Trend analysis of rainfall in Satluj River Basin, Himachal Pradesh, India

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ABSTRACT

Testing the significance of observed trends in hydro-meteorological time series has received a great attention recently, especially in connection with climate change. The changing pattern of rainfall deserves urgent and systematic attention for planning, development, utilisation and management of water resources. The daily data on variable were converted to monthly and then computed to seasonal and annual series. Annual rainfall (mm/yr) was calculated as the sum of monthly values. The missing values in the data were computed by using average method. The records of rainfall were subjected to trend analysis by using both non-parametric (Mann-Kendall test) and parametric (linear regression analysis) procedures. For better understanding of the observed trends, data were computed into standardised precipitation indices (SPI). These standardised data series were plotted against time and the linear trends observed were represented graphically. Trend analysis results of rainfall show that out of 15 annual trends 6 (40\%) are increasing and 9 (60\%) are decreasing in nature where 1 (6.6\%) is statistically significant (increasing) and 2 (13.3\%) are statistically significant (decreasing) at 95\% confidence level. Similarly, the changes were investigated for the four seasons: winter (December-March), pre-monsoon (April-June), monsoon (July-September) and post-monsoon (October-November). The analysis of rainfall, annual as well as seasonal, of different gauge stations in Satluj River Basin showed a large variability in the trends and magnitudes from 1984 to 2010. The rainfall shows great temporal and spatial variations, unequal seasonal distribution with frequent departures from normal. Majority of gauge stations have experienced decreasing trends, both on seasonal and
annual scales. Some were statistically significant at 95% confidence level. The sensitivity of rainfall variations provides important insight regarding the responses and vulnerability of different areas to climate change. It will further strengthen the formulation of future strategy for management of water resources.

**Keywords:** Mann-Kendall test; Rainfall; Regression; Satluj River Basin; Trend analysis

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1. **INTRODUCTION**

Climate change arising from anthropogenic driven emissions of greenhouse gases has emerged as one of the most important environmental issues in the last two decades. Information about impacts of climate change is required at global, regional and basin scales for a variety of purposes. The consequences of climate change on Indian sub-continent, especially the mountainous regions are poorly understood. The Himalayan region has large and intricate network of river systems which is reinforced by the snowmelt, glaciemelt and rainfall. Many of major rivers originating in this region have their upper catchments covered by snow/glacier. The altitude and climatic change induced temperature variability are expected to play major role on rainfall pattern.

An understanding of rainfall response in a river basin under changing climatic conditions will help to resolve potential issues associated with hydro-meteorological disasters and availability of water for agriculture, industry, hydropower, domestic use etc. The changing pattern of regional precipitation deserves urgent and systematic attention over a basin which provides an insight view of historical trends. Therefore, information on trend analysis over a basin scale is of utmost importance for planning, development and utilisation of water resources.

The assessment of hydro-climatic trends of river basin can provide a perspective assessment on catchment dynamics. Detection of temporal trends is one of the important objectives of environmental monitoring. Trend analysis has proved to be useful tool for effective water resources planning, design and management since trend detection of hydrological variables provides a useful information on the possibility of change in tendencies of the variables in future (Hamilton *et al.*, 2001; Yue and Wang, 2004).

One of the most significant potential consequences of climate change may be alteration in regional hydrological cycle. For this reason, it becomes very important to investigate the changes in the spatial and temporal pattern of rainfall in order to improve water management strategies.

Necessity of the hour is to concentrate on the studies, how the possible climate change will affect the intensity, temporal and spatial variability of rainfall patterns in river basins. It became utmost important to study the impacts of climate change and its variability on changing rainfall pattern in river for designing regional and national long term developmental strategies which are supposed to be benign in nature i.e. sustainable. Therefore, one large catchment (Satluj) is selected for the present study.
Climatic variability and change in precipitation pattern will affect the runoff in the river basin. The changes in the amount and seasonal distribution of precipitation have potentially serious implications for the hydrological regimes of catchment area.

The nature of climate change and its impact on rainfall of the Satluj River Basin have been studied inadequately because of inaccessibility, terrain ruggedness and sparse network of gauge stations. The present study tries to fill this vacuum by studying the trend analysis of rainfall.

Testing the significance of observed trends in hydrological and meteorological time series has received a great attention recently, especially in connection with the assessment of observed changes in the natural and human environment due to global warming. This is reflected by a huge number of studies carried out over the last three decades, dealing with the assessment of significance of trends in a variety of natural time series.

The global average precipitation is projected to increase, but both increases and decreases are expected at regional and continental scales (Dore, 2005). The annual and seasonal precipitation trends over Iran for the period 1966-2005 have been analysed using the Mann-Kendall test, the Sen’s slope estimator and the linear regression. The results indicated a decreasing trend in annual precipitation at about 60% of the stations.

The decreasing trends were significant at seven stations at the 95% and 99% confidence levels. On the seasonal scale, the trends in the spring and winter precipitations time series were mostly negative. The highest numbers of stations with significant trends occurred in winter while no significant positive or negative trends were detected by the trend tests in autumn precipitation (Tabari and Talaee, 2011). Buffoni et al. (1999) studied series of annual and seasonal precipitation over Italy for the period 1833-1996. Their results showed a decreasing trend in annual series, but it was statistically significant only in the central-southern parts. On a seasonal basis, a decreasing trend was significant only for spring in central-southern and for autumn in the North. Liu et al. (2008) investigated the spatial and temporal patterns of the precipitation trends in the Yellow River Basin, China.

The results showed a decreasing trend in most of stations. Kampata et al. (2008) investigated the trends of precipitation data from the head stream regions of the Zambezi River Basin in Zambia and showed marginal downward insignificant trends. Zhang et al. (2008) analysed annual, winter and summer precipitation records and found an increasing trend in annual, summer and winter precipitation in the middle and lower sections of the Yangtze River. A statistical analysis of annual and seasonal precipitation has been performed over cumulated rainfall series in a region of southern Italy (Calabria). The results had shown a decreasing trend for annual and winter-autumn rainfall and an increasing trend for summer precipitation (Caloiiero et al., 2011). In Germany, a positive linear tendency in heavy precipitation for the winter, spring and autumn seasons was found. In the summer season, however, heavy precipitation exhibits mostly negative trends (Zolina et al., 2008).

In India, various attempts have been made to determine the trends in the rainfall over the country as a whole and also on regional scales. Studies related to changes in rainfall over Indian region have shown that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley and Parthasarathy, 1984; Thapliyal and Kulshreshtha, 1991). In the Himalayan region, Sharma et al. (2000) showed an increase in the annual precipitation for the period 1943-1993.

The analysis of long datasets for studying the spatial and temporal variations in precipitation in the Upper Indus Basin showed no significant trend from 1895 to 1960 but
from 1961 to 1999, there was statistically significant increase in winter, summer and annual precipitation (Archer and Fowler, 2004).

The frequency of heavy rain events during the southwest monsoon has shown an increasing trend over certain parts of the country (Sinha Ray and Srivastava, 1999). On the other hand, a decreasing trend has been observed during winter, pre-monsoon and post-monsoon season.

Most of the rainfall studies are confined to the analysis of annual and seasonal series of trends for some individual gauge stations in the river basins. Singh et al. (2008) while studying the seasonal and annual trends of changes in rainfall, rainy days, heaviest rain and relative humidity over the last century for nine different river basins in northwest and central India have shown increasing trends both in annual rainfall and relative humidity. Seasonal analysis showed maximum increase in rainfall during post-monsoon, followed by pre-monsoon season. There were least variations in the monsoon rainfall during the last century and winter rainfall has shown a decreasing trend.

2. STUDY AREA

The Satluj River (Vedic name - Satudri and Sanskrit name - Shatadru), also known as the Langqên (Chinese) and Sutlej (Indian), is the principal and easternmost tributary of the Indus River system. The basin area falls in Lahaul & Spiti, Kinnaur, Shimla, Kullu, Mandi, Solan and Bilaspur districts of Himachal Pradesh. The geographical limits of area lie between 30°45′ N to 33°00′ N latitudes and 76°15′ E to 79°00′ E longitudes in the western Himalayas (Figure 1). The total catchment area of Satluj River, from origin to Bhakra dam, is about 56,875 km² (21,960 Sq. miles). The upper part of river basin is considerably wider than the lower one.

In Himachal Pradesh, Satluj Basin has catchment area of 20,398 Km² which is 30.7% of the total catchment area of river systems (SCST & E, 2006). Indian part of river up to Bhakra Dam is elongated in shape and covers the part of outer (Shiwalik range), middle (Dhauladhar range) and greater Himalayas (Zaskar range).

Satluj River originates from the southern slopes of Kailash Mountains i.e. from Rakas Lake, near the Mansarovar Lake as Longcchen Khabab River at an elevation of about 4,572 m (15,000 ft), above msl. Total length of river is approximately 1,448 km (320 Km in China, 758 Km in India and 370 Km in Pakistan). It enters India from East of Shipki La (altitude – 3,048 m, above msl) after traversing a length of about 320 km (200 miles) in the Tibetan province of Nari Khorsam, through a narrow gorge in the Kinnaur district of Himachal Pradesh and flows in southwesterly direction.

The river is supported by a number of mighty tributaries on either side. Main tributaries are Spiti, Baspa and Gambhar at Khab, Karchham and Kangri at an elevation of 2,600, 1,750 and 450 m above msl respectively. Near Rampur, it crosses the Dhauladhar range and then traverses through a series of successive Shiwalik ranges. Before leaving the Himachal Pradesh, it cuts a gorge in Naina Devi Dhar and mingles with the water of Govind Sagar Lake. It enters the plains of Punjab near Bhakra where Asia’s one of the highest gravity multipurpose dam (Capacity to generate electricity -1,325 MW and height - 740 ft/225.55 m) has been constructed. It finally drains into the main Indus River in Pakistan.
Figure 1. Schematic showing the study area map of Satluj River Basin up to Bhakra Dam, Himachal Pradesh.
Based on the amount of annual precipitation and the variation in temperature, the study area, from North to South, has been divided into three broad climatic zones (Figure 2). Each zone is characterised by its own peculiarities of climatic factors, geomorphic and topographic features (Gupta et al., 1994; Bartarya et al., 1996):

1. **Semi-arid to arid temperate zone (Cold desert)** - This zone lies in the upper Satluj Valley, upstream from Morang. Towards North of Morang, the cold desert conditions prevail which are characterised by very low monsoonal precipitation, high speed of cold winds and the precipitation generally occurs in the form of snowfall during winter season.

2. **Sub-humid to humid temperate zone** - This zone covers the middle Satluj Valley between the Wangtu and Morang. It is the transitional zone which receives low rainfall during the monsoon period and moderate to heavy snowfall in the higher reaches during winter.

3. **Wet temperate or Monsoonal zone** - It lies in the lower Satluj Valley downstream of Wangtu. This zone is under the great influence of monsoonal winds and receives heavy rainfall during rainy season from mid June to mid September.

![Figure 2](image_url)  
**Figure 2.** Longitudinal profile of Satluj River from Shipki La to Bhakra Dam. Three climatic zones are demarcated along with the major thrusts.

The fall of Satluj from its source to the plain areas is very uniform. A gross fall of 2,180 m is available in the river bed from Shipki La to Bhakra in a length of about 320 km (Figure 2). The altitude in the study area increases from West to East and South to North. Based on
broad climatic conditions, the Satluj River Basin has following four seasons: Winter (December to March), Pre-monsoon (April to June), Monsoon (July to September), Post-monsoon (October, November).

3. MATERIALS AND METHODS

For the considered study area, records of rainfall were subjected to trend analysis by Mann-Kendall and regression coefficient test. In order to determine the degree and rate of change in rainfall trends, long-term data sets are required. Burn and Elnur (2002) stated that a minimum record length of 25 years ensures validity of the trend results statistically. The present analytical study on the spatial and temporal trends is based on the available meteorological data from Bhakra Beas Management Board (BBMB), Nangal. The trends were identified by investigating the time series of different observation stations distributed over the Indian part of Satluj River Basin. Paucity of long term data restricts the study as length available was 27 years. Data was scarce especially in the upper catchment area because of inadequate hydro-meteorological networks in the high altitude regions with rugged terrain and poor accessibility.

In order to investigate trends in time series, observational records were prepared. The daily data were converted to monthly and then computed to seasonal and annual series. Annual precipitation (mm/yr) was calculated as sum of monthly values. The missing values in the data were computed by using average method. To bring uniformity and facilitate comparison between the annual and seasonal responses, yearly standardised precipitation indices (SPI) can be computed by subtracting the mean and dividing by the standard deviation of the rainfall data series. The SPI data series are then subjected to trend analysis by statistical techniques (Pant and Rupakumar, 1997; Shreshtha et al., 2000; Bhutiyan et al., 2008). These standardised time series data were then plotted against time and the linear trends observed were represented graphically. The linear trend values, represented by the slope of a simple least square regression line with time as independent variable gave the magnitude of rise or fall. Apart from annual, the changes were investigated for the four seasons: winter (December-March), pre-monsoon (April-June), monsoon (July-September) and post-monsoon (October-November).

The location (longitude and latitude) and altitude of rainfall gauge stations are shown in Table 1 and figure 3. The altitude of the meteorological stations varied from 481 to 3,756 m.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude and longitude</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rampur</td>
<td>31°27'15&quot; &amp; 77°38'40&quot;</td>
<td>1,302</td>
</tr>
<tr>
<td>Suni</td>
<td>31°14'15&quot; &amp; 77°06'30&quot;</td>
<td>843</td>
</tr>
<tr>
<td>Kasol</td>
<td>31°21'25&quot; &amp; 76°52'42&quot;</td>
<td>809</td>
</tr>
<tr>
<td>Bhakra</td>
<td>31°24'53&quot; &amp; 76°25'59&quot;</td>
<td>588</td>
</tr>
<tr>
<td>Namgia</td>
<td>31°48'11&quot; &amp; 78°38'34&quot;</td>
<td>3,083</td>
</tr>
<tr>
<td>Location</td>
<td>Latitude/Longitude</td>
<td>Distance (km)</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Rakchham</td>
<td>31° 23' 30&quot; &amp; 78° 21' 20&quot;</td>
<td>3,282</td>
</tr>
<tr>
<td>Kalpa</td>
<td>31° 32' 25&quot; &amp; 78° 15' 30&quot;</td>
<td>2,633</td>
</tr>
<tr>
<td>Kaza</td>
<td>32° 13' 30&quot; &amp; 78° 04' 20&quot;</td>
<td>3,756</td>
</tr>
<tr>
<td>Swarghat</td>
<td>31° 42' 23&quot; &amp; 76° 44' 58&quot;</td>
<td>1,314</td>
</tr>
<tr>
<td>Bilaspur</td>
<td>31° 20' 00&quot; &amp; 76° 45' 00&quot;</td>
<td>481</td>
</tr>
<tr>
<td>Kahu</td>
<td>31° 12' 13&quot; &amp; 76° 47' 15&quot;</td>
<td>651</td>
</tr>
<tr>
<td>Berthin</td>
<td>31° 28' 15&quot; &amp; 76° 37' 20&quot;</td>
<td>656</td>
</tr>
<tr>
<td>Naina Devi</td>
<td>31° 19' 10&quot; &amp; 76° 32' 16&quot;</td>
<td>739</td>
</tr>
<tr>
<td>Kuddi</td>
<td>31° 23' 23&quot; &amp; 76° 47' 25&quot;</td>
<td>659</td>
</tr>
<tr>
<td>Daslehra</td>
<td>31° 24' 00&quot; &amp; 76° 33' 00&quot;</td>
<td>801</td>
</tr>
</tbody>
</table>

**Figure 3.** Location of rainfall gauge stations in Satluj River Basin.
In order to investigate the trends, several statistical techniques are currently available. In the present study, trend analysis have been made by using both non-parametric (Mann-Kendall test) and parametric (linear regression analysis) procedures. Parametric tests assume that the random variable is normally distributed and homo-sedastic (homogeneous variance). Non-parametric tests make no assumption for probability distribution. The purpose of trend analysis is to determine if the values of a random variable generally increase (or decrease) over some period of time in statistical terms (Helsel and Hirsch, 1992).

3.1. Mann-Kendall test

The non-parametric tests are more suitable for non-normally distributed, censored data, including missing values which are frequently encountered in hydro-meteorological time series (Hirsch and Slack, 1984; Yue and Pilon, 2004). The Mann-Kendall trend test has therefore been widely used for testing trends in many natural time series that deviate significantly from the Normal distribution, such as temperature. The MK test was found to be an effective tool for identifying trends in hydrologic and other related variables, resistant to the effect of extreme values (Hirsch et al., 1982; Burn, 1994). This test has been applied to temperature, precipitation and stream flow data series (Yu et al., 1993; Douglas et al., 2000; Yue et al., 2003; Burn et al., 2004). The MK test applied in this study is a rank based method for evaluating the presence of trends in time series data, without specifying whether the trend is linear or nonlinear.

To identify the trends in the climatic variables with reference to climate change, the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) has been applied in hydro-meteorological data. Mann originally used this test and Kendall subsequently derived the test for statistical distribution. The co-variances between Mann-Kendall statistics were proposed by Dietz and Kileen (1981) and the test was extended in order to include seasonality (Hirsch and Slack, 1984). The test compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987). In the present study, test was applied to mean temperature for determining monotonic trends.

The MK test has two parameters i.e. significant level, indicates the trend’s strength and the slope magnitude, indicates the direction as well as magnitude of the trend. The data values are evaluated as an ordered time series. Each data value is compared to all subsequent data values. The initial value of the Mann-Kendall statistic, \( S \), is assumed to be 0 (e.g., no trend). If a data value from a later time period is higher than a data value from an earlier time period, \( S \) is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value sampled earlier, \( S \) is decremented by 1. The net result of all such increments and decrements yields the final value of \( S \). A very high positive value of \( S \) is an indicator of an increasing trend and a very low negative value indicates a decreasing trend. However, it is necessary to compute the probability associated with \( S \) and the sample size, \( n \), to statistically quantify the significance of the trend. So, the MK test considers only the relative values of all terms in the series \( X = \{x_1, x_2, \ldots, x_n\} \) to be analysed. The Mann-Kendall statistic \( S \) which is the sum of the differences between the data points is defined as (Salas, 1992)

\[
S = \sum_{t=1}^{N-1} \sum_{j=t+1}^{N} \text{sgn}(x_j - x_t)
\]
where: $x_i$ and $x_j$ are the sequential data values and $n$ is the number of data points. Let $x_j - x_i = \theta$.

The value of sign ($\theta$) is computed as

$$\text{sgn}(\theta) = \begin{cases} 
1 & \text{if } \theta > 1, \\
0 & \text{if } \theta = 1, \\
-1 & \text{if } \theta < 1.
\end{cases}$$

For large samples ($n > 10$), the test is conducted using a normal distribution (Helsel and Hirsch, 1992) with mean $E(S)$ and variance $\text{Var}(S)$. Kendall (1975) obtained the theoretical mean and variance of $S$ under the assumption of no trend as:

$$E(S) = 0$$

$$\text{Var}(S) = \frac{1}{18} \left( N(N - 1)(2N + 5) \right. - \left. \sum_{k=1}^{n} t_k(t_k - 1)(2t_k + 5) \right),$$

where $t_k$ is the extent of any given tie (number of $x$’s involved in a given tie), and $\sum t_k$ denotes the sum of the terms $t_k(t_k - 1)(2t_k + 5)$ which are evaluated and summed for each tie of the $t_k$ number in the data. The standard normal variable $Z$ is computed by:

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

Compute the probability associated with this normalised test statistic. The trend is said to be decreasing if $Z$ is negative and the computed probability is greater than the level of significance. If the q-value is less than or equal to the significance level then it is correct to reject the null hypothesis that a trend does not exist in the data set. The trend is said to be increasing if the $Z$ is positive and the computed probability is greater than the level of significance. If the computed probability is less than the level of significance, there is no trend. If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis $H_0$ of having no trend in the data series is rejected at $\alpha$ level of significance in a two-sided test. Thus, in a two-tailed test for trend, the null hypothesis, that there is no trend in the dataset, is either rejected or accepted depending on whether the calculated $Z$ statistics is more than or less than the critical value of
Z-statistics obtained from the normal distribution table at 5% significance level. Significance levels (p-values) for each trend test can be obtained as:

\[ p = 2[1 - \Phi|Z|] \]

where \( \Phi \) denotes the cumulative distribution function (cdf) of a standard normal variant.

3.2. Pre-Whitney

However, a basic assumption for the original Mann-Kendall test is that the data should be random and identically distributed which is seldom the case in natural time series. It has been long known (Cox and Stuart, 1955) that positive serial correlation among the observations would increase the chance of a significant answer even in the absence of a trend. The presence of serial correlation can complicate the identification of trends that a positive serial correlation can increase the expected number of false positive outcomes for MK test (Von Storch and Navarra, 1995). So, before applying the MK test, the data series was tested for serial correlation. In order to limit the influence of serial correlation, pre-whitening was proposed by Von Storch (1995). Bayazit and Önöz (2007) suggested that pre-whitening should be avoided when the test has a high power, the slope of trend is high, and the sample size is large (i.e., \( n \geq 50 \)).

In present study, Mann-Kendall test was used in conjunction with the widely used method of pre-whitening. If the lag -1 auto-correlation \( r_1 \) was found to be non-significant at 95% confidence level, then the MK test was applied directly to the original data series \( x_1, x_2, \ldots, x_t \). Otherwise, the test was applied to the pre-processed data series \( x_2 - r_1 x_1, x_3 - r_1 x_2, \ldots, x_t - r_1 x_{t-1} \) referred to as ‘pre-whitened’ (Von Storch and Navarra, 1995; Partal and Kahya, 2006). The pre-whitening removes serial correlation from the data by means of the following formula:

\[ X'_t = x_t - r_1 x_{t-1} \]

where \( x_t \) is the original time series value for time interval \( t \), \( X'_t \) is the pre-whitened time series value and \( r_1 \) is the lag -1 autocorrelation coefficient that can be expressed as:

\[ r_1 = \frac{1}{n-1} \sum_{t=1}^{n-1} [X_t - E(X_t)][X_{t+1} - E(X_{t+1})] \]

\[ \frac{1}{n} \sum_{t=1}^{n} [X_t - E(X_t)]^2 \]

where \( E(x_t) \) is the mean of the sample data. Von Storch and Navarra (1995) also demonstrated that pre-whitening operation is not necessary for \( r_1 \leq 0.1 \).

3.2.1. Regression

The changes in annual and seasonal rainfall were plotted against time and the trend was examined by fitting the linear regression line. Linear regression analysis indicates the
tendency rate (slope) using least squares at the 95% confidence level, indicates the mean temporal change of the studied variable. Positive values of the slope show increasing trends, while negative values indicate decreasing trends. The total change during the period under observation is obtained by multiplying the slope with the number of years (Tabari and Marofi, 2010; Tabari et al., 2010a, b). The parametric test considers the linear regression of the random variable $Y$ on $X$, expressed as:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

4. RESULTS AND DISCUSSION

The analysis of rainfall, annual as well as seasonal, of different observation sites in the basin showed a large variability in the trends and magnitudes. Figures (4-18) and Tables (2-3) show the results of trend analysis of rainfall in the winter, pre-monsoon, monsoon and post-monsoon seasons along with mean annual rainfall in the river basin, relatively for shorter time-span of about 27 years (1984-2010).

The Figure 4 indicates that the annual rainfall has shown decreasing but statistically insignificant trend with episodic fluctuations. Seasonal analysis shows that the increasing and decreasing trends were observed during pre-monsoon and monsoon respectively, but statistically insignificant.

As there was no rainfall during winter and negligible during post-monsoon, so no trend has been detected. The analysis shows decreasing trend with the exception of some periodic behaviour.

![A). Annual](image-url)
B). Winter

Linear trend

\[ y = 0.0141x - 0.1976 \]

\[ R^2 = 0.0125 \]

C). Pre-monsoon

Linear trend

\[ y = 0.0141x - 0.1976 \]

\[ R^2 = 0.0125 \]
Figure 4. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Kaza gauge station of Satluj River Basin.
The Figure 5 indicates that the annual rainfall has shown increasing trend which is statistically significant, with episodic fluctuations. Seasonal analysis shows that maximum increasing trend was observed during pre-monsoon, followed by winter and monsoon respectively which are statistically significant, while the post-monsoon has insignificantly decreasing trend. The analysis shows overall increasing trend in the rainfall pattern.
C). Pre-monsoon

\[ y = 0.058x - 0.823 \]
\[ R^2 = 0.218^* \]

D). Monsoon

\[ y = 0.047x - 0.661 \]
\[ R^2 = 0.140^* \]
**Figure 5.** Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Rakchham gauge station of Satluj River Basin (*Significant at 95% confidence level).
B). Winter

\[ y = -0.033x + 0.5457 \]
\[ R^2 = 0.0957 \]

C). Pre-monsoon

\[ y = -0.0323x + 0.4528 \]
\[ R^2 = 0.0659 \]
Figure 6. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Namgia gauge station of Satluj River Basin.
The Figure 6 indicates that the annual rainfall has shown decreasing trend but statistically insignificant, with episodic fluctuations. Seasonal analysis shows that maximum decreasing trend was observed during winter, followed by pre-monsoon and post-monsoon but all are statistically insignificant, while the monsoon has shown increasing trend which is statistically insignificant.

A). Annual

B). Winter
y = -0.0012x + 0.0169
R² = 0.9605

C). Pre-monsoon

y = 0.059x - 0.835
R² = 0.224*

D). Monsoon
Figure 7. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Kalpa gauge station of Satluj River (*Significant at 95% confidence level).

The Figure 7 indicates that the annual rainfall has shown increasing trend which is statistically insignificant with episodic fluctuations. The slightly decreasing trend was observed during winter and post-monsoon but statistically insignificant, while the pre-monsoon has shown no trend. The monsoon season has shown increasing trend which is statistically significant, having very high $r^2$ value.
B). Winter

\[ y = -0.0325x + 0.4065 \]
\[ R^2 = 0.0529 \]

C). Pre-monsoon

\[ y = -0.0089x + 0.1111 \]
\[ R^2 = 0.0039 \]
Figure 8. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Swarghat gauge station of Satluj River Basin (*Significant at 95% confidence level).
The Figure 8 indicates that the annual rainfall has shown decreasing trend which is statistically significant. Seasonal analysis shows that maximum decreasing trend was observed during monsoon, followed by winter, post-monsoon and pre-monsoon but all are statistically insignificant. The overall analysis shows decreasing trend with the exception of some periodic behaviour.
C). Pre-monsoon

\[ y = 0.0437x - 0.612 \]

\[ R^2 = 0.1203 \]

D). Monsoon

\[ y = 0.0431x - 0.6029 \]

\[ R^2 = 0.1168 \]
Figure 9. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Rampur gauge station of Satluj River Basin.

The Figure 9 indicates that the annual rainfall has shown increasing trend which is statistically insignificant with episodic fluctuations. The increasing trend was observed during pre-monsoon, followed by monsoon but statistically insignificant. The winter season has shown decreasing trend, followed by post-monsoon which are statistically insignificant.
B). Winter

\[ y = -0.0356x + 0.4979 \]
\[ R^2 = 0.0797 \]

C). Pre-monsoon

\[ y = 0.0281x - 0.3932 \]
\[ R^2 = 0.0497 \]
Figure 10. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Suni gauge station of Satluj River.
The Figure 10 indicates that the annual rainfall has shown increasing trend which is statistically insignificant with episodic fluctuations. The increasing trend was observed during pre-monsoon, followed by monsoon but statistically insignificant. The winter season displays a decreasing trend, followed by post-monsoon which are statistically insignificant.
C). Pre-monsoon

\[ y = 0.0162x - 0.2274 \]

\[ R^2 = 0.0166 \]

D). Monsoon

\[ y = -0.0081x + 0.1135 \]

\[ R^2 = 0.0041 \]
Figure 11. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Kasol gauge station of Satluj River.

The Figure 11 indicates that the annual rainfall has shown decreasing trend which is statistically insignificant. Seasonal analysis shows that maximum decreasing trend was observed during winter, followed by post-monsoon and monsoon but all are statistically insignificant. Although increasing trend was observed during pre-monsoon but statistically insignificant. The overall analysis shows decreasing trend with the exception of some periodic behaviour.
B). Winter

\[ y = -0.0299x + 0.3729 \]

\[ R^2 = 0.0502 \]

C). Pre-monsoon

\[ y = 0.0104x - 0.1488 \]

\[ R^2 = 0.0061 \]
Figure 12. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Daslehra gauge station of Satluj River Basin.
The Figure 12 indicates that the annual rainfall has shown decreasing trend which is statistically insignificant. Seasonal analysis shows that maximum decreasing trend was observed during winter, followed by monsoon and post-monsoon but all are statistically insignificant. Although increasing trend was observed during pre-monsoon but statistically insignificant. The overall analysis shows decreasing trend with the exception of some periodic behaviour.

A). Annual

B). Winter
C). Pre-monsoon

\[ y = 0.0084x - 0.1047 \]

\[ R^2 = 0.0035 \]

D). Monsoon

\[ y = 0.0258x - 0.3219 \]

\[ R^2 = 0.0332 \]
**Figure 13.** Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Naina Devi gauge station of Satluj River Basin (*Significant at 95% confidence level).

The Figure 13 indicates that the annual rainfall has shown increasing trend but statistically insignificant with episodic fluctuations. Seasonal analysis shows that maximum increasing trend was observed during winter which is statistically significant, followed by monsoon and pre-monsoon but statistically insignificant, while the post-monsoon season has no trend. The analysis shows overall increasing trend in the rainfall pattern.
B). Winter

\[ y = -0.048x + 0.684 \]

\[ R^2 = 0.150^* \]

C). Pre-monsoon

\[ y = -0.0013x + 0.0175 \]

\[ R^2 = 1E-04 \]
Figure 14. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Berthin gauge station of Satluj River Basin (*Significant at 95% confidence level).
The Figure 14 indicates that the annual rainfall has shown decreasing trend which is statistically insignificant. Seasonal analysis shows that maximum decreasing trend was observed during winter which is statistically significant, followed by post-monsoon and monsoon but statistically insignificant. Almost no trend was observed during pre-monsoon season. The overall analysis shows decreasing trend with the exception of some periodic behaviour.

A). Annual

\[ y = -0.062x + 0.874 \]
\[ R^2 = 0.245^* \]

B). Winter

\[ y = -0.048x + 0.679 \]
\[ R^2 = 0.148^* \]
C). Pre-monsoon

\[ y = -0.0286x + 0.4007 \]

\[ R^2 = 0.0516 \]

D). Monsoon

\[ y = -0.0448x + 0.6279 \]

\[ R^2 = 0.1267 \]
Figure 15. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Kuddi (Ali) gauge station of Satluj River (*Significant at 95% confidence level).

The Figure 15 indicates that the annual rainfall has shown decreasing trend which is statistically significant with some periodic behaviour. Seasonal analysis shows that maximum decreasing trend was observed during winter which is statistically significant, followed by monsoon, post-monsoon and pre-monsoon but all are statistically insignificant.
B). Winter

\[ y = -0.0335x + 0.4687 \]

\[ R^2 = 0.0706 \]

C). Pre-monsoon

\[ y = 0.0347x - 0.4859 \]

\[ R^2 = 0.0759 \]
Figure 16. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Kahu gauge station of Satluj River.
The Figure 16 indicates that the annual rainfall has shown decreasing trend which is statistically insignificant. Seasonal analysis shows that maximum decreasing trend was observed during winter, followed by post-monsoon and monsoon but all are statistically insignificant. Although increasing trend was observed during pre-monsoon but statistically insignificant. The overall analysis shows decreasing trend with the exception of some periodic behaviour.
C). Pre-monsoon

\[ y = -0.0001x - 0.0272 \]

\[ R^2 = 1 \times 10^{-6} \]

D). Monsoon

\[ y = 0.0064x - 0.147 \]

\[ R^2 = 0.0026 \]
Figure 17. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Bilaspur gauge station of Satluj River Basin.

The Figure 17 indicates that the annual rainfall has shown almost no trend with the exception of some episodic fluctuations. The figures also show slightly increasing and decreasing trends during monsoon and post-monsoon respectively but statistically insignificant. Almost no trend was observed during winter and pre-monsoon. The overall analysis shows no trend with the exception of some periodic behaviour.
B). Winter

\[ y = 0.0248x + 0.347 \quad R^2 = 0.0387 \]

C). Pre-monsoon

\[ y = 0.0083x - 0.1161 \quad R^2 = 0.0043 \]
Figure 18. Temporal variations (annual as well as seasonal) and linear trends in total rainfall at Bhakra gauge station of Satluj River.
The Figure 18 indicates that the annual rainfall has followed a decreasing trend which is statistically insignificant. Seasonal analysis shows that maximum decreasing trend was observed during monsoon, followed by winter and post-monsoon but all are statistically insignificant. Although slightly increasing but statistically insignificant trend was observed during pre-monsoon. The overall analysis shows decreasing trend with the exception of some episodic fluctuations.

Table 2. Results of trend analysis of rainfall in Satluj River Basin.

<table>
<thead>
<tr>
<th>S. No. Station</th>
<th>Mann-Kendall A</th>
<th>Mann-Kendall ( S_1 )</th>
<th>Mann-Kendall ( S_2 )</th>
<th>Mann-Kendall ( S_3 )</th>
<th>Mann-Kendall ( S_4 )</th>
<th>Linear regression A</th>
<th>Linear regression ( S_1 )</th>
<th>Linear regression ( S_2 )</th>
<th>Linear regression ( S_3 )</th>
<th>Linear regression ( S_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kaza</td>
<td>(-.70)</td>
<td>+(.62)</td>
<td>(-.50)</td>
<td>+(.95)</td>
<td>(-.56)</td>
<td>--</td>
<td>+(.57)</td>
<td>--</td>
<td>--</td>
<td>+(.90)</td>
</tr>
<tr>
<td>2. Rakchham</td>
<td>+(.00)*</td>
<td>+(.01)*</td>
<td>+(.04)*</td>
<td>+(.04)*</td>
<td>+(.93)</td>
<td>+(.00)*</td>
<td>+(.02)*</td>
<td>+(.01)*</td>
<td>+(.05)*</td>
<td>-(.79)</td>
</tr>
<tr>
<td>3. Namgia</td>
<td>-(.51)</td>
<td>-(.29)</td>
<td>-(.50)</td>
<td>+(.36)</td>
<td>-(.100)</td>
<td>-(.36)</td>
<td>-(.12)</td>
<td>-(.20)</td>
<td>+(.43)</td>
<td>-(.67)</td>
</tr>
<tr>
<td>4. Kalpa</td>
<td>+(.68)</td>
<td>-(.57)</td>
<td>-(.90)</td>
<td>+(.03)*</td>
<td>-(.80)</td>
<td>+(.47)</td>
<td>-(.24)</td>
<td>-(.96)</td>
<td>+(.01)*</td>
<td>-(.43)</td>
</tr>
<tr>
<td>5. Swarghat</td>
<td>-(.05)*</td>
<td>-(.27)</td>
<td>-(.64)</td>
<td>-(.07)</td>
<td>-(.88)</td>
<td>-(.04)*</td>
<td>-(.28)</td>
<td>-(.77)</td>
<td>-(.06)</td>
<td>-(.42)</td>
</tr>
<tr>
<td>6. Rampur</td>
<td>+(.56)</td>
<td>-(.41)</td>
<td>+(.06)</td>
<td>+(.26)</td>
<td>-(.87)</td>
<td>+(.16)</td>
<td>-(.21)</td>
<td>+(.07)</td>
<td>+(.08)</td>
<td>-(.57)</td>
</tr>
<tr>
<td>7. Suni</td>
<td>+(.80)</td>
<td>-(.34)</td>
<td>+(.28)</td>
<td>+(.25)</td>
<td>-(.68)</td>
<td>+(.57)</td>
<td>-(.15)</td>
<td>+(.26)</td>
<td>+(.44)</td>
<td>-(.65)</td>
</tr>
<tr>
<td>8. Kasol</td>
<td>-(.31)</td>
<td>-(.07)</td>
<td>+(.41)</td>
<td>-(.87)</td>
<td>-(.80)</td>
<td>-(.39)</td>
<td>-(.09)</td>
<td>+(.52)</td>
<td>-.75</td>
<td>-(.23)</td>
</tr>
<tr>
<td>9. Daslehra</td>
<td>-(.32)</td>
<td>-(.30)</td>
<td>+(.98)</td>
<td>-(.39)</td>
<td>-(.27)</td>
<td>-(.28)</td>
<td>-(.29)</td>
<td>+(.71)</td>
<td>-(.36)</td>
<td>-(.41)</td>
</tr>
<tr>
<td>10. Naina Devi</td>
<td>+(.12)</td>
<td>+(.04)*</td>
<td>+(.84)</td>
<td>+(.71)</td>
<td>-(.88)</td>
<td>+(.17)</td>
<td>+(.03)*</td>
<td>+(.78)</td>
<td>+(.39)</td>
<td>-(.90)</td>
</tr>
<tr>
<td>11. Berthin</td>
<td>-(.10)</td>
<td>-(.05)*</td>
<td>-(.98)</td>
<td>-(.46)</td>
<td>-(.60)</td>
<td>-(.06)</td>
<td>-(.04)*</td>
<td>-(.96)</td>
<td>-(.27)</td>
<td>-(.25)</td>
</tr>
<tr>
<td>12. Kuddi</td>
<td>-(.01)*</td>
<td>-(.03)*</td>
<td>-(.41)</td>
<td>-(.17)</td>
<td>-(.87)</td>
<td>-(.01)*</td>
<td>-(.05)*</td>
<td>-(.25)</td>
<td>-(.07)</td>
<td>-(.21)</td>
</tr>
<tr>
<td>13. Kahu</td>
<td>-(.46)</td>
<td>-(.19)</td>
<td>+(.26)</td>
<td>-(.54)</td>
<td>-(.98)</td>
<td>-(.53)</td>
<td>-(.18)</td>
<td>+(.16)</td>
<td>-(.49)</td>
<td>-(.37)</td>
</tr>
<tr>
<td>14. Bilaspur</td>
<td>+(.100)</td>
<td>-(.71)</td>
<td>-(.97)</td>
<td>+(.97)</td>
<td>-(.34)</td>
<td>+(.92)</td>
<td>-(.97)</td>
<td>-.99</td>
<td>+(.80)</td>
<td>-(.72)</td>
</tr>
<tr>
<td>15. Bhakra</td>
<td>-(.10)</td>
<td>-(.51)</td>
<td>+(.56)</td>
<td>-(.11)</td>
<td>-(.55)</td>
<td>-(.09)</td>
<td>-(.32)</td>
<td>+(.74)</td>
<td>-(.07)</td>
<td>-(.39)</td>
</tr>
</tbody>
</table>

*S: Significance at 95% confidence level. (+) increasing, (-) decreasing. A: Annual, S1: Winter; S2: Pre-monsoon; S3: Monsoon; S4: Post-monsoon

The trend analysis results (Table 2) of rainfall through non-parametric Mann-Kendall and parametric linear regression tests indicate that the annual rainfall at Rakchham, Kalpa, Rampur, Suni, Naina Devi and Bilaspur shows increasing but Kaza, Namgia, Swarghat, Kasol, Daslehra, Berthin, Kuddi, Kahu and Bhakra show decreasing trends. Out of them, only Rakchham is statistically significant (increasing) and Swarghat and Kuddi are statistically significant (decreasing) at 95% confidence level. During winter, Rakchham and Naina Devi display increasing trends which are statistically significant.

Kalpa, Namgia, Swarghat, Rampur, Suni, Kasol, Bilaspur, Daslehra, Berthin, Kuddi, Kahu and Bhakra show decreasing trends where only Berthin and Kuddi are statistically significant. During pre-monsoon, Kaza, Rakchham, Rampur, Suni, Kasol, Daslehra, Naina Devi, Kahu and Bhakra show increasing where only Rakchham shows statistically significant trend. But Namgia, Kalpa, Swarghat, Berthin, Kuddi and Bilaspur show statistically
insignificant decreasing trends. During monsoon, Rakchham, Namgia, Kalpa, Rampur, Suni, Naina Devi and Bilaspur show increasing where only Rakchham and Kalpa show statistically significant trends. But Kaza, Swarghat, Kasol, Daslehra, Berthin, Kuddi, Kahu and Bhakra has shown statistically insignificant decreasing trends. During post-monsoon, only Kaza shows increasing and statistically insignificant trend. Rakchham, Namgia, Kalpa, Rampur, Suni, Swarghat, Kasol, Naina Devi, Bilaspur, Daslehra, Berthin, Kuddi, Kahu and Bhakra show decreasing trends which are statistically insignificant.

Table 3. Trend test results of rainfall.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>No. of trends</th>
<th>No. of increasing trends (significant)</th>
<th>% (sign)</th>
<th>No. of decreasing trends (significant)</th>
<th>% (sign)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>15</td>
<td>6(1)</td>
<td>40(6.6)</td>
<td>9(2)</td>
<td>60(13.3)</td>
</tr>
<tr>
<td>Winter</td>
<td>15</td>
<td>2(2)</td>
<td>13.3(13.3)</td>
<td>13(2)</td>
<td>86.6(13.3)</td>
</tr>
<tr>
<td>Pre-monsoon</td>
<td>15</td>
<td>9(1)</td>
<td>60(6.6)</td>
<td>6(0)</td>
<td>40(0)</td>
</tr>
<tr>
<td>Monsoon</td>
<td>15</td>
<td>7(2)</td>
<td>46.6(13.3)</td>
<td>8(0)</td>
<td>53.9(0)</td>
</tr>
<tr>
<td>Post-monsoon</td>
<td>15</td>
<td>1(0)</td>
<td>6.6(0)</td>
<td>14(0)</td>
<td>73.3(0)</td>
</tr>
</tbody>
</table>

# Significance at 95% confidence level.

Trend analysis results of rainfall (Table 3) show that out of 15 annual trends 6 (40%) are increasing and 9 (60%) are decreasing in nature where 1 (6.6%) is statistically significant (increasing) and 2 (13.3%) are statistically significant (decreasing) at 95% confidence level. During winter, 2 (13.3%) are showing statistically significant increasing trend but 13 (86.6%) are showing decreasing trends where 2 (13.3%) are statistically significant. During pre-monsoon, 9 (60%) are increasing but 6 (40%) are decreasing in nature where only 1 (6.6%) is statistically significant (increasing). During monsoon, 7 (46.6%) are showing increasing where 2 (13.3%) are statistically significant. But 8 (53.9%) are showing decreasing trends where all are statistically significant at 95% confidence level. During post-monsoon, only 1 (6.6%) is increasing but statistically significant. 14 (73.3%) are decreasing in nature where none is statistically significant.

The results indicate remarkable differences among the observation stations with negative and positive trends. The trends found by the linear regression were almost similar to Mann-Kendall test. The analysis shows mixed patterns of change where only few data series has significant trends. The rainfall at some gauge stations showed statistically significant increasing trends at the 95% confidence levels. The analysis indicates episodic fluctuations in rainfall pattern which may have been caused due to changing climatic conditions. The uneven distribution of rain, its intensity and periodicity, shows the irregular pattern at various locations. The analysis shows that the study area reveals significant increasing/decreasing trends in rainfall, at 95% confidence level, appear to have a response to climate change. The analysis of annual as well as seasonal rainfall for the Satluj River Basin indicates significant changes from 1984 to 2010. There is a clear contrast in the rainfall pattern between the high and low altitude mountainous region where the orographic effect plays a significant role.

Shifts in climatic regimes, particularly precipitation, in space and time, would impact heavily on the river systems originating in mountain areas (Beniston et al., 1997) like Satluj
River Basin. The sensitivity of rainfall variations provides important insight regarding the responses and vulnerability of such mountainous areas to the vagaries of climate change. Due to climate change, the rainfall patterns are changing. The monsoons penetrating deeper into the cold deserts in Satluj River Basin have become a matter of concern. Shifts of precipitation in the form of rainfall towards upstream could have major environmental consequences. The influence of climate change on hydrologic processes, especially in mountain basins is paramount for understanding, forecasting and mitigating water related hazards. The impacts of climatic change in the form of irregular precipitation and increased intensity and frequency of the flooding events, likely became obstacles to the sustainable development of a life-sustaining system.

5. CONCLUSIONS

Trend analysis of historical data concluded that the spatial and temporal variations in rainfall pattern are due to climate change. The rainfall in the basin shows great temporal and spatial variations, unequal seasonal and geographical distribution with frequent departures from normal. The monsoons penetrating deeper into the cold deserts in Satluj River Basin have become a matter of concern. It is predicted that the glaciers will receive more precipitation in the form of rainfall rather than snowfall. Shifts of precipitation in the form of rainfall towards upstream could have major environmental consequences. Information from trend analysis will be useful in the planning, development and management of water resources in the study area. Densification of rainfall gauge stations will further strengthen the formulation of future strategy for the management of river catchment area.

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References


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