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Rainfall and Temperature in the Limpopo River Basin, Southern Africa: Means, Variations, and Trends from 1979 to 2013

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Abstract: Understanding temporal and spatial characteristics of regional climate is essential for decision making in water resource management. Established statistical and GIS techniques were used to evaluate annual and seasonal variations of rainfall and temperature in time and space from 1979 to 2013 in the Limpopo River Basin (LRB). Annual means of rainfall in the LRB varied between 160 and 1109 mm, generally from west to east of the basin during the study period. Annual minimum and maximum temperature ranged from 8 °C in the south to 20 °C in the east of the basin, and 23 °C in the south of the basin to 32 °C in the east. The respective coefficients of variation (CVs) of these variables showed an inverse pattern to the annual values, with rainfall having high CV values (28% to 70% from east to west of the basin) compared to temperature CV values. Seasonal variations followed similar patterns as annual variations for the individual variables examined. Trend analysis showed upward trends for both annual and seasonal rainfall in most parts of the basin, except for the winter season which showed a decreasing trend. Analysis of minimum temperature on an annual basis and for the winter season and spring season shows upward trends during the study period over the whole basin while minimum temperature for summer and autumn showed decreasing trends. Maximum temperature, by contrast, showed decreasing trends on an annual, summer, autumn, and spring basis but an increasing trend for winter during the study period in most parts of the basin.

Keywords: statistical significance; trend analysis; watershed hydrology; water availability; semi-arid region

1. Introduction

Water is an important resource for the economic and social well-being of humankind [1,2]. In semi-arid regions such as the LRB, adequate water supply to support agriculture, industry, and domestic use is an enduring problem. Water scarcity in the LRB is the result of the basin's highly variable climate, typified by frequent extreme seasonality, intense El Niño-Southern Oscillation (ENSO) events, and interactions with oceanic climates from both Atlantic and Indian Oceans, that render rainfall and runoff unreliable in the basin [3–5]. The ENSO events have been linked to drought and flood events in Southern Africa [6,7]. For the past two decades, the LRB experienced some of the most damaging droughts [8–10]. For example, the 1991–1992 drought affected approximately 86 million people, of which 20 million were at serious risk of starvation [10]. The 2005−2006 drought damaged 72,500 hectares of cultivated cropland in Botswana, resulting in considerable economic losses.

While the LRB is recurrently associated with drought-related influences, flood risks and flood events are also major concerns, particularly in the lower LRB of Mozambique. Of the major floods that occurred in the past, flooding in 2000 and 2013 was the most noticeable. More than 500 deaths were reported for the 2000 flood event, two million people were displaced, more than 20,000 cattle drowned, and more than 1400 km^2 of farmland were inundated in Mozambique [10,11]. Subsequent economic losses for Botswana were estimated to be more than US $285 million [12]. The 2013 event caused approximately 50 deaths and displaced 150,000 in Mozambique [11].

Population growth, urbanization, industrial development, and increasing agricultural activities [13,14] continue to place pressure on water resources in the basin. Additional dams are continually built, and groundwater resources are intensively used when rivers and dams are dry [8], leading to chronic freshwater problems in the region. The effects of climate variability and change further add uncertainty to the freshwater availability problem. Research shows that climate change will lead to rises in temperature, evaporative demands, and changes in rainfall and runoff patterns in Southern African regions [15], resulting in increased frequency of flooding and drought as well as a reduction in groundwater recharge [5,16,17]. These patterns, however, are expected to vary throughout the region, including the LRB, which means different areas may experience different levels of water problems in the future. To effectively manage water resources in the LRB, it is important to understand past and present trends, variability, and characteristics of key factors such as climate that control freshwater availability. The study sought to document precipitation and temperature variations in time and space in the regional basin of Limpopo River as a major step toward increased understanding of regional water distribution for human and environmental needs.

2. Materials and Methods

2.1. Study Area

The Limpopo River is one of the longest rivers in southern Africa, with a drainage area of approximately 415,000 km^2. The basin is shared among four countries, namely, Botswana, Mozambique, South Africa and Zimbabwe, which contain 20%, 15%, 45%, and 20%, respectively, of the total drainage area of the basin. The Limpopo River Basin has 27 recognized major watersheds, of which four fall in Botswana, three in Mozambique, 12 in South Africa, three in Zimbabwe, and five are shared between at least two countries (Figure 1).

Nearly 17 million people live and work in the LRB. By 2040, the LRB's population is projected to be 23 million [9,18,19]. Agriculture is primarily rainfed despite the high variability of rainfall.

The climate of the LRB is influenced by prevailing dry continental tropical, equatorial convergence zone, moist maritime subtropical eastern, and marine western Mediterranean air masses [8]. These create an arid climate condition in the basin. Mean annual rainfall in the basin varies considerably, between 200 in the west of the basin and 1500 mm/year in the east, with the bulk of the basin receiving less than 500 mm/year. The rainy season is short, with 95% of the rainfall occurring between October and April. Annual rainy days seldom exceed 50 calendar days. Rainfall in the basin also varies significantly between years, causing frequent flood events during wet years and droughts during dry years. Monthly rainfall during wet years can reach 340 mm, from a minimum of 50 mm to a maximum of 100 mm for normal rainy months. Mean daily air temperature across the basin varies from 0 °C in winter to 36 °C in summer. Evaporation over the basin is 1970 mm/year on average, with a range of 800 to 2400 mm/year [8].

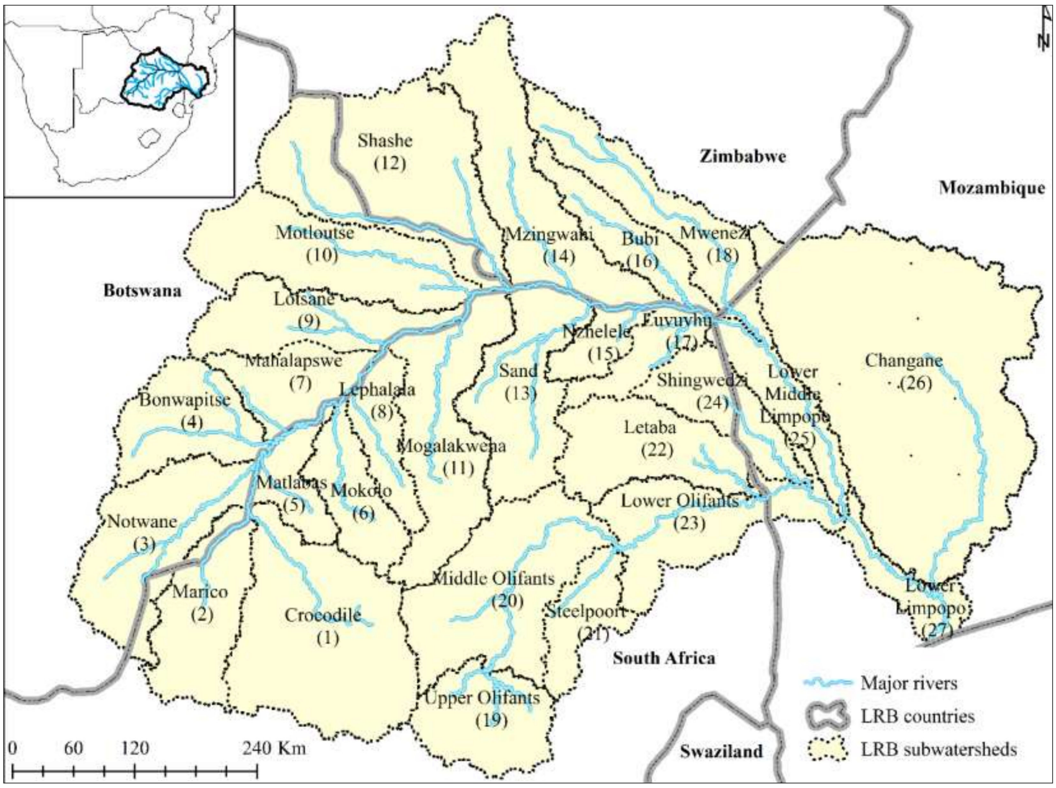

Figure 1. The Limpopo River Basin in Southern Africa and its twenty-seven designated subbasins, herein referred to as watersheds.

2.2. Data Used

Daily rainfall, and maximum and minimum temperature gridded data for 375 locations within the LRB were extracted for a period of 35 years (January 1979 to December 2013) from the Climate Forecast System Reanalysis (CFSR) global weather database (https://globalweather.tamu.edu/). The CFSR weather data were generated by using conventional meteorological gauge observations and satellite irradiances coupled with advanced modeling of atmosphere, ocean, and land surface systems at 38 km resolution [20]. Daily rainfall values were compiled into total annual rainfall time series while time series of mean annual temperature was used for the analysis. In order to maintain consistency among data sources for the analysis of precipitation and temperature variations in the basin, only CFSR data were used. Some researchers have used more than one reanalysis product to account for uncertainties associated with individual data [21–24]. Depending on regional elevation patterns, one product may capture more realistic variations in precipitation compared with other products [22–24].

2.3. Assessment of Variations in Rainfall and Temperature in the Limpopo River Basin

Daily rainfall, and daily minimum and maximum air temperature records we compiled into annual and seasonal means. Seasonal datasets were obtained by aggregating daily data into monthly values, which were summed to construct four southern hemisphere seasons, consisting of summer (December-January-February), Fall/Autumn (March-April-May), winter (June-July-August), and Spring (September-October-November). Coefficients of variation (CVs) (i.e., standard deviation over the mean, expressed in %) were also computed for annual and seasonal rainfall, and maximum and minimum air temperature. The long-term mean is used in this study because it has long been utilized by hydrologists, climatologists, and producers in Southern Africa to discuss natural calamities such as famine or flood [17]. CV has also been used frequently to characterize hydrological systems since it gives an indication of inter-annual or seasonal variability of hydroclimatic conditions of a region [17].

Contour maps were created with the calculated means and CVs to show spatial variations of long-term annual and seasonal rainfall and temperature across the LRB.

2.4. Trend Analysis of Rainfall and Temperature in the Limpopo River Basin

Temporal trends in annual and seasonal rainfall, and minimum and maximum temperature were determined using the modified non-parametric Mann-Kendall test (MK; [25,26]. Magnitudes of these trends were also estimated with the Theil-Sen slope estimator (TSE; [25,26]. The modified MK test is commonly used in long-term hydrological trend assessment studies owning to its robustness against inherent outliers, autocorrelation, and non-normal distribution of a dataset [25,26]. The test is very reliable for detecting monotonic trends in environmental time series data [25,26]. For a series X_1, X_2, X_3, ... Xn, the MK test statistic (S) is calculated as [27,28]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(Xj - Xi) \tag{1}$$

where X_i and X_j represent sequential datapoints in the data, n is the length of the dataset, and

$$\text{sgn}(\theta) = \begin{cases} 1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

where θ represents the difference between two sequential datapoints. The null hypothesis "H0" of no trend is rejected with a p-value less than the significance level or if the calculated Z-statistic is larger than the critical value of the Z-value obtained from the normal distribution table. The analysis conducted in this study used a 10% significance level. The variance of S is calculated as:

$$V(s) = \frac{n(n-1)(2n+5) - \sum_{\text{i}=1}^{\text{n}} t_i i(i-1)(2i+5)}{18} \tag{3}$$

The modified MK trend test statistic Z is given by:

$$Z = \left\{ \begin{array}{ll} \frac{S-1}{\sqrt{V(S)^*}} & for\ \text{S} > 0 \\ 0 & for\ S = 0 \\ \frac{S+1}{\sqrt{V(S)^*}} & for\ \text{S} < 0 \end{array} \right\} \tag{4}$$

where the sign of S gives the direction of the trend. A negative sign indicates a decreasing trend, and a positive value indicates an increasing trend. The modified variance of S denoted by $V(S)^*$ is computed as:

$$V(S)* = V(S)\frac{n}{n*} \tag{5}$$

and

$$\frac{n}{n*} = \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n} (n-i)(n-i-1)(n-i-2)ri \tag{6}$$

where ri is the lag-i significant autocorrelation coefficient of rank i in the time series dataset. The autocorrelation coefficient is calculated as:

$$rk = \frac{\frac{1}{n-k} \sum_{i=1}^{n-k} (X_i - \overline{X})(X_{i+k} - \overline{X})}{\frac{1}{n} \sum_{i=1}^{n} (X_i - \overline{X})^2} \tag{7}$$

Since the MK statistic (S) does not indicate the magnitude of the slope, the TSE was used to compute the magnitude of trend as follows [29,30]

$$\beta = median\left[\frac{X_j - X_i}{j - i}\right] for\ \mathrm{i}\ < \mathrm{j} \tag{8}$$

where β is the median for all possible combinations of pairs of any two datapoints in the entire time series dataset. X_i and X_j are the sequential datapoints, where $i < j$.

3. Results and Discussion

3.1. Long-Term Means of Rainfall and Temperature in the Limpopo River Basin

3.1.1. Rainfall

Mean annual rainfall over the LRB varied between a minimum of 160 mm in the west of the basin (Notwane, Lephalala, and parts of Lotsane and Motloutse watersheds) to a maximum of 1152 mm (ws 27: Lower Limpopo) in the east of the basin (Figures 1 and 2). From the 375 gridded locations analyzed for rainfall, 30% of the basin received less than 300 mm, 66% receives more than 300 mm and less than 500 mm while 4% received more than 500 mm/year. Coefficients of variation for annual rainfall calculated for the 1979−2013 period varied from 28% in Lower Limpopo (ws 27) in the east to 70% in the west of the basin. West watersheds include Notwane (ws 3), Bonwapitse (ws 4), Matlabas (ws 5), Mokolo (ws 5), Mahalapswe (ws 7), and Lephalala (ws 8) (Figures 1 and 3). High CVs were found in the western watersheds, including watersheds in Botswana and southwest of South Africa, classified as a semi-arid region compared to the temperate east part of the basin that includes the east of South Africa and Mozambique (Figure 3).

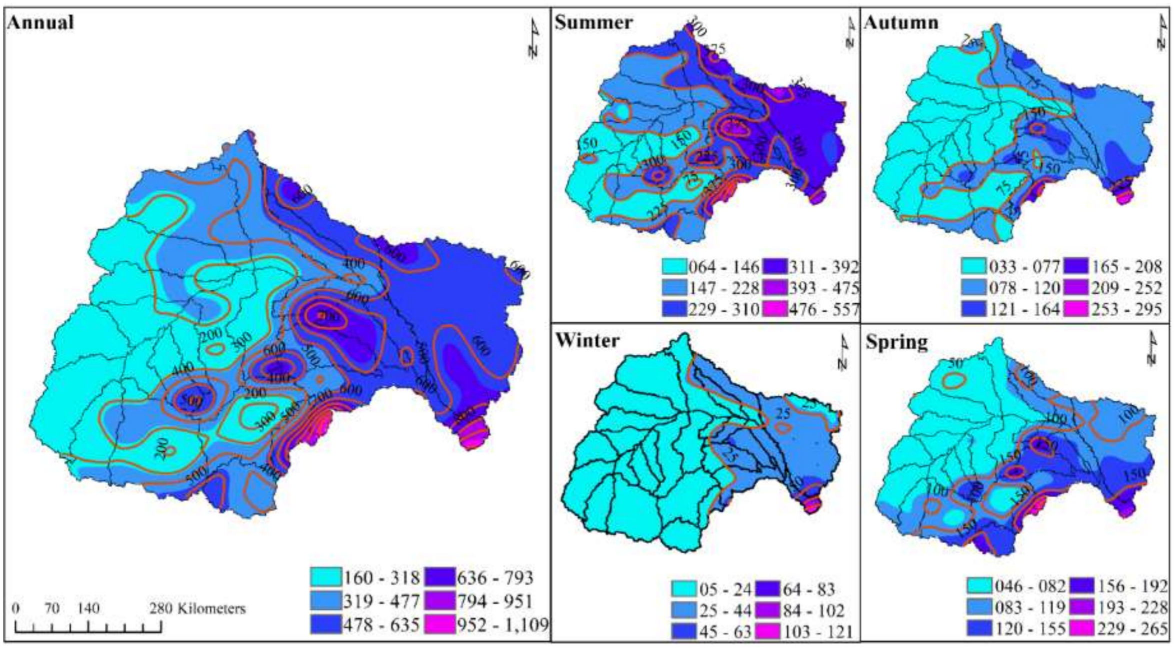

Figure 2. Mean annual and seasonal rainfall from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as Summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

Seasonal analysis showed that most of the basin's rainfall occurred in summer during the 35-year study period (Figure 2), with a range of 64 to 557 mm from west (ws 3−8) to east (ws 21: Steelpoort), while minimal rainfall occurred in winter, ranging from five mm in 15 of the watersheds in the west to 120 mm in Lower Limpopo (ws 27) in the east of the basin (Figures 1 and 2). Autumn and spring rainfall ranged between 33 and 295 mm, and between 46 and 265 mm, respectively (Figure 2). The CV values for the seasons revealed high variability comparable to annual CVs, especially for summer and spring seasons whose CVs ranged between 40% and 38% in the east of the basin, and 94 and 82% in the west, respectively (Figure 3). Autumn and winter CVs for the east are 44% and 37% (Figure 3), comparable to the annual CV values in the same region (east). Calculated CV values are very high in the west of the basin (128% and 221%, respectively) compared to annual CVs in the west. It appears, based on these results, that there was a high variability in autumn and winter rainfall in the west of the basin compared to the temperate east of the basin (Figure 3).

Other researchers also reported these east to west and north to south decreasing patterns in rainfall in the Southern Africa region, including the LRB [3,5,31]. Low rainfall in the west of the basin is likely the result of being far from rain forming processes such as the Inter-Tropical Convergence Zone (ITCZ) and southwest Indian Ocean cyclone that control the frequency and duration of incident rainfall events in the northern and eastern parts of the basin [31]. Migration of ITCZ to south of the equator during the Southern Hemisphere summer leads to abundant rainfall in areas north of the LRB (Figure 2) compared to the southern and western parts of the basin [31,32]. Low rainfall in the west of the basin in summer is exacerbated by the presence of a seasonal subtropical anticyclone, usually at 700 hPa, known as the Botswana Upper High Influence (BUHI) [33]. This influential atmospheric mechanism creates unfavorable conditions for rainfall by diverting the migration of rain-bearing ITCZ out of the region [32]. Although the south of the basin receives low rainfall amounts (Figure 2), pockets of high rainfall can be observed around the Drakensberg escarpment in South Africa due to orographic effects [16]. Orographic effects induce rainfall by forcing moist air to cool rapidly when passing over areas of high relief (e.g., Drakensberg mountains), causing moisture to precipitate in the form of rainfall on the windward side of the relief [34]. Winter rainfall in the east is mostly produced by cold fronts and associated tropical cyclones [35,36]. The highly variable rainfall events in Southern Africa as depicted in the LRB can be attributed to the ENSO phenomenon, which strongly influences the southeastern parts of the region where the LRB is located [37].

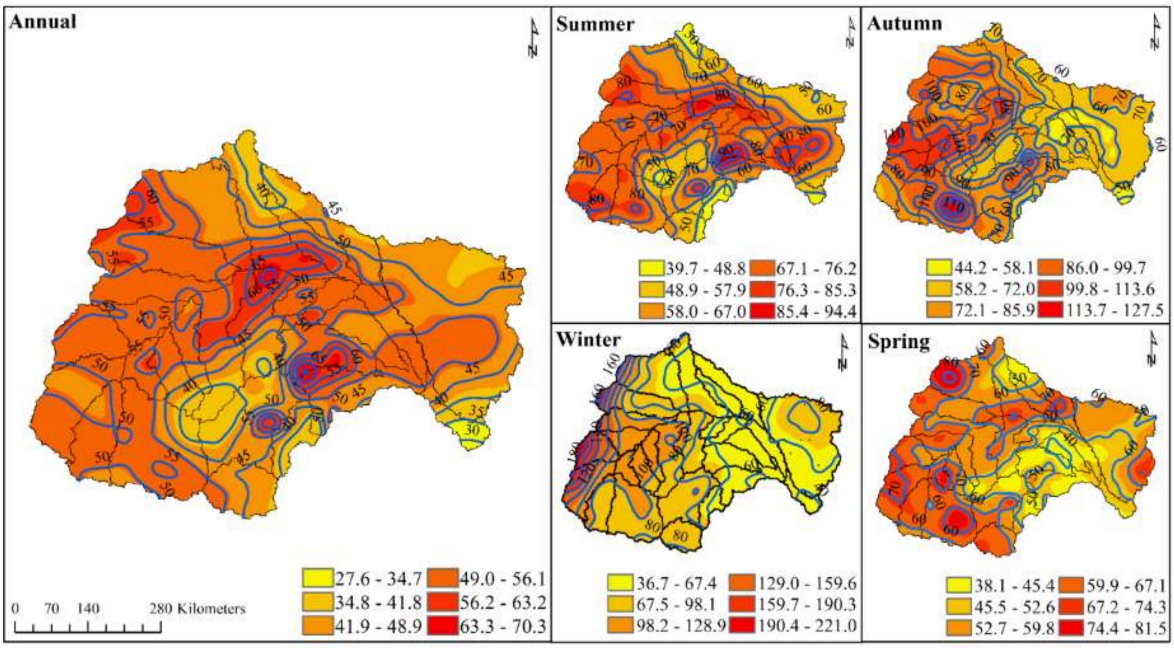

Figure 3. Annual and seasonal CVs for rainfall from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

3.1.2. Minimum and Maximum Temperature

Mean annual minimum and maximum temperature showed similar patterns to those of annual rainfall, increasing gradually from west to east and from south to north of the basin (Figures 4 and 5). Mean annual minimum temperature ranged from 8 °C in the south of the basin (Crocodile (ws 1), Upper Olifants (ws 19), Middle Olifants (ws 20), Steelpoort (ws 21) watersheds) to 20 °C in the east (Lower Middle Limpopo (ws 25), Changane (ws 26), and Lower Limpopo (ws 27)) (Figures 1 and 4). Mean annual maximum temperature ranged from 23 to 32 °C for the entire basin, increasing from south to east of the basin. Low temperatures in the south and west of the basin, including South Africa, may be attributed to oceanic and elevated altitude influences. The cold upwelling current from the Atlantic ocean known as the Benguela system brings cold waters to the west coast of the region, which in turn contribute to lowering temperatures in the west [38]. As expected, high elevation areas of the basin become colder than other regions (Figures 4 and 5). Coefficients of variation for both annual minimum and maximum temperature ranged from 2% to 10%, and 3% to 6%, respectively during the study period (Figures 6 and 7). This is indicative of a relatively minimal variability in temperature during the study period (i.e., 1979−2013) (Figures 4 and 5). This is expected as temperature generally varies less than rainfall (Figures 4 and 5).

Seasonal analysis showed that summer minimum temperature was higher than the minimum temperature of all other seasons, with a range of 12 °C in the south and some pockets in middle of the basin to 23% in the east of the basin (Figure 4). Spring minimum temperature ranged from 9.4 °C to 20 °C, followed by autumn with a range of 7.3 to 20 °C and winter ranging from 1.9 to 16.1 °C.

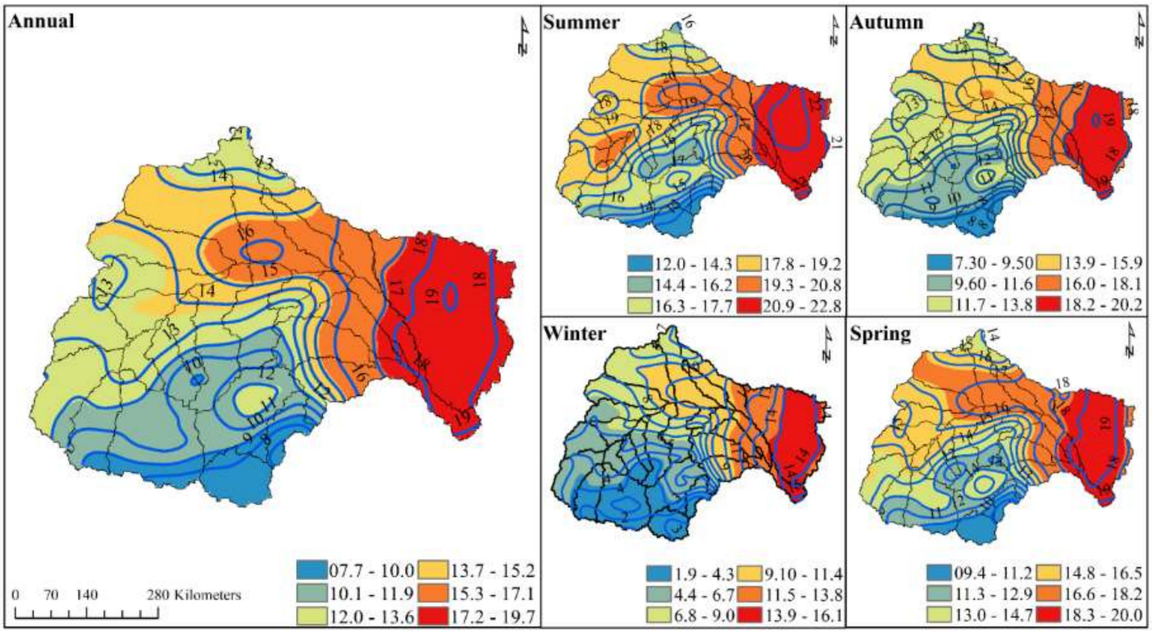

Figure 4. Mean annual and seasonal minimum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as Summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

Spatial variations in minimum temperature are similar to annual minimum temperature variations (Figure 6). In all four seasons, high variability in temperature (i.e., high CV) was observed in the south and southwest of the basin (Figure 6) compared to the east of the basin. Less variability in minimum temperature is observed in the summer season (2.2%–6.1%), followed by spring (2.3%–8.3%), and Autumn (2.5%–14.6%), while more variability is experienced in winter, with CVs of 3.5% in the north and east of the basin and over 50% in the south and west of the basin (Figure 6).

Seasonal maximum temperature followed the pattern of annual maximum temperature during the study period (Figure 5), with summer, autumn, winter and spring seasons' maximum temperature ranging from 25 to 35 °C, 22 to 31 °C, 18 to 28 °C, and 24 to 34 °C, respectively (Figure 5). As expected, maximum temperature in summer was the highest, followed by spring, autumn and winter; seasonal variability of maximum temperature is fairly comparable for all the seasons compared to minimum temperatures (Figures 6 and 7). Unlike minimum temperature, less variation in maximum temperature was detected in middle and east of the basin in summer and winter seasons (Figures 1 and 7). Less variability is also observed in maximum temperature in the west and northeast of the basin, mostly in spring (Figures 1 and 7). In autumn, pockets of minimal variability are observable only in the middle of the basin, along the Limpopo River (Figure 7).

Spatial variations observed in both minimum and maximum temperature on annual and seasonal time steps in the basin were consistent with observations made by other researchers for the Southern Africa region, inclusive of the LRB [39–41]. Overall, annual and seasonal rainfall over the study period showed decreasing trends, spanning from east to west of the basin, while minimum and maximum temperatures decreased from south to west and north to east during the study period. The observed patterns in inter-annual rainfall are highly variable throughout the basin across seasons, especially in the west, adding to the complexity of managing water resources in the LRB where events such as floods and droughts are prevalent.

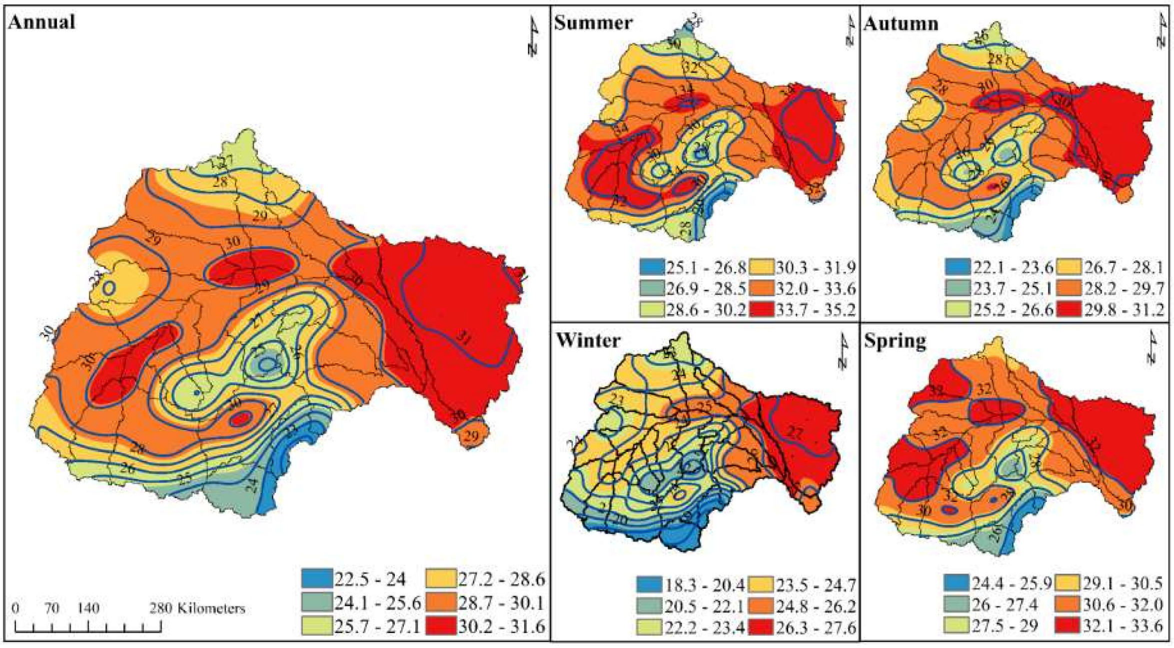

Figure 5. Mean annual and seasonal maximum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

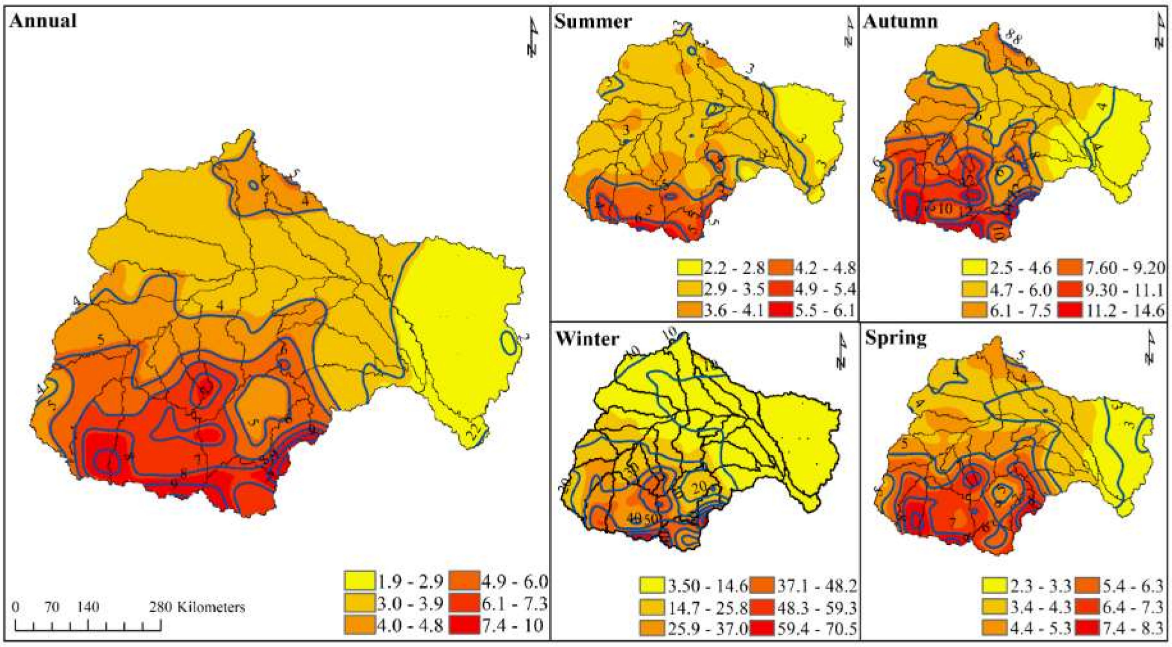

Figure 6. Annual and seasonal CVs for minimum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

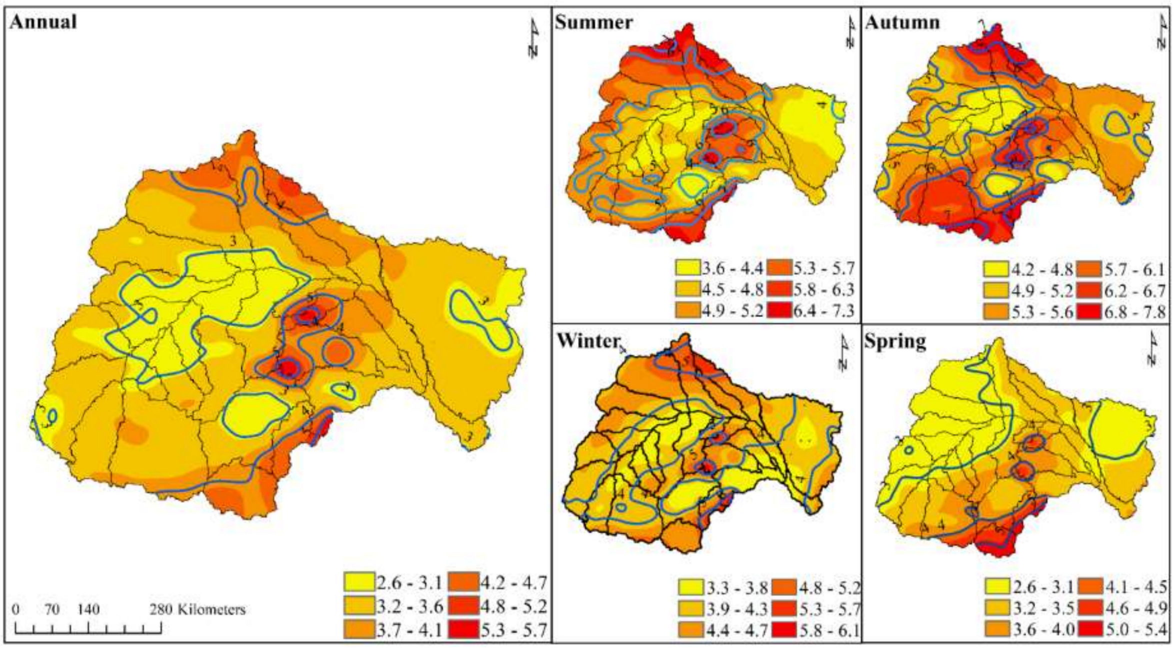

Figure 7. Annual and seasonal CVs for maximum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

3.2. Trends and Trend Magnitudes of Rainfall and Temperature in the Limpopo River Basin

3.2.1. Rainfall

Annual rainfall exhibited increasing trends between 1979 and 2013 in most of the watersheds within the LRB, except in three watersheds in the south of the basin (the whole of ws 19: Upper Olifants watershed and a few areas in ws 1 and ws 2 (Crocodile and Marico watersheds)) (see Figures 1 and 8). Of the 375 gridded locations analyzed for the entire basin, 361 (96%) showed overall increasing trends with 73% being statistically significant. The remaining 14 locations (4%) showed a slightly decreasing trend (Figure 8). Magnitudes of upward trends in annual rainfall ranged from 0.02 mm to 0.46 mm during the study period for the whole of the LRB. Downward trends observed in a few locations in the south of the basin varied from a minimum of −0.11 mm in the Upper Olifants (ws 19) to a maximum of −0.003 mm in the Crocodile (ws 1) watersheds (Figures 1 and 8). Although most studies report no trend in annual rainfall for Southern Africa (including the LRB) prior to 1970, statistically significant increased trends in rainfall events after the year 1970 have been reported in different parts of the region [16,42,43]. These reports are consistent with the results found in the present study which analyzed data from 1979 to 2013. Analysis of future climate scenarios also indicated that there is a slight increasing trend in annual rainfall for western Zimbabwe, Botswana, and Namibia [5].

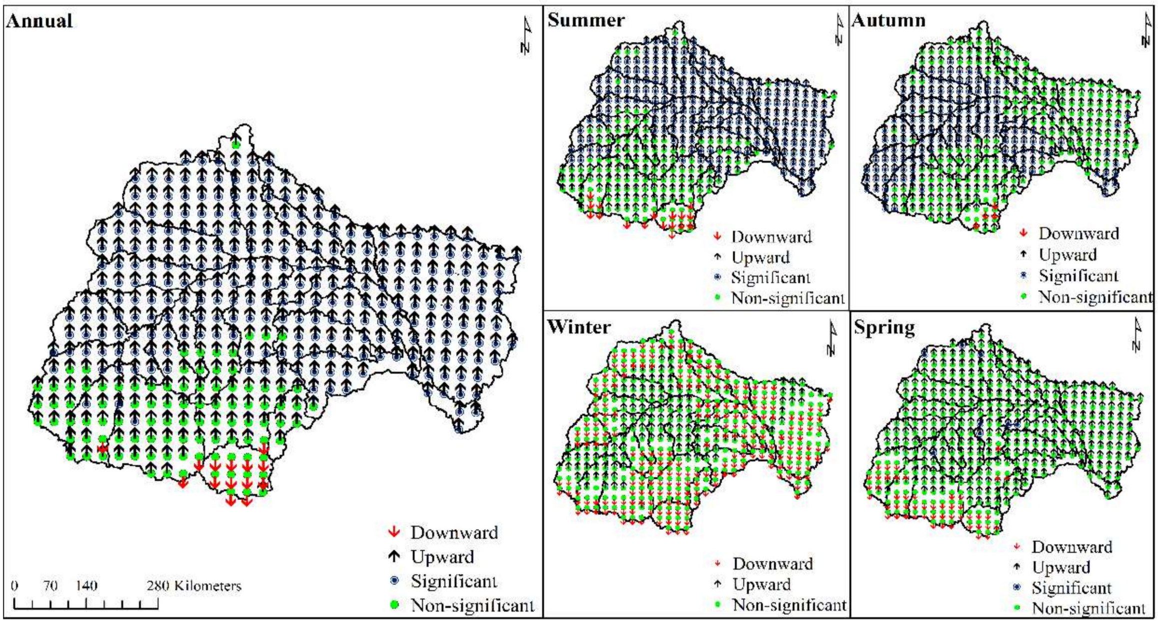

Figure 8. Trends in annual and seasonal rainfall in the Limpopo River Basin.

Seasonal analysis of rainfall for summer showed statistically significant increasing trends for most of the 375 locations in the north and east of the basin, while few locations in the south of the basin showed statistically non-significant upward and downward trends over the study period (Figure 8). Autumn rainfall revealed a statistically significant increasing trend in the west and middle of the basin, and the remaining basin areas showed overall statistically non-significant increasing trends during the study period (Figures 1 and 8). Winter rainfall showed statistically non-significant trends in the entire basin, with downward trends in most locations of the basin (Figure 8). Statistically significant upward trends are noticeable in spring rainfall (Figure 8), although in only 2% of the entire basin area as most locations in the basin revealed statistically non-significant increasing trends (Figure 8). Few locations in the southwest revealed statistically non-significant downward trends in spring rainfall during the study period (Figure 8).

In terms of trend magnitudes, summer had an upward trend with magnitudes of 0.001 to 0.41 mm and a downward trend magnitude of −0.09 to −0.005 mm during the study period. The magnitude for the downward trend in winter ranged from −0.2 to −0.003 mm, which is higher than the downward trend magnitude in annual rainfall. The magnitude of the upward trend for winter rainfall varied between 0.003 and 0.15 mm during the study period. As mentioned earlier, the south, in addition to being far from rain-forming processes (e.g., ITCZ), is highly urbanized with many transformations to the landscape ecosystems, causing highly variable rainfall (Figure 3).

3.2.2. Minimum Temperature

All of the 375 gridded locations examined in the basin showed increasing trends in annual minimum temperature (Figure 9). Of the 375 gridded locations, 105 (28%) locations had statistically significant upward trends (ws 3−7 and ws 20−23), while the increasing trends were not statistically significant for the other 270 points (72%) (ws 1, 8−19, 20 and 26) (Figure 9). The magnitude of trends in annual minimum temperature ranged from 0.003 to 0.52 °C for the 35-year study period. Among the four seasons, winter showed the highest number of gridded locations for minimum mean temperature (66 points or 18%) with statistically significant increasing trends, followed by spring (61; 16%), summer (22; 6%), and autumn (8; 2%) (Figure 9). The spring season also showed many locations with statistically significant and non-significant increasing trends, except for three gridded locations in the south of the basin (0.8%) out of 375, which exhibited a decreasing trend (ws 1: Crocodile) (Figure 9). Summer and autumn seasons showed approximately 158 (42%) and 160 (43%) locations with downward trends (Figure 9). Magnitudes of trends in minimum temperature for the winter season ranged between 0.003 and 0.37 °C. This is comparable to the magnitudes of annual minimum temperature trends which ranged between 0.003 and 0.52 °C during the study period. The magnitudes of the summer, autumn, and spring trends varied between −0.2 and 0.35 °C, −0.19 and 0.29 °C, and −0.05 and 0.41 °C, respectively.

These results are consistent with other studies conducted for the Southern African region (e.g., [5,43,44]), where seasonal and annual minimum temperatures were shown to increase in the region [45]. Beside the heavily forested eastern part of the basin that revealed statistically significant increasing trends in minimum temperature, there is no distinct pattern in statistically significant or non-significant trends for the remainder of the basin (Figure 9).

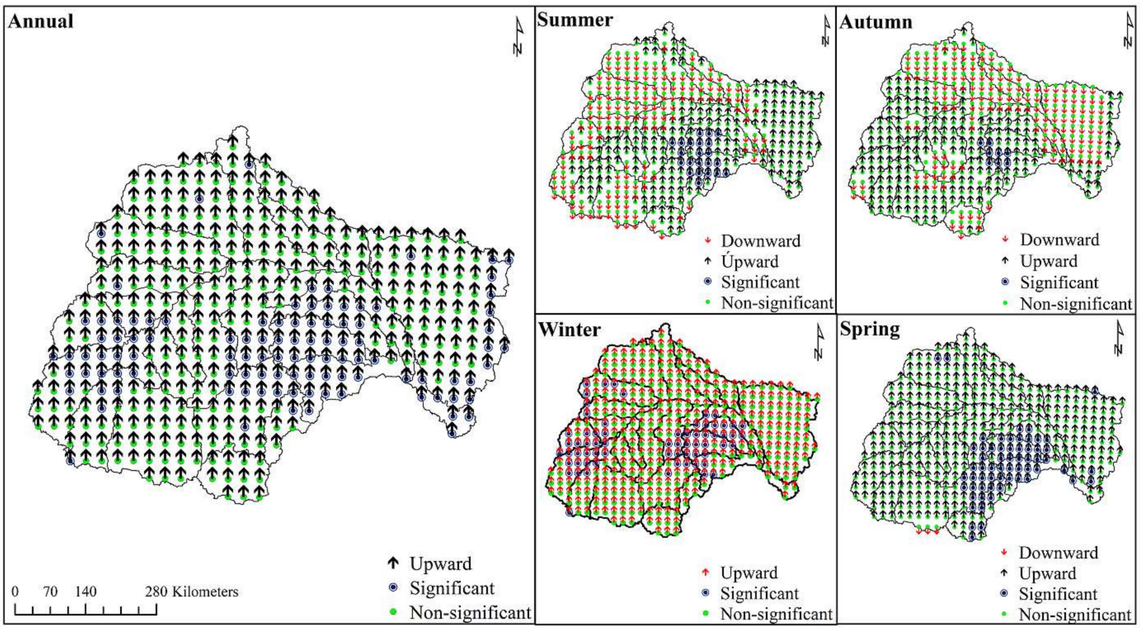

Figure 9. Trends in annual and seasonal minimum temperature in the Limpopo River Basin.

3.2.3. Maximum Temperature

A total of 36% (136) of the gridded locations analyzed for annual maximum temperature showed increasing trends, extending from the middle to the south of the basin during the study period (Figure 10). The basin watersheds with increasing trends include Crocodile (ws 1), Matlabas (ws 5), Mokolo (ws 6), Lephalala (ws 8), Mogalakwena (ws 11), Upper and Lower Olifants (ws 19 and ws 20) (Figures 1 and 10). A total of 64% (236) of the locations in the basin showed a decreasing trend during the 1979−2013 study period (Figures 1 and 10). Only 7% of the gridded locations had statistically significant increasing annual trends (Figure 10). Magnitudes of increasing trends for annual maximum temperature ranged from 0.003 to 0.39 °C, while decreasing trends ranged from −0.2 °C to −0.003 °C. Trends of annual maximum temperature found in this study coincide with the published literature for the Southern African region where mixed increasing or decreasing trends were reported [39,42,45]. Maximum temperature for summer and autumn seasons revealed similar patterns to annual maximum temperature trends during the study period, where most of the northern watersheds of the basin exhibited a decreasing trend versus an increasing trend in the south (Figures 1 and 10). Summer appears to have more temperature measurement locations with statistically significant decreasing trends compared to other seasons (Figure 10). Winter and spring maximum temperature showed many of the gridded locations with upward trends, except at very few locations (less than 10 locations) in the south. The spring season also had many locations with statistically significant increasing trends compared to the winter maximum temperature (Figure 10). Magnitudes of increasing trends (for both statistically significant and non-significant) in maximum temperature varied between 0.005 and 0.27 °C, 0.03 and 0.21 °C, 0.03 and 0.33 °C, and 0.02 and 0.44 °C for summer, autumn, winter, and spring, respectively. Decreasing trend magnitudes ranged from −0.031 to −0.005 °C, −0.29 to −0.00032 °C, −0.005 to 0.0032 °C for summer, autumn, and winter, maximum temperature, while spring had only one temperature observation location out of the 375 with a decreasing magnitude of −0.002 °C.

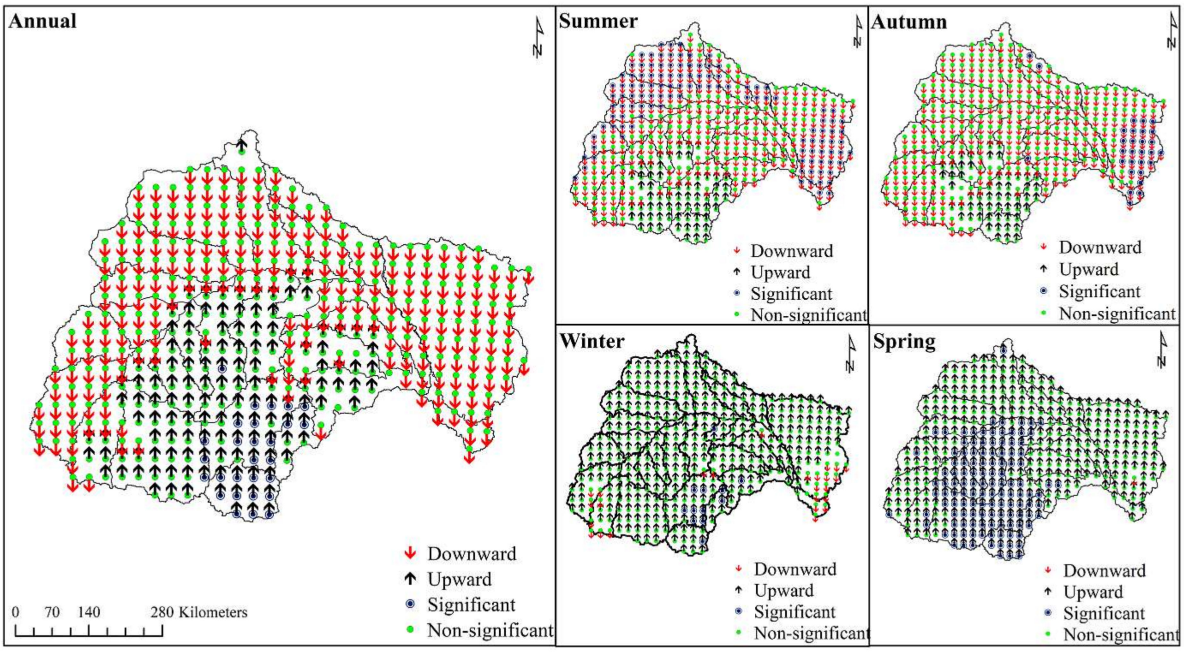

Figure 10. Trends in annual and seasonal maximum temperature in the Limpopo River Basin.

A comparison between the overall minimum and maximum temperature trends revealed an increasing trend for minimum temperature and a decreasing trend for maximum temperature for most of the basin (Figures 9 and 10), suggesting that the diurnal range between minimum and maximum temperature decreased over time. Similar increasing and decreasing trends in respective minimum and maximum temperature in the region have been by other researchers [46].

In general, rainfall, although increasing, was highly variable in the basin. Other researchers reported decreases in annual rainfall in some parts of the basin [47]. The increasing rainfall trends in this study are generally consistent with a number of studies carried out for the Southern African region (e.g., [48,49]. Research also reported no changes in average rainfall events [50], especially in the Zimbabwean part of the basin. The differences in results may be attributable to differences in time frames of the studies. For example, Mazvimavi (2008) [50] used time series data that spanned from 1892 to 2000, and Love's (2009) [47] study covered a period of 1930 to 2004. This study used data from 1979 to 2013.

While increasing trends in rainfall will likely result in augmentation of water in the basin, demands from population growth and associated activities in the basin are also increasing, putting constant pressure on water resources [16]. The highly variable rainfall is not reliable for rainfed agriculture, which is a common practice in the LRB. The analysis shows increasing trends in minimum temperature for the LRB. Not only does this influence ET processes in the basin, but it also has considerable implications for water availability. Increased temperature leads to increased ET, which in turn results in increased irrigation demands in water-scarce areas such as the LRB. While maximum temperature showed non-significant downward trends, minimum temperature showed statistically significant increasing trends in most of the basin, suggesting an overall average temperature increase in the basin. As mentioned above, this would eventually affect ET processes with implications for soil water and streamflow changes [51–53].

4. Summary and Conclusions

Rainfall, minimum temperature, and maximum temperature were analyzed for annual and seasonal means, variability, and trends in the LRB from 1979 to 2013.

- Annual and seasonal rainfall means were found to decrease from east to west with a range of 1109 mm for watersheds in Mozambique to 160 mm for those in Botswana. Annual and seasonal CV values are high in the west and lowest in the east, indicating high variability in the west compared to the east of the basin. Annual, summer, autumn and spring rainfall showed increasing trends while winter rainfall showed decreasing trends in most locations of the basin, with increasing magnitudes of 0.001 to 0.46 mm, and −0.2 to −0.0003 mm for decreasing trends.
- Minimum annual and seasonal temperature means gradually increased from west to east and from south to north of the basin, ranging from 1.9 in winter to 22.8 °C in summer. Annual and seasonal CV decreased from south to north and was lowest in the east. Annual, winter and spring minimum temperature increased in almost all areas of the basin while summer and autumn had mixed trends. The magnitudes of trends ranged from −0.2 to 0.41 °C across seasons.
- Annual and seasonal means of maximum temperature are lowest in the south and highest in east of the basin, with a range of 18.3 to 35.2 °C. The CVs for annual and seasonal maximum temperature are lowest in the middle of the basin and highest in the south and north. Decreasing maximum temperatures are observed in the northern parts of the basin on an annual, summer and autumn basis, while winter and spring seasons show increasing trends in the basin. The magnitudes of these trends range between −0.29 and 0.39 °C.

Increasing trends in rainfall suggest increased available water in the basin; however, population increase, changes in land use, and intensification of agriculture activities continue to put pressure on water resources in the basin. The high CV values for annual and seasonal rainfall substantiate the highly variable nature of rainfall with the potential to contribute to unpredicted flooding and drought in the region. The trends detected in temperature, especially increasing trends in minimum temperature, are also important for regional energy and water balances.

Water practitioners and policy makers must take these into account when developing flood and drought mitigation strategies and measures. Adoption of sustainable practices to bring changes in management, water technology and infrastructure, and raising awareness would be useful to develop resiliency against water risks in the basin. While this study analyzed climatic variations in the LRB, it did not explicitly include the impacts that these changes in climate would have on water resources (e.g., streamflow, soil moisture). Contingent on data availability, studies of land use change, land management activities, climate variability, and climate change impacts on water resources would provide further insight into the subsequent ecosystem and hydrological responses in the basin.

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