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Analysis of spatio-temporal trend of solar radiation in the agro climatic zone-I of Bihar

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Abstract
In this paper, climatological and spatiotemporal variability of solar radiation and its trend analysis, fluctuations, and abrupt changes are studied in seven districts in agro-climatic Zone-I of Bihar. Descriptive statistics and non-parametric statistical tests have been employed to evaluate the variability and trend patterns. The descriptive results revealed that lower variability was observed in annual and seasonal solar radiation. At spatial scales, the variability of solar radiation was observed to be higher in Vaishali and Gopalganj districts, while lower variability was observed in the West Champaran district. After trends analysis, the non-parametric tests revealed the statistically significant decreasing trends observed in the annual and winter seasons for all seven districts. In the case of summer, autumn, and spring seasons, most of the districts also observed significant decreasing trends. The rate of decrease in solar radiation was observed the highest in the Gopalganj district (for annual, summer, and autumn seasons) and Vaishali district (for winter and spring seasons). According to Pettitt Mann-Whitney (PMW) test, the results found that most districts saw a shift between 1997 and 2012. Overall, this study has added to the knowledge in determining the most vulnerable areas in Bihar (agro-climatic Zone-I) to solar radiation.

Keywords: Solar radiation, trend analysis, non-parametric test, Sen's slop estimator, and PMW test

1. Introduction

On the earth, sunlight is the primary energy source for the earth's surface environment and is observable as sunshine when it is above the horizon. Solar radiation has a massive impact on global climate change and human actions such as agricultural production, medical sector, solar power generation, etc. The spatial and temporal distributions of the clear-sky conditions provide a significant hint for assessing how human activity and natural variability affect climate change. The environment, water cycle, and earth's surface temperature are all severely impacted by variations in solar radiation (Haverkort *et al.*, 1991; Ramanathan *et al.*, 1997; Cao *et al.*, 2005) [5, 12, 3]. Solar radiation concentration at a given location is affected by latitude, geography, season, time, and atmospheric conditions. Therefore, the study of solar radiation at the regional level is critical for identifying the impact of solar irradiation on ecosystems and proper assessment of variability and changes in pattern, as well as the existence of trends in solar radiation over different spatial horizons.

In the recent past, non-parametric statistical tests have been used by many researchers to assess trends in solar radiation (Singh and Kumar, 2016; Lawin *et al.*, 2019; Tersoo *et al.*, 2020; Mahima *et al.*, 2021; Ahmed and Ogedengbe, 2021; Eladawy *et al.*, 2021) [14, 7, 15, 8, 1, 4]. However, non-parametric tests are most widely used for trend analysis of solar radiation. The non-parametric tests have many advantages, such as requiring fewer assumptions, handling missing data, and independence of the data distribution. In this context, the present work provides information and knowledge on the spatial variability and trend patterns of surface solar radiation in Bihar's agro-climatic Zone-I from 1984 to 2020 using non-parametric tests. The findings contribute to a better understanding and knowledge of the availability and variability of solar energy resources.

2. Data and Methodology

2.1 Study Area

Bihar is located in the Indo-Gangetic plains, between latitude 24°-27° N and longitude 82°-88° E, and has a total geographical area of 94,163 square kilometres. The climate is subtropical and classified into three agro-climatic zones: Zone-I (North-West Alluvial Plains), Zone-II

(North-East Alluvial Plains), and Zone-III (South Alluvial Plains). In this study, seven districts of agro-climatic Zone-I of Bihar *viz*., East Champaran, West Champaran, Gopalganj, Muzaffarpur, Saran, Siwan, and Vaishali have taken and are represented in Figure 1.

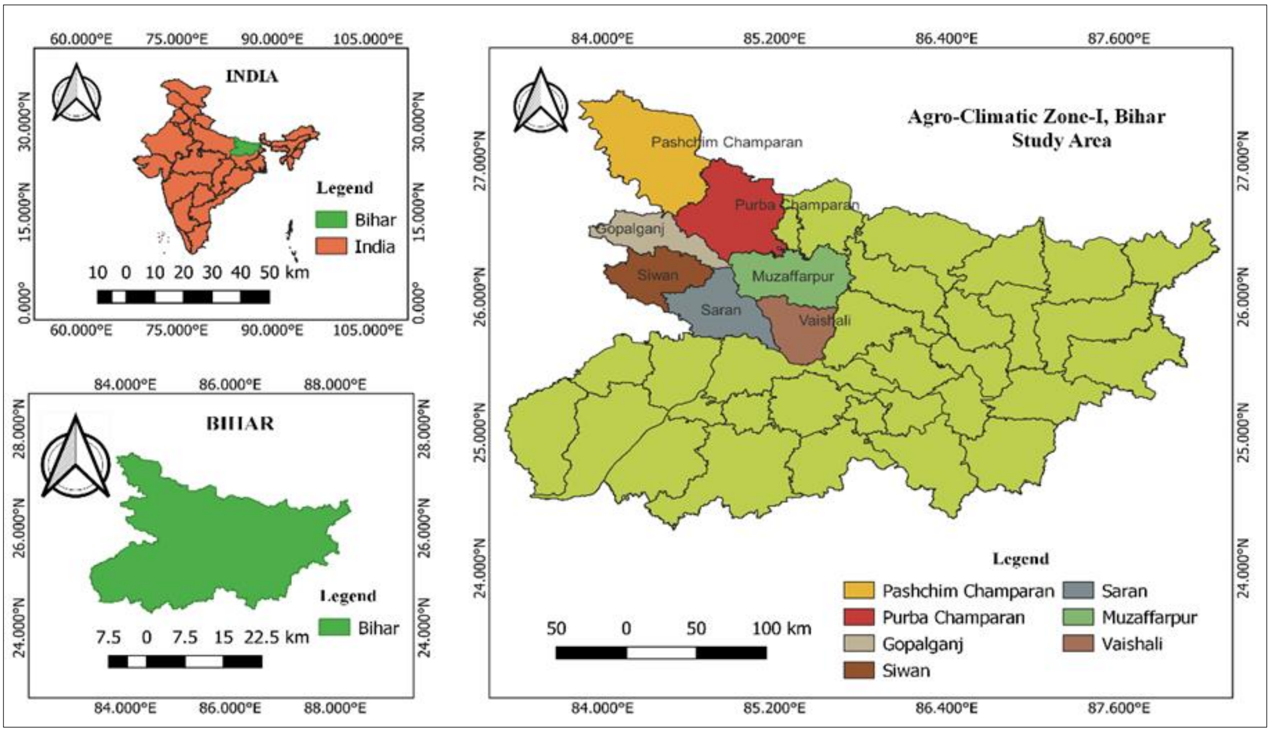

Fig 1: The study area of agro-climatic Zone-I, Bihar, India.

2.2 Study Data

Historical (1984 to 2020) monthly solar radiation (MJ/m^2) data for all seven districts were collected from the National Aeronautics and Space Administration (NASA) organization "Prediction of Worldwide Energy Resource" (POWER) [2]. The trend analysis has been carried out on an annual and seasonal basis, and the seasons are winter (Dec–Feb), spring (Mar-May), summer (June–Aug), and autumn (Sept–Nov).

2.3 The methodology used for determining the trend in solar radiation

The non-parametric tests have been used for the trend detections in solar radiation. The non-parametric tests such as the Mann-Kendall test, Sen's slop estimator, and Pettitt Mann-Whitney (PMW) tests have been used, and whole procedures were carried out on R programming.

2.3.1 Mann-Kendall (MK) test

Mann Kendall test (Mann, 1945 and Kendall, 1975) [9, 6] has been used for identifying trends in the time series data. It is a non-parametric statistical test widely used in trend analysis for climatological studies. The advantage of a non-parametric test over a parametric test, it does not require the data to be normally distributed. The *MK* test statistics (S) for solar radiation can be computed as follows.

Null hypothesis (H_0): Three is no trend present

Alternative hypothesis (H_1): Three is the presence of the trend in the data

The Mann-Kendall test statistic (S):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k), \quad (1)$$

Where n is the number of data points, X_j is the observed value at time j, and X_k is the observed value at time K. The value of $sgn(X_j - X_k)$ is computed as follows:

$$sgn(X_j - X_k) = \begin{cases} +1, (X_j - X_k) > 0 \\ 0, (X_j - X_k) = 0 \\ -1, (X_j - X_k) < 0 \end{cases}, \quad (2)$$

For large samples (n >10), the test is conducted using a normal approximation (Z statistics) with the mean and the variance as follows:

$$E(S) = 0, \quad (3)$$

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right], \quad (4)$$

where q is the number of tied (zero difference between compared values) groups and t_p is the number of data values in the p^{th} group. Test statistic Z is as follows:

$$Z = \begin{cases} \frac{S-1}{Var(S)} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{Var(S)} \; if \; S < 0 \end{cases} \quad (5)$$

A statistically significant trend is evaluated using the Z value; the positive value of Z indicates an increasing trend and its negative value a decreasing trend. Null hypothesis (H_0) is tested at 5% level of significance ($Z_{0.05} = 1.96$).

2.3.2 Sen's slope estimator

To estimate the true slope of an existing trend (as change per year) the, Sen's non-parametric method has been used. Sen's method (Sen, 1968 and Pingale *et al*., 2014) [13, 11] can be used in cases where the trend can be assumed to be linear.

$$Q = Median\left(\frac{X_j - X_k}{j-k}\right), \quad (6)$$

Where Q is the magnitude of the trend estimate. Sen's slope indicates an increasing trend for positive value and a decreasing trend for negative value in the time series data.

2.3.3 Pettitt Mann-Whitney (PMW) test

The PMW test (Pettitt, 1979) [10] distinguishes the most likely change year in the yearly time series sequence. The PMW test statistics can be computed as follows;

Assume a time series $\{X_1, X_2, ..., X_n\}$ with a length n and where t is the time of the most likely change point. Two samples, $\{X_1, X_2, ..., X_t\}$ and $\{X_{t+1}, X_{t+2}, ..., X_n\}$, can then be derived by dividing the time series at time t. An index, U_t, is derived as:

$$U_t = \sum_{i=1}^{t}\sum_{j=1}^{n} sgn(X_i - X_j), \quad (7)$$

$$sgn(X_i - X_j) = \begin{cases} +1 \; if \; (X_i - X_j) > 0 \\ 0 \; if (X_i - X_j) = 0 \\ -1 \; if (X_i - X_j) < 0 \end{cases}, \quad (8)$$

A plot of U_t against t for a time series with no change point would result in a continually increasing value of U_t. However, if there is a change point (even a local change point), then U_t would increase up to the change point and then begin to decrease. This increase followed by a decrease may occur several times in a time series, indicating several local change points. So there is still the question of determining the most significant change point. We can identify the most significant change point $K_t$where the value of $|U_t|$ is maximum.

$$K_t = \max_{1 \le t \le T} |U_t|, \quad (9)$$

The approximated significance probability *P(t)* for a change point is given as:

$$P = 1 - exp\left[\frac{-6K_t^2}{n^3+n^2}\right], \quad (10)$$

The change point is statistically significant at the time t with a significance level of α when probability P(t) exceeds $1 - \alpha$. The autocorrelation coefficient distinguishes the nearness of serial correlation within the data series.

3. Results and Discussion

3.1 Solar Radiation Variability

To check the spatio-temporal variability in solar radiation, the descriptive statistics such as mean, standard deviation (*SD*), and coefficient of variation (*CV*) of annual and seasonal (winter, spring, summer, and autumn) solar radiation have been computed, and that are represented in Tables 1 to 3. The results revealed that lower variability was observed in annual and seasonal solar radiation. Among seasonal solar radiation, the highest variation was recorded in the winter seasons, followed by summer and autumn seasons, while lower variation occurred in the spring season. At spatial scales, the variability of solar radiation was observed higher in Vaishali district (for spring, summer, and annual seasons) and Gopalganj district (for winter and autumn seasons), while lower variability was observed in West Champaran district. The highest point of average solar radiation data recorded are 24.235, 18.532, 17.992, 16.951, and 15.361 MJ/m^2 for spring, annual, summer, autumn, and winter seasons, respectively.

Table 1: Descriptive statistical results of solar radiation for Saran and Gopalganj districts

Seasons	Saran			Gopalganj		
	Mean (MJ/m^2)	Standard Deviation	CV (%)	Mean (MJ/m^2)	Standard Deviation	CV (%)
Winter	15.192	1.235	8.129	15.063	1.476	9.796
Spring	23.308	1.275	5.471	24.235	1.261	5.202
Summer	17.658	1.275	7.221	17.878	1.430	7.997
Autumn	16.470	1.026	6.231	16.951	1.098	6.478
Annual	18.116	0.918	5.069	18.532	1.049	5.661

Table 2: Descriptive statistical results of solar radiation for Siwan and Vaishali districts

Seasons	Siwan			Vaishali		
	Mean (MJ/m^2)	Standard Deviation	CV (%)	Mean (MJ/m^2)	Standard Deviation	CV (%)
Winter	15.100	1.399	9.263	15.361	1.487	9.678
Spring	24.042	1.197	4.980	23.487	1.396	5.945
Summer	17.709	1.378	7.782	17.514	1.406	8.027
Autumn	16.764	1.027	6.123	16.564	1.054	6.362
Annual	18.404	0.996	5.413	18.232	1.109	6.083

Table 3: Descriptive statistical results of solar radiation for Muzaffarpur, West Champaran, and East Champaran districts

Seasons	Muzaffarpur			West Champaran			East Champaran		
	Mean (MJ/m^2)	SD	CV (%)	Mean (MJ/m^2)	SD	CV (%)	Mean (MJ/m^2)	SD	CV (%)
Winter	15.228	1.353	8.885	15.353	0.878	5.719	15.163	1.375	9.066
Spring	23.926	1.197	5.001	23.345	0.953	4.084	23.984	1.191	4.967
Summer	17.922	1.316	7.343	17.165	1.201	6.999	17.816	1.319	7.404
Autumn	16.850	0.930	5.518	16.787	0.721	4.298	16.807	0.973	5.788
Annual	18.480	0.902	4.880	18.163	0.553	3.044	18.442	0.946	5.130

SD = Standard Deviation

3.2 Non-parametric trend analysis

For the statistical trend analysis of solar radiation for different locations, non-parametric tests such as *MK* test, Sen's slope estimator, and PMW test have been used. The value of test results for annual and seasonal is summarized in Tables 4 to 6. The non-parametric trend analysis revealed statistically significant decreasing trends in annual and winter seasons for all seven districts. In the case of summer, autumn, and spring seasons, most of the districts also showed significant decreasing trends that can be easily visualized in Figures 2 to 8. The magnitude obtained from Sen's slope estimator showed that the highest decreasing rate occurred in Gopalganj district (for annual (-0.078 MJ/m^2 year^{-1}), summer (-0.063 MJ/m^2 year^{-1}), autumn seasons (-0.055 MJ/m^2 year^{-1})) and Vaishali district (for winter (-0.115 MJ/m^2 year^{-1}) and spring seasons (-0.097 MJ/m^2 year^{-1})). According to the PMW test, the majority of the districts in annual and autumn seasons saw a shift in the year 1997. In the case of summer seasons, the most probable year of changes occurred in the years 1997, 1998, and 2012, while in winter and spring seasons, the most probable year of changes happened in the years 2000, 2005, 2006, and 2012 at most of the districts.

Table 4: Non-parametric statistical test results of solar radiation for Saran and Gopalganj districts

Seasons	Saran			Gopalganj		
	MK test (Z value)	Sen's slope estimate	PMW test (K)	MK test (Z value)	Sen's slope estimate	PMW test (K)
Annual	-4.448*	-0.059	2011	-5.219*	-0.078	1997
Summer	-1.871NS	-0.040	2012	-2.799*	-0.063	1997
Autumn	-1.688NS	-0.026	2012	-3.427*	-0.055	1997
Winter	-4.827*	-0.086	2009	-5.677*	-0.106	2006
Spring	-3.401*	-0.067	2012	-4.421*	-0.086	2005

Table 5: Non-parametric statistical test results of solar radiation for Saran and Gopalganj districts

Seasons	Siwan			Vaishali		
	MK test (Z value)	Sen's slope estimate	PMW test (K)	MK test (Z value)	Sen's slope estimate	PMW test (K)
Annual	-5.115*	-0.072	1997	-4.644*	-0.078	1997
Summer	-3.256*	-0.062	1998	-2.014*	-0.053	2012
Autumn	-3.035*	-0.044	1997	-3.270*	-0.052	1997
Winter	-5.704*	-0.105	2006	-5.846*	-0.115	2000
Spring	-4.317*	-0.081	2005	-4.617*	-0.097	2000

Table 6: Non-parametric statistical test results of solar radiation for West Champaran, East Champaran, and Muzaffarpur districts

Seasons	West Champaran			Muzaffarpur			East Champaran		
	MK test (Z value)	Sen's slope estimate	PMW test (K)	MK test (Z value)	Sen's slope estimate	PMW test (K)	MK test (Z value)	Sen's slope estimate	PMW test (K)
Annual	-4.266*	-0.031	1997	-5.208*	-0.065	1997	-5.115*	-0.068	1997
Summer	-1.556NS	-0.032	1997	-1.936NS	-0.037	1998	-3.074*	-0.057	1998
Autumn	-0.850NS	-0.009	2008	-2.956*	-0.043	1997	-3.074*	-0.042	1997
Winter	-4.515*	-0.056	2007	-5.886*	-0.104	2000	-5.809*	-0.104	2006
Spring	-1.922NS	-0.031	2012	-4.015*	-0.076	2012	-4.291*	-0.077	2005

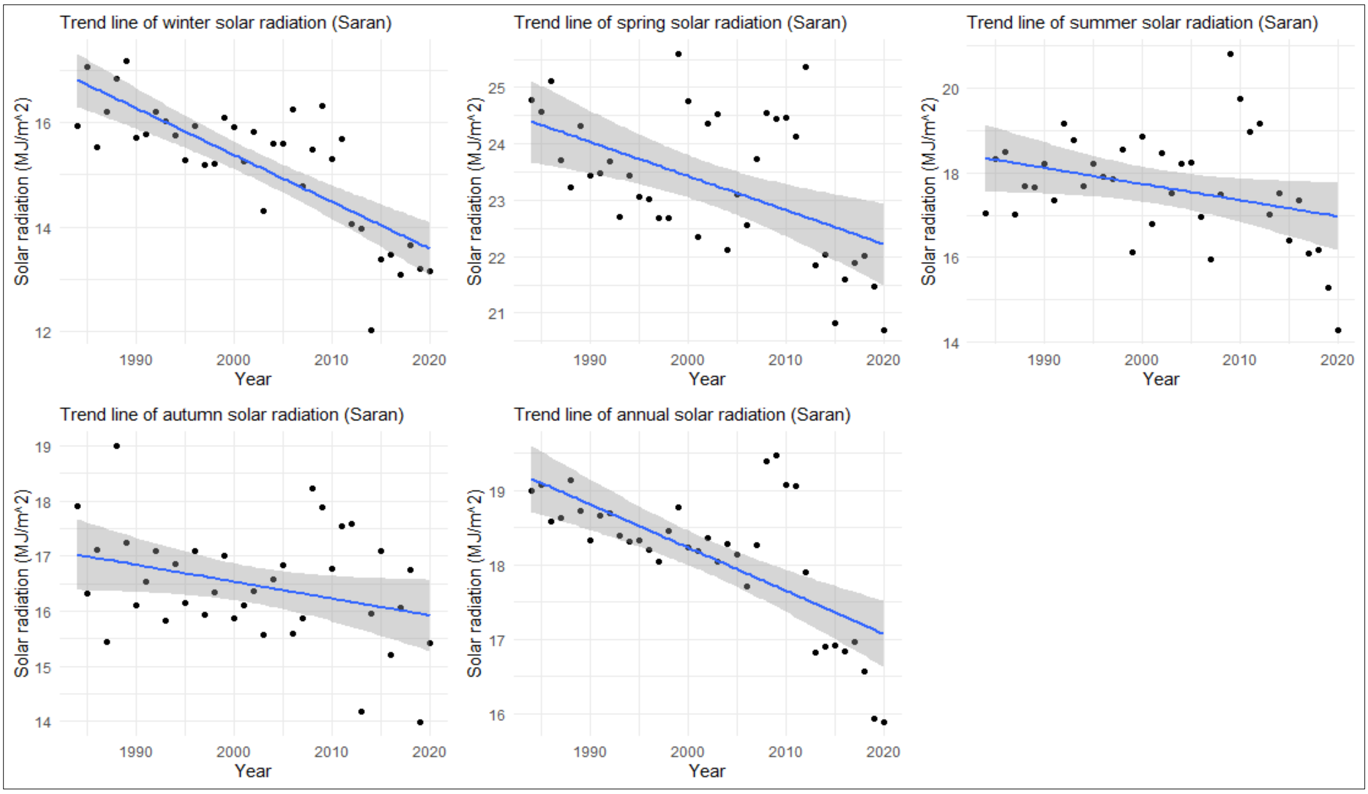

Fig 2: Annual and seasonal trend plots for solar radiation in Saran district

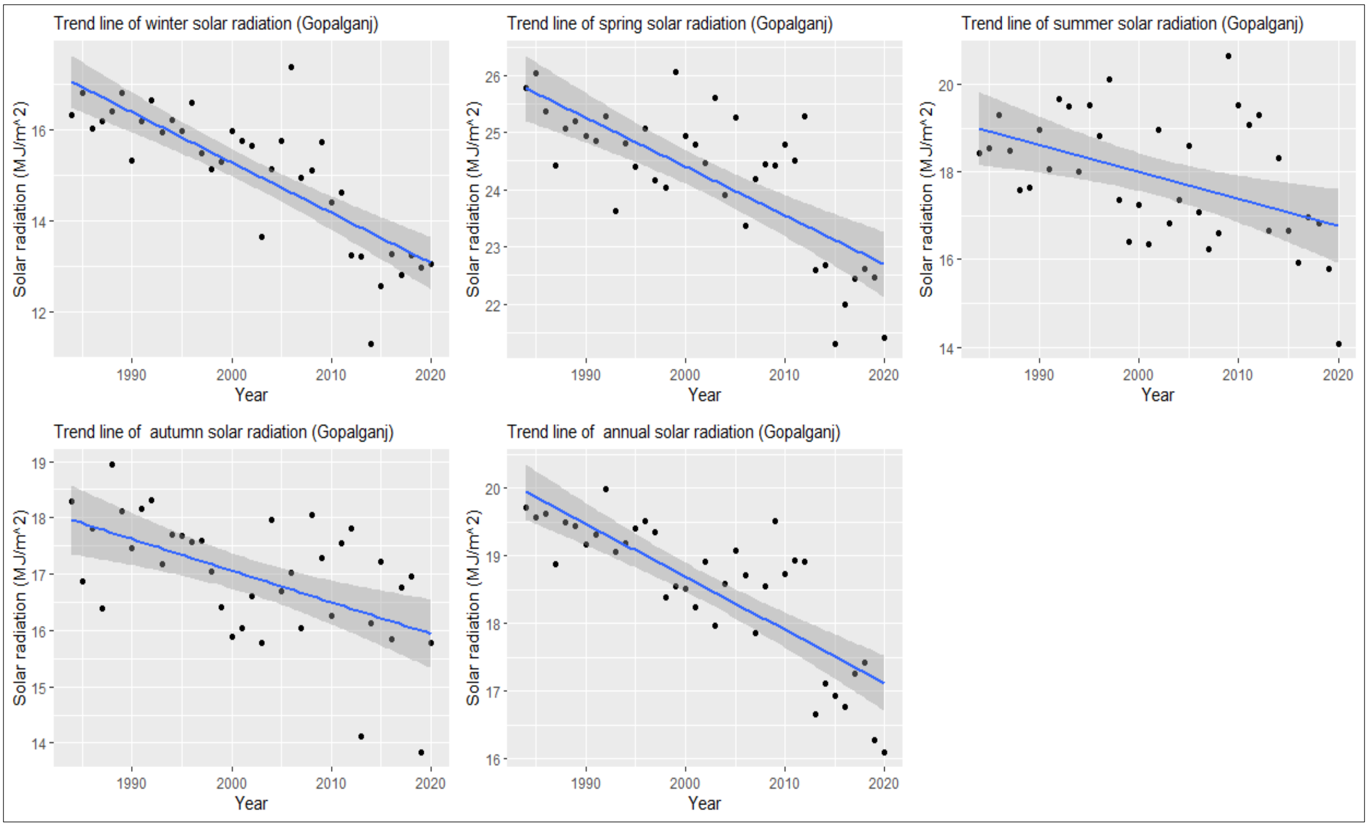

Fig 3: Annual and seasonal trend plots for solar radiation in the Gopalganj district

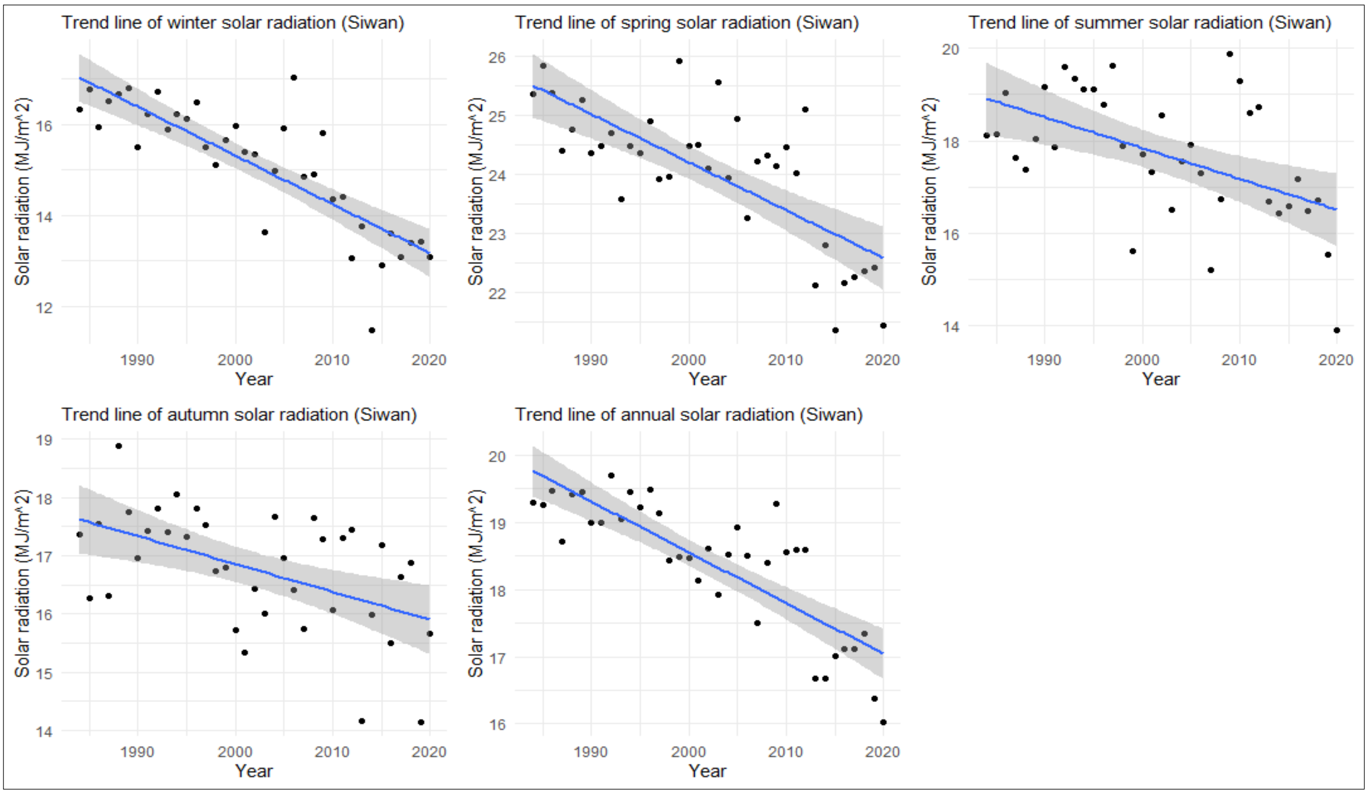

Fig 4: Annual and seasonal trend plots for solar radiation in Siwan district

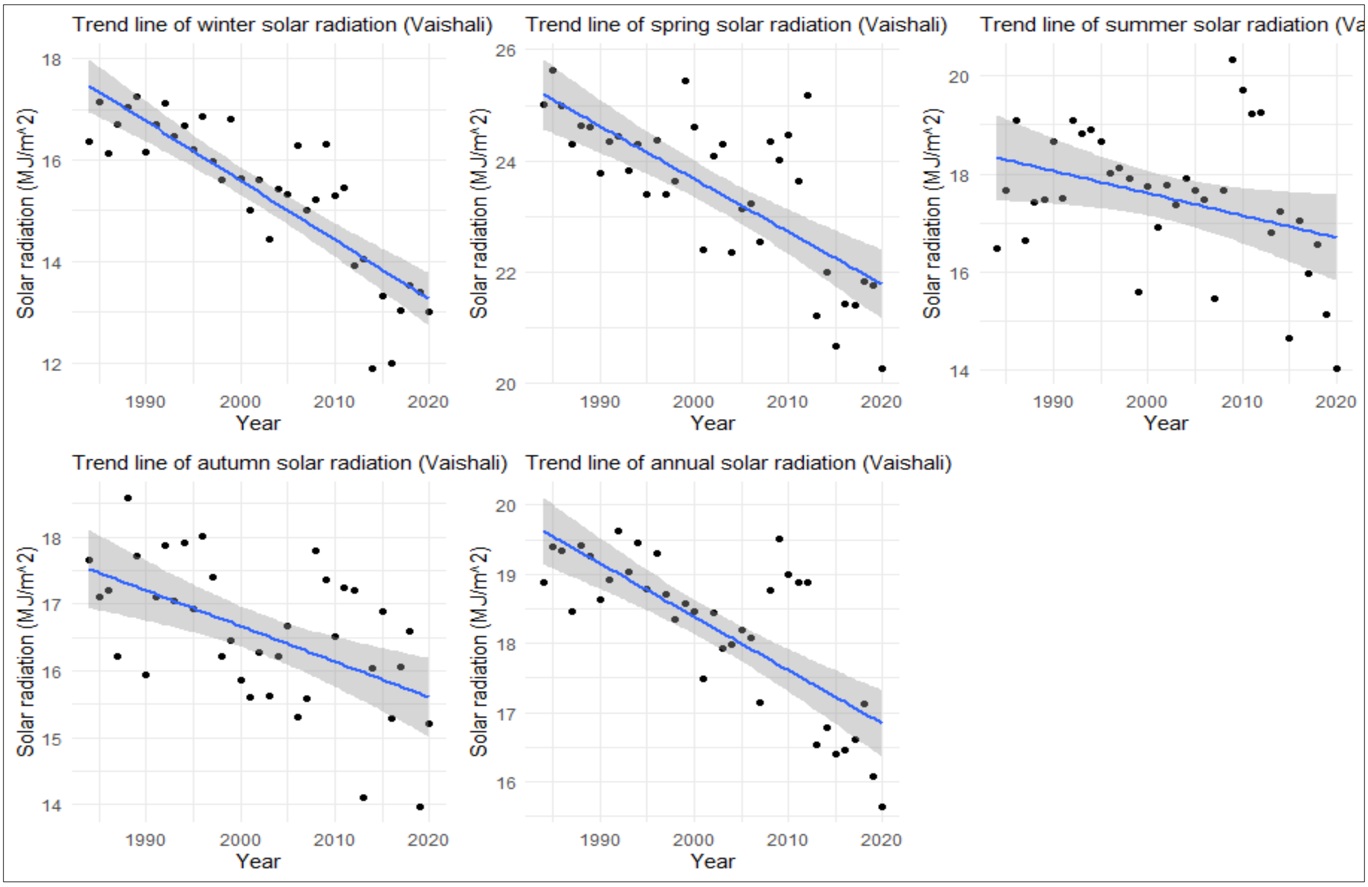

Fig 5: Annual and seasonal trend plots for solar radiation in Vaishali district

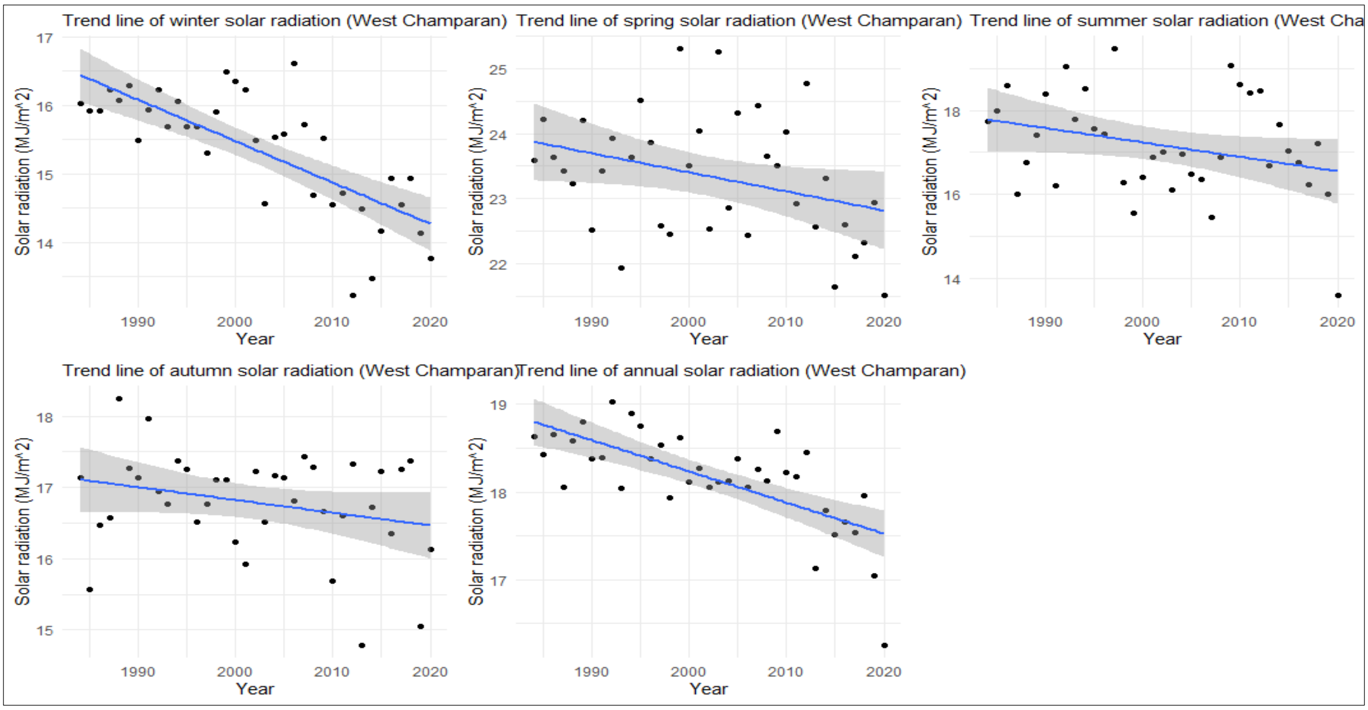

Fig 6: Annual and seasonal trend plots for solar radiation in West Champaran district.

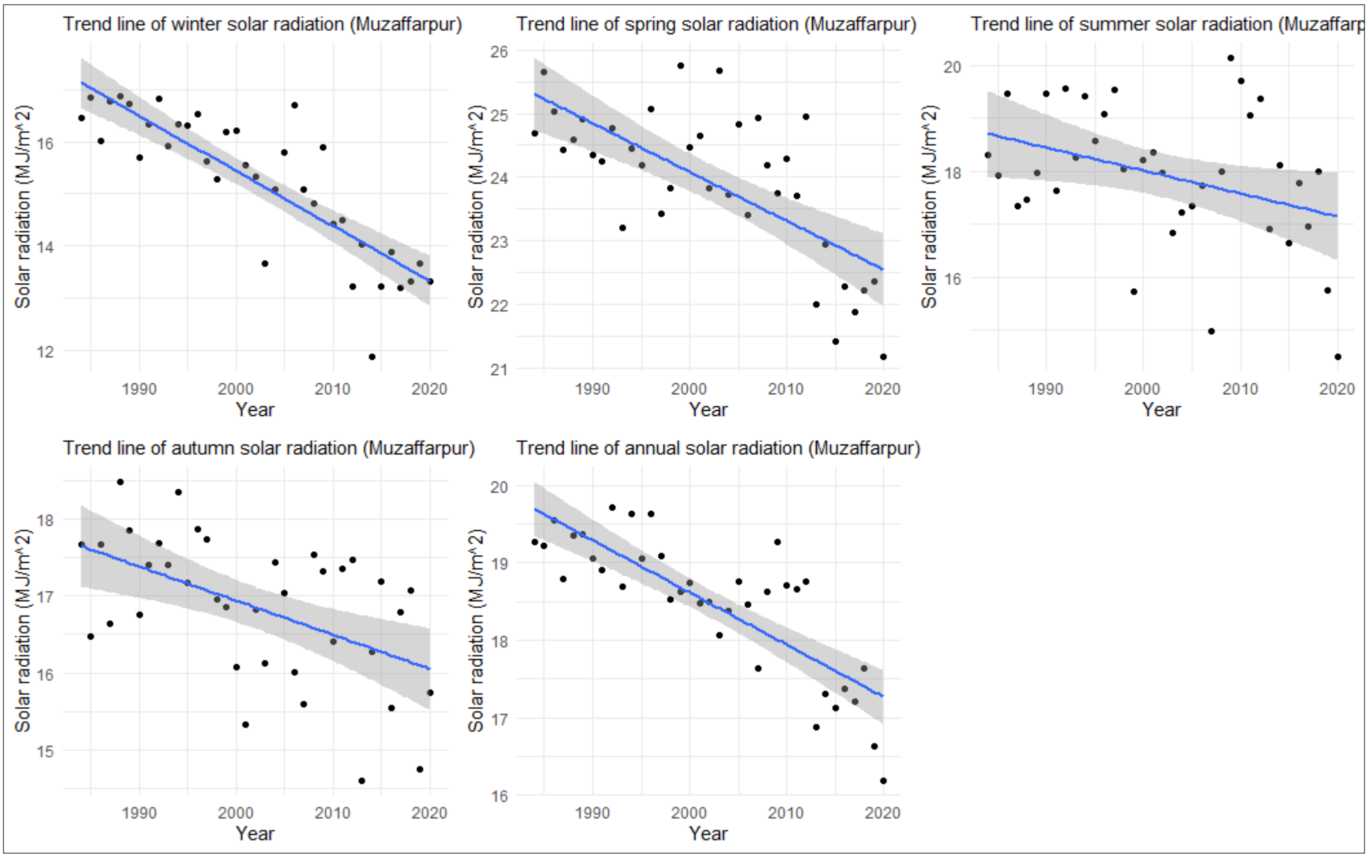

Fig 7: Annual and seasonal trend plots for solar radiation in Muzaffarpur district

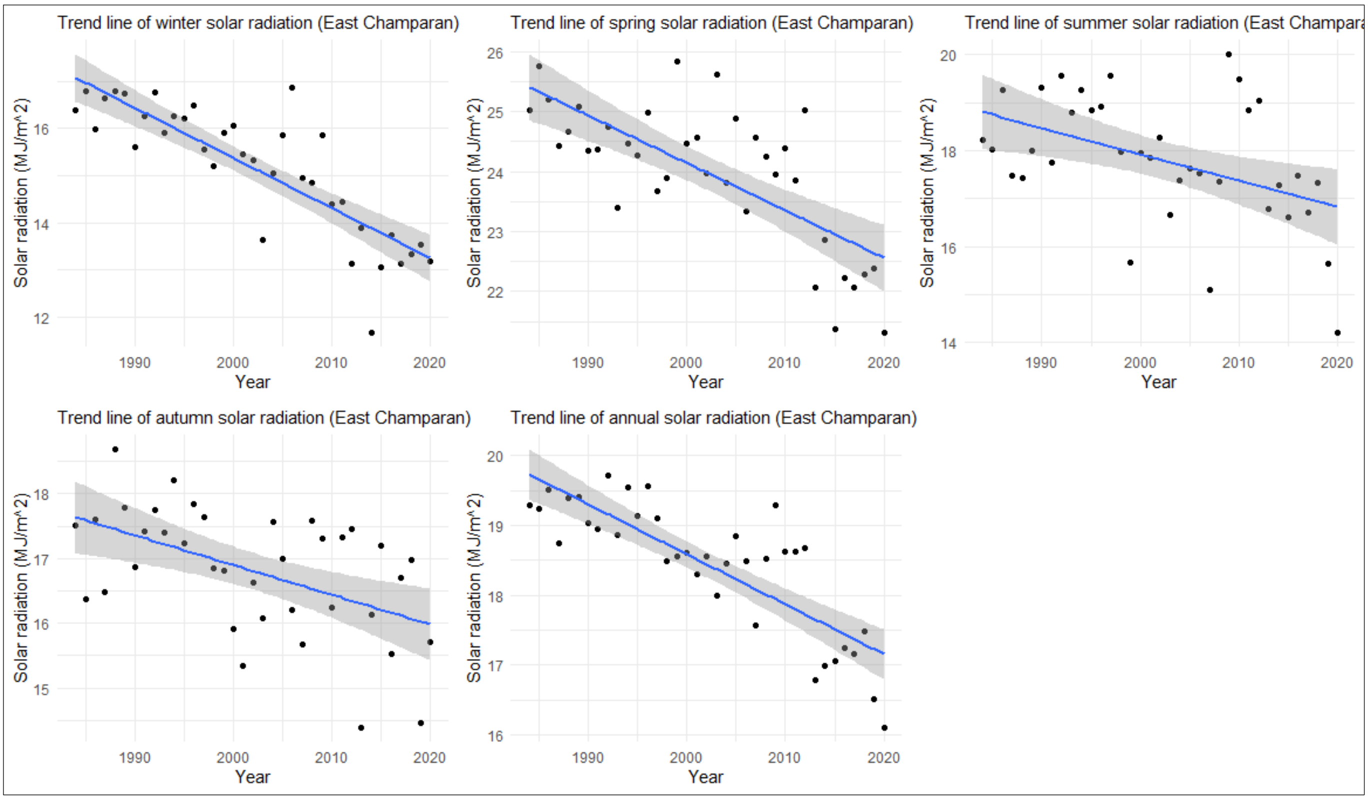

Fig 8: Annual and seasonal trend plots for solar radiation in East Champaran district

4. Conclusions

The present work, which uses surface solar radiation data collected from 1984 to 2020, provides information and knowledge on the spatial variability in the agro-climatic Zone-I of Bihar. The study also evaluated the annual and seasonal trends of solar radiation. The results of descriptive statistics revealed that lower variability was observed in annual and seasonal solar radiation. At spatial scales, the variability of solar radiation was observed to be higher in Vaishali and Gopalganj districts, while lower variability was observed in the West Champaran district. The non-parametric trend analysis found statistically significant decreasing trends in annual and winter seasons for all seven districts. In the case of summer, autumn, and spring seasons, most of the districts also observed significant decreasing trends. The significant decreasing trend in solar radiation is likely due to atmospheric changes when increasing in cloudiness, precipitations, heavy fog, and aerosol concentration occurs. Finally, this study has added to the body of knowledge in terms of determining the most vulnerable areas in Bihar (agro-climatic Zone-I) to solar radiation. A more detailed analysis of solar radiation over other agro-climatic zones in the state is also required to understand the solar radiation trend over the state of Bihar.

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6. Declarations

6.1 Conflict Interests: The authors declare that they have no conflict of interest.

6.2 Ethical approval

The authors confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

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