Analysis of precipitation variability over Satluj Basin, Himachal Pradesh, India: 1901–2013

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ABSTRACT

Himachal Pradesh is a mountainous state in the Indian Himalayas, which spreads over an area of 55,000 km^2. The state has a unique geography, which influences the climatic variability of the state. In the present study, Satluj Basin has been considered as a study area. This basin experiences frequent floods, erratic distribution of rainfall and climatic variabilities, which causes extensive damage over the basin. Precipitation is one of the most crucial meteorological variables which determines the impact of climate change in the Himalayan landmass. For spatial and temporal variation of precipitation, long-term precipitation data of 113 years (1901–2013) was utilized. Further, non-parametric, i.e. Mann–Kendall (MK) and modified Mann–Kendall (MMK) tests, were performed to check possible trends and Sen's slope estimator (SSE) test was used for determining the change in magnitude over the basin at 95% level of significance. The entire analysis was performed on a monthly, annual and seasonal (pre-monsoon, monsoon, post-monsoon and winter) basis. In this study, it was noticed that both positive and negative trends are detected in monthly and seasonal time series. It was also noticed that similar results have been estimated in MK, MMK and Sen's slope estimator tests during 1901–2013.

Key words | climate change, rainfall variability, Satluj Basin, trend analysis

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INTRODUCTION

Climate change is a long-term phenomenon which influences various natural and anthropogenic factors. Nowadays, climate change is a major issue due to hazardous events such as heavy rain, flood, drought, cyclone, high temperature, snow and glacier melt. Day by day, natural and man-made factors alter the symmetry of the hydrological cycle in many places over the world. Water surplus and deficit are both inter-dependent to hydro-meteorological variability over space and time. Long-term climatic variability and its unevenness are considered as climate change. Best management practices will be beneficial for climatic threats or hazards with natural resources managements/strategies. Discrepancy in precipitation over different time frames, i.e. monthly, seasonally and annually, in a watershed is impacted by hydrological variability. The precipitation variability controls the hydrological problems, vegetation and agriculture. For optimization of farm production an exact knowledge of precipitation and soil characteristics is important (Gajbhiye *et al.* 2015, 2016).

Determination of crop growth is highly dependent on the occurrence and variability of precipitation and temperature (Chandniha *et al.* 2016; Pal *et al.* 2019; Prabhakar *et al.* 2019). Appropriate action should be taken for the planning, development, utilisation and management of water resources since precipitation is changing rapidly (Kumar *et al.* 2015). It is difficult to understand the repercussions of climate change on the Indian landmass continent, mainly in the highland mountainous regions. During the past decade, many researchers have studied the changing variability and shift in position or direction of precipitation in

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different regions (Roy & Balling 2005; Tabari & Talaee 2011; Mondal *et al.* 2012; Hamid *et al.* 2014; Kumar *et al.* 2015; Warwade *et al.* 2015; Chauhan *et al.* 2016). Long-term precipitation data sets are used for understanding the global water cycle. The changes in rainfall pattern, risk of glacial lake outburst floods (GLOFs), increase in temperature, rise of sea level and an increase in intensity and frequency of uttermost weather events are some of the important impacts of climate change. Due to the variation in height, the Satluj Basin has great variation in its climate. In Satluj Basin, climatic variability varies from hot to sub-humid in the southern part to glacier and alpine in the northern part of the basin whereas the precipitation is received from the western disturbance.

The western threats pass over the northwestern part during the winter. In the Himalayan region the river Satluj is one of the major rivers in Northern India, and it is the longest of the five tributaries of the Indus river which is reinforced by snowmelt, glacier melt, and rainfall. This may be related to the conversion of snow to rain as a result of climatic warming during this period. Precipitation variability is expected to play a major role in the discharge pattern of this river. Many factors such as rainfall distribution, climate change, land use etc. affect the transformation from rainfall to streamflow (Yaseen *et al.* 2019).

A trend study helps to investigate the general pattern of change over time in hydrometeorological variables, especially for water resource projects at temporal and spatial scales. Satluj Basin has great variation in its climate due to its height. Satluj Basin receives precipitation from western threats. Satluj valley faces the heavy monsoon of the outer Himalayas and heavy snowfall of the arid Tibetan. With the problems described above, the objective of this study was to explore the variability of precipitation in Satluj Basin, Himachal Pradesh, India, using 113 years (1901–2013) of precipitation data.

MATERIAL AND METHODS

Study area

The area of Satluj River Basin is situated approximately between 30°22–32°42 N longitude and 75°57–78°51 east latitude (Figure 1) in Himachal Pradesh, India where more than 90% of the catchment ranges above 1,525 m above mean sea level (msl) and the elevation of permanent snowline is about 5,400 m. The Satluj Basin is divided into four parts: Tibet plateau, Spiti valley and Khab to Nathpa that include many V-shaped valleys cirques, glaciers, U-shaped and hanging valley moraines and Nathpa dam site to Bhakhra. The Satluj Basin is known for variation in its biodiversity due to the extreme variation of height. The upper reaches (Spiti and Kinnaur) of Satluj Basin have less vegetation. The major forest type of the cold desert area has dry alpine scrubs and falls under elevation ranges of 3,600–5,000 m above sea level (MSL).

Data used

Hydro-meteorological data has been collected from the Indian Meteorological Department (IMD) website for

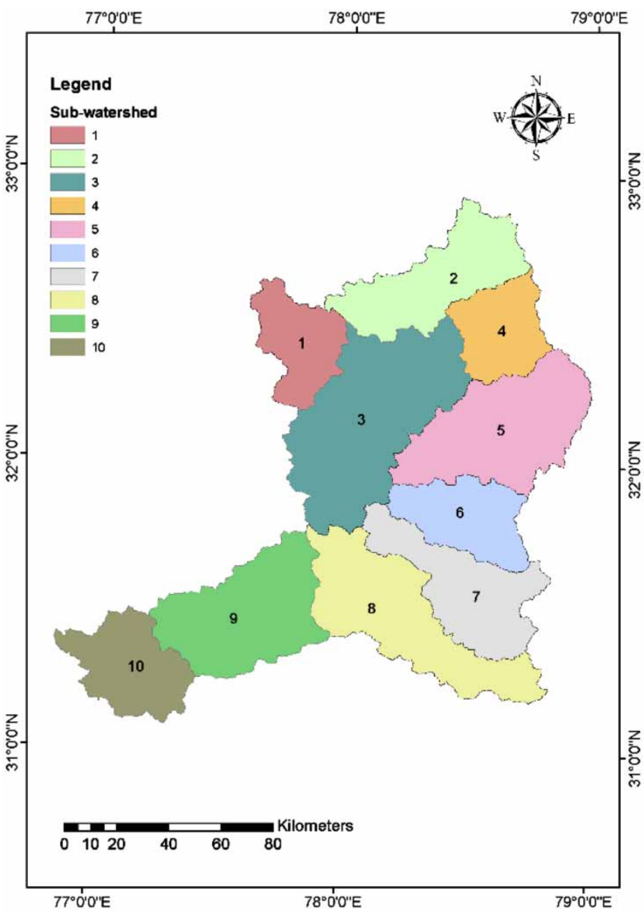

Figure 1 | Location map of Satluj Basin (study area).

Table 1 | Z-statistics values of monthly rainfall using MK for the 10 sub-basins of Satluj watershed during 1901–2013

SW	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.906	2.146	−0.437	−1.045	−0.402	0.816	−1.380	0.593	0.727	−0.030	2.237	1.362
2	1.345	3.362	1.082	0.169	0.042	1.556	2.390	2.340	2.295	0.432	2.479	1.757
3	−0.129	1.149	−0.923	−1.459	−0.826	−0.437	−2.672*	−0.531	−0.437	−0.639	1.814	0.842
4	−0.002	1.387	−0.690	−1.568	−0.675	−0.040	−1.412	0.610	0.228	−0.603	1.956	0.499
5	−0.963	0.489	−1.849	−1.876	−1.246	−1.005	−1.717	0.278	−0.496	−1.220	1.372	−0.040
6	−0.844	0.546	−1.893	−1.861	−1.064	−0.722	−1.161	0.702	−0.213	−1.096	1.411	−0.094
7	−0.744	0.553	−1.975*	−1.677	−0.519	0.399	0.124	1.754	0.481	−0.936	1.306	−0.318
8	−0.476	0.809	−1.618	−1.449	−0.444	0.332	0.030	1.295	0.563	−0.707	1.382	−0.206
9	−1.370	−0.496	−0.829	−1.893	0.767	0.742	−3.119*	−4.355*	−0.881	−1.633	0.638	−1.502
10	−0.623	1.226	−1.084	−2.506	−0.201	0.077	0.702	0.722	0.777	−1.042	1.243	−0.752

*Significant at the 5% level.

113 years (1901–2013). The monthly precipitation data of 10 stations was obtained to investigate the spatial and temporal variability of the precipitation. For the Satluj Basin, trend analysis for precipitation was performed on a monthly, seasonal (pre-monsoon, monsoon, post-monsoon and winter) and annual basis.

Statistical tests used for trend analysis

Mann–Kendall test/modified Mann–Kendall test

The MK test is widely used for detecting meteorological trends (Yilma & Zanke 2004; Mekonnen & Woldeamlak 2014; Tabari *et al.* 2015). It is a nonparametric test that results in a series of particularly important weather trends which are linear or nonlinear (Yue & Hashino 2003). For determining a monotonic positive and negative trend, it is necessary that long-term precipitation time series are auto correlated or normalized. In the data series the proximity of the serial correlation is distinguished by autocorrelation coefficient (Siegel & Castellan 1988).

Sen's slope estimator

SSE test calculates the slope (i.e. the rate of linear change). To forecast the trend's magnitude, Theil (1950) and Sen (1968) slope estimators are used.

Table 2 | Z-statistics values of monthly rainfall using MMK for the 10 sub-basins of Satluj watershed during 1901–2013

SW	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.815	2.354*	−0.437	−1.642	−0.468	0.495	−1.187	0.632	0.727	−0.029	1.887	1.476
2	1.215	3.362*	1.045	0.169	0.035	1.407	3.281*	2.465*	2.295*	0.462	2.419*	1.757
3	−0.120	1.286	−0.923	−1.644	−0.957	−0.278	−2.672*	−0.528	−0.437	−0.655	1.514	1.004
4	−0.002	1.906	−0.774	−1.793	−0.714	−0.024	−1.322	0.655	0.228	−1.320	1.851	0.881
5	−0.867	1.077	−2.123*	−2.147*	−1.246	−0.564	−1.350	0.258	−0.496	−4.783*	1.206	−0.049
6	−0.759	0.987	−1.893	−2.123*	−0.998	−0.393	−0.902	0.652	−0.213	−4.556*	1.261	−0.118
7	−0.667	0.992	−1.975*	−1.895	−0.519	0.224	0.098	1.337	0.481	−6.481*	1.421	−0.348
8	−0.476	1.208	−1.618	−1.636	−0.444	0.235	0.031	1.288	0.563	−1.418	1.517	−0.224
9	−1.370	−0.496	−1.157	−2.113*	0.767	0.884	−2.794*	−4.626*	−0.963	−1.808	0.586	−1.602
10	−0.718	1.226	−1.217	−2.852*	−0.209	0.082	0.739	0.747	0.777	−1.718	1.213	−0.796

*Significant at the 5% level.

Table 3 | Z-statistics values for seasonal and annual rainfall using MK for the 10 sub-basins of Satluj watershed during 1901–2013

SW	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1	1.819	−1.122	0.462	1.253	2.873
2	4.298	0.757	3.590	1.851	3.868
3	0.154	−1.794	−0.854	0.392	1.697
4	0.866	−1.834	0.471	0.228	1.243
5	−0.375	−2.583*	−0.099	−0.452	0.236
6	−0.117	−2.685*	0.474	−0.439	0.107
7	0.730	−2.506*	1.568	−0.524	0.052
8	0.863	−2.243*	1.290	−0.395	0.203
9	−4.102*	−0.648	−3.844*	−0.911	−2.387*
10	0.801	−2.072*	1.553	−0.672	0.094

*Significant at the 5% level.

Coefficient of variance (CV) test

Variation in rainfall can be calculated by CV, i.e. high CV means high variation. Variations from the mean are identified with CV, and are dependent on mean and standard deviations of the series (Landsea & Gray 1992).

Inverse distance weighted technique

For the spatial maps of precipitation, the inverse distance weighted (IDW) interpolation technique was used (Singh & Chowdhury 1986; Lebel *et al.* 1987). The inverse distance weighting tool is available in ArcMap. The proportionality between the weight of any existing point and existing point distance from the proposed point is set by the IDW method (Chen & Liu 2012).

Table 4 | Z-statistics values for seasonal and annual rainfall using MMK for the 10 sub-basins of Satluj watershed during 1901–2013

SW	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1	1.540	−0.953	0.432	0.915	2.697*
2	4.103*	0.532	3.685*	1.984*	2.524*
3	0.189	−1.529	−0.752	0.363	1.639
4	0.866	−2.047*	0.397	0.187	1.281
5	−0.354	−2.886*	−0.084	−0.374	0.223
6	−0.110	−3.009*	0.407	−0.404	0.100
7	0.691	−3.155*	1.201	−0.491	0.049
8	0.863	−2.801*	1.227	−0.329	0.197
9	−4.102*	−0.615	−3.844*	−0.911	−2.772*
10	0.746	−1.810	1.912	−0.572	0.069

*Significant at the 5% level.

RESULTS AND DISCUSSION

Statistical characteristics of annual and seasonal precipitation during 1901–2013

The mean and standard deviation (SD) of the annual rainfall data of Satluj Basin varied from 0.1 to 682.4 and 0.1 to 311 mm respectively. Seasonal precipitation mean value varied from 0.1 to 682.4 mm.

Precipitation data series for Mann–Kendall test

Monthly trends

Tables 1 and 2 show the MK and MMK statistics at 5% significance level, respectively. A positive z-statistics value indicates an increasing trend whereas a negative value indicates a decreasing trend. MK and MMK both showed 39 and 45% of the values fall under negative trend(s) respectively. Out of 120 cases (10 SW × 12 months) at 5% significance level, 47 cases showed a positive trend, 60 cases showed a negative trend, and five cases showed a negative significant trend. The MMK statistics of all 120 cases is shown in Table 2 where 53 cases showed a negative trend, 48 cases showed a positive trend, 12 cases showed a negatively significant trend and six cases showed a positively significant trend at 5% significant level. The month of November most likely showed a positive trend for all SWS in both MK and MMK test. Both MK and MMK showed an almost similar number of statistically significant trends.

Annual and seasonal trends

The results of trend analysis at 5% significant level for seasonal and annual precipitation data for the period of 1901–2013 using MK and MMK for the 10 SW of Satluj watershed are shown in Tables 3 and 4. In MMK only, SW-2 showed a positively significant trend in the post-monsoon season. In both MK and MMK statistics, almost similar results were given for annual and seasonal precipitation data series. For pre-monsoon in both MK and MMK only SW-2 showed a

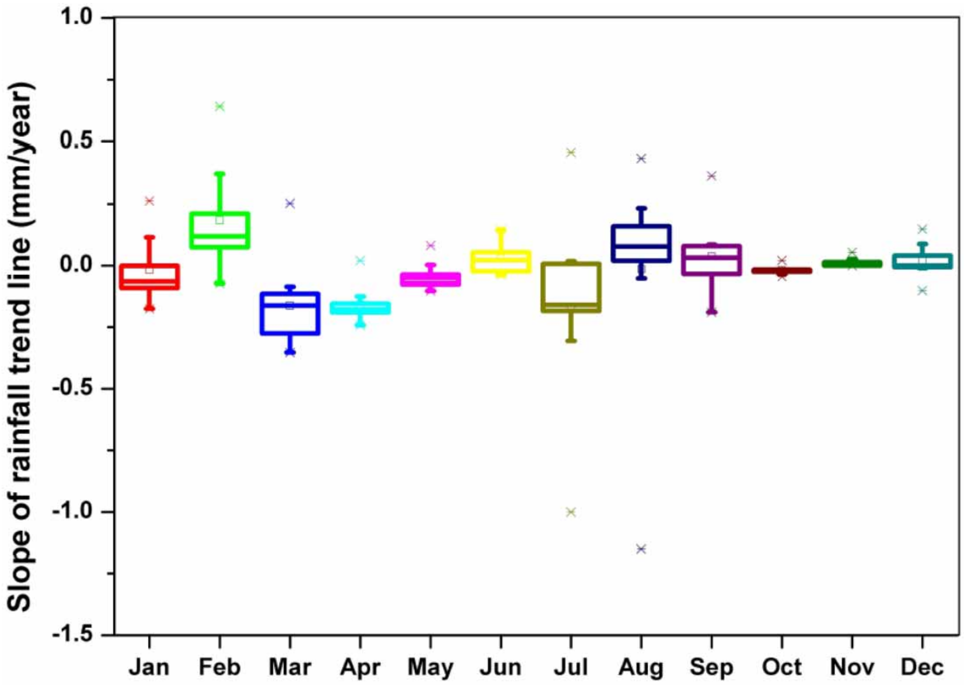

Figure 2 | Box plots of the Sen slopes for monthly trends.

positive trend. A negative significant trend was found in 5 SW in pre-monsoon in both the MK and MMK tests.

Assessment of the magnitude of the trend slope

Monthly precipitation data

A large variation is observed in the magnitude and direction of the precipitation trends for Satluj Basin (all 10 SW). Figure 2 shows a box plot of the Sen slope for the precipitation time series on a monthly basis for the period 1901–2013. The medians of five months' slopes showed a negative value. Out of 12 whiskers (i.e. vertical lines) the lowest point value was observed in the month of August (–1.15 mm/year) and the highest point value was observed in the month of February (0.64 mm/year).

A total of 120 values were considered for detecting the trends for the period of 1901–2013 on a monthly basis, see

Table 5 | The Sen slope of monthly rainfall data for Satluj watershed during 1901–2013

SW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.115	0.372	–0.086	–0.125	–0.037	0.054	–0.184	0.061	0.079	0.000	0.026	0.087
2	0.262	0.641	0.252	0.020	0.003	0.145	0.458	0.434	0.364	0.021	0.054	0.148
3	–0.020	0.190	–0.163	–0.191	–0.079	–0.023	–0.306	–0.052	–0.044	–0.017	0.007	0.041
4	–0.001	0.210	–0.148	–0.190	–0.077	–0.003	–0.182	0.077	0.032	–0.020	0.014	0.026
5	–0.077	0.045	–0.225	–0.155	–0.077	–0.038	–0.144	0.019	–0.034	–0.023	0.000	0.000
6	–0.106	0.074	–0.353	–0.242	–0.103	–0.039	–0.160	0.088	–0.019	–0.034	0.000	0.000
7	–0.091	0.083	–0.342	–0.210	–0.050	0.026	0.017	0.233	0.060	–0.025	0.006	–0.011
8	–0.064	0.119	–0.276	–0.179	–0.042	0.022	0.006	0.160	0.085	–0.022	0.008	–0.006
9	–0.175	–0.073	–0.115	–0.163	0.081	0.110	–1.000	–1.150	–0.189	–0.045	0.000	–0.102
10	–0.095	0.180	–0.196	–0.254	–0.027	0.011	0.128	0.125	0.156	–0.035	0.009	–0.050

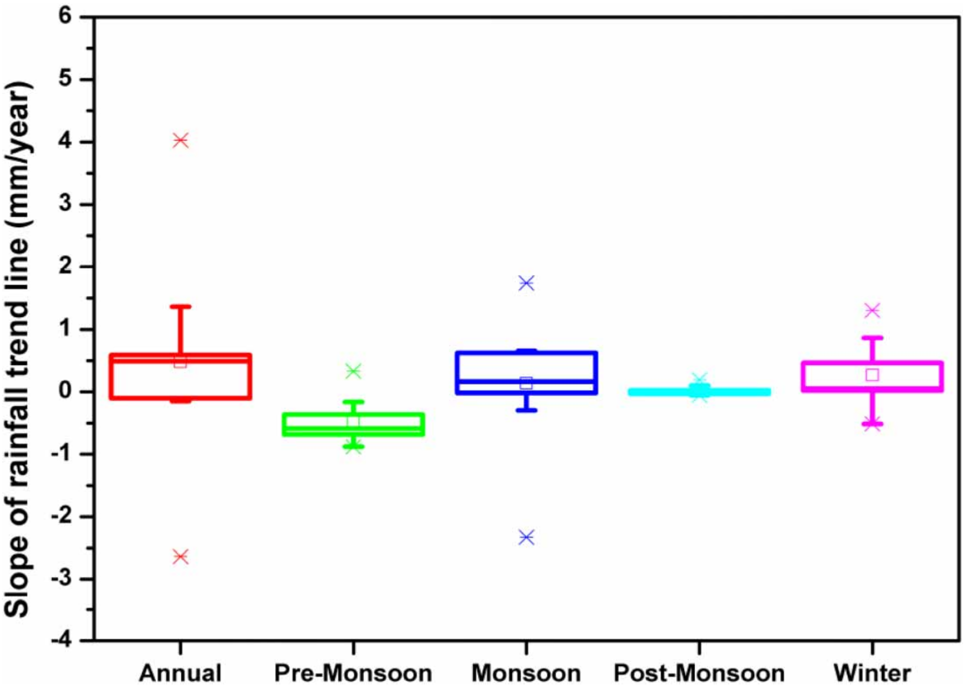

Figure 3 | Box plots of the Sen slopes for annual and seasonal trend.

Table 5. Out of the 120 cases 62 values were negative and 58 values were positive. The month of November had all positive values whereas the month of February had mostly negative values except for one sub-basin.

Annual and seasonal precipitation data

Figure 3 shows a box plot of slopes for annual and seasonal time series data sets during 1901–2013. The median of the slopes was located above the zero line except for pre-monsoon which is below zero. In the annual precipitation series, the magnitude of the positive trend ranged from 0.12 to 4.02 mm/year respectively. For the seasonal precipitation data, from Table 6, out of 40 slope values, 21 were positive and 19 were negative. The pre-monsoon gave most of the negative values expect for one sub basin which has the value of 0.33 mm/year, and the magnitude of the negative trend ranged from 0.16 to 0.87.

Table 6 | The Sen slope for seasonal and annual rainfall data for Satluj watershed during 1901–2013

SW	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1	1.361	–0.366	0.157	0.104	0.862
2	4.029	0.331	1.742	0.194	1.305
3	0.121	–0.616	–0.296	0.025	0.464
4	0.516	–0.556	0.165	0.017	0.368
5	–0.150	–0.556	–0.017	–0.020	0.041
6	–0.101	–0.878	0.163	–0.032	0.047
7	0.568	–0.781	0.655	–0.030	0.015
8	0.588	–0.684	0.531	–0.025	0.056
9	–2.637	–0.164	–2.326	–0.054	–0.512
10	0.489	–0.587	0.623	–0.051	0.021

Seasonal and annual precipitation variability analysis

In order to investigate the inter annual rainfall variability and its trend, Arc-Map 10.2 software was used to generate and plot the spatial patterns of the trends over the whole watershed by applying the inverse distance weighted (IDW) interpolation technique. The inverse distance weighting tool available in ArcMap was used to develop inter annual variability and its trends annually, pre-monsoon, post-monsoon and in the winter season, as shown in Figure 4. These maps clearly present inter annual variability in rainfall pattern in the study area. These maps are useful to understand the pattern and its variability so that the

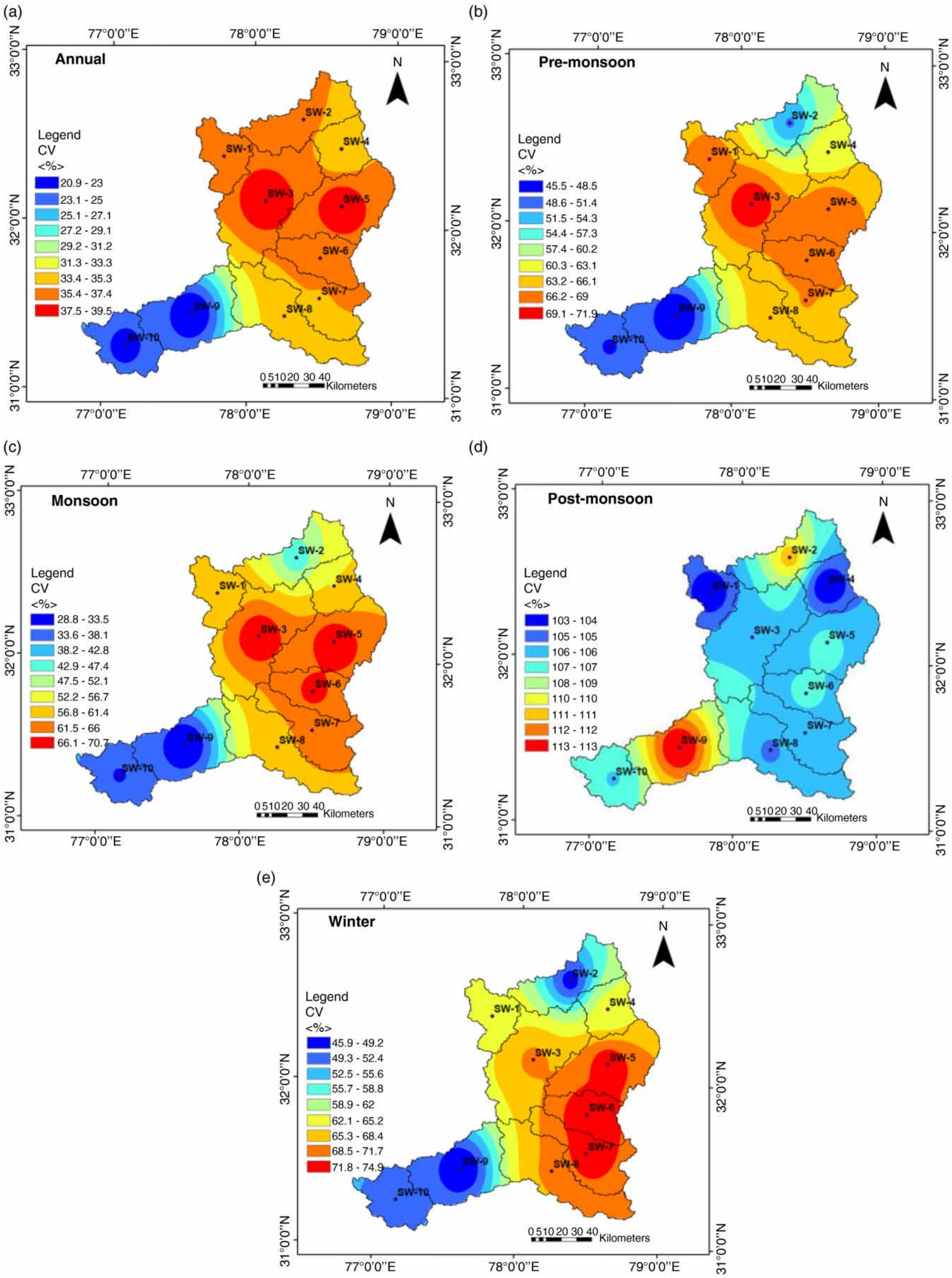

Figure 4 | Inter annual variability of precipitation (%CV) and its trends: (a) annual; (b) pre-monsoon; (c) monsoon; (d) post-monsoon and (e) winter season.

appropriate water management practices may be planned in accordance with the upcoming demands.

The analysis of the precipitation variability using CV for 1901–2013 for Satluj Basin indicates that the inter-annual variability of post-monsoon precipitation is greater than that of annual precipitation. Variation is lowest for annual and monsoon precipitation when minimum values of CV are 20.89 and 28.82%, respectively, as shown in Figure 4. The minimum values of CV for precipitation in the other seasons are 103.25% (post-monsoon), 45.94% (winter), and 45.54% (pre-monsoon). The value of CV is found to be highest in SW2 for three seasons: 71.2% for pre-monsoon, 70.66% for monsoon and 69.20% for winter. For post-monsoon season the highest value of CV was found in SW 9 with a value of 113.26%.

CONCLUSIONS

This study emphasizes long-term trends analysis using the MK, MMK and Sen's slope estimator tests for the period 1901–2013. Further, spatio-temporal analysis results are also estimated for all sub-basins over Satluj River Basin. Spatial maps are prepared as per CV (%) values of each sub-basin. The consequences of the rainfall variability in the mountainous region are poorly understood, therefore it is important to evaluate this variability from time to time. The analysis of variability and trends of monthly, annual and seasonal precipitation time series data were analysed for 10 SW of Satluj Basin for the period of 1901–2013. From the results of the study, it is concluded that both MK and MMK give almost similar results. The annual season for both MK and MMK show a positive significant trend except for two SW which show a negative significant trend (i.e. SW 2 and SW 9 respectively). In a monthly seasonal trend for both MK and MMK, 55% of the values are indicated by a negative trend (either statistically significant or non-significant) and the month of November indicates a positive trend for all the SW. The pre-monsoon season for both MK and MMK show a negative trend except for SW 2 which shows a positive trend. The IDW statistic considers deviations from the average by taking CV (%). The CV of inter annual precipitation is an index of climatic risk. The higher the CV (%), the more variable the year to year (i.e. inter-annual) rainfall of a locality is. The basin shows the inter-annual variability of post-monsoon precipitation greater than that of annual precipitation. The winter season shows a positive trend except for SW 9 which shows a negative trend. For determining the water availability and demand it is important to understand the trend and variability of precipitation for proper management of agriculture, water resource and policy and planning.

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