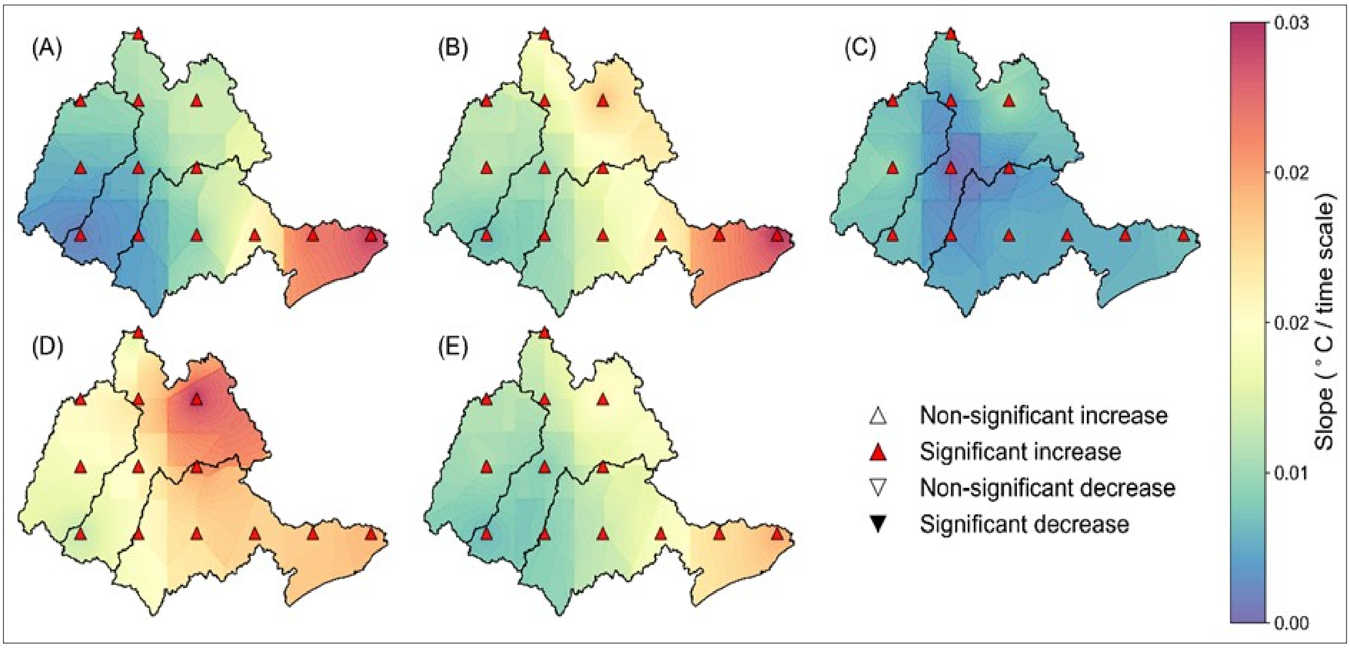

**Fig. 6.** Spatio-temporal trend analysis of $T_{max}$ across the MRB (1980-2024). The maps illustrate the magnitude and statistical significance of trends for (A) summer, (B) monsoon, (C) post-monsoon, (D) winter and (E) annual $T_{max}$.

phases, thereby influencing the productivity of major crops like rice, greengram, blackgram, wheat, maize, mustard, sunflower, potato and wheat etc. Some crops like fruit and nut trees are benefited from increased chilling hour accumulation which would be favoured by the increase in DTR (22).

The overall findings of this research based on Innovative Trend Analysis across the Mahanadi basin presented a clear sign of climate change impact for manifesting spatiotemporal variability in rainfall, streamflow and temperature, as shown in Fig. 8. The results revealed that the UMRB experiences increasing rainfall and rising temperatures, however, the corresponding decline in streamflow suggests increasing evapotranspiration losses, increased dam regulation on river flow, intensive irrigation and overuse of groundwater, which is demanding urgent measures for water harvesting, groundwater recharge, scientific irrigation management, cultivation of low duty crops and afforestation (14). In the MMRB, the situation is more critical with a consistent decline in both rainfall and streamflow, coupled with rising temperatures, highlighting the need for climate-resilient agriculture, construction of rainwater harvesting structures and lining of the canal systems etc. The LMRB has shown a positive rainfall trend in monsoon and post-monsoon seasons and the streamflow also has shown a positive trend except the summer season. This may be due to higher flow accumulation in lower sub-basin from the upper catchments and less infiltration of water due to

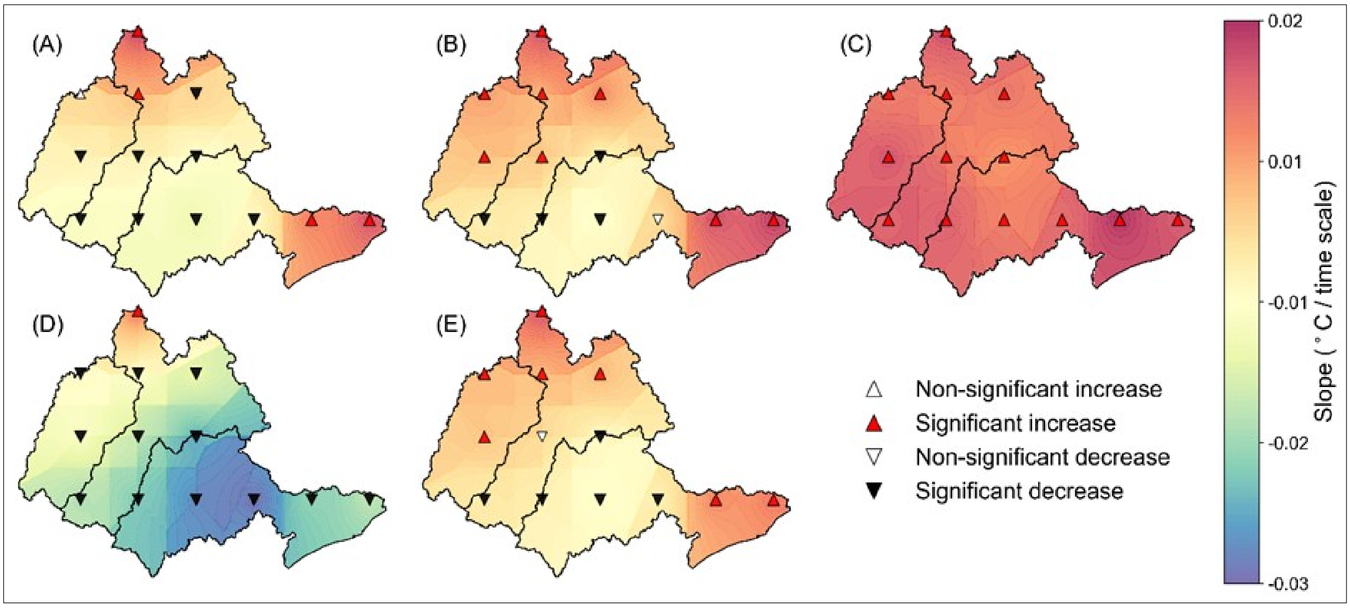

**Fig. 7.** Spatio-temporal trend analysis of $T_{min}$ across the MRB (1980-2024). The maps show the magnitude and statistical significance of trends for (A) summer, (B) monsoon, (C) post-monsoon, (D) winter and (E) annual $T_{min}$.

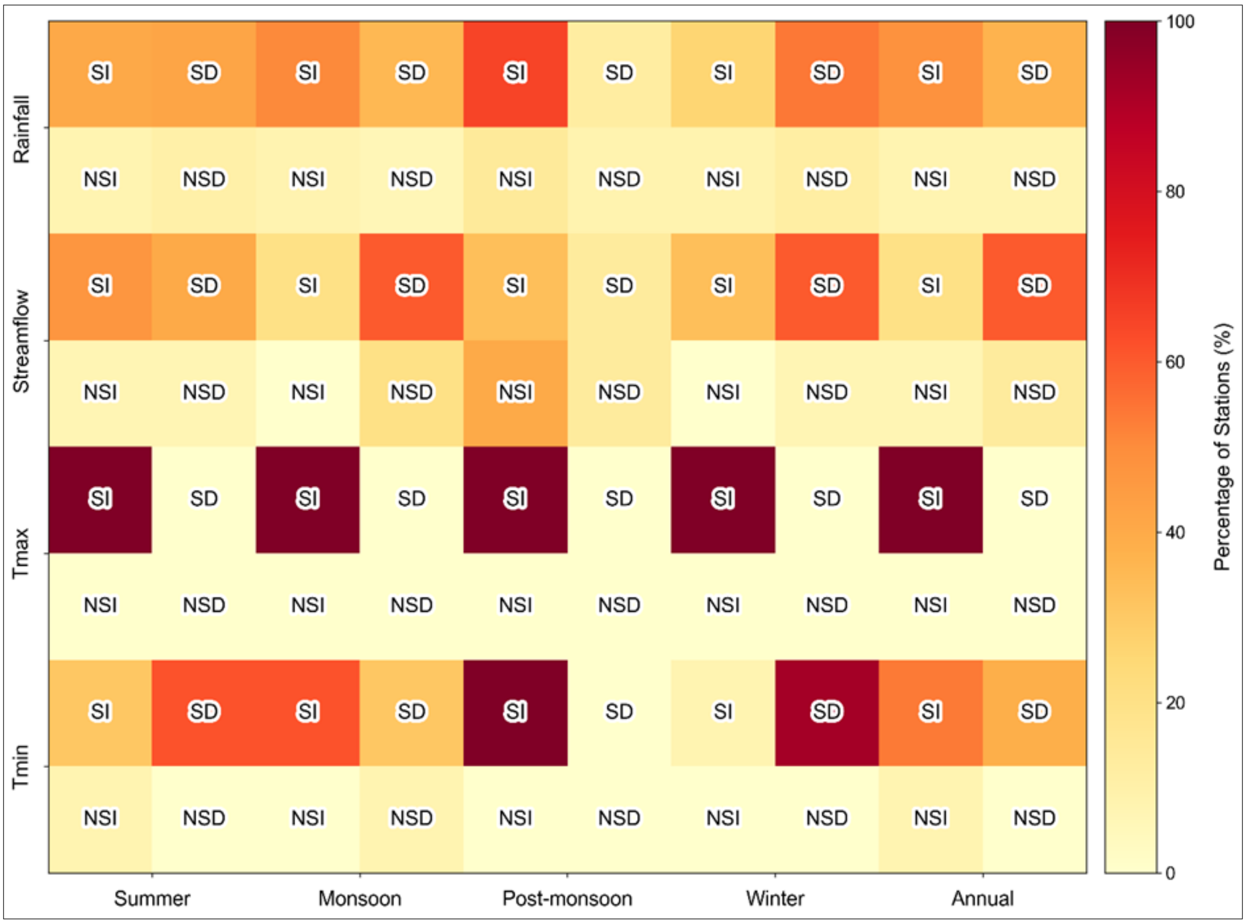

**Fig. 8.** Heatmap showing the percentage of stations exhibiting significant increasing (SI), significant decreasing (SD), non-significant increasing (NSI), or non-significant decreasing (NSD) trends for all 4 hydro-climatic variables across different seasons and annually for the entire MRB.

high water table condition particularly in Mahanadi delta. The $T_{max}$ has shown an increased trend at all the grid stations and all seasons throughout the basin which underscores the urgency of adaptation strategies such as heat-tolerant crop varieties, improved irrigation scheduling practices, microclimate buffering using agroforestry and integrated watershed management. This study supports earlier findings (18) from the Kantamal catchment of the Mahanadi River Basin which showed decreasing rainfall and increasing temperature trends using the modified Mann-Kendall test (6). The analysis revealed a significant decline in annual rainfall, with 20 out of 27 stations in the Kantamal catchment have shown decreasing trends and only 2 stations showed non-significant increases. In this study the trends of climatic variables along with streamflow have been analysed for the entire Mahanadi Basin. The results can help to plan targeted measures in the upper, middle and lower catchments to strengthen agricultural resilience against ongoing and future challenges of climate variability and water stress.

## Conclusion

In this study the ITA technique is used to study the trend in hydro-climatic variables and their effect on agriculture in the Mahanadi basin of eastern India. The study revealed clear evidence of hydro-climatic shift across the Mahanadi River Basin and confirmed the growing climate-induced stress on water resources and agriculture sectors. The results highlight a clear indication of spatial variability in rainfall, declining streamflow and rising temperatures which are jointly altering the basin's hydrological balance. Increase in evapotranspiration driven by the increase in temperature enhancing blue and green water loss mechanism in basin. These shifts indicate that the water availability of the basin is changing differently at various sub-basins under the influence of climate variability and anthropogenic factors. The MMRB has emerged as the most vulnerable sub-basin, facing the dual pressures of declining rainfall and diminishing river discharge followed by UMRB and LMRB.

The findings underscore that a uniform policy approach will be inadequate for addressing the diverse climatic challenges across the sub-basins. Instead, region-specific, integrated and adaptive management strategies are required. The recommended sub-basin-wise policy interventions are as follows:

- Upper Mahanadi Sub-basin (UMRB): Watershed management, afforestation and water conservation measures should be prioritised in this region to improve infiltration, recharge groundwater and reduce surface runoff. Efficient irrigation methods such as micro-irrigation and irrigation scheduling should be promoted to enhance water-use efficiency and support sustainable agricultural production across the region.
- Middle Mahanadi Sub-basin (MMRB): More focus should be given on the demand-side management and water conservation in this region. This includes promoting drought-resilient crop varieties, improving irrigation efficiency through methods like micro-irrigation and canal lining and constructing a distributed network of water harvesting structures to secure water for critical periods.
- Lower Mahanadi Sub-basin (LMRB): In this region, focus should be given on floodplain restoration, wetland conservation and improved drainage management to stabilise downstream flows and maintain ecological balance. Additionally, the adoption of climate-smart flood-management strategies and deltaic agriculture adaptation practices is crucial to safeguard the productive lowlands from hydrological extremes and ensure long-term agricultural sustainability.

Overall, a proactive, evidence-based and spatially differentiated interventions are essential to build resilience, ensure sustainable water resource management and protect the livelihoods of small and marginal farmers of the basin. Beyond these management priorities, future research should be focused on linking ITA-derived hydro-climatic trends with process-based hydrological and crop simulation models for better understanding the interactions among climate, water balance parameters and agriculture practices of the Mahanadi river basin.

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## Authors' contributions

SLR carried out conceptualisation, methodology, code, formal analysis, data curation, writing original draft and visualisation. APS performed methodology, supervision, investigation, writing, review and editing. JCP carried out Validation, investigation, writing, review and editing. DMD made conceptualisation, methodology, validation, writing, review and editing. SKR and PPJ made resources, data curation, writing, review and editing. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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