Assessment of Spatio-temporal variation of Rainfall over Semi-Arid Basin, Gujarat, Western India using GIS and MATLAB

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Abstract

During recent decades, Indian River Basins have experienced highly erractic rainfall patterns because of changing climate and rapid urbanization. In this study, we evaluated variability in rainfall between 1981-2020 over the Mahi River Basin (MRB) using India Meteorological Department (IMD) daily gridded rainfall dataset. To examine the change in precipitation patterns, we evaluated trends in annual, seasonal, monthly rainfall using non-parametric Mann Kendall test and Sen's Slope estimation. It was observed that annual and monsoon season rainfall increased during the last 40 years with a rate of change of 3.07 mm and 3.854 mm per year. Monthly rainfall analysis indicated a significant increase in September rainfall (2.57mm/year) indicating a shift in ISM and delay in retreat of monsoon over the basin. Finally, we estimated trends in dry/wet days and low, moderate and heavy rainfall events and observed an increase in wet days and moderate and heavy events respectively. The research highlights the changing pattern of rainfall over the basin and the implications of variable rainfall for water resource management.

Keywords- Mahi River, Mann-Kendall, heavy rainfall, wet days

1. Introduction

Systematic investigation of rainfall characteristics under climate change scenario is significant for food and water security, disaster risk reduction and water resource management. Rainfall is regarded as the most important hydrological component regulating processes associated with the feedback interaction between atmosphere and hydrosphere (Trenberth 2011; Sun et al. 2018). Accurate precipitation measurement at reliable spatial and temporal scale thus, becomes essential for monitoring the variability in rainfall, estimation of hydrological components (soil moisture, evapotranspiration) from hydrological modelling and meteorological forecasting (Choubey, Kumari, and Chander 2023).

Rainfall characteristics over a region - magnitude, intensity and spatial distribution are adversely affected by climate change which in turn impacts the overall hydrological regime (Mishra and Lilhare 2016; Ali, Mishra, and Pai 2014). Human induced global warming causes increased water holding capacity of the atmosphere leading to intense precipitation (Trenberth 2011; Huntington 2006; Pai et al. 2015; Feng, Porporato, and Rodriguez-Iturbe 2013). This could lead to an enhanced risk of flooding in regions experiencing short-duration intense precipitation and flash droughts over regions with low rainfall (Trenberth et al. 2003; Mishra, Aadhar, and Mahto 2021; Feng, Porporato, and Rodriguez-Iturbe 2013). High variability in rainfall is expected to severely impact food and water security over Indian subcontinent as the Indian Summer Monsoon (ISM) is the primary source of freshwater availability (Mishra, Aadhar, and Mahto 2021; Dash et al. 2009; Hrudya, Varikoden, and Vishnu 2021).

Multiple studies have been conducted to study the variability in long-term rainfall over major India River Basins (Gosain, Rao, and Basuray 2006; Dubey and Sharma 2018; Swarnkar et al. 2021; Sharma, Sharma, and Panda 2022; Bisht et al. 2018; Deshpande, Kothawale, and Kulkarni 2016; Chaubey et al. 2022; Singh et al. 2008; Srivastava et al. 2021). Gosain, Rao, and Basuray (2006) evaluated the future precipitation projections and reported a reduced rainfall (by 20%) in Krishna Basin and an increased rainfall in all the sub-basins of Mahanadi. Singh et al. (2008) evaluated annual and seasonal trends in rainfall characteristics in the last century in 9 major river basins of northwest India and reported an increase in annual rainfall and a decline in number of rainy days in majority of the river basins. Deshpande, Kothawale, and Kulkarni (2016) evaluated trends in rainfall using IMD gridded rainfall datasets and reported an increasing rainfall trend in river basins along peninsular India (Krishna) and a decreasing rainfall trend in Ganga and Narmada rivers respectively. Bisht et al. (2018). examined trends in annual, seasonal and extreme rainfall events for 85 major Indian sub-basins during 1901-2015. They reported an increase in extreme rainfall for the majority of the basins and cited urbanization as the possible cause of increment. Similarly, Srivastava et al. (2021) analyzed long term trends (1901-2016) in rainfall over Kosi River basin and reported a decline in annual and monsoon rainfall. Swarnkar et al. (2021) examined the hydrological impacts of rainfall variability in the Ganga River basin in the last century. They observed an increasing trend in ISM rainfall along the mountainous region and a decline in rainfall along the alluvial plains with combined influence of natural vegetation. Sharma, Sharma, and Panda (2022) estimated trends in precipitation extremes in Mahi River basin during 1970-2019 and observed an increase in consecutive dry days (CDD) and a decline in consecutive wet days (CWD) indicating regional drying. Chaubey et al. (2022) evaluated trends in extreme rainfall events over major river basins of India during 1901-2019. They suggested that there is a remarkable shift in occurrence of extreme rainfall from northeast rivers towards northwest rivers of India in the last 40 years (1981-2019).

It is reported that the highest variability in rainfall is expected to be along the northwestern parts of India characterised by orographic rainfall (Kumar and Perry 2019; Dave, James, and Ray 2017; Todmal 2020). Moreover, small river basins experience higher rainfall variability over shorter duration due to the altercations in micro climatic variables (Min et al. 2011; Parry 2007). Further, a river basin is the fundamental hydrological unit of a region regulating regional climate. In the present study, we investigated the variability in rainfall regime over the Mahi River Basin (MRB), Western India during 1981-2020 using IMD (0.25X 0.25) daily gridded rainfall dataset and various thresholds of rainfall characteristics to understand the overall change in rainfall patterns and examine the possible causes and implications.

2. Datasets and Methods

2.1 Description of the Study Area

Mahi River Basin is a major west flowing river of India extending through three states with a total drainage area of 34842 km^2 (Figure 1). The basin is characterized by intensive agriculture with 63.3% of the land area is used for agriculture and 4.34 % is covered with water bodies (https://indiawris.gov.in). MRB is divided into two climatic zones - the major part of the basin experiences tropical wet climate while the northern part is characterized by subtropical wet climate. The basin receives an average annual rainfall of 785 mm and 90% of the rainfall occurs during the southwest monsoon period (June-October). 43 IMD Gauge stations are functional in the basin for monitoring daily rainfall. Since the basin drains through 3 major states of India, it becomes imperative to monitor the current and future hydrological state of the basin as western India is characterized by semi-arid climate and low water availability. Any significant change in surface water availability owing to rainfall variability could lead to inter state conflicts and water management crisis. We performed our study over the Mahi basin delineated by the CWC and India-WRIS (https://www.india.gov.in/watershed-atlas-india).

Figure 1: Geographical location of the Mahi River Basin

2.2 Data

To investigate the state of rainfall over the basin, we utilized 40 years (1981-2020) of India Meteorological Department (IMD) daily gridded rainfall data available at 0.25X 0.25 spatial resolution. For the detailed description of the dataset, methodology employed to develop the dataset and its application, refer to (Pai et al. 2014, 2015). The major advantage of using IMD gridded dataset is that it can capture the intrinsic variability in rainfall along the western region of India characterized by low daily rainfall due to the dense network of rain gauges (refer to Figure 1 in (Pai et al. 2014)).

2.3 Methodology

To detect the trend in rainfall time series data over Mahi Basin, two non-parametric tests namely, Mann Kendall and Sen's Slope were employed. A non-parametric test can be applied to any independent times series data as it does not require any specific distribution of the dataset (Bisht et al. 2018). The Mann-Kendall test is employed to detect the presence of any monotonic increasing or decreasing trend in a data (Mann 1945). The Mann-Kendall test statistic is defined as

$$S = \Sigma_{i=1}^{n-1} \Sigma_{j=i+1}^{n} sgn\left(X_j - X_i\right)$$

where n represents the length of the dataset and X_i and X_j represents data points at j and k $(j > k)$ respectively. The $sgn\left(X_i - X_j\right)$ is represented as:

$$sgn\left(X_j - Xi\right) = \begin{cases} -1 & \text{if } X_j - Xi < 0 \\ 0 & \text{if } X_j - X_i = 0 \\ 1 & X_j - X_i > 0 \end{cases}$$

And the Variance $Var(S)$ is represented as:

$$Var(s) = \frac{n(n-1)(2n+5) - \Sigma_{i=1}^{m} t_i(t_i - 1)(2ti + 5)}{18}$$

where $V(s)$ is the variance in S, m is the number of tied groups, t_i is the size of the ith group. The standard normal test statistics is given as:

$$Z = \begin{cases} \frac{S+1}{\sqrt{V(S)}} & if, S < 0 \\ 0 & if, S = 0 \\ \frac{S-1}{\sqrt{V(S)}} & if, S > 0 \end{cases}$$

A positive or negative value of Z indicates an increasing or decreasing trend. A trend is significant if $|\text{Z}| > Z_1 - \frac{\alpha}{2}$ To estimate the magnitude of change in rainfall characteristics, we employed Sen's Slope which is calculated as

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right), j > 1$$

where β is the rate of change in each dataset (Sen 1968). Trends in rainfall characteristics were calculated using multiple thresholds illustrated in Table 1. IMD (2021) have defined thresholds for dry/wet days and low, moderate and extreme rainfall events for the Indian sub-continent.

Table 1: Thresholds for rainfall characteristics defined by (IMD 2021)

S.No.	Rainfall Characteristics	Threshold (mm/day)
1	Dry Days	< 2.5mm
2	Wet Days	> 2.5mm
3	Low event	< 15.6 mm
4	Moderate event	> 15.6 mm and < 64.4 mm
5	heavy event	> 64.4 mm

3. Results and Discussion

To investigate the variability in rainfall over the Mahi River Basin (referred to as MRB hereafter), we determined trends in annual, seasonal and monthly rainfall using Mann-Kendall and Sen's Slope method. Further, we examined the variability in rainfall characteristics using predefined rainfall thresholds. Section 3.1 evaluates the trends in annual and seasonal rainfall over MRB, Section 3.2 deals with variability in monthly rainfall during 1981-2020 and section 3.3 illustrates trends in rainfall characteristics (rainfall duration and intensity) respectively.

3.1 Variability in Annual and Seasonal Rainfall

Long term (1981-2020) trend in annual rainfall was computed using IMD gridded daily rainfall over MRB. It is observed that MRB witnessed an annual rainfall of 856.599 mm with a standard deviation of 236.083 between 1981-2020. The basin witnessed an increase in annual rainfall in the last 40 years, particularly after 2000 (Figure 2). Mann-Kendall trend analysis over the basin revealed an increasing trend (insignificant) in annual rainfall with a rate of change of 3.07 mm/year (Sen's Slope).

Figure 2: Average annual rainfall distribution over MRB during 1981-2020 (upper panel). Variability in annual rainfall anomaly and linear change over MRB (lower panel).

For classification of months into seasons, we used the IMD seasonal classification i.e. Monsoon (JJAS), post monsoon (ON), winter (DJF) and pre monsoon (MAM). It is observed that MRB receives 95 % of annual rainfall during ISM season (June, July, August and September). The monsoon season experienced an increase in rainfall during the last 40 years (3.85 mm/year) and the trend was found to be significant at 95% confidence interval. Post monsoon season witnessed a decline in rainfall with an insignificant decreasing trend. The other two seasons did not show any significant change in rainfall trend (Figure 3).

Figure 3: Seasonal variability in rainfall anomaly over MRB. The blue bars represents positive rainfall anomaly and red line depicts negative rainfall anomaly for the particular year.

Figure 4 shows the spatial distribution of rainfall trend over MRB. For monsoon season, northern parts of the basin witnessed the highest positive rate of change indicating that the upper MRB experienced an increment in monsoon rainfall in the last 40 years. On the other hand, a significant decline in post monsoon rainfall was observed along the north and central parts of the basin. Spatial distribution of rainfall trends clearly indicates that there is no change in rainfall during winter and pre monsoon rainfall. The observations are consistent with similar studies (Singh et al. 2008; Dave, James, and Ray 2017; Sharma, Sharma, and Panda 2022; Pawar et al. 2023). Pawar et al. (2023) reported no significant trend in annual, monsoon and post monsoon rainfall over the basin during 1901-2012. A significant increasing trend in monsoon rainfall indicates that the last 20 years contributed to the increase in monsoon rainfall. Srivastava et al. (2021) have cited moderate to high mean convective precipitation as the major contributor to increasing rainfall trend. An abrupt shift in rainfall pattern over a shorter duration can further be attributed to weakening of Southern Oscillation Index (SOI) as result of human induced warming (Maharana, Agnihotri, and Dimri 2021; Todmal et al. 2022). A westward shift in monsoon trough over southeast Asia also contributed to the increase in ISM rainfall (Preethi et al. 2017). Guhathakurta and Saji (2013; Todmal et al. 2022) have also observed a decline in post monsoon rainfall attributed to weakening of El Nino Southern Oscillation (ENSO) and the impact of ENSO-IOD on sub-divisional rainfall (Choubey, Kumari, and Chander 2023).

Figure 4: Spatial distribution of magnitude of change (mm/year) in rainfall for each season during 1981-2020 over MRB. * Shows the grids with a significant trend.

3.2 Trends in Rainfall Intensities

We evaluated the variability in rainfall events using multiple rainfall thresholds described in Table 1. It must be noted that we computed the trends in rainfall characteristics for monsoon season as 95% of the annual rainfall occurs during June, July, August and September respectively. Figure 5 shows the distribution of dry (rainfall <2.5 mm/day) and wet (rainfall>2.5 mm/day) days in the last 40 years during the ISM rainfall. It was observed that dry day events have decreased, and wet day events have increased over MRB in the last 40 years. However, the trend was found to be insignificant for both events.

Figure 5: Variability in dry/wet days over MRB during 1981-2020.

Figure 6 shows the spatial distribution in dry and wet days over MRB. It is observed that eastern parts of the basin receive maximum number of wet days during ISM followed by southern region. On the contrary, upper MRB is characterized by frequent dry spell during monsoon season. However, spatial trend analysis of wet/dry spells indicate that upper MRB witnessed an increase in number of wet spells whereas eastern basins witnessed a decline in number of wet spells indicating a clear shift in the onset and progress of ISM over MRB. An increase in average annual rainfall and an increasing trend in number of wet days indicate that the region has shifted towards wet climate in the last 40 years. The characteristics of dry/wet spells are closely associated with regional climate. A shift in patterns of wet and dry days is attributed to variable temperature and moisture conditions (Choubey, Kumari, and Chander 2023). Maharana, Agnihotri, and Dimri (2021) have argued that a recent shift in dry and wet zones are attributed to increase in convective activity.

Figure 6: Spatial variability in dry/wet days over MRB between 1981-2020. The grids with * represent a significant trend.

We further analyzed the trends in low, moderate and heavy rainfall events over MRB to study the variability in rainfall intensity during ISM. It is observed that low rainfall events have declined while moderate and heavy rainfall events have witnessed an increase over MRB during 1981-2020 (Figure 7).

Figure 7: Variability in low (upper panel), moderate (middle panel) and heavy rainfall over MRB

However, the trend was found to be insignificant for all the three thresholds. Figure 8 represents the spatial distribution of low, moderate and heavy rainfall over MRB. It is interesting to note that although upper MRB witnessed the highest number of low rainfall events during ISM, an increase in occurrence of moderate events and a decreasing trend in low events was observed. This clearly indicates a shift in ISM towards upper MRB in the last 40 years. For heavy rainfall events, central and eastern parts received the highest number of events during 1981-2020 respectively. Goswami et al. (2006) reported an increase in frequency and magnitude of extreme rainfall events over central India. On the contrary, Ghosh et al. 2012) reported no significant increase in heavy rainfall. The contradiction in trends of rainfall characteristics is due to the difference in analysis approach and study period (Ali, Mishra, and Pai 2014). It is observed that heavy rainfall events have significantly increased under warming climate because of rapid urbanization. (Chaubey et al. 2022; Lu et al. 2019). An increase in moderate and heavy rainfall and a decline in low rainfall events results in frequent occurrence of floods and droughts in a region. Chaubey et al. (2022) have argued that an increase in extreme rainfall over Indian River Basins (IRBs) is linked with global teleconnections (El Niño–Southern Oscillation and Pacific Decadal Oscillation) and causes inter annual variability in annual rainfall. The results observed are consistent with the findings of Chaubey et al. (2022) who found a marked shift in occurrence of heavy rainfall from northeastern IRBs towards western IRBs. Increased occurrence of heavy rainfall is further attributed to increased frequency of Indian Ocean Diople (IOD) (Cai et al. 2014).

Figure 8: Spatial distribution of trends in low, moderate and heavy rainfall events over MRB during 1981-2020. The * represents grids with significant trend.

3.3 Trends in Monthly Rainfall

We examined the variability in rainfall at monthly scale by computing mean, standard deviation, maximum and minimum rainfall and determined the magnitude of change in rainfall during 1981-2020. The statistics observed is shown in Table 2. It is clear that MRB received maximum rainfall during August (298.44 mm) followed by July (290.58) and September (130.03) respectively. The monthly distribution of rainfall over MRB is represented as a whisker plot (Figure 9). It is clear from Figure 9 that a unimodal distribution in rainfall is prevalent over MRB. High rainfall during August and September months is due to the widespread wet spells during the active phase of ISM over the region. Trend analysis of monthly rainfall indicated that September month witnessed a significant increasing trend

(2.57mm) while an insignificant increasing trend was observed for July (0.79 mm) and August (0.64 mm) respectively.

Figure 9: Distribution of monthly rainfall over MRB represented as a whisker plot

Table 2: Statistics of rainfall variability over MRB

Duration	Mean	Trend	Change (mm)
Annual	856.59	Increasing	3.07
Monsoon	814.64	Increasing*	3.85
Post Monsoon	29.54	Decreasing	-0.42
Winter	5.26	No Change	0
Pre-Monsoon	7.15	No Change	0.01
January	2.38	No Change	0
February	1.25	No Change	0
March	0.82	No Change	0
April	1.85	No Change	0
May	4.47	No Change	0
June	95.57	Increasing	0.22
July	290.58	Increasing	0.79
August	298.44	Increasing	0.64
September	130.03	Increasing*	2.57
October	23.22	Decreasing	-0.1
November	6.31	No Change	0
December	1.62	No Change	0

Increasing trend for rainfall during ISM months indicates that the ISM has intensified over the region that has led to an increase in annual rainfall. Further, the increasing trend in rainfall for September month indicates a shifting pattern of ISM towards later months (August and September). The results obtained indicate a shifting pattern in withdrawal of ISM due to delay in onset and withdrawal in late September. Onset and retreat of monsoon rainfall over a region is governed by inter annual variations in ENDO and IOD (Misra, Bhardwaj, and Mishra 2018). Traditionally, ISM starts to retreat in mid-September in Western India. However, recent studies have observed a prolonged delay in ISM retreat due to development of low-pressure systems and atmosphere-ocean interactions. The prolonged delay and shifting pattern of rainfall towards later months could significantly impact the agricultural patterns as Indian agriculture is primarily dependent on ISM onset, progress and retreat (Chaubey et al. 2022; Todmal 2020).

4. Conclusion

In the present study, we evaluated trends in long term rainfall (1981-2020) over the Mahi River Basin (MRB) using IMD daily gridded rainfall. It was observed that MRB experienced an increasing trend in annual and monsoon season rainfall and a decreasing trend in post monsoon season rainfall. The frequency of wet days (rainfall > 2.5) mm have increased over the basin. Further, it was observed that low rainfall events have decreased while moderate and heavy rainfall have increased over MRB during ISM in the last 40 years. Finally, we evaluated trends in monthly rainfall and observed a significant increasing trend in September. This indicates a shifting pattern of rainfall towards later monsoon month attributed to delay in ISM retreat. Impacts of ENSO, IOD and POD combined with weakening convective activity over the region have resulted in high rainfall variability over MRB. Further, climate change induced global warming and urbanization at region scale also affects the characteristics of rainfall. Therefore, an increase in occurrence of moderate and heavy rainfall events was obtained over the study area that could lead to frequent occurrence of droughts and floods in the region. The study over a major river basin in western India has implications in the field of water resource management, flood forecasting and disaster risk reduction and weather forecasting. The present study focuses on addressing these issues through the lens of rainfall alterations and understanding the change in precipitation patterns over MRB. The results obtained can be useful for water management in the region and modifications in agricultural patterns based on regional rainfall characteristics as observed from trends in the last 40 years.

Acknowledgements

Saurabh Choubey would like to thank the DST- Inspire fellowship program, Department of science and technology (DST), for providing the necessary financial support for the research (DST/INSPIRE/03/2019/002055). The authors would like to thank the Central University of Gujarat, Gandhinagar and Space Applications Centre, Ahmedabad, for providing the platform for the research work. The authors would also like to acknowledge Indian Meteorological Department, Pune for making the data available in the public domain for free access.

Author Contributions

Dr. Rina Kumari: Conceptualizations; Saurabh Choubey: data curation and analysis, writing-original draft; Dr. Rina Kumari and Dr. Shard Chander: supervision; Dr. Rina Kumari and Dr. Shard Chander : Manuscript Finalization. All authors have read and agreed to the published version of the manuscript.

Data Availability

The daily gridded rainfall data used in this study are openly available to download at https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Funding

The Saurabh Choubey received DST Inspire JRF (DST/INSPIRE/03/2019/002055) and the work is part of his Ph.D.

Conflict of Interest

The authors decalre no conflict of interest relevant to this study.

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Figures

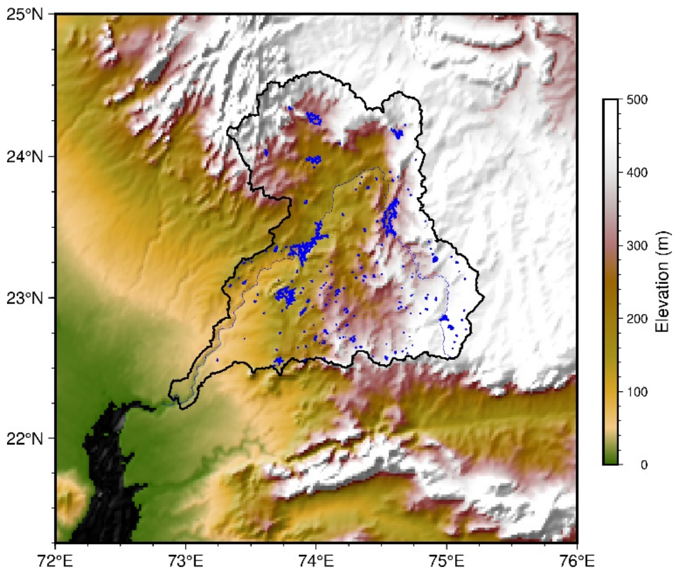

Figure 1: Geographical location of the Mahi River Basin

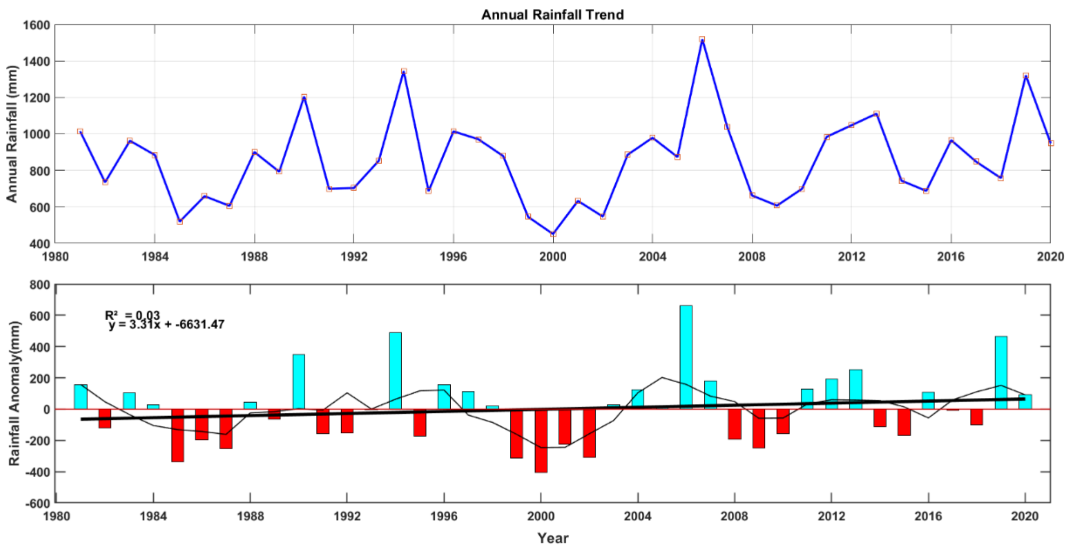

Figure 2: Average annual rainfall distribution over MRB during 1981-2020 (upper panel). Variability in annual rainfall anomaly and linear change over MRB (lower panel).

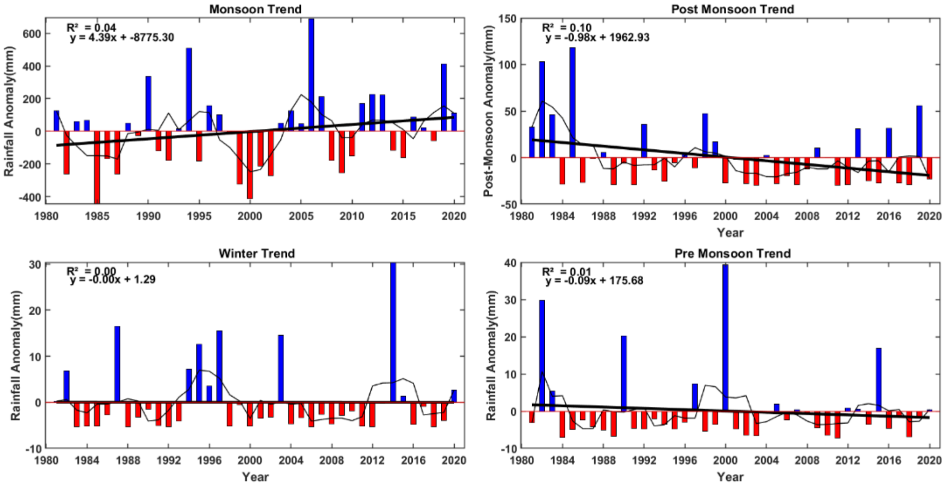

Figure 3: Seasonal variability in rainfall anomaly over MRB. The blue bars represents positive rainfall anomaly and red line depicts negative rainfall anomaly for the particular year.

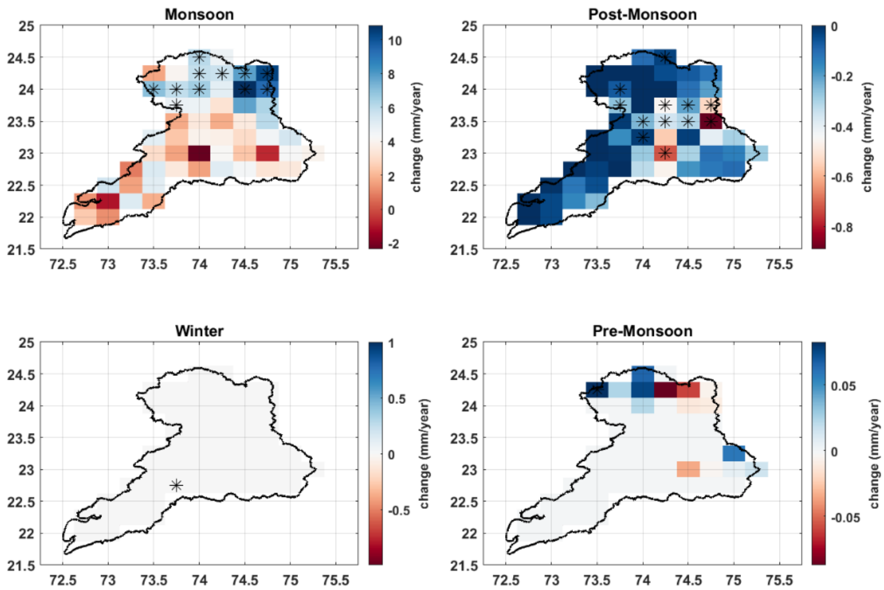

Figure 4: Spatial distribution of magnitude of change (mm/year) in rainfall for each season during 1981-2020 over MRB. * Shows the grids with a significant trend.

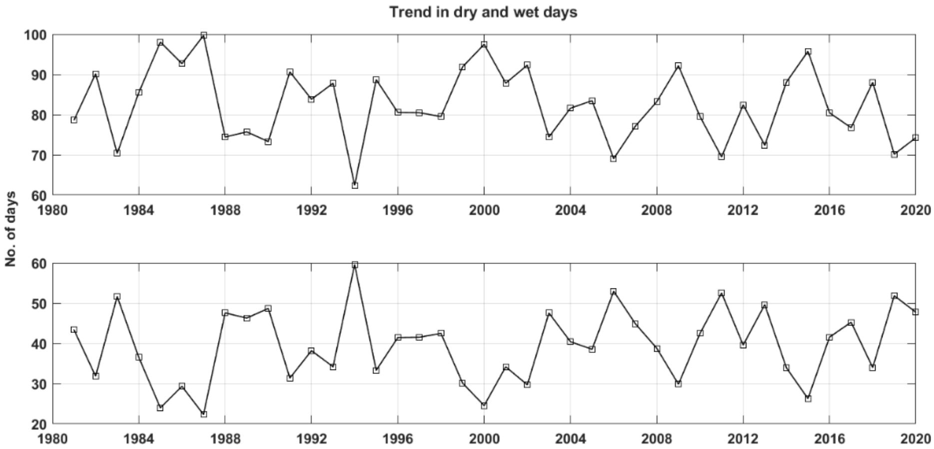

Figure 5: Variability in dry/wet days over MRB during 1981-2020.

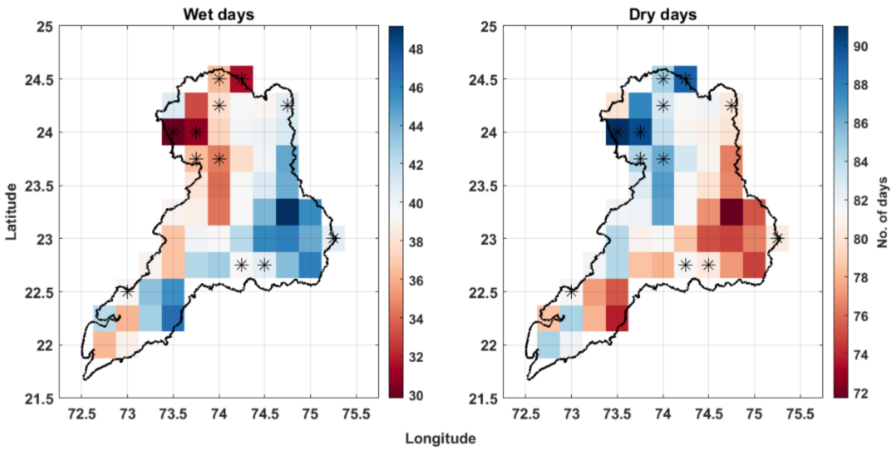

Figure 6: Spatial variability in dry/wet days over MRB between 1981-2020. The grids with * represent a significant trend.

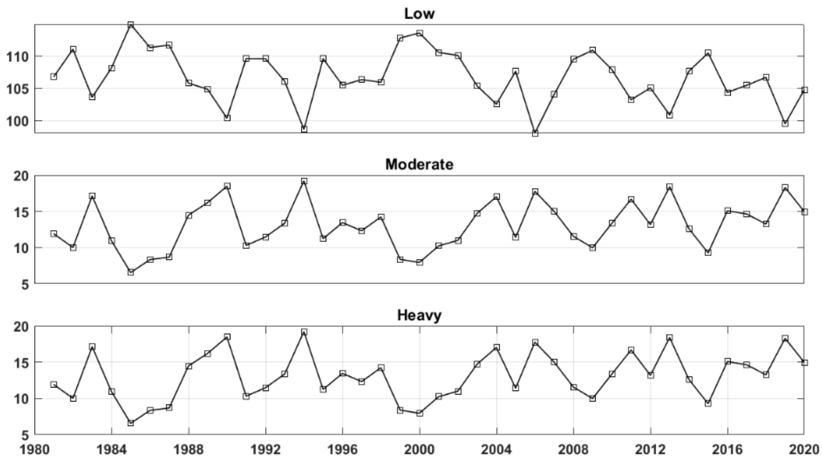

Figure 7: Variability in low (upper panel), moderate (middle panel) and heavy rainfall over MRB

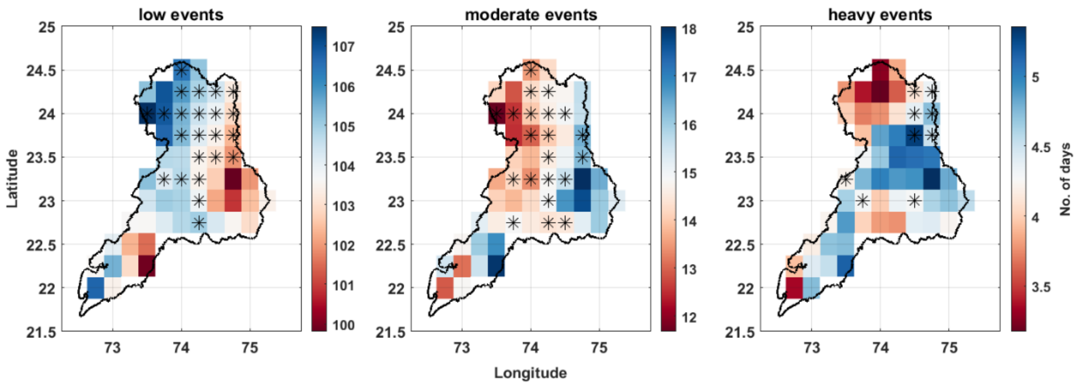

Figure 8: Spatial distribution of trends in low, moderate and heavy rainfall events over MRB during 1981-2020. The * represents grids with significant trend.

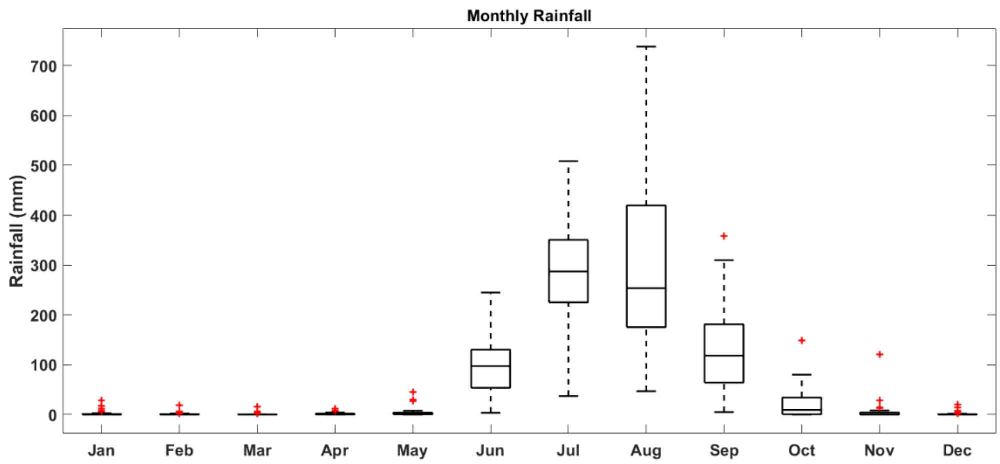

Figure 9: Distribution of monthly rainfall over MRB represented as a whisker plot