Extreme rainfall signatures under changing climate in semi-arid northern highlands of Ethiopia

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Gebremedhin Kiros1,2,3*, Amba Shetty1 and Lakshman Nandagiri1

Abstract: Statistical analysis of continuous daily climate data and extensive weather records are important to evaluate possible long-term, hydrologic/climatic changes at local and regional scales. In the present study, daily rainfall data recorded in the period 1971–2013 (43 years) at seven meteorological stations distributed in the Geba River basin, northern Ethiopia were used to study trends in extreme rainfall indices at different temporal scales. The selected rainfall indices focus on intensity, frequency, and duration of extreme rainfall measures. The Mann–Kendall trend test results show that decreasing tendencies in the rainfall indices have predominantly observed in several stations, even though most of the stations did not show statistically significant trend over time at 95% significance level during the study period. In majority of the extreme rainfall indices, station Abiadi which is located at the downstream of the basin showed statistically significant increasing trend, while decreasing trend in very heavy rainfall days (R20mm) for Adigrat station, and consecutive dry days (CDD) and highest rainfall amount in one-day period (RX1day) for Mek’ele.

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PUBLIC INTEREST STATEMENT

Extreme rainfall events are meteorological threats that cause great destruction and many casualties in the biosphere. This paper examines the trends in extreme rainfall from seven daily time series in northern Highlands of Ethiopia. Rainfall data were converted into indices. In total, 12 indices were used for daily extreme rainfall. A Mann–Kendall non-parametric trend test for trend detection was used to evaluate the existence of monotonic trends in these rainfall data. Results showed that decreasing tendencies in the rainfall indices have predominantly detected in several stations, though most of the stations did not show statistically significant trend over time at 95% significance level during the span of the study period. These results could enhance the implementation of adaptation systems to flood risk.
showed statistically significant at the 95% level of significance. Results of this study contribute to climate change research in the region and provide inputs for better planning toward adapting to changing climate.

Subjects: Climatology; Meteorology; Earth Systems Science; Surface Hydrology; Environmental Studies; Environmental Change & Pollution; Statistics

Keywords: climate change; Geba catchment; Mann–Kendall; northern Ethiopia; rainfall indices; trend analysis

1. Introduction

The changes at local, regional, and global rainfall have been experienced throughout at different time scales over the past decades, which are expected to result from changes in climate and variability. Particularly, as a result of the predicted impact on the public and ecosystems, changes in extreme rainfall are of major concern; an extreme weather or climate occurrence is usually defined as that have extreme values of certain important meteorological variables above (or below) a given pre-existing high thresholds near the upper (or lower) climaxes of the range of detected standards of the variable (IPCC, 2012). In fact, climatic variability can be described as the annual differences in values of particular climatic variables where large areas of the earth represent inconsistency. As part of their normal climate over both limited duration and long-lasting periods and climate projections recommend that inconsistency is likely to increase extreme weather events in the future and might become more frequent in sub-Saharan Africa (Cooper et al., 2008; Field, 2012; Omondi, Awange, Forootan, Ogallo, & Barakiza, 2013). However, climate change and projections are dispiriting, challenging, and complex to understand at different levels as the impacts, risks, and uncertainty with the science about the subject. At present, perhaps this is true that in the entire science of meteorology and climatology the subject of change in climate is one of the most debatable scenarios (Kalumba et al., 2013). Rainfall is the principal element of weather systems, so that examination of monthly, annual, and seasonal trend analyses of historical climatic parameter and its behavior is significant for thoughtful the climate variability. It is also crucial as baseline for the impact assessment of climate changes on water resources and natural behavior of ecosystem as a whole in semi-arid environment because rainfall is highly variable spatially across the globe using various statistical procedures (Opiyo, Nyangito, Wasonga, & Omendi, 2014; Wagesho, Goel, & Jain, 2013).

At the global scale several studies have conducted for the indices of extreme rainfall and have reported consistently increasing trends, nevertheless the findings may differ at local and regional level. Unpredicted differences in rainfall characteristics and changes over small distances cannot be ignored, regardless of general trends, relevant generating mechanisms, the local rainfall arrangement, and other specificities. Some examples of these studies are the following: for global scale, Frich et al. (2002), Alexander et al. (2006) and IPCC (2007) for the western Indian Ocean countries, Vincent et al. (2011), Wang, Chen, and Chen (2013), Zhai, Zhang, Wan, and Pan (2005) and Jiang, Hu, Wang, Zhang, and Tong (2013) for China; Alexander et al. (2007) for Australia; Aguilar et al. (2005) for Central America and northern South America; Zhang et al. (2010) for Canada; New et al. (2006) for southern and western Africa; Klein Tank et al. (2006) for Central and southern Asia; at the European level, Moberg and Jones (2005), Moberg, Jones, Lister, and Walther (2006) and Karagiannidis, Karacostas, Maheras, and Makrogiannis (2012), Xoplaki, González-Rouco, Luterbacher, and Wanner (2004), Norrant and Dougoudroit (2006) for the Mediterranean region; Van den Besselaar, Klein Tank, and Buishand (2012) and García-Barrón, Morales, and Sousa (2013) for mainland Portugal. Across eastern Africa region, there are climatic trends studied previously (Moyo et al., 2012; Mwangi & Desanker, 2007; Opiyo et al., 2014; Schreck & Semazzi, 2004; Wagesho et al., 2013) revealed that within the arid and semi-arid environments there has been high inter-annual rainfall variations in the region. Over the past decades, Deressa, Hassan, and Ringler (2011) observed a complex rainfall pattern was characterized by irregular trends for the past 50 years in southern Ethiopia. On the other hand, Afewerki (2012) discovered except one station showed increasing trend while statistically insignificant all the stations showed deceasing trends in the mean annual rainfall
of analysis in the northern Ethiopia. Furthermore, Angassa and Oba (2007) revealed deceasing trends in the mean annual rainfall analysis at Borana in the southern Ethiopia.

In general there is a declining trend in most of the stations, though there is no statistically significant extreme rainfall trend have been identified for the Gebo River basin except one station Abiadi which showed statistically significant increasing trend for most of the extreme rainfall indices. Hence, the findings of this study are in agreement with some other studies that examined changes in rainfall in East Africa, where some studies found a slight existence of decreasing leaning in extreme rainfall indices; Seleshi and Zanke (2004), Seleshi and Demaree (1995). In contrast, they reported that over the northwestern and southern Ethiopia there was no recent trend in rainfall for the period 1965 to 2002. Bewket and Conway (2007) reported incongruous results in the annual and seasonal rainfall trends within the stations of the region while allowing for rainfall data of the Amhara Region (northwest Ethiopia). On the other hand, other studies did not show any substantial trend in the northern and northeastern part of the nation (Cheung, Senay, & Singh, 2008; Mezehausken, 2004; Seleshi & Camberlin, 2006). Therefore, in the arid and semi-arid environments it was concluded that variability in rainfall at different scales is seen as normal occurrence. Comparably, in the neighboring country Kenya, in the predominantly arid and semi-arid environments different studies suggest that there is slightly significant rainfall variation from year to year and these trends may continue with increasing the wet season and at the same time offsetting decrease in the drier months (Opiyo et al., 2014).

It is crucial to mitigate the adverse impact of change in climate and variation while understanding climatic trends and magnitude and would guide the community to make strategic, long-term decisions that affect their future wellbeing. The aim of this study is mainly to evaluate extreme daily rainfall signatures under changing the climate in semi-arid environments of the Gebo River Basin located in northern Ethiopia. The main objective of this study is detection and analysis of significant trends or fluctuations in historical extreme rainfall recorded at seven meteorological stations spanning the period 1971–2013 (43 years) within the basin using non-parametric Mann–Kendall statistical test approach.

2. Material and methods

2.1. Study area
The Gebo River basin, located in northern Ethiopia between 38°38′E and 39°48′E and 13°18′N and 14°15′N, is a major tributary of the Tekeze (the Sudanese called Atbara) River, which is the last tributary of the Nile (Figure 1). The basin is surrounded by the Danakil basin in the east, by the Tekeze River basin in the south and the Werie River basin in the west. The Gebo River originates from the Mugulat mountains near Adigrat in the north and the Atsbi horst in the northeast and flows south and then westward to join the River Tekeze on its way to Sudan (Zenebe et al., 2013). The basin has a total area of 5,137 km². The Gebo joins the Tekeze River at the confluence known as Chemoy. The elevation ranges from 920 m above mean sea level at Chemoy valley at the last outlet point where it joins the Tekeze River to 3,301 m above mean sea level at the Mugulat Mountains near Adigrat. Climatic conditions in the study area are quite diverse due to considerable differences in the altitude and relief. About 80% of the annual rainfall in the Gebo basin occurs in the Kiremt (rainy) season from June to September and 63% of the annual rainfall is the peak which is recorded in July and August. The mean temperature varies from a minimum average of 6.5°C in the Atsbi plateaus to a maximum average of 32°C at Agbe in the Avergele lowlands.

2.2. Data used
Daily rainfall data series for 18 stations in and around the Gebo basin were obtained from the Ethiopia National Meteorological Agency. Only seven stations were taken for analysis after quality control which is subjected to homogeneity test and these are Abiadi, Adigudem, Adigrat, Hawzien, Mek’ele, Senkata, and Wukro for the period of 1971–2013. Table 1 lists the climate stations used in
this study with their coordinates, elevations, observation period, and the observed mean rainfall values of the stations in the study area.

2.3. Extreme rainfall indices
A total of 12 extreme rainfall indices were selected in this study for examining the changes in the frequency, intensity, and quantity of extremes in total rainfall calculated from daily data in the Geba River basin. The definition and description of selected important indices is given in Table 2; the joint Commission for Climatology/World Climate Research program-Climate Variability and Predictability/Joint Commission for Oceanography and Marine Meteorology (CCl/WCRP-CLIVAR/JCOMM) Expert Team Climate Change Detection and Monitoring Indices (ETCCDMI) (Alexander et al., 2006; Peterson et al., 2001) were clearly put the definition for these indices and revised by Zhang et al. (2011). Here, the extreme indices were considered at monthly and annual scale for each discrete station in the study area.
2.4. The Mann–Kendall Trend Analysis

The main purpose of the Mann–Kendall (MK) test (Gilbert, 1987; Kendall, 1975; Mann, 1945) is to assess statistically whether there is a monotonic decreasing or increasing tendency of the variable of importance over time. A monotonic positive (negative) leaning indicates that the variable is consistently increasing (decreasing) through time; however the trend may or may not be linear. The Mann–Kendall test is a statistical test which is extensively applied for the analysis of trend in hydro-climatic time series (Yue & Wang, 2004). Hirsch, Slack, and Smith (1982) indicated that changes are noteworthy or of outsized magnitude and to measure these findings the Mann–Kendall test is best regarded as an examining analysis and is the most appropriately used to identify the status of the stations. The trend or the measurements be normally distributed is not a requirement, if exist, is linear. Though the performance of the test can be adversely affected, the Mann–Kendall test can be conducted if there are missing values and values lower than one or more limits of detection. The assumption of individuality necessitates that the period among samples be satisfactorily outsized so that there is no correlation between amounts collected at different periods.

The method for the Mann–Kendall test contemplates the time sequences of \( n \) data points and \( X_k \) and \( X_j \) as two subsets of data where \( k = 1, 2, 3, ..., n-1 \) and \( j = k + 1, k + 2, k + 3 ... n \). The recorded values as an ordered time series are assessed. Each records value is related with all succeeding data values. The statistic \( S \) is incremented by one, if a data value from a next time period is greater than a data value from previous time period. On the other hand, \( S \) is decremented by 1, if the data value from a next time period is lesser than a data value appraised previous. The collective result of all such increase and decrease yields the final value of \( S \) (Drapela & Drapelova, 2011).

Therefore, the Mann–Kendall \( S \) Statistic trend test for a time series is computed as follows:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign} (X_j - X_k)
\]  

(1)
where, \( X_j \) and \( X_k \) are the annual values in years \( j \) and \( k \), respectively (Motiee & McBean, 2009) as can be understood from the above equation. The test statistic be contingent not on their definite values occasioning in a spreading free test statistic rather on the ranks of the observations, because for any distribution, the ranks remain the same.

If \( n < 10 \), the value of \(|S|\) is related directly to the hypothetical scattering of \( S \) which is resulting by Mann–Kendall. The two tailed test is used at certain level of possibility. A null hypothesis is a statistical hypothesis and is the default or original hypothesis while an alternative hypothesis is any hypothesis other than the null. Hence, \( H_0 \) is rejected in favor of \( H_1 \) if the absolute value of \( S \) equals or exceeds a specified value \( Sa_{\alpha/2} \), where \( Sa_{\alpha/2} \) is the smallest \( S \) which has the probability less than \( \alpha/2 \) to appear in case of no trend. A positive (negative) value of \( S \) indicates an upward (downward) trend.

For \( n \geq 10 \), the statistic \( S \) is approximately normally distributed with the mean and variance as follows (Kendall, 1975):

\[
E(S) = 0
\]

\[
\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}
\]

Where \( n \) is the number of observations. The existence of tied ranks (equal observations) in the data results in a reduction of the variance \( \text{Var}(S) \) for the \( S \)-statistic is defined by:

\[
\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} tp(tp-1)(2tp+5)}{18}
\]

Where \( t_p \) is the number of ties for the \( p^{th} \) value and \( q \) is the number of tied values this means the summation term in the numerator is used only if the data series contains tied values. The standardized test statistic \( Z_s \) is calculated as follows (Motiee & McBean, 2009).

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

The test statistic \( Z_s \) is used a measure of significance of trend. In fact, this test statistic is used to test the null hypothesis, \( H_0 \). If \( |Z_s| \) is greater than \( Z_{\alpha/2} \), where \( \alpha \) represents the chosen significance level (e.g. 5% with \( Z_{0.025} = 1.96 \)) then the null hypothesis is invalid implying that the trend is significant.

The linear slopes where the magnitudes of trends are calculated using the Thiel–Sen Approach (TSA) (Sen, 1968; Thiel, 1950) which is defined in non-parametric statistics, there is a method for robustly fitting a line to a set of points that chooses the median of the slopes of all lines through pairs of two-dimensional sample points. The TSA slope \( \beta \) is given by:

\[
\beta = \text{median} \left[ \frac{X_j - X_k}{j-k} \right] \text{ for all } k < j
\]

Where, \( X_k \) and \( X_j \) are data at time point’s \( k \) and \( j \), respectively. If the total number of data points in the series is \( n \), then there will be \( \frac{n(n-1)}{2} \) slope estimates and the test statistic \( \beta \) Sen is the median of all slope estimates. Positive and negative sign of test statistics indicate increasing and decreasing trends, respectively.
To achieve the objectives of this study, a research methodology was formulated. This involved trend analysis of extreme rainfall indices in the Geba river basin. Figure 2 depicts the flow of tasks performed in the study.

For performing the statistical Mann–Kendall test software Addinsoft’s XLSTAT 2015 is applied. Rainfall data for the seven stations in the Geba River basin the null hypothesis is tested at 95% confidence level. Besides, to compare the results obtained from the Mann–Kendall test, linear trend lines are plotted for each station using Microsoft Excel.

3. Results and discussion

3.1. Seasonal patterns and mean spatial variability of rainfall

Rainfall is among the most important climatic component which is scattered very irregularly in the study area. The climate is considered by a large temporal and spatial variation. Rainfall can be as high as or greater than 945 mm per year in downstream locations and less than 300 mm per year in the mid and upper reaches of the basin. The mean annual rainfall estimates from the historical records indicate that the rainfall of the study area is 633 mm, however, the rainfall was not uniformly distributed over the estimated time period (1971–2013). Furthermore, the mean annual Kiremt (“main rains” season) rainfall is more than 80% of the annual rainfall with a peak in July and August where 70% of the total annual rainfall were documented in these peak months whereas remarkable contribution of the total annual rainfall has happened in the Belg (“small rains” season, March–May) 15%. Most of the areas receive less rainfall annually representing the presence of spatial variations in rainfall dependable with relief and elevation differences in addition to the late start of rainfall in June in the early end in September. Temporally, during the Kiremt season (“main rains” season, June–September); the upper stream parts of the study area obtain less rainfall as compared to the downstream. Climatologically, drought shows the insufficiency of rainfall compared to usual rainfall in a specified region and the main effect of drought is felt in semi-arid regions where the manifestation of drought years is fairly higher.

Ethiopian rainfall is considered by high inter-annual inconsistency as the rainfall in the tropical semi-arid and arid areas exhibit such variability. The annual rainfall CV of the station in the Geba
River basin ranging from relatively a minimum of 23.52% to a maximum of 47.3% this represents that the variability in rainfall totals among the rainfall gage stations is very high. While considering the analysis of variability of Kiremt season rainfall, which is directly distressing agricultural production in most portions of the country, all of the seven stations showed evidence of a CV above 25% (Table 3). The Kiremt season which is the long rains (June to September) produce 508.65 mm more than (80%) and the Belg season where the short rains (March–May) bring about 95.27 mm (15%) of the total annual rainfall in the study area. Therefore, about 96% of the total annual rainfall of the Geba River basin occurs in the Kiremt and Belg seasons. The coefficient of variation for the analysis of rainfall for the rainy (Kiremt) and small rains (Belg) seasons rainfall over the stations of the Geba River basin is highly variable ranging from 29.34 to 62.81% and 59.81 to 135%, respectively, this further indicated that the mean CV of the extended rainfall season is found to be 46%, which is lesser than that of the short rainfall season, CV = 96%.

Generally, the Belg (March–May) and the Bega (dry season: October–February) rainfall is much more inconsistent than the Kiremt rainfall. This study corroborates and could be compared to conclusions made by similar studies (Bewket & Conway, 2007; Mersha, 1999). These studies analyzed variability of rainfall data from 12 stations of Amhara region of Ethiopia. Mersha (1999, 2003) also reported that in areas of low annual rainfall there is higher variability in rainfall. The Kiremt rainfall contribution to the annual total of the study area ranges from 69.81% in Senkata in the upper part of the River basin to just about 90.6% in Adigudem in the middle part of the catchment (Table 2). The contribution of the Belg rainfall is significant to the annual total in the upper stream stations of Adigrat, Hawzien, and Senkata. Because of the southeasterly winds from the Indian Ocean blustering in the direction of a thermal low (cyclone) which progresses in the southern part of Sudan in the course of the Belg season these stations record rainfall during the Belg season (Seleshi & Camberlin, 2006; Seleshi & Zanke, 2004).

In a given region, the deviancy of the rainfall from the standard or normal rainfall indicated that there is meteorological drought. In semi-arid regions, the occurrence of drought years is comparatively high compared to the other climatic regions where the major impact of drought is experiencing (Bewket & Conway, 2007). Consequently, within this circumstance the temporal and inter-annual variations of annual rainfall in the Geba River basin were analyzed in terms of the standardized rainfall anomaly. The standardized rainfall anomalies were calculated as follows:

$$SRA = \frac{(P_t - P_m)}{\sigma}$$  \hspace{1cm} (8)

Where SRA is standardized rainfall anomaly, $P_t$ is annual rainfall in year $t$, $P_m$ is long-term mean annual rainfall over a period of observation and $\sigma$ is standard deviation of annual rainfall over the period of observation.

### Table 3. Annual and seasonal rainfall (mm) and their coefficient of variation (CV), and the average contribution of these seasons (in percent) and the highest monthly rainfall (mm) estimated over the period 1971–2013

<table>
<thead>
<tr>
<th>Stations name</th>
<th>Annual Mean</th>
<th>CV (%)</th>
<th>Kiremt Mean</th>
<th>CV (%)</th>
<th>Average contribution (%)</th>
<th>Bega Mean</th>
<th>CV (%)</th>
<th>Average contribution (%)</th>
<th>Belg Mean</th>
<th>CV (%)</th>
<th>Average contribution (%)</th>
<th>Highest monthly rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abiadi</td>
<td>879.86</td>
<td>41.57</td>
<td>799.96</td>
<td>45.67</td>
<td>88.49</td>
<td>36.72</td>
<td>163.75</td>
<td>4.17</td>
<td>64.56</td>
<td>100.93</td>
<td>7.34</td>
<td>323.21</td>
</tr>
<tr>
<td>Adigudem</td>
<td>513.27</td>
<td>40.09</td>
<td>465.46</td>
<td>46.65</td>
<td>90.57</td>
<td>8.33</td>
<td>131.95</td>
<td>1.62</td>
<td>40.08</td>
<td>76.27</td>
<td>7.81</td>
<td>207.19</td>
</tr>
<tr>
<td>Adigrat</td>
<td>555.46</td>
<td>26.28</td>
<td>360.81</td>
<td>37.38</td>
<td>63.55</td>
<td>62.55</td>
<td>91.1</td>
<td>11.26</td>
<td>139.93</td>
<td>59.81</td>
<td>25.19</td>
<td>161.45</td>
</tr>
<tr>
<td>Hawzien</td>
<td>571.89</td>
<td>37.74</td>
<td>467.78</td>
<td>58.9</td>
<td>71.69</td>
<td>38.48</td>
<td>133.2</td>
<td>6.73</td>
<td>123.43</td>
<td>135.01</td>
<td>21.58</td>
<td>196.89</td>
</tr>
<tr>
<td>Mek’ele</td>
<td>573.25</td>
<td>23.52</td>
<td>459.13</td>
<td>29.34</td>
<td>80.93</td>
<td>20.02</td>
<td>109.16</td>
<td>3.49</td>
<td>89.34</td>
<td>71.97</td>
<td>15.58</td>
<td>196.07</td>
</tr>
<tr>
<td>Senkata</td>
<td>600.54</td>
<td>42.16</td>
<td>491.6</td>
<td>62.81</td>
<td>69.81</td>
<td>48.31</td>
<td>124.73</td>
<td>8.05</td>
<td>132.99</td>
<td>126.6</td>
<td>22.14</td>
<td>194.87</td>
</tr>
<tr>
<td>Wukra</td>
<td>614.27</td>
<td>47.3</td>
<td>515.79</td>
<td>42.96</td>
<td>83.58</td>
<td>24.34</td>
<td>176.94</td>
<td>3.96</td>
<td>76.55</td>
<td>103.64</td>
<td>12.46</td>
<td>220.06</td>
</tr>
</tbody>
</table>
The temporal analysis showed that the arrangement of rainfall in the study area revealed fairly often a very high variability over time and is highlighted with positive and negative anomalies (Figure 3). As a result, in statistical point of view years that are showed negative standardized rainfall anomalies could be represented as meteorological droughts years with respect to the long-term annual mean of rainfall, where a period of negative rainfall anomalies is viewed as drought condition and the rest of the other rainfall periods are described as normal years.

The standardized anomalies of annual rainfall at the seven stations are shown in Figure 4. From the total number of stations, the percentage of negative standardized anomalies varied from 46.5% (in Hawzien) to 60.5% (in Mek’ele and Senkata) for 1997–2013 span of time. Rainfall showed high variability, with no consistent positive and negative anomalies.

As shown in Figure 4 the computed annual mean rainfall and standardized anomalies within the year under consideration (1971–2013) over Geba River basin. Figure 4 shows the standardized rainfall deviations where 1973, 1974, 1989, 1990, 1993–1999, 2003, 2004, 2007, 2010–2012 are years with above average rainfall with 1995 showing the highest positive rainfall anomaly while the other years show rainfall below normal with 1986 showing the lowest negative rainfall deviation for Abiadi station. At Adigudem station, annual rainfall has shown positive anomalies for 1973, 1989–1996, 1998–2001, 2003, 2006, 2007, 2009, 2012 with 1998 revealed the highest positive anomaly while the other years show rainfall below normal with 1985 showing lowest negative rainfall deviation from the average. Annual rainfall showed negative anomaly for the years 1979–1990 for Adigrat station though there are years with a positive anomaly which have a tendency to be succeeded by another year with a positive anomaly as do years with negative anomalies with 1977 that showed the highest positive rainfall anomaly while 1989 showed the lowest negative rainfall deviation.


Generally, throughout the driest and wettest years of the long-term study period the annual rainfall have been 1.224 and 3.162 (for Abiadi), 1.403 and 3.213 (for Adigudem), 1.723 and 3.073 (for Adigrat), 2.076 and 3.161 (for Hawzien), 1.397 and 2.822 (for Mek’ele), 1.365 and 2.601 (for Senkata).
The standardized anomalies results obtained show a fluctuating rainfall pattern across the years over the Geba River basin which makes it hard to easily forecast rainfall trend for a future season.
The lower rainfall amounts in the meteorological drought years might have serious agricultural implications as most crops planted during this time have been adversely affected by this drought.

3.2. Observed trends and extreme rainfall indices

Information regarding the extreme rainfall indices, such as in terms of rainfall type, frequency, intensity and extremes, etc., is specified in the Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) (Alexander et al., 2006). The extreme rainfall indices can be categorized into two groups: one group calculates the frequency (number of cases) of the index exceeding or not exceeding its defined threshold (CDD, CWD, R10mm, R20mm and R25mm), while the second one measures the rainfall depth (mm) or intensity (mm per day) (RX1day, RX5day, PRCPOTOT, SDII, R90P, R95P and R99P). The partition of magnitude and frequency is expected that can give an additional insight into the often slight differences of the climatic regions across the northern highlands of Ethiopia. In addition, it is likely obvious that these indices are also important for the probable impact assessment of climate changes on semi-arid and arid activities related to agriculture, water resources, sustainable development, and other sectors.

The time series trend analyses results of 12 extreme rainfall indices estimated over the period of 1971–2013 are summarized in Tables 4 and 5. Table 4 shows the frequency (number of cases) of the index exceeding or not exceeding its defined threshold in rainfall indices calculated individually for the 7 station’s data and the corresponding statistically significant results at the 5% significance level and the Sen’s magnitude. In addition, Table 5 shows the trends in the rainfall depth (mm) or intensity (mm per day) of the extreme rainfall indices and their corresponding Sen’s magnitude.

3.2.1. Trends in the wet-day annual total rainfall (PRECTOT) and simple daily rainfall intensity (SDII) Indices

Generally any discussion on changes to extremes of rainfall begins with changes of PRCPOTOT index at local and regional levels. This is probably the most important parameter reflecting rainfall variations over the entire year which is one of twelve rainfall indices analyzed in this study. Positive trends in PRCPOTOT occurred on stations Abiadi, Adigrat and Wukro indicated by the Sen’s slope that ranged from 0.21 to 14.14 mm per year (Table 5). However, only one station Abiadi that showed statistically significant positive trend at a 5% significance level. The remaining four stations showed decreasing trends and none of the stations showed statistically significant rainfall totals in the 1971 to 2013 period which decreased on average 1.2 mm per year.

Further analysis indicated that one index that considers not only the total amount of rainfall throughout the year but also reflects a change in daily rainfall is the Simple Daily Intensity Index (SDII). This index combines the amount of annual rainfall totals and the number of days when rainfall (≥1 mm) actually occurs. The results for the SDII and PRCPOTOT indices show the considerable inter-annual variability where the lowest SDII rainfall index (<8.0 mm) occurred in different years (Table 4) for their respective stations which were the driest periods on record, and these incidences coincided temporally with the lowest PRCPOTOT of the rainfall indices (<500 mm).

<table>
<thead>
<tr>
<th>Stations</th>
<th>Occurrence of lowest SDII</th>
<th>Occurrence of highest SDII</th>
</tr>
</thead>
</table>
The stations with the highest values of SDII (>16 mm for Abiadi, >12 mm for Adigudem, >11 mm for Adigrat and Mek'ele, >13 mm for Hawzien and Wukro and >15 mm for Senkata) were also showed the highest PRCPTOT (>900 mm for Abiadi, Senkata and Wukro, and >700 mm for rest of the other stations) happened in the corresponding years. Most climate stations located in the Gebo River basin had experienced a decreasing trend for magnitude ranging from −0.02 to 0.05 mm per day per year except two stations (Abiadi and Adigrat which range from 0.14 to 0.21 per day per year) located in the downstream and upstream sections of the river basin, respectively and were statistically insignificant at 5% significance level. Only Abiadi station showed statistically significant increasing trend in the 1941–2007 period (Table 6). These results are relevant to the variation in rainfall based on the SDII index and have significant influence to the future reliability of water resources for the purpose of different activities, agricultural strengthening, and ecological sustainability and possibly increase of flood risk.

### 3.3. Changes in the extreme rainfall frequency indices

#### 3.3.1 Maximum length of indices for the dry and wet periods

Values of rainfall indices for R10mm, R20mm, R25mm, CDD and CWD are shown in Tables 5 and 6. A measure of change to drier conditions among the indices is the Consecutive Dry Days (CDD) index. Results of trend magnitudes (days per year) for stations with increasing for CWD and decreasing

<table>
<thead>
<tr>
<th>Stations</th>
<th>PRCPTOT</th>
<th>R10mm</th>
<th>R20mm</th>
<th>R25mm</th>
<th>CDD</th>
<th>CWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abiadi</td>
<td>0.001</td>
<td>14.14</td>
<td>0.001</td>
<td>1.28</td>
<td>0.038</td>
<td>0.20</td>
</tr>
<tr>
<td>Adigudem</td>
<td>0.875</td>
<td>−0.42</td>
<td>0.159</td>
<td>−0.14</td>
<td>0.893</td>
<td>0.00</td>
</tr>
<tr>
<td>Adigrat</td>
<td>0.942</td>
<td>0.219</td>
<td>0.695</td>
<td>0.00</td>
<td>0.043</td>
<td>−0.08</td>
</tr>
<tr>
<td>Hawzien</td>
<td>0.278</td>
<td>−2.35</td>
<td>0.896</td>
<td>0.00</td>
<td>0.261</td>
<td>−0.05</td>
</tr>
<tr>
<td>Mek’ele</td>
<td>0.594</td>
<td>−1.15</td>
<td>0.249</td>
<td>−0.08</td>
<td>0.643</td>
<td>0.00</td>
</tr>
<tr>
<td>Senkata</td>
<td>0.739</td>
<td>−0.82</td>
<td>0.291</td>
<td>−0.09</td>
<td>0.17</td>
<td>−0.08</td>
</tr>
<tr>
<td>Wukro</td>
<td>0.603</td>
<td>1.028</td>
<td>0.507</td>
<td>0.074</td>
<td>0.42</td>
<td>0.034</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stations</th>
<th>R90P</th>
<th>R95P</th>
<th>R99P</th>
<th>SDII</th>
<th>RX1day</th>
<th>RX5day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abiadi</td>
<td>0.004</td>
<td>3.481</td>
<td>0.020</td>
<td>2.29</td>
<td>0.126</td>
<td>0.35</td>
</tr>
<tr>
<td>Adigudem</td>
<td>1.00</td>
<td>0.046</td>
<td>0.950</td>
<td>0.03</td>
<td>0.771</td>
<td>0.037</td>
</tr>
<tr>
<td>Adigrat</td>
<td>0.603</td>
<td>0.369</td>
<td>0.868</td>
<td>0.075</td>
<td>0.367</td>
<td>0.12</td>
</tr>
<tr>
<td>Hawzien</td>
<td>0.429</td>
<td>−0.715</td>
<td>0.205</td>
<td>−0.71</td>
<td>0.515</td>
<td>−0.149</td>
</tr>
<tr>
<td>Mek’ele</td>
<td>0.901</td>
<td>0.176</td>
<td>0.884</td>
<td>−0.047</td>
<td>0.234</td>
<td>−0.195</td>
</tr>
<tr>
<td>Senkata</td>
<td>0.950</td>
<td>0.055</td>
<td>0.967</td>
<td>0.037</td>
<td>0.769</td>
<td>0.103</td>
</tr>
<tr>
<td>Wukro</td>
<td>0.708</td>
<td>0.378</td>
<td>0.917</td>
<td>−0.10</td>
<td>0.884</td>
<td>0.056</td>
</tr>
</tbody>
</table>

The results are relevant to the variation in rainfall based on the SDII index and have significant influence to the future reliability of water resources for the purpose of different activities, agricultural strengthening, and ecological sustainability and possibly increase of flood risk.
trends for CDD at $\alpha = 0.05$ significant level (Table 5). Decreasing trends of the CDD index was detected for Abiadi, Adigudem, Adigrat and Mek’ele stations examined in this study with a Sen’s slope ranged from $-0.09$ to $-0.9$ days per year contraindicating. Seleshi and Camberlin (2006) found no trend on the dry spell of extreme intensity. Out of 7 stations, two stations, Hawzien and Wukro showed positive trend and one station showed no trend at all. Although there is high variability in trends for all the stations only Mek’ele showed statistically significant positive trend indicating increase in CDD. If the CDD is a measure of dryness; whereas the CWD index, on the contrary, revealed the time-series variations that can direct to wetter conditions. CWD over the Geba River basin increased at stations Abiadi, Adigudem and Hawzien however, only one station Adigudem showed statistically significant trends in magnitude that ranged between 0.036 and 0.143 days per year (Table 5). Further analysis indicated that annual rainfall indices for CWD showed the lowest values ($<5$ mm) in 1971 for Wukro, 1971, 1980 and 1982 for Senkata, 1985 for Adigudem and Mek’ele, 1990 for Hawzien, 2001 for Abiadi and 2009 for Adigrat.

3.3.2. Daily rainfall of absolute threshold indices
Results of trend magnitudes days per year for stations with statistically significant changes to R10mm and R20mm at $\alpha = 0.05$ significant level are shown in (Table 5). The number of cases (annual count number of days) with daily rainfall equal to or exceeding the 10, 20 and 25 mm limits is the measure of persistence of intense rainfall, defined as the R10mm, R20mm and R25mm indices. The R10mm decreased in the stations Adigudem, Mek’ele, and Senkata with a trends magnitude ranging from $-0.08$ to $-0.14$ days per year, but the trend is not statistically significant. In addition, in stations Abiadi and Wukro the R10mm index showed increasing trends having a trends magnitude 0.6 and 0.074 days per year, respectively, however only Abiadi revealed statistically significant trend. Further analysis revealed that there are more stations with a significant change to R20mm than to R10mm and R25mm. Only two stations showed a significant change to R20mm with a mixture of decreasing and increasing trends, ranging from $-0.05$ to 0.308 days per year (Table 5). Over the Geba River basin stations Abiadi and Wukro showed positive trend however, only Abiadi showed statistically significant trend. There are three stations Adigrat, Hawzien, and Senkata which are located in the upstream of the catchment revealed a decreasing trend, but only Adigrat showed statistically significant trend at the 95% confidence level. This is consistent with the decreasing and increasing trends detected for the 25 mm index where three stations showed decreasing two stations showed increasing and two with no trend at all.

3.4. Changes in the extreme rainfall depth and intensity indices
3.4.1. Extreme rainfall Indices for 1-day and 5-day event durations
On the basis of results obtained for the RX1day index (Table 6); the monthly maximum one-day rainfall of four stations located in the Geba River basin decreased with the magnitudes of change ranging from $-0.001$ to $-0.013$ mm per year. Some positive changes were seen for stations Abiadi and Wukro. Abiadi station showed statistically significant increasing trend and also Mek’ele station showed decreasing statistically significant trends and one station showed no trend. The trend magnitudes for stations with increasing changes are ranging from 0.024 to 4.81x$^{-5}$ mm per year. For the RX5day index which corresponds to the maximum consecutive 5-day rainfall amount (a potential indicator of flood producing events), four out of the seven stations in the study area showed positive changes (Table 6) of which two stations showed statistically significant change. Three stations (Adigudem, Adigrat, and Mek’ele) also show negative change, but none of them showed statistically significant. The trend magnitude for stations showed decreasing trend ranged from $-0.02$ to $-0.037$ and increasing changes ranged from 0.012 to 0.202 mm per year.
3.4.2. The percentile threshold indices of daily rainfall events

The heavy rainfall that surpasses the 90th, 95th, and 99th percentile thresholds are measured by R90P, R95P, and R99P indices. For extreme rainfall measures that surpassed the R90P, R95P, and R99P thresholds generally showed increasing trends in most of the stations; however only Abiadi showed statistically significant positive trend at 5% significance level in the 1971–2013 period. The trend in the R99P index is positive and ranged from 0.037 to 0.35 mm per year in the 1971–2013 periods. The R95P index exhibited slight increase for all the stations (0.031 to 2.29 mm per year) for the 43 year data, while the contribution of the rainfall due to very wet days (above the 95th percentile) to the total rainfall varied between 101.46 and 167.65 mm. In these indices, only Abiadi showed statistically significant trend. The R90P index has a trend pattern similar to R95P, although more pronounced with an increase (0.046 to 3.481 mm per year). On average, the contribution of rainfall on wet days (above the 90th percentile) to the total annual rainfall varied between 160.24 and 262.42 mm in the in 1971–2013 period. Across all the indices, Hawzien stations showed a decreasing pattern with a trend magnitude of −0.715, −0.71, and −0.149 mm per year for R90P, R95P, and R99P, respectively (Table 5). Moreover, to help visualize the extent of spatial variations of selected indices, the station wise map of those indices were shown in the Figures 5–8.
Figure 6. Trends in 1971–2013 for the (a) 10 mm, (b) 20 mm, and (c) 25 mm.

Figure 7. Trends in 1971–2013 for (a) RX1day, (b) RX5day, and (c) SDII.
4. Conclusions

This study showed that there is substantial spatial variability in mean annual, seasonal, and trends of historical (1971–2013) rainfall recorded at seven stations in semi-arid areas of the Geba River basin, northern Ethiopia. Seasonal rainfall inconsistency is higher throughout Bega and Belg seasons in the most of the stations. In contrast, Kiremt rainfall variability which directly distresses agricultural production is less variable over stations in the study area. Investigation of a set of 12 extreme rainfall indices, resulting from daily data recorded at the meteorological stations scattered across the Geba River basin with possible changes to these indices were analyzed in the 1971–2013 period. Most of climate stations analyzed for Geba River basin showed decreasing trends in the number of CDD index. In contrast, increasing trends were detected for the number of CWD, but no trend was identified over majority of the climate stations analyzed in this study. In terms of PRCPTOP, the annual total rainfall during wet days, four stations showed a decreasing trend and three stations showed increasing trends. Furthermore, decreasing trends have been found in the extreme rainfall indices, R10mm and R20mm and R25mm, in most of the stations except Abiadi and Wukro, which respectively represent the number of days when rainfall equal or exceed 10 or 20 or 25 mm (R10mm/ R20mm/R25mm).

For the monthly maximum 1-day (RX1day) and 5-day (RX5day) rainfall index, a mix of decreasing (Adigudem, Adigrat, and Mek’ele) and increasing (Abiadi and Wukro) trends were detected in the stations of the River basin. The annual total rainfall when daily rainfall exceeds 90, 95, or 99% threshold index, R90P/R95P/R99P, an increasing trends seen in most of the stations and mostly positive trends were observed for R90P. However, decreasing trends were detected for R90P/R95P/R99P in Hawzien and Mek’ele stations. Like other indices, the rainfall intensity index, SDII, showed decreasing trends in stations Adigudem, Hawzien, Mek’ele, and Senkata however, increasing trends in Abiadi, Adigrat, and Wukro. Even though, there is an increase or decrease trend in the extreme rainfall trend test analysis, the majority of stations did not show statistically significant change over study period, except Abiadi station showed statistically significant increasing trend for most of the extreme rainfall indices (PRCPTOT, R10mm, R20mm, R25mm, R90P, R95P, R99P, SDII, RX1D, and...
RX5D) at the 95% confidence level. In general, the findings of this study are in agreement with other studies that examined changes in rainfall in East Africa. Thus, results of this study contribute to climate change research in the region and provide inputs for better planning toward adapting to changing climate. Further research is needed to obtain a better understanding of regional and seasonal changes of rainfall in relation to other climatic factors, especially temperature, and how such changes will potentially impact on water resources, agricultural productivity, and the environment in northern Ethiopia.

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Cover image
The Source of this image is ASTER Global Digital Elevation Model and downloaded the ASTER DEM data for free from the USGS Earth Explorer and clipped for the purpose of this study.

References


