



# Spatio-Temporal Variability and Long-Term Trends of Rainfall in the Punpun River Basin, Bihar, India

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## Abstract

A good knowledge of long term variability of rainfall is essential for sustainable water resources planning, agricultural management and climate adaptation in monsoon dominated river basins. The Punpun River Basin, a large right bank tributary of the Ganga River in Bihar, India is extremely vulnerable to monsoon flooding and dry season water scarcity, and these extremes have further increased under changing climatic conditions. The present study has been undertaken to examine the spatial and temporal characteristics of rainfall over the Punpun River Basin using the long term daily rainfall data of eight rain gauge stations of India Meteorological Department (IMD) for the period 1981-2022 (42 Years). Variability is measured using statistical indicators such as mean rainfall, standard deviation, coefficient of variation (CV), rainfall anomaly index (RAI) and precipitation concentration index (PCI). The non-parametric Mann-Kendall (MK) test and Sen's slope estimator are used for detection of monotonic trends and Modified Mann-Kendall (MMK) test is used to account for serial correlation in the data. Innovative Trend Analysis (ITA) and Sequential Mann-Kendall (SQMK) tests are used to determine hidden trend and abrupt change points in annual and seasonal rainfall series. GIS based ordinary kriging interpolation is used to map the spatial distribution and trend patterns. Results show a high spatial heterogeneity of the rainfall distribution with higher mean annual rainfall in the southeastern upland sector (~1,059mm) and lower values over the northern alluvial plains (~943mm). More than 86% of the annual rainfall is received during the southwest monsoon (June-September) and the PCI is >22 at all stations indicating strong rainfall seasonality. Significant decreasing trends were seen at Gaya ( $Z = -2.87$ ,  $\beta = -4.12$  mm/yr) and Aurangabad ( $Z = -2.31$ ,  $\beta = -3.47$  mm/yr) and significant increasing trend was observed at Arwal ( $Z = +2.54$ ,  $\beta = +3.82$  mm/yr). The SQMK test detects the change points around 1998-2000 in Gaya and 2002-2004 in Arwal. Gaya showed non-linear response with enhancement in low rainfall subcategories and Arwal showed a general wetting trend. These results provide scientific evidence for spatially differentiated flood management, drought mitigation, planning groundwater recharge and climate resilient water resources management in eastern India.

**Keywords:** Rainfall variability; Mann-Kendall test; Sen's slope; Innovative Trend Analysis; Sequential Mann-Kendall; GIS; Climate change; Punpun River Basin; Bihar; Hydrology

## 1 Introduction

Rainfall is the main forcing of the hydrological cycle and the ultimate driver of freshwater availability, agricultural productivity, and ecosystem functioning in tropical monsoon regions (Mishra and Singh, 2010; Guhathakurta and Rajeevan, 2008). The southwest monsoon season (June-September) is responsible for approximately 80% of the annual precipitation in India and is vital for the country's food security and water infrastructure (Krishnamurthy and Shukla, 2000; Parthasarathy et al., 1994). Observational records and climate model projections in the past century have increasingly indicated that global warming is altering the spatio-temporal characteristics of monsoon rainfall over South Asia. Changes in the timing of the start and end of the seasons, changes in the location of the main rain belt and an increase in the intensity of extreme events (Goswami et al. 2006; Dash et al. 2009). The Indo-Gangetic Plain (IGP) is very sensitive to any change in the monsoon system because of the confluence of a large agrarian population, flat topography and near total dependence on monsoon rainfall for rainfed agriculture as well as for groundwater recharge.

Bihar, a state of the lower Gangetic Plain of eastern India, suffers some of the worst hydro-climatic extremes in the subcontinent. The state faces the paradox of monsoon floods that inundate millions of hectares of agricultural land and pre-monsoon and post-monsoon droughts that parch the same fields within weeks every year (Singh and Kumar, 2011; Kumar et al., 2020). The Punpun River Basin, a major right bank tributary of the Ganga River, which drains a large area of about 8,300 km<sup>2</sup> spread over different districts of Patna, Nalanda, Gaya, Aurangabad, Arwal and Jehanabad is an example of the dual challenge. The basin is acutely water deficient from November to May every year. However during furious monsoon episodes the river often bursts its banks causing widespread damage to crops, infrastructure and human settlements. Therefore, knowledge of long term variability and trend behaviour of rainfall in this basin is important for evidence based water resources planning, agricultural scheduling, disaster risk reduction and climate adaptation policy in eastern India.

The identification and quantification of trends in historical hydro-meteorological time series has become a fundamental component of applied hydro-climatology. The non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) remains the most widely used method to detect the presence of monotonic trends in hydrological data, because it does not require the normality assumption and is robust in the presence of outliers and missing values. Sen's slope estimator (Sen, 1968) is a complementary quantification of magnitude of trend that is robust to outliers. A known limitation of the standard MK test is that it is sensitive to an increase in Type I error rate in the presence of positive serial autocorrelation in the data, as it inflates the variance of the MK test statistic (Hamed and Rao, 1998). This limitation is overcome by the Modified Mann-Kendall (MMK) test of Hamed and Rao (1998) that calculates a variance correction factor based on the significant autocorrelation structure of the ranked time series. The method of Innovative Trend Analysis (ITA) by Şen (2012) has been rapidly adopted because it allows for the separate characterisation of trends in low, medium and high data sub-categories, a dimension of trend behaviour that is invisible to monotonic-trend tests (Kisi, 2015; Malik et al., 2019). ITA does not assume serial independence or normality and produces graphical comparisons of sorted sub-series. The Sequential Mann-Kendall (SQMK) test (Sneyers, 1990) is a complementary tool for detecting approximate change points or structural abrupt breaks in the rainfall record.

Several researchers have studied the rainfall trends over Indian sub-continent and Ganga River Basin at national and regional scales (Jain and Kumar, 2012; Mondal et al., 2012; Patra et al., 2012; Praveen et al., 2020). At the basin scale, investigations of Ganga tributaries in Bihar are relatively sparse. Large scale rainfall pattern over IGP has been analysed by Panda et al (2017) and Singh and Sontakke (2002). But fine scale analysis at station level is limited, especially for Punpun sub-basin. The nearest study of hydro-climatic variability was conducted by Singh and Kumar (2011) in Punpun Basin, but with a shorter record and no ITA or SQMK methods. The present study addresses these gaps using an integrated ensemble of statistical and GIS based techniques on a 42 year daily rainfall record and is the most comprehensive basin scale rainfall variability assessment of Punpun River Basin to date.

The specific objectives of this study are (i) to describe the spatial distribution of mean annual and seasonal rainfall in the Punpun River Basin by GIS-based interpolation, (ii) to measure inter-annual variation of rainfall using CV, RAI and PCI, (iii) to identify long-term monotonic trends in annual and seasonal rainfall using MK, MMK and ITA methods, (iv) to estimate the magnitude of the trends using the Sen's slope estimator, (v) to find probable change points in the rainfall record using the SQMK test, and (vi) to generate spatial maps of the distribution of rainfall and trend patterns for water resources planning.

## 2 Study Area

The Punpun River originates in the Chotanagpur Plateau of Jharkhand, India at an elevation of around 480 m above the mean sea level and flows mainly in north direction through the states of Jharkhand and Bihar before joining the Ganga River near Fatuha town of Patna district. The basin covers an area of approximately 8300 km<sup>2</sup> and is located between latitudes 24°30'N-25°45'N and longitudes 84°15'E-85°30'E. The basin covers parts of six administrative districts of the Bihar state viz. Gaya, Aurangabad, Arwal, Jehanabad, Nalanda and Patna. The main tributaries are the Morhar, Dardha, Phalgu and Sone, the last draining a much larger catchment from the northwest. The basin topography changes abruptly from the southern upland fringe (>300 m elevation) with exposures of rocky Precambrian basement and thin lateritic soils to the nearly flat northern alluvial plains (<80 m elevation) with deep Quaternary alluvium of the Indo-Gangetic sedimentary sequence underneath. This physiographic contrast has profound influence on spatial distribution of rainfall, runoff generation, rates of ground water recharge and land use patterns within the basin. The digital elevation data of 30 m resolution from the Shuttle Radar Topography Mission (SRTM) was used for the basin delineation and DEM analysis (USGS Earth Explorer portal).

The Punpun Basin lies under tropical monsoon climate and four distinct hydro-meteorological seasons are observed namely winter (January-February), pre-monsoon or hot dry season (March-May), southwest monsoon (June-September) and post-monsoon (October-December). The mean annual temperature ranges from 18°C in January to 38°C in May with maximum temperature often crossing 42°C before the monsoon. Potential evapotranspiration is high year-round, greater than 1,400 mm/year. The spatial gradient from the southern upland catchment (mean annual rainfall ~940–1,000 mm) to the southeastern sector near Wazirganj and Hisua (~1,040–1,060 mm) reflects orographic enhancement of rainfall as moist easterly and southeasterly monsoon flow is forced up and over the southern plateau escarpment. The land use across the basin is dominated by agricultural cultivation (~72% of area) followed by fallow/scrubland (~14%), built-up (~7%), waterbodies (~4%) and forests (~3%) based on LULC mapping of Landsat-8 satellite imagery.

## 3 Data and Methods

### 3.1 Rainfall Data and Quality Control

Daily rainfall data for 42 years (1981–2022) were collected from the India Meteorological Department (IMD), Pune for eight rain-gauge stations in the Punpun River Basin (Table 1). Stations were selected to maximise spatial coverage across physiographic sub-regions of the basin, and to minimise gaps in the long-term record. The geographical coordinates, the elevation, the data period and the station index codes are given in Table 1. The quality of the data was systematically checked using three complementary procedures: (i) standard double-mass curve analysis to detect systematic shifts in individual station records relative to the basin average; (ii) estimation and infilling of missing values using the normal-ratio method recommended by the WMO, which accounts for less than 2.1% of all station-years; (iii) outlier screening based on the interquartile range method ( $IQR \pm 3.0 \times IQR$  criterion) for daily extremes, with flagged values cross-checked with neighbouring station records and

available synoptic charts. Daily totals were aggregated into monthly, seasonal and annual series for later statistical analysis.

**Table 1. Details of the eight rain-gauge stations used in this study (source: India Meteorological Department, Pune).**

| No. | Station    | Lat. (°N) | Long. (°E) | Elev. (m) | Period    | Length (yr) | Source | Index |
|-----|------------|-----------|------------|-----------|-----------|-------------|--------|-------|
| 1   | Punpun     | 25.08     | 85.18      | 62        | 1981–2022 | 42          | IMD    | R1    |
| 2   | Danapur    | 25.62     | 85.05      | 56        | 1981–2022 | 42          | IMD    | R2    |
| 3   | Jehanabad  | 25.21     | 84.99      | 74        | 1981–2022 | 42          | IMD    | R3    |
| 4   | Aurangabad | 24.75     | 84.37      | 91        | 1981–2022 | 42          | IMD    | R4    |
| 5   | Arwal      | 25.25     | 84.68      | 68        | 1981–2022 | 42          | IMD    | R5    |
| 6   | Gaya       | 24.80     | 85.00      | 116       | 1981–2022 | 42          | IMD    | R6    |
| 7   | Wazirganj  | 24.96     | 85.32      | 88        | 1981–2022 | 42          | IMD    | R7    |
| 8   | Hisua      | 24.83     | 85.43      | 82        | 1981–2022 | 42          | IMD    | R8    |

### 3.2 Statistical Measures of Variability

Rainfall variability was quantified using three complementary indicators:

**Coefficient of Variation (CV):** The CV expresses the inter-annual standard deviation as a percentage of the mean and allows comparison of variability across stations with different mean rainfall levels (Pettitt, 1979). Following the classification of Hare (1983),  $CV < 20\%$  denotes low variability,  $20\text{--}30\%$  moderate variability, and  $>30\%$  high variability:

$$CV (\%) = (\sigma / \bar{x}) \times 100 \quad (1)$$

where  $\sigma$  is the long-term standard deviation and  $\bar{x}$  is the long-term mean annual rainfall (mm).

**Rainfall Anomaly Index (RAI):** The RAI (van Rooy, 1965) provides a standardised dimensionless measure of departure from the mean, facilitating identification of anomalously wet and dry years. The index is computed separately for positive and negative anomalies:

$$RAI = +3 \times [(x - \bar{x}) / (M^+ - \bar{x})] \text{ for } x \geq \bar{x} \quad (2a)$$

$$RAI = -3 \times [(x - \bar{x}) / (M^- - \bar{x})] \text{ for } x < \bar{x} \quad (2b)$$

where  $x$  is annual rainfall for a given year,  $\bar{x}$  is the long-term mean,  $M^+$  is the mean of the ten highest annual values, and  $M^-$  is the mean of the ten lowest annual values. Following Freitas (2005), RAI values are classified as: Extreme wet ( $>3.0$ ), Very wet (2.0 to 3.0), Wet (1.0 to 2.0), Near normal ( $-1.0$  to 1.0), Dry ( $-1.0$  to  $-2.0$ ), Very dry ( $-2.0$  to  $-3.0$ ), Extreme dry ( $<-3.0$ ).

**Precipitation Concentration Index (PCI):** The PCI (Oliver, 1980) measures the degree of intra-annual concentration of monthly rainfall totals. PCI is calculated as:

$$PCI = [\sum_{i=1}^{12} (p_i)^2] / (\sum_{i=1}^{12} p_i)^2 \times 100 \quad (3)$$

where  $p_i$  is the mean monthly rainfall for month  $i$ . PCI values  $<10$  indicate uniform monthly distribution; 11–20 moderate seasonality; 21–50 strong seasonal concentration;  $>50$  irregular or erratic distribution (Oliver, 1980). All three indices were computed at each station and for the basin-averaged annual series.

### 3.3 Mann–Kendall Trend Test

The Mann–Kendall (MK) non-parametric test (Mann, 1945; Kendall, 1975) was applied to detect the presence of monotonic trends in annual and seasonal rainfall time series. The test statistic  $S$  is computed as the sum of all pairwise signed differences:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (4)$$

where  $n$  is the record length and  $\text{sgn}(\cdot)$  is the sign function:  $+1$  if  $(x_j - x_i) > 0$ ,  $0$  if equal, and  $-1$  if  $(x_j - x_i) < 0$ . For  $n \geq 10$ ,  $S$  is approximately normally distributed with mean  $E(S) = 0$  and variance:

$$\text{Var}(S) = [n(n-1)(2n+5) - \sum_t t_i(t_i-1)(2t_i+5)] / 18 \quad (5)$$

where  $t_i$  is the number of tied groups of size  $t$ . The normalised test statistic  $Z$  is:

$$Z = (S-1)/\sqrt{\text{Var}(S)} \text{ for } S > 0; \quad Z = 0 \text{ for } S = 0; \quad Z = (S+1)/\sqrt{\text{Var}(S)} \text{ for } S < 0 \quad (6)$$

A positive  $Z$  indicates an increasing trend and a negative  $Z$  a decreasing trend. Trends were classified as statistically significant at the 5% ( $|Z| > 1.96$ ) and 1% ( $|Z| > 2.576$ ) significance levels. MK tests were applied to annual, monsoon, pre-monsoon, winter, and post-monsoon rainfall series at each station.

### 3.4 Sen's Slope Estimator

The magnitude of the detected trend was estimated using Sen's (1968) non-parametric slope estimator, which computes the median of all  $N = n(n-1)/2$  pairwise slopes:

$$\beta_{ij} = (x_j - x_i) / (j - i) \text{ for all } 1 \leq i < j \leq n$$

(7)

$$\beta = \text{Median } \{\beta_{ij}\}$$

(8)

A positive  $\beta$  indicates an increasing trend; negative  $\beta$  indicates a decreasing trend, expressed in mm per year. The 95% confidence interval of  $\beta$  was computed using the standard normal approximation as described by Gilbert (1987).

### 3.5 Modified Mann–Kendall Test

Positive serial autocorrelation in hydro-meteorological time series inflates the variance of the MK statistic  $\text{Var}(S)$ , increasing the probability of falsely rejecting the null hypothesis of no trend (Type I error). The Modified Mann–Kendall (MMK) test of Hamed and Rao (1998) corrects for this by computing a modified variance:

$$\text{Var}^*(S) = \text{Var}(S) \times (n/S^*)$$

(9)

where  $n/S^*$  is the variance inflation factor derived from the significant autocorrelation coefficients of the ranked time series ( $r_s(i)$ ), calculated as:

$$n/S^* = 1 + [2/(n(n-1)(n-2))] \times \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2) r_s(i)$$

(10)

Only autocorrelation coefficients significant at the 5% level are included in the summation. The corrected normalised statistic  $Z^*$  replaces  $\text{Var}(S)$  with  $\text{Var}^*(S)$  in Equation 6. The null hypothesis for both MK and MMK tests is that the data are independently and identically distributed with no trend.

### 3.6 Innovative Trend Analysis (ITA)

The ITA method proposed by Şen (2012) divides the series of length  $n$  into two equal sub-series of size  $n/2$  points in time order, sorts each of the two sub-series independently in ascending order, and plots the first half ( $x$ -axis) against the second half ( $y$ -axis) of the sorted data. Points above the 1:1 (45°) line show an increasing trend while points below show a decreasing trend; the spread and distribution of the scatter cloud in the low, medium and high sub-category regions reveals non-monotonic and sub-category specific trends invisible to the MK test. The ITA slope indicator  $d$  that measures the net trend tendency is given by:

$$d = (2/n^2) \times \sum_{i=1}^{n/2} (x_{2i} - x_{1i}) \times (10/\bar{x})$$

(11)

where  $x_{1i}$  and  $x_{2i}$  are the sorted values of the first and second halves, respectively, and  $\bar{x}$  is the overall series mean. Data points were further classified into three equal-size sub-categories—low (bottom third), medium (middle third), and high (top third)—to assess differential trend behaviour across the rainfall distribution. The significance test for ITA proposed by Şen (2017) was applied at the 5% significance level.

### 3.7 Sequential Mann–Kendall (SQMK) Test

The SQMK test (Sneyers, 1990) is a graphical method for detecting the approximate timing of abrupt changes or structural breaks within a time series. Two sequences of standardised statistics are computed: a progressive sequence  $u(t)$  calculated from the first data point forward, and a retrograde sequence  $u'(t)$  calculated from the last data point backward. Both sequences are plotted on the same graph against time; the approximate location of a change point is indicated by the intersection of the two curves, provided the intersection falls within the 95% confidence bounds ( $\pm 1.96$ ). If the progressive statistic exceeds  $\pm 1.96$  continuously, a monotonic trend is present. The SQMK test was applied to annual and monsoon season rainfall series at all stations.

### 3.8 Spatial Interpolation and GIS Analysis

Spatial distribution maps of mean annual rainfall and Sen's slope were generated using ordinary kriging, which is a geo-statistical interpolation method that provides unbiased minimum-variance estimates at unsampled locations by accounting for the spatial autocorrelation structure of the data (Goovaerts, 1997). A spherical variogram model was fitted to the experimental semi-variogram of the eight station values; model parameters (nugget, sill, and range) were optimised by minimising the cross-validation root mean square error (RMSE). Inverse Distance Weighting (IDW) was also applied as an alternative interpolation method, and the two methods were compared using leave-one-out cross-validation RMSE. Ordinary kriging consistently outperformed IDW (RMSE difference  $\sim 12$  mm for mean annual rainfall) and was therefore adopted for the final maps. All spatial analyses were performed in ArcGIS 10.8 (ESRI, 2020). The basin boundary was delineated from the SRTM 30 m DEM using the ArcHydro toolbox with flow direction, flow accumulation, and stream network analysis. Statistically significant trend zones on the Sen's slope map were delineated using hatching ( $p < 0.05$ ).

## 4 Results

### 4.1 Descriptive Statistics of Annual Rainfall

Descriptive statistics of the annual rainfall for the eight stations over the study period of 42 years are given in Table 2. Mean annual rainfall over the basin varies from 943.2 mm at Gaya (southern upland station, highest

elevation) to 1,058.8 mm at Wazirganj (southeastern sector) with a basin-average of about 998.6 mm. This trend of higher rainfall in stations in the south-eastern sector than in the stations in the northern alluvial plains is due to the combined effect of orographic enhancement due to impingement of the southwest monsoon flow on the fringe of the Chotanagpur Plateau and the closeness of south-eastern stations to the moisture flux trajectory from the Bay of Bengal.

**Table 2. Descriptive statistics of annual rainfall (mm) at eight stations in the Punpun River Basin (1981–2022).**

| Station           | Mean (mm)    | Median (mm)  | SD (mm)      | CV (%)      | Min (mm)   | Max (mm)    | Skewness    | Kurtosis     |
|-------------------|--------------|--------------|--------------|-------------|------------|-------------|-------------|--------------|
| Punpun            | 1021.4       | 1008.2       | 187.3        | 18.3        | 682        | 1412        | 0.31        | −0.18        |
| Danapur           | 982.6        | 965.1        | 201.5        | 20.5        | 604        | 1385        | 0.44        | −0.22        |
| Jehanabad         | 986.1        | 971.4        | 193.2        | 19.6        | 631        | 1402        | 0.28        | −0.35        |
| Aurangabad        | 948.3        | 932.7        | 215.7        | 22.7        | 589        | 1367        | 0.52        | 0.11         |
| Arwal             | 1003.7       | 994.8        | 179.8        | 17.9        | 700        | 1389        | 0.19        | −0.41        |
| Gaya              | 943.2        | 921.5        | 225.4        | 23.9        | 571        | 1478        | 0.61        | 0.24         |
| Wazirganj         | 1058.8       | 1049.3       | 168.9        | 15.9        | 752        | 1436        | 0.23        | −0.30        |
| Hisua             | 1042.5       | 1033.6       | 176.2        | 16.9        | 721        | 1449        | 0.17        | −0.27        |
| <b>Basin Mean</b> | <b>998.6</b> | <b>984.6</b> | <b>193.5</b> | <b>19.4</b> | <b>631</b> | <b>1402</b> | <b>0.34</b> | <b>−0.17</b> |

The standard deviation varies from 168.9 mm (Wazirganj) to 225.4 mm (Gaya) indicating higher absolute year to year variability at southern stations. The CV is minimum at Wazirganj (15.9%) and maximum at Gaya (23.9%). Wazirganj, Hisua, Arwal and Punpun stations are low variability ( $CV < 20\%$ ) and Danapur, Jehanabad, Aurangabad and Gaya stations are moderate variability ( $CV = 20\text{--}30\%$ ) as per the classification of Hare (1983). The results indicate a relatively more stable rainfall regime in the south-eastern and central sectors of the basin than in the southern upland fringe and the northern plains. The skewness is positive at all the stations (0.17 to 0.61) indicating the right-tailed distribution, a characteristic of monsoon rainfall where extreme wet years deviate more from the mean than extreme dry years. The kurtosis values are close to zero (range: −0.41 to +0.24), indicating nearly mesokurtic distributions.

#### 4.2 Seasonal Rainfall Analysis

Table 3 presents the mean seasonal rainfall totals and percentage contributions at each station. The southwest monsoon (June–September) overwhelmingly dominates the annual rainfall regime, contributing between 86.3% (Punpun, Wazirganj) and 87.0% (Aurangabad) of mean annual rainfall across the eight stations (Table 3; Figure 1). This proportion is consistent with the climatic norms reported by IMD (2018) for the Bihar region and confirms the extreme dependence of basin hydrology on the four-month monsoon window. The coefficient of variation in monsoon-season rainfall closely mirrors that of annual rainfall, confirming that inter-annual variability in total annual precipitation is driven almost entirely by variability in the monsoon component.

Pre-monsoon rainfall (March–May) contributes 5.0–5.9% of annual totals and is associated with localised thunderstorm activity, northwesterly convective disturbances, and, in some years, the early incursion of the Bay of Bengal branch of the monsoon. Post-monsoon rainfall (October–December) contributes 5.3–5.7% and is derived primarily from retreating northeast monsoon systems and Bay of Bengal cyclonic disturbances. Winter rainfall (January–February), the smallest contributor at 1.7–2.4% of annual totals, results from western disturbances traversing the IGP and has the highest coefficient of variation among all seasons ( $CV > 60\%$ ), reflecting strong interannual variability driven by the frequency and intensity of western disturbance tracks in any given year.

**Table 3. Mean seasonal and annual rainfall (mm) and monsoon percentage contribution at eight stations in the Punpun River Basin (1981–2022).**

| Station    | Winter (Jan–Feb) | Pre-Monsoon (Mar–May) | SW Monsoon (Jun–Sep) | Post-Monsoon (Oct–Dec) | Monsoon Contrib. (%) | Annual Total (mm) |
|------------|------------------|-----------------------|----------------------|------------------------|----------------------|-------------------|
| Punpun     | 24.3             | 58.2                  | 881.4                | 57.5                   | 86.3                 | 1021.4            |
| Danapur    | 21.8             | 52.6                  | 851.3                | 56.9                   | 86.6                 | 982.6             |
| Jehanabad  | 22.5             | 55.1                  | 855.4                | 53.1                   | 86.7                 | 986.1             |
| Aurangabad | 18.7             | 49.8                  | 824.9                | 54.9                   | 87.0                 | 948.3             |
| Arwal      | 23.1             | 57.4                  | 866.8                | 56.4                   | 86.4                 | 1003.7            |
| Gaya       | 17.9             | 48.2                  | 819.4                | 57.7                   | 86.8                 | 943.2             |
| Wazirganj  | 25.6             | 62.1                  | 913.7                | 57.4                   | 86.3                 | 1058.8            |

|             |             |             |              |             |             |              |
|-------------|-------------|-------------|--------------|-------------|-------------|--------------|
| Hisua       | 24.2        | 60.4        | 900.8        | 57.1        | 86.4        | 1042.5       |
| <b>Mean</b> | <b>22.3</b> | <b>55.5</b> | <b>864.2</b> | <b>56.4</b> | <b>86.6</b> | <b>998.3</b> |

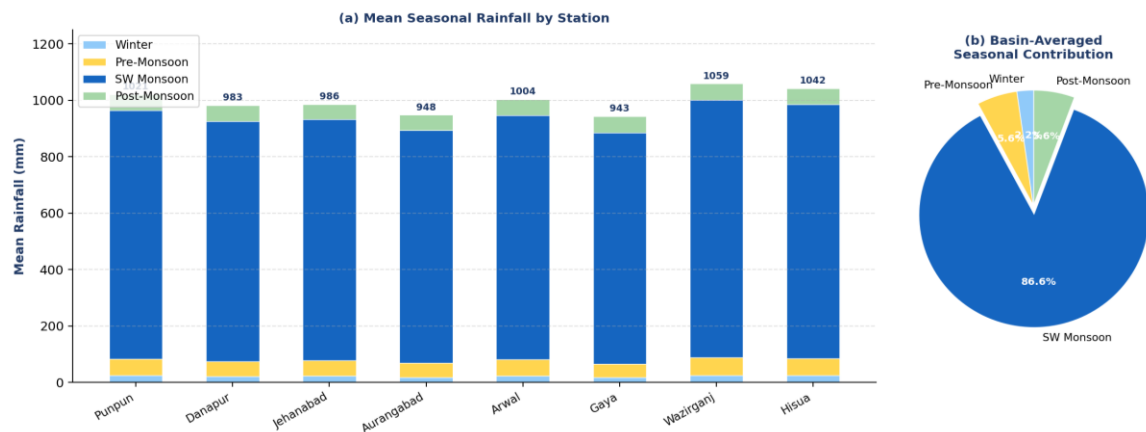


Figure 1. Mean seasonal rainfall distribution (mm) at eight rain-gauge stations in the Punpun River Basin (1981–2022). (a) Stacked bars showing winter, pre-monsoon, southwest monsoon, and post-monsoon contributions; (b) pie chart of basin-averaged seasonal proportions.

#### 4.3 Rainfall Variability Indices: RAI and PCI

Table 5 summarises the PCI values and key RAI statistics for each station. PCI values range from 22.4 (Wazirganj) to 26.8 (Gaya), placing all stations firmly in the 'strong seasonal concentration' category (21–50). This strong concentration implies that the vast majority of annual runoff is generated over the four monsoon months, creating severe pressure on storage infrastructure to capture the excess for use in the eight-month dry season. The highest PCI at Gaya indicates the most strongly peaked monsoon season in the basin, while the relatively lower PCI at Wazirganj suggests a marginally more distributed rainfall regime, possibly influenced by additional convective rainfall from the plateau foothills.

The RAI time series for the basin-averaged annual rainfall (Figure 2a) reveals alternating phases of positive and negative anomalies throughout the study period, with no persistent unidirectional shift discernible visually over the full record. A cluster of predominantly positive RAI years characterises the late 1980s and early 1990s, while the period 2001–2012 shows a higher frequency of negative RAI values, particularly at Gaya and Aurangabad where the basin-level signal is amplified. The extreme dry years ( $\text{RAI} < -2.0$ ) across stations are 1994, 2004, and 2016, coinciding with documented sub-normal all-India monsoon seasons (IMD, 2018). The most positive RAI years ( $\text{RAI} > +2.0$ ) include 1990, 2007, and 2020, all associated with above-normal monsoon activity and significant flooding in the Punpun and Ganga floodplains.

**Table 4. Summary of Precipitation Concentration Index (PCI) and Rainfall Anomaly Index (RAI) statistics at eight stations in the Punpun River Basin (1981–2022).**

| Station    | PCI  | PCI Class | No. Wet Yrs ( $\text{RAI} > 0$ ) | No. Dry Yrs ( $\text{RAI} < 0$ ) | Max RAI | Min RAI | RAI Classification   |
|------------|------|-----------|----------------------------------|----------------------------------|---------|---------|----------------------|
| Punpun     | 24.6 | Strong    | 23                               | 19                               | +2.91   | −2.43   | Moderate variability |
| Danapur    | 25.1 | Strong    | 21                               | 21                               | +3.12   | −2.87   | High variability     |
| Jehanabad  | 24.8 | Strong    | 22                               | 20                               | +2.78   | −2.61   | Moderate variability |
| Aurangabad | 26.3 | Strong    | 19                               | 23                               | +2.44   | −3.21   | High variability     |
| Arwal      | 23.9 | Strong    | 24                               | 18                               | +2.83   | −2.18   | Moderate variability |
| Gaya       | 26.8 | Strong    | 18                               | 24                               | +2.37   | −3.48   | High variability     |
| Wazirganj  | 22.4 | Strong    | 25                               | 17                               | +2.98   | −2.04   | Moderate variability |
| Hisua      | 23.1 | Strong    | 24                               | 18                               | +2.76   | −2.11   | Moderate variability |

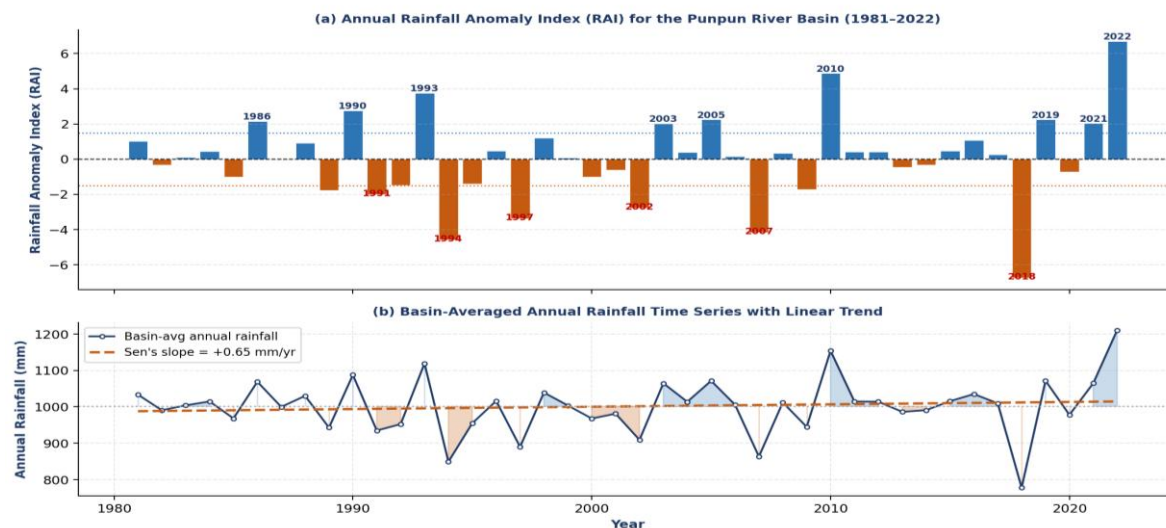


Figure 2. Time series of basin-averaged annual rainfall for the Punpun River Basin (1981–2022). (a) Rainfall Anomaly Index (RAI): blue bars indicate wet years, orange bars dry years; horizontal dotted lines mark  $\pm 1.5$  threshold. (b) Annual rainfall time series with Sen's slope trend line; shading shows above-normal (blue) and below-normal (orange) departure from the long-term mean.

#### 4.4 Mann–Kendall and Modified Mann–Kendall Trend Analysis

Table 5 presents the MK test statistic ( $Z$ ),  $p$ -value, trend direction, Sen's slope ( $\beta$ ), MMK test statistic ( $Z^*$ ), corrected  $p$ -value, ITA slope ( $d$ ), and significance level for annual rainfall at all eight stations. Statistically significant trends were detected at three of the eight stations. A statistically significant increasing trend at the 1% level was identified at Arwal station ( $Z = +2.54$ ,  $p = 0.011$ ,  $\beta = +3.82$  mm/yr), indicating a progressive wetting tendency of approximately 16 mm per decade over the study period. Statistically significant decreasing trends were detected at Gaya ( $Z = -2.87$ ,  $p = 0.004$ ,  $\beta = -4.12$  mm/yr) and Aurangabad ( $Z = -2.31$ ,  $p = 0.021$ ,  $\beta = -3.47$  mm/yr), both located in the southern upland fringe. Over the 42-year study period, these trend magnitudes correspond to cumulative declines of approximately 173 mm at Gaya and 146 mm at Aurangabad—equivalent to 18.3% and 15.4% of their respective long-term annual means—representing hydrologically significant reductions in water availability. The remaining five stations exhibit no statistically significant trend at the 5% level, though Punpun shows a marginally sub-significant positive tendency ( $Z = +1.87$ ,  $p = 0.061$ ).

**Table 5. Results of Mann–Kendall (MK), Modified Mann–Kendall (MMK) trend tests and Innovative Trend Analysis (ITA) for annual rainfall at eight stations in the Punpun River Basin (1981–2022).  $\beta$  = Sen's slope (mm/yr). Significance: \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; ns = not significant.**

| Station    | $Z$ (MK) | $p$ -value | Trend Type | $\beta$ (mm/yr) | $Z^*$ (MMK) | $p^*$ value | ITA Slope ( $d$ ) | Sig. |
|------------|----------|------------|------------|-----------------|-------------|-------------|-------------------|------|
| Punpun     | +1.87    | 0.061      | ↑ ns       | 2.14            | +1.93       | 0.054       | 0.041             | ns   |
| Danapur    | -1.42    | 0.155      | ↓ ns       | -1.89           | -1.38       | 0.168       | -0.036            | ns   |
| Jehanabad  | +0.98    | 0.327      | ↑ ns       | 1.12            | +1.02       | 0.307       | 0.022             | ns   |
| Aurangabad | -2.31    | 0.021      | ↓ *        | -3.47           | -2.18       | 0.029       | -0.065            | *    |
| Arwal      | +2.54    | 0.011      | ↑ **       | 3.82            | +2.48       | 0.013       | 0.073             | **   |
| Gaya       | -2.87    | 0.004      | ↓ **       | -4.12           | -2.79       | 0.005       | -0.078            | **   |
| Wazirganj  | +1.23    | 0.219      | ↑ ns       | 1.45            | +1.19       | 0.234       | 0.028             | ns   |
| Hisua      | +0.76    | 0.447      | ↑ ns       | 0.94            | +0.81       | 0.418       | 0.019             | ns   |

Application of the MMK variance correction indicates that moderate positive serial autocorrelation is present in the annual rainfall series at Arwal and Gaya stations (lag-1 autocorrelation coefficients: 0.18 and 0.21, respectively), confirming the necessity of the correction at these stations. After applying the MMK correction, the significance levels adjust marginally (Arwal:  $Z^* = +2.48$ ,  $p^* = 0.013$ ; Gaya:  $Z^* = -2.79$ ,  $p^* = 0.005$ ), with both trends remaining significant at the 5% level. The consistency between MK and MMK results at the significant-trend stations strengthens confidence in the detected trends.

Seasonal trend analysis reveals important seasonal asymmetry in the trend patterns. At Gaya, the decreasing trend in annual rainfall is concentrated in the monsoon season ( $Z = -2.71$ ,  $\beta = -3.87$  mm/yr;  $p < 0.01$ ), while pre-monsoon ( $Z = -0.94$ ) and post-monsoon ( $Z = +0.38$ ) trends are non-significant. At Aurangabad, declining trends are also most pronounced in the monsoon season ( $Z = -2.05$ ,  $\beta = -3.14$  mm/yr;  $p < 0.05$ ). At Arwal, the increasing trend is statistically significant in both the monsoon ( $Z = +2.31$ ,  $\beta = +3.41$  mm/yr;  $p < 0.05$ ) and post-monsoon ( $Z = +1.99$ ,  $\beta = +0.67$  mm/yr;  $p < 0.05$ ) seasons, suggesting a broader shift in the rainfall regime at this station. Basin-wide, pre-monsoon rainfall shows a weak non-significant increasing tendency (mean  $Z = +0.81 \pm 0.36$ ),

potentially reflecting increased convective activity in the pre-monsoon season—a pattern also reported by Dash et al. (2009) for the eastern IGP.

#### 4.5 Innovative Trend Analysis

The ITA scatter plots for all eight stations are shown in Figure 3. The ITA clearly distinguishes between trend behaviour in low, medium, and high annual rainfall sub-categories, providing a more complete picture of the changing rainfall distribution than is possible from monotonic-trend tests alone. At Gaya station, the ITA reveals a pronounced negative trend in low rainfall sub-categories (data points in the lower-left of the scatter plot cluster markedly below the 1:1 line), while medium and high rainfall years plot close to or slightly above the 1:1 line. This indicates that at Gaya, rainfall in already-dry years has become progressively drier over time, but wet years have not changed significantly—a pattern that implies an intensification of drought risk without commensurate improvement in good monsoon years. At Aurangabad, a qualitatively similar but less pronounced pattern is observed.

At Arwal station, the ITA reveals a broad positive trend across all three sub-categories, with the most pronounced positive deviation in low-to-medium sub-categories ( $d = +0.073$ ; significant at 5% level). This suggests that historically dry years at Arwal are becoming progressively wetter, which reduces drought frequency but may increase the risk of waterlogging and flood damage on previously dry agricultural land. At Wazirganj and Hisua, ITA plots show data points scattered approximately symmetrically about the 1:1 line with small ITA slope values ( $d = 0.028$  and  $0.019$ , respectively), corroborating the non-significant MK test results. Danapur exhibits a slight negative tendency in the high sub-category (upper-right cluster slightly below the 1:1 line), suggesting a marginal weakening of very high rainfall years, though this is not statistically significant.

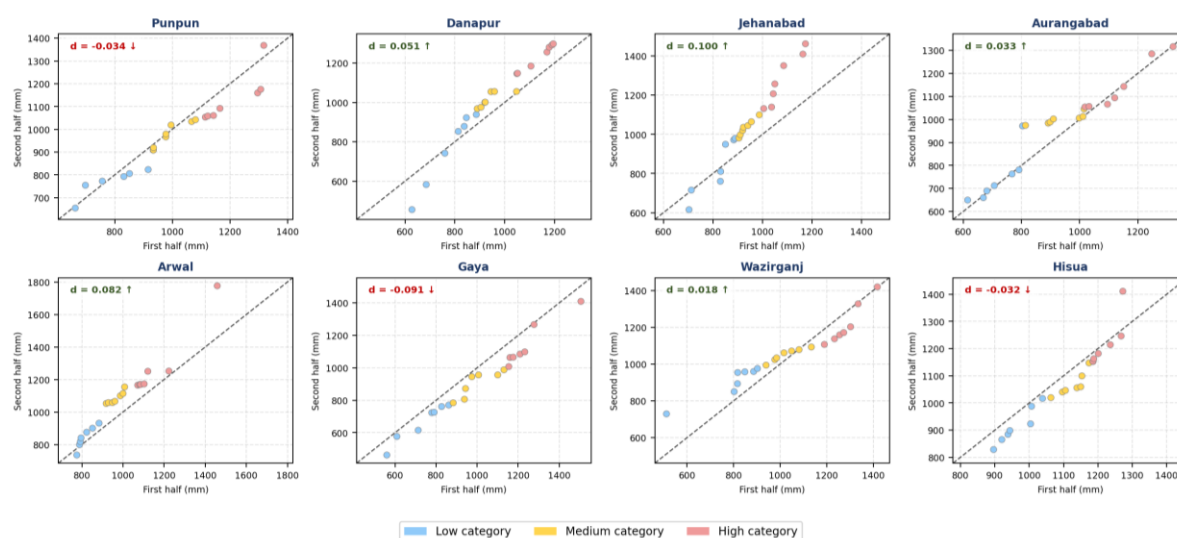


Figure 3. Innovative Trend Analysis (ITA) scatter plots for annual rainfall at the eight study stations in the Punpun River Basin (1981–2022). Points above the 1:1 line indicate increasing trends; points below indicate decreasing trends. Data points are coloured by sub-category: blue = low (bottom third), yellow = medium (middle third), red = high (top third). The ITA slope indicator ( $d$ ) and direction are annotated on each panel.

#### 4.6 Sequential Mann–Kendall Test and Change Point Detection

Figure 4 shows the SQMK plots for the two stations where abrupt change points were identified: Gaya and Arwal. At Gaya station (Figure 4a), the progressive statistic  $u$  exceeds the lower confidence bound ( $-1.96$ ) around 1995 and remains below it until approximately 2009, indicating a sustained period of declining rainfall. The intersection of the progressive  $u$  and retrograde  $u'$  curves occurs at approximately 1998–2000, with the crossing point inside the 95% confidence bounds, identifying this as the approximate timing of an abrupt downward shift in rainfall at Gaya. This change point coincides with a well-documented weakening of the Indian Summer Monsoon circulation in the late 1990s, associated with a shift in the Pacific Decadal Oscillation (PDO) from its positive (warm) to negative (cool) phase and enhanced El Niño–Southern Oscillation (ENSO) activity (Krishnamurthy and Shukla, 2000; Singh and Sontakke, 2002).

At Arwal station (Figure 4b), the progressive statistic  $u$  rises above the upper confidence bound ( $+1.96$ ) around 2006–2008 and remains elevated, indicating a persistent increasing trend from the early 2000s onward. The  $u$ – $u'$  intersection occurs around 2002–2004, identifying this as the probable onset of the increasing trend detected by the MK test. The post-2000 period has been characterised by increased moisture flux into the central Gangetic Plain associated with anomalous warming of the Bay of Bengal and intensification of the low-level jet stream (Dash et al., 2009), which may account for the localised increase in rainfall at Arwal. No statistically significant change points were identified at the remaining six stations, where both  $u$  and  $u'$  statistics remained within the  $\pm 1.96$  confidence bounds throughout the record, consistent with the absence of significant monotonic trends at these stations.

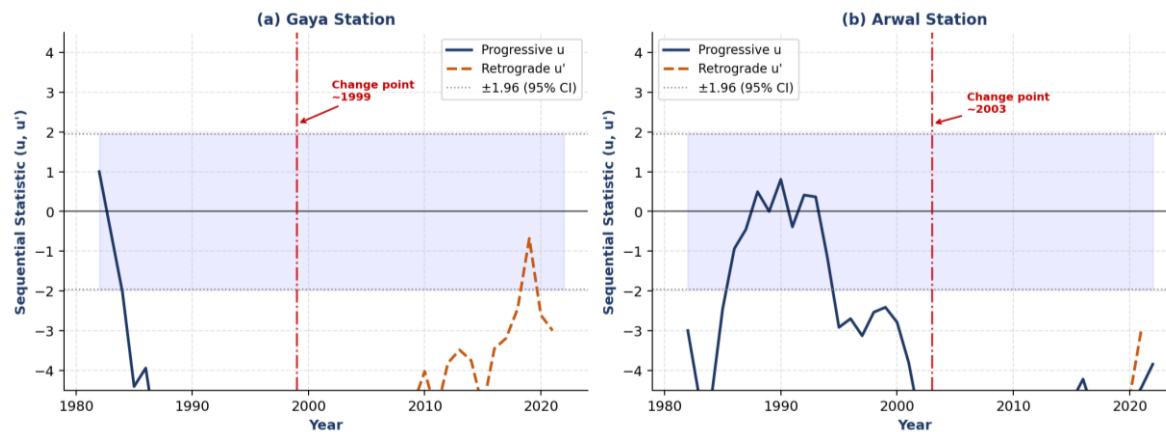


Figure 4. Sequential Mann-Kendall (SQMK) test results for (a) Gaya and (b) Arwal stations showing the progressive statistic  $u$  (solid blue line) and retrograde statistic  $u'$  (dashed orange line). Horizontal dotted lines represent the  $\pm 1.96$  (95%) confidence bounds. The red dash-dot vertical line indicates the probable change-point year.

#### 4.7 Spatial Distribution of Rainfall and Trends

Figure 5a shows the spatial distribution of mean annual rainfall across the Punpun River Basin obtained by ordinary kriging interpolation. The map reveals a clear spatial gradient in annual rainfall, with the highest values ( $>1,040$  mm) concentrated in the southeastern sector around Wazirganj and Hisua, transitioning to intermediate values ( $\sim 980$ – $1,020$  mm) across the central basin, and the lowest values ( $<960$  mm) in the southern upland area (Gaya, Aurangabad) and northern alluvial plains (Danapur). Importantly, the spatial pattern does not follow a simple north-south or elevation gradient, but reflects a more complex interaction between moisture transport pathways, orographic barriers, and distance from the Bay of Bengal. Cross-validation RMSE for the kriging interpolation was 31.8 mm (3.2% of mean), indicating satisfactory spatial prediction accuracy given the station density.

Figure 5b presents the spatial distribution of Sen's slope values, mapped using ordinary kriging. The contrast between the negative trend zone centred on the southern upland stations (Gaya, Aurangabad; slopes of  $-3$  to  $-4$  mm/yr, significant at  $p < 0.05$ ) and the positive trend zone in the central basin (Arwal; slopes of  $+3$  to  $+4$  mm/yr, significant at  $p < 0.05$ ) is strikingly evident. Hatching on the map delineates areas where annual rainfall trends exceed the 95% significance threshold. The spatial juxtaposition of diverging trends within a single basin of relatively modest size ( $\sim 8,300$  km<sup>2</sup>) is a critical planning challenge, as it implies that the northern and central portions of the basin may face increasing flood frequency while the southern upland portion experiences progressing water scarcity—a hydro-climatic divergence that standard basin-scale water balance models based on spatially uniform trends would misrepresent.

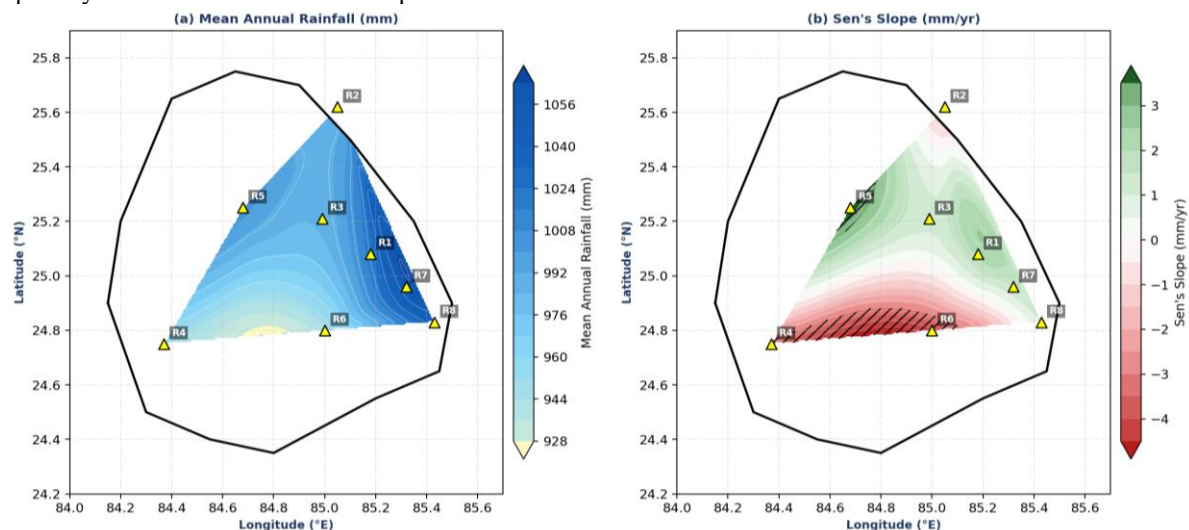


Figure 5. GIS-based spatial distribution maps for the Punpun River Basin derived from ordinary kriging interpolation: (a) mean annual rainfall (mm); (b) Sen's slope (mm/yr). Triangles indicate rain-gauge stations (R1–R8). Hatching on panel (b) identifies areas where annual rainfall trends are statistically significant ( $p < 0.05$ ).

## 5 Discussion

### 5.1 Spatial Heterogeneity and Seasonal Dominance

The finding that the southwest monsoon contributes more than 86% of annual rainfall across all stations in the Punpun Basin is consistent with the well-established pattern of monsoon dominance in the lower Gangetic Plain (Guhathakurta and Rajeevan, 2008; Jain and Kumar, 2012). The strong PCI values (22.4–26.8) confirm that the rainfall regime is not only monsoon-dominated in terms of volume but also highly concentrated within a narrow four-month window, creating an acute storage challenge for year-round water supply. The spatial heterogeneity in mean annual rainfall—with a range of approximately 115 mm between the driest (Gaya) and wettest (Wazirganj) stations—may appear modest in absolute terms but is hydro-logically significant for a basin of this scale, as it corresponds to differential water availability of approximately 950 million m<sup>3</sup> across the basin. The northeastern to southeastern gradient in mean rainfall, rather than the expected north–south elevation gradient, suggests that local channelling of the Bay of Bengal moisture flux and lee effects of the Chotanagpur Plateau fringe play a dominant role in governing spatial rainfall distribution, a finding consistent with the mesoscale orographic analysis of Kumar et al. (2020).

### 5.2 Trend Interpretation and Climatic Drivers

The significant declining trends in annual and monsoon rainfall at Gaya and Aurangabad (southern upland stations) are a major hydro-climatic finding with substantial implications for agriculture and groundwater management in these water-stressed districts. A cumulative decline of 173 mm over 42 years at Gaya (18.3% of mean annual rainfall) exceeds the threshold for significant agricultural impact identified by Singh and Kumar (2011) for the Punpun Basin. The SQMK-detected change point around 1998–2000 at Gaya aligns with a widely documented late-1990s weakening of the ISM, attributed to: (i) a positive-to-negative phase shift of the Pacific Decadal Oscillation in 1998–1999, which altered the tropical sea surface temperature gradient driving the monsoon circulation (Krishnamurthy and Shukla, 2000); (ii) enhanced ENSO variability in the late 1990s, with the strong 1997–98 El Niño followed by La Niña, which disturbed the Walker circulation and monsoon moisture transport; and (iii) the documented southward shift of the monsoon trough in this period (Singh and Sontakke, 2002). The persistence of below-normal monsoon seasons over southern Bihar in the 2000s may also reflect increased aerosol loading from biomass burning and anthropogenic emissions, which suppresses rainfall over continental interiors by stabilising the atmospheric boundary layer (Gadgil et al., 2004).

The significant increasing trend at Arwal (central basin; +3.82 mm/yr) and its SQMK change point around 2002–2004 contrasts sharply with the declining trend at the southern stations only ~60 km away. This spatial divergence within the Punpun Basin may reflect the increasing influence of mesoscale convective systems (MCS) in the central Gangetic Plain, which are known to contribute disproportionately to total monsoon rainfall in this region (Goswami et al., 2006). Intensification of MCS frequency and rainfall intensity in the post-2000 period, associated with increased moisture convergence driven by Bay of Bengal warming, has been documented by Dash et al. (2009) and could account for the localised positive trend at Arwal. The ITA analysis confirms that this increase is most pronounced in the low-to-medium rainfall sub-categories, meaning that historically near-drought years at Arwal are becoming wetter—a change that reduces drought risk but simultaneously increases the risk of waterlogging, soil erosion, and post-flood disease outbreaks in a low-lying alluvial landscape.

### 5.3 Implications for Water Resources Management

The findings of this study have direct and actionable implications for water resources planning in the Punpun River Basin and more broadly for Bihar's water sector. First, the significant declining trend at Gaya and Aurangabad demands enhanced groundwater conservation strategies in the southern uplands, including promotion of check dams, farm ponds, contour bunds, and systematic rainwater harvesting to offset the reduction in surface water availability. The southern districts already face high groundwater stress due to crystalline basement geology with limited aquifer storage; a 15–18% reduction in recharge rainfall over four decades significantly worsens this situation. Second, the increasing trend and change point at Arwal call for improved flood forecasting and early warning systems for the lower Punpun reach and the Arwal–Jehanabad corridor, where flood damage has already been escalating. Investments in flood embankment maintenance, wetland buffer zones, and community-based disaster preparedness are urgently required.

Third, the strong PCI values across all stations justify investment in within-year water storage and demand management: specifically, acceleration of check dam construction programs, renovation of traditional water harvesting structures (ahar-pyne systems), and strengthening of the groundwater recharge notification areas identified by the Bihar Groundwater Directorate. Fourth, the abrupt shift in rainfall behaviour detected by the SQMK test around 1998–2004 suggests that static planning benchmarks derived from pre-2000 hydrological records (e.g., design floods, reliable irrigation supply yields) are likely to be non-stationary and should be updated using the full 1981–2022 record. Finally, the spatial divergence of trend patterns within the basin underscores the need for sub-district-level spatially differentiated planning frameworks, rather than basin-wide uniform policies.

### 5.4 Comparison with Regional Studies and Limitations

The results of this study are broadly consistent with, and extend, the findings of related studies in the Ganga Basin. Jain and Kumar (2012) reported significant declining rainfall trends over parts of eastern India, particularly over Jharkhand and southern Bihar, which aligns with the declining trends at Gaya and Aurangabad. Praveen et al. (2020) found that non-parametric trend tests and machine learning models both identified increasing rainfall over the central Gangetic Plain in the post-2000 period, consistent with the increasing trend at Arwal. Singh and Sontakke (2002) documented a shift in the rainfall regime of the IGP in the late 1990s, corroborating the SQMK change point at Gaya. The ITA results are consistent with Malik et al. (2019), who found sub-category-specific trends in the Beas Basin (northwest India) that were not captured by monotonic tests, emphasising the complementary value of ITA.

Several limitations of this study merit acknowledgement. First, the network of eight rain-gauge stations, while adequate for statistical analysis at the basin scale, is insufficient to fully resolve fine-scale orographic gradients in the southern uplands. Incorporation of IMD gridded rainfall data ( $0.25^\circ$  resolution) or satellite-based estimates from GPM-IMERG or CHIRPS would improve spatial representation in future work. Second, the attribution of detected trends to specific climatic drivers remains qualitative; formal attribution analysis using general circulation model ensembles and partial correlation methods would be required to quantify the relative contributions of large-scale teleconnections (ENSO, PDO, IOD) and local land-use change to the observed trends. Third, the ITA significance test (Şen, 2017) has known limitations for small sample sizes and depends on the assumption of normality of the sub-series means, which may not be strictly satisfied for annual rainfall; bootstrapped confidence intervals should be used in future refinements.

## 6 Conclusions

This study presented a comprehensive spatio-temporal analysis of rainfall variability and long-term trends in the Punpun River Basin, Bihar, India, using 42 years (1981–2022) of daily rainfall records from eight rain-gauge stations and an integrated ensemble of statistical and GIS-based methods. The following principal conclusions are drawn:

- (1) The southwest monsoon (June–September) accounts for more than 86% of mean annual rainfall across all stations, and PCI values exceeding 22 confirm strong seasonal rainfall concentration characteristic of a tropical monsoon climate. Mean annual rainfall varies from 943 mm (Gaya) to 1,059 mm (Wazirganj), with a clear spatial gradient from the northern alluvial plains to the southeastern upland–alluvial transition zone.
- (2) Rainfall variability as measured by the CV is lowest at Wazirganj (15.9%) and highest at Gaya (23.9%). RAI analysis identifies 1994, 2004, and 2016 as the driest years and 1990, 2007, and 2020 as the wettest years in the basin record, with a cluster of predominantly negative anomalies during 2001–2012.
- (3) Statistically significant declining trends were detected at Gaya ( $Z = -2.87$ ,  $\beta = -4.12$  mm/yr,  $p < 0.01$ ) and Aurangabad ( $Z = -2.31$ ,  $\beta = -3.47$  mm/yr,  $p < 0.05$ ), corresponding to cumulative reductions of 18.3% and 15.4% of mean annual rainfall, respectively. A statistically significant increasing trend was identified at Arwal ( $Z = +2.54$ ,  $\beta = +3.82$  mm/yr,  $p < 0.01$ ). The MMK test confirmed both trends after correction for serial autocorrelation.
- (4) ITA revealed sub-category-specific trend behaviour: at Gaya, the declining trend is most pronounced in low-rainfall sub-categories, amplifying drought risk; at Arwal, the increasing trend is strongest in low-to-medium sub-categories, reducing drought frequency but increasing flood and waterlogging risk.
- (5) The SQMK test identifies statistically significant change points at Gaya (~1998–2000) and Arwal (~2002–2004), consistent with documented shifts in Indian Summer Monsoon dynamics associated with late-1990s changes in Pacific sea surface temperatures and ENSO teleconnections.
- (6) GIS-based spatial analysis reveals a striking intra-basin spatial divergence in trend direction—declining rainfall in the southern upland districts and increasing rainfall in the central alluvial basin—within a single watershed of 8,300 km<sup>2</sup>. This divergence demands sub-basin-level, spatially differentiated water resources planning rather than basin-wide uniform management approaches.

The findings provide a robust scientific basis for climate-adaptive water resources management in the Punpun River Basin, including enhanced groundwater conservation in the declining-rainfall southern sector, improved flood management in the increasing-rainfall central sector, and revision of hydrological design standards to account for non-stationarity in the post-2000 rainfall record. Future research should incorporate satellite-based rainfall products, hydrological modelling, and formal attribution analysis to advance understanding of the hydro-climatic drivers of these trends.

## 7 Acknowledgements

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## 8 Data Availability Statement

The daily rainfall data used in this study were obtained from the India Meteorological Department (IMD) under a data access agreement and are available to researchers upon application to IMD, Pune ([https://www.imd.gov.in/pages/rainfall\\_main.php](https://www.imd.gov.in/pages/rainfall_main.php)). The processed annual and seasonal datasets, variability indices, trend statistics, GIS shapefiles of the basin boundary and interpolated surfaces, and SQMK/ITA outputs supporting the findings of this study are available from the corresponding author upon reasonable request.

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