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Climate Change Impacts on Rainfall Extremes and Historical Rainfall Trends Over Upper Krishna River Basin, Maharashtra, India

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***Abstract*:** The present study was an attempt to examine the spatiotemporal variability of precipitation over a part of the Upper Krishna River Basin confined in Maharashtra state having a geographical area of 15,190 km^2. Daily rainfall data of 15 stations located in the study area for the period of 52 years from 1970 to 2021 were analysed using Man-Kendall's test and Sen's slope estimator test. Almost all stations showed a non-significant rising trend in monsoon rainfall out of which four stations viz. Shahuwadi (12.53 mm/year), Sangli (2.27 mm/year), Karad (3.51 mm/year), and Wai (4.83 mm/year) showed a significant rising trend in monsoon rainfall. Islampur and Tasgaon stations located in Sangli district showed non-significant falling trend. For the decade 2010-2020 all stations showed rising trend in annual rainfall. Six stations in Kolhapur and Satara districts of Maharashtra viz. Kolhapur, Hatkalangale, Shahuwadi, Panhala, Satara, Mahabaleshwar, Wai, and Koregaon showed the presence of extreme rainfall events in the last three decades. Also, many stations observed a rise in the total number of heavy rainfall days for the last decade.

***Keywords*:** Trend analysis, Man-Kendall's test, Extreme event analysis, Upper Krishna River Basin

Water is one of the most important factors influencing the agricultural production. In India precipitation is majorly in the form of rainfall. The annual rainfall is the important factor for determining the availability of water for agriculture and other usages. The changes in the pattern of rainfall affect the availability of water as well as increases the danger of frequent draughts and floods. It is therefore essential to study trends in rainfall. Indian monsoon rainfall as a whole does not show any specific trend, but over some specific areas of country significant trends were observed in the annual rainfall. As an influence of changing climate, a decreasing trend in the all-India annual, as well as summer monsoon mean rainfall during 1951-2015, was observed over the Indo-Gangetic Plains and the Western Ghats with the increase in the frequency of localized heavy rain occurrences over India (Kulkarni et al 2020). Consequently, regional trends in rainfall patterns need to be studied carefully.

In the present study a part of the Upper Krishna sub-basin contributing runoff up to Kurundwad (located in Kolhapur district) was selected to observe rainfall trends. Krishna river basin is the second largest river basin (22.6 % of the geographical area) of Maharashtra. Out of seven sub-basins of Krishna, a part of Upper Krishna, Upper Bhima, and a small part of Lower Bhima falls in Maharashtra (Sharma and Paithankar 2014).

Studies on variability in the rainfall patterns over the Krishna River basin and its sub-basins for analysing trends of drought events, occurrences of rainfall extremes, and spatiotemporal rainfall variability (using IMD gridded rainfall dataset) have been reported by various workers (Mahajan and Dodamani 2015, Tirupathi et al 2018, Harshavardhan et al 2020).

Harshavardhan et al (2020) found significant trends in annual and seasonal rainfall over the Krishna River Basin based on IMD gridded rainfall datasets. In the present study, an attempt has been made to perform the station-based rainfall variability analysis for the upper Krishna River basin.

MATERIAL AND METHODS

Study area: The Krishna is the second largest eastward draining interstate river basin in peninsular India. The basin is situated between the Deccan Plateau covering large areas of the states of Maharashtra, Karnataka, Andhra, and Telangana. Krishna River drains an area of 2,58,948 km^2. The overall basin area comprises 7 sub-basins. The area selected for the current study is located in the upper Krishna basin partly in the Satara, Sangali, and Kolhapur districts of Maharashtra state having a geographical area of 15,190 km^2. The study area is confined between 73^{0}34'38'' E to 74^{0}50'30'' E and 16^{0}18'50'' N to 18^{0}03'07'' N. Average annual rainfall over the region varied from 636 to 5870 mm over the study period.

Data used: Daily rainfall data of 15 rain gauge stations located in the study area were obtained from India Meteorological Department data portal (Table 1). Daily rainfall data for the period from 1970 to 2021 were summed up to prepare annual, monthly, seasonal (winter (December to February), summer (March-May), monsoon (June-September), and post-monsoon (October-November)) data series. For missing data estimation, three methods viz. normal ratio method, modified normal ratio method, and inverse distance method (Subramanya 1994) were tried for each station with missing data. Station-wise suitable method based on root mean square error and the correlation coefficient was decided and missing data were estimated.

Trend analysis: The presence of a monotonic increasing or decreasing trend was tested using the non-parametric Mann-Kendall test (Mann 1945, Kendall 1995). The magnitude of change was estimated using Sen's slope test (Sen 1968). The significance of the results was tested at 90, 95 and 99 % confidence levels.

Mann-Kendall Test:

The Mann-Kendall statistic S is given as;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \dots (1)$$

The test is being applied to sequential time series 'x_i' and 'x_j' with 'n' number of observations.

Where;

$$\mathrm{sgn}\left(x_j - x_i\right) = \begin{cases} +1, & (x_j - x_i) > 0 \\ 0, & (x_j - x_i) = 0 \\ -1, & (x_j - x_i) < 0 \end{cases} \quad \dots (2)$$

the variance statistic;

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \quad \dots (3)$$

In which, t_i= number of ties up to sample i.

Statistic Z is given as;

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}\,(S)}}, S > 0 \\ 0, \quad S = 0 \\ \frac{S-1}{\sqrt{\mathrm{var}\,(S)}}, S < 0 \end{cases} \quad \dots (4)$$

A positive or negative value of 'Z' indicates upward or downward trend, respectively. The significance of the results was tested at 90, 95 and 99 % confidence levels.

Sen's slope estimator test:

Slope (T_j)of the trend line is computed as;

$$T_j = \frac{x_j - x_k}{j-k} \quad \dots (5)$$

Where;

Table 1. Data used for analysis

Name of location	Latitude (N) (degrees)	Longitude (E) (degrees)	Period
Kolhapur	16.70	74.23	1970-2021
Shirol	16.73	74.60	1970-2021
Hatkalangale	16.75	74.41	1970-2021
Shahuwadi	16.83	73.95	1970-2021
Panhala	16.83	74.11	1970-2021
Sangli	16.85	74.60	1970-2021
Shirala	16.96	74.15	1970-2020
Islampur	17.05	74.26	1970-2021
Tasgaon	17.03	74.60	1970-2021
Karad	17.28	74.18	1970-2021
Vaduj	17.60	75.45	1970-2020
Satara	17.68	73.98	1970-2020
Mahabaleshwar	17.93	73.66	1970-2021
Wai	17.93	73.90	1970-2021
Koregoan	17.70	74.16	1970-2020

x_j and x_k are data values at time 'j' and 'k' (j>k), respectively. Sen's estimator of slope is given as:

$$Q_i = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd} \\ \frac{1}{2}\left(T_{N/2} + T_{\frac{N+2}{2}}\right) & N \text{ is even} \end{cases} \quad \dots (6)$$

At the end slope magnitude is calculated by two-sided test at 100(1-α) % confidence level and true slope is obtained by non-parametric test. Positive value of 'Q_i' indicates an increasing trend while negative value gives decreasing trend in the time series.

Extreme event analysis: The entire study period was divided into five decades and the number of events in the category of severe draught, moderate draught, excess rainfall, and extreme rainfall was computed as 'extreme events' for each station. Rainfall events were classified as (Thirupathia et al 2018);

Severe draught: Deficiency of ISMR >50 %

Moderate draught: Deficiency of ISMR between 26-50 %

Dry year: Deficiency of ISMR between 15-25 %

Normal year: ISMR between +15 to-15 %

Wet year: Excess of ISMR between 15-25 %

Excess rainfall: Excess of ISMR between 26-50 %

Extreme rainfall: Excess of ISMR >50 %

Heavy rainfall days: A day is called 'heavy rainfall day' if the rainfall of that day is 64.5 mm or more according to India Meteorological Department. This includes very heavy (i.e., 124.5–244.5 mm) and extremely heavy rainfall (i.e., >244.5 mm) (Guhathakurta et al 2011). Station-wise heavy rainfall days were counted and summed up on a decade basis (Table 6).

RESULTS AND DISCUSSION

Statistical properties of annual and seasonal rainfall: Annual and seasonal rainfall of all stations of Upper Krishna River Basin for the study period 1970-2021 were analyzed using basic statistical indices (Table 2). Annual mean ranged from 557.6 mm to 5870.08 mm. Seasonal mean rainfall varied from 395.72 mm to 5467.22 mm. Overall all stations showed variable deviations in annual and monsoon rainfall from the mean.

Trends in annual and monsoon rainfall: It is essential to analyse trends in precipitation and their spatial and temporal variability in order to identify climate-related changes and recommend suitable water resource management methods for the future. In the study area, trends in monthly, annual, and seasonal, time scales were examined. Station-wise details of trend statistic for annual and seasonal rainfall (Q is mm/year) in UKRB was estimated (Table 3). Almost all stations showed a non-significant rising trend in monsoon rainfall out of which four stations viz. Shahuwadi (12.53 mm/year), Sangli (2.27 mm/year), Karad (3.51 mm/year), and Wai (4.83 mm/year) showed a significant rising trend in monsoon (JJAS) rainfall of variable magnitudes over last 52 years. For, Islampur and Tasgaon stations non-significant downward trend was observed over a study period of 1970-2021 (Fig. 1).

In the case of annual total rainfall; a significant decreasing trend was observed at Tasgaon station (4.23 mm/year) and a significant rising trend was for Shahuwadi (12.71 mm/year) and Sangli station (2.97 mm/year). Out of the remaining

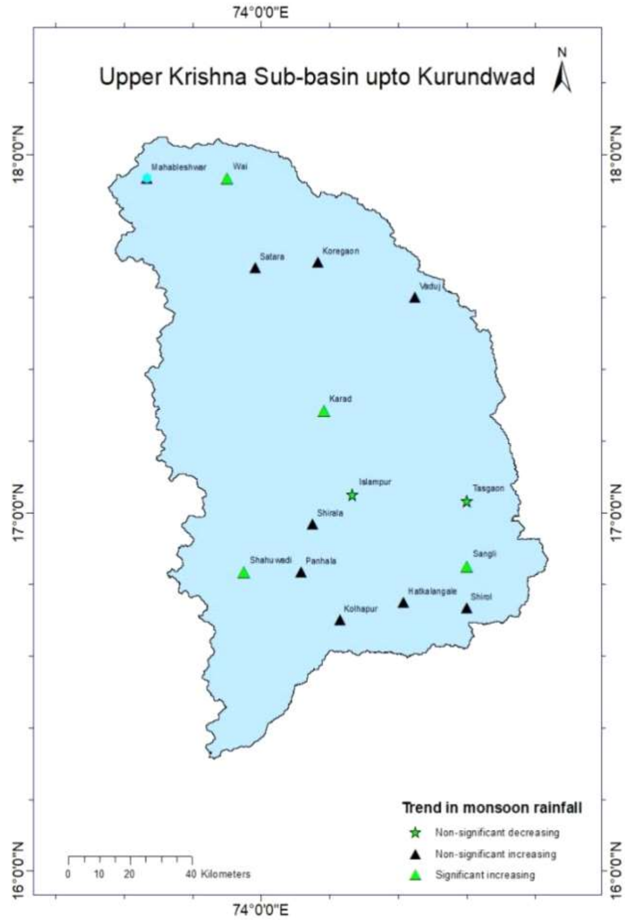

Fig. 1. Location of rain gauge stations and nature of trend for monsoon rainfall

Table 2. Station wise statistical properties of annual and monsoon rainfall

Station	Annual rainfall (mm)		Mean (mm)		Standard deviation (mm)		Coefficient of variation (%)	
	Minimum	Maximum	Annual	Monsoon	Annual	Monsoon	Annual	Monsoon
Kolhapur	568.80	1954.90	1074.89	838.76	284.26	259.92	26.45	30.99
Shirol	193.50	1192.70	636.27	433.65	238.47	168.76	37.48	38.92
Hatkalangale	317.90	1609.60	787.55	555.88	239.00	191.78	30.35	34.50
Shahuwadi	1082.00	3450.50	2070.24	1751.54	518.81	504.49	25.06	28.80
Panhala	918.70	2735.00	1703.80	1464.96	446.46	427.28	26.20	29.17
Sangli	255.20	1690.43	674.33	433.72	230.09	155.71	34.12	35.90
Shirala	481.80	1838.30	1093.19	906.73	282.06	284.07	25.80	31.33
Islampur	291.00	1412.60	734.63	541.71	259.12	213.09	35.27	39.34
Tasgaon	186.60	1142.70	596.47	426.37	213.69	154.45	35.83	36.22
Karad	368.20	1328.00	780.73	594.16	203.23	195.01	26.03	32.82
Vaduj	153.80	1006.10	557.60	395.72	194.68	157.25	34.91	39.74
Satara	583.70	1849.10	1039.56	855.69	279.25	284.42	26.86	33.24
Mahabaleshwar	3514.00	8841.10	5870.08	5467.22	1191.36	1199.08	20.30	21.93
Wai	395.70	1574.30	961.52	702.28	264.74	246.04	27.53	35.03
Koregoan	318.80	1435.50	765.73	586.33	248.11	217.42	32.40	37.08

stations' a non-significant rising trend in annual total rainfall was observed for Kolhapur, Shirol, Hatkalangale, Panhala, Shirala, Karad, Vaduj, Mahabaleshwar, and Wai stations. The rising trend magnitude was of order 0.18 to 12.71 mm/year. Islampur, Satara and Koregaon stations showed a non-significant falling trend.

An entire study period was divided into five decades and trends in annual rainfall magnitudes were also studied on a decadal basis. Mann-Kendall's trend statistic and magnitudes of the trend for the decade 2010-2020 were estimated by Sen's slope estimator method (Table 4). Almost all stations showed a rising trend in the annual rainfall of which, Kolhapur and Shirala stations showed a significant increasing trend in annual rainfall over the last decade (2010-2020). The magnitude of a positive trend was found to be 62.15 mm /year for Kolhapur and 49.78 mm/year for Shirala. Although, statistically non-significant but Mahabaleshwar station showed a rising trend in the annual rainfall of magnitude 150 mm/year over the last decade. For Hatkalangale and Wai non-significant negative trend in annual rainfall was observed over the last decade.

In general, all stations in the Upper Krishna River Basin showed a rising trend in the annual rainfall except four stations viz. Islampur, Tasgaon, Satara, and Koregaon showed decreasing trend in annual rainfall. Therefore, it was concluded that the overall basin was subjected to a rise in monsoon rainfall (Fig. 2).

Extreme rainfall events and heavy rainfall days: Extreme

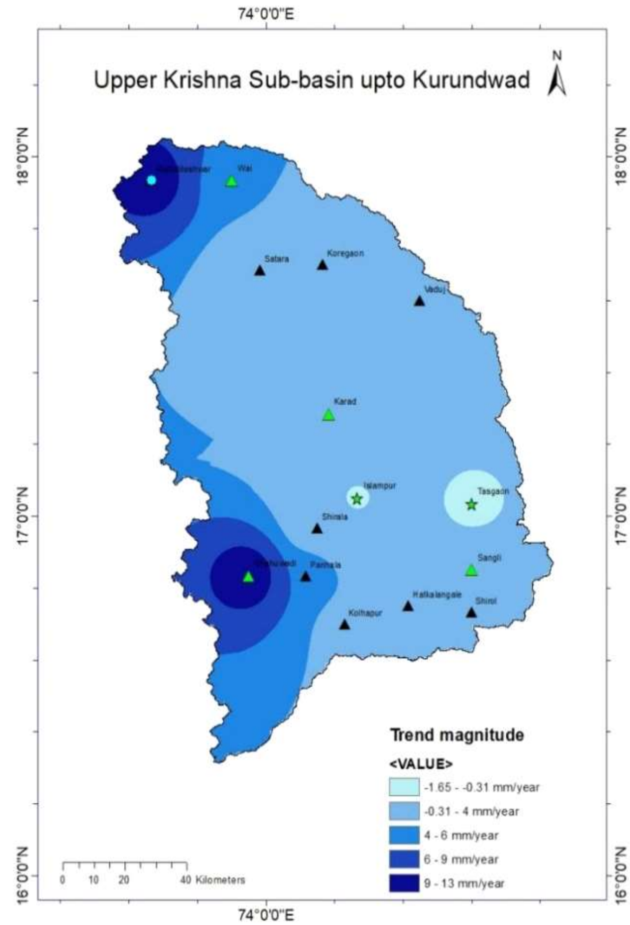

Fig. 2. Magnitude of trend (mm/year) in monsoon rainfall

Table 3. Station wise details of trend statistic (Z) for annual and seasonal rainfall (Q is mm/year) in UKRB

Location	AAR	Annual		Winter		Summer		Monsoon		Post- monsoon	
		Z	Q	Z	Q	Z	Q	Z	Q	Z	Q
Kolhapur	1074.9	0.67	1.63	0.24	0.00	-1.68+	-0.65	1.37	3.12	0.17	0.15
Shirol	636.3	0.08	0.18	0.51	0.00	-1.52	-0.52	0.45	0.92	0.41	0.28
Hatkalangale	787.5	0.84	1.74	0.88	0.00	-2.50*	-0.89	1.43	2.13	1.33	1.00
Shahuwadi	2070.2	2.79**	12.71	0.65	0.00	-0.72	-0.13	2.83**	12.53	-0.18	-0.19
Panhala	1703.8	1.19	5.56	0.50	0.00	-2.01	-0.57	1.51	5.95	0.42	0.35
Sangli	674.3	1.79+	2.97	1.00	0.00	-0.02	0	1.95*	2.27	1.86+	1.40
Shirala	1093.2	0.15	0.40	0.15	0.00	-1.14	-0.38	0.33	1.26	-0.51	-0.40
Islampur	734.6	-0.51	-1.69	0.99	0.00	-2.27*	-0.54	-0.44	-0.71	0.71	0.60
Tasgaon	596.5	-1.93+	-4.23	0.14	0.00	-3.18*	-1.17	-0.86	-1.66	-0.73	-0.53
Karad	780.7	1.45	2.64	-0.31	0.00	-2.21*	-0.64	2.56*	3.51	-0.09	-0.09
Vaduj	557.6	0.79	-1.47	-0.28	0.00	-1.96	-0.39	1.62	2.88	-0.18	-0.14
Satara	1039.6	-0.08	-0.20	0.44	0.00	-1.96	-0.64	0.47	1.17	0.16	0.10
Mahabaleshwar	5870.1	1.19	12.57	1.19	0.00	0.06	0.07	1.05	11.03	0.59	0.66
Wai	961.5	1.60	3.55	-0.36	0.00	-1.92+	4.83	2.11*	4.83	-0.20	-0.21
Koregoan	765.7	-0.52	-1.36	-0.38	0.00	-2.18*	-0.63	0.21	0.39	-0.63	-0.48

+ Significant at 90 % confidence interval; * Significant at 95 % confidence interval, ** Significant at 99 % confidence interval

Table 4. Trend in annual rainfall during period 2010-2020

Station	Trend statistic (Q) & magnitude of trend (Z, mm/year)	
Kolhapur	Z	2.40
	Q	62.15
Shirol	Z	1.03
	Q	20.23
Hatkalangale	Z	-0.34
	Q	-4.14
Shahuwadi	Z	0.75
	Q	15.92
Panhala	Z	1.30
	Q	78.23
Sangli	Z	1.58
	Q	29.92
Shirala	Z	2.02
	Q	49.78
Islampur	Z	0.00
	Q	-2.09
Tasgaon	Z	0.89
	Q	27.64
Karad	Z	1.44
	Q	16.95
Vaduj	Z	1.56
	Q	48.63
Satara	Z	0.62
	Q	24.23
Mahabaleshwar	Z	1.44
	Q	150.55
Wai	Z	-0.34
	Q	-14.69
Koregaon	Z	0.47
	Q	13.60

rainfall events represent the years with an excess of ISMR by 50 % or more. Six stations in Kolhapur and Satara districts of Maharashtra viz. Kolhapur, Hatkalangale, Shahuwadi, Panhala, Satara, Mahabaleshwar, Wai, and Koregaon showed the extreme rainfall events in the last three decades (Table 5). Whereas, for the rest of the stations' the number of extreme rainfall events was more or less the same throughout the study period. Six stations Kolhapur, Shahuwadi, Pahnala, Karad, Mahabaleshwar, and Wai were observed with rise in the total number of heavy rainfall days for the last decade (Table 6).

CONCLUSION

Analysis of the trend in annual and seasonal rainfall over the Upper Krishna River Basin was performed using observed daily rainfall data from 1970 through 2021. The entire Upper Krishna River Basin was observed with a positive trend in annual and monsoon rainfall. An increase in the occurrence of extreme rainfall events was observed in many parts of the basin in Satara and Kolhapur districts of Maharashtra. Occurrences of heavy rainfall days in many stations of the basin in Satara and Kolhapur districts particularly during 1990 -2020 (last 3 decades) from a total study period of 52 years were also observed. This indicated that, rainfall over a part of the Upper Krishna River Basin in Maharashtra had been significantly altered due to the effects of climate change. This analysis may be supportive in the planning of mitigation measures for controlling future extremes.

Table 5. Station wise number of extreme rainfall events

Name of location	Number of extreme rainfall events (excess of ISMR>50 %)				
	1970-1979	1980-1989	1990-1999	2000-2009	2010-2021
Kolhapur	0	0	0	2	1
Shirol	0	2	1	2	1
Hatkalangale	0	0	1	3	2
Shahuwadi	0	0	0	2	1
Panhala	0	0	0	3	1
Sangli	0	0	1	2	0
Shirala	0	1	0	1	2
Islampur	1	0	1	2	1
Tasgaon	1	2	1	1	1
Karad	1	0	1	3	1
Vaduj	0	1	0	2	2
Satara	0	0	0	2	1
Mahabaleshwar	0	0	0	2	1
Wai	0	0	1	2	1
Koregoan	0	0	0	3	1

Table 6. Station wise number of heavy rainfall days

Name of location	Number of heavy rainfall days (daily rainfall > 64.3 mm)					
	1970-1979	1980-1989	1990-1999	2000-2009	2010-2021	Percent rise /fall
Kolhapur	12	12	12	11	22	100.0 (In last decade)
Shirol	10	5	9	8	4	random pattern
Hatkalangale	3	5	6	11	8	100.0 (In last 3 decades)
Shahuwadi	41	38	68	77	72	28.5 (In last 3 decades)
Panhala	32	23	58	49	54	52.0 (In last 3 decades)
Sangli	5	10	8	14	6	random pattern
Shirala	20	14	18	13	19	random pattern
Islampur	9	8	10	10	1	-89.2 (In last decade)
Tasgaon	9	9	9	2	3	-72.2 (In last 2 decades)
Karad	7	5	12	13	10	83.3 (In last 3 decades)
Vaduj	10	6	4	6	7	random pattern
Satara	21	16	16	22	20	random pattern
Mahabaleshwar	291	248	309	298	362	26.6 (In last decade)
Wai	12	12	23	21	16	66.7 (In last 3 decades)
Koregoan	6	6	8	16	5	random pattern

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