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Rainfall and Temperature Trend Analysis using Mann-Kendall and Sen's Slope Estimator Test in Makueni County, Kenya

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Abstract: This study sought to analyze annual, seasonal, and monthly rainfall and temperature (minimum and maximum) trends in Makueni County from 1991 to 2020 using the Mann–Kendall (MK) trend test and Theil-Sen's slope estimator. Data analysis was done in R software. The findings revealed a declining trend in annual and seasonal (short and long rain seasons) rainfall, albeit statistically insignificant. Similarly, monthly rainfall exhibited a downward trend in nine of the twelve months. This decline, however, was only significant in June. The findings revealed a statistically significant upward trend in the county's annual and seasonal minimum and maximum temperatures across the study period. Similarly, monthly analysis revealed a statistically significant increasing temperature (both minimum and maximum) trend in at least nine of the twelve months. When the data was analyzed by sub county, the results revealed differing trends in annual, seasonal and monthly rainfall patterns with some sub counties experiencing increased rainfall and others decreased rainfall. However, annual, seasonal and monthly temperature (minimum and maximum) analysis revealed an increasing trend in all the sub counties with the most of the observations being statistically significant. These patterns suggest that Makueni county is already experiencing climate change. The findings serve as a foundation for sound climate change policy decisions in the county. They also suggest the need for the development of climate change adaptation strategies targeted at mitigating risks and increasing resilience to climate shocks.

1. Introduction

Climate change is a global environmental challenge with serious ramifications on every sector across the globe. This unprecedented change is attributable to human activities which have resulted into increased emission of greenhouse gases. Records indicate that greenhouse gas concentrations in the atmosphere have been on the rise since 1750, reaching annual averages of 410 ppm, 1866 ppb, and 332 ppb for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), respectively in 2019 (IPCC, 2021). From 2010 to 2019, average annual greenhouse gas emissions were higher than any preceding decade (IPCC, 2022). These greenhouse gases have resulted in global warming through human-enhanced greenhouse effect. As a result, global temperatures have been rising, with each of the last four decades being successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99°C higher than 1850–1900 (IPCC, 2021). Increased rainfall variability has also been evident in different parts of the world (Kotir, 2011). These changes in temperature and rainfall patterns have resulted into devastating impacts on the natural environment and human systems.

Africa is a region characterized by different climatic regimes ranging from high arid to very humid and they remain highly variable and unpredictable (Schraven *et al*., 2020). A warming trend has been observed in the continent with an average increase of approximately +0.3^{0}C per decade from 1991-2021. The year 2021 was the fourth warmest year on record in Africa with near surface mean air temperature estimated at 0.68^{0}C above the 1981-2010 average. This warming has been more rapid compared to the global average, and has been associated with increased heat waves and hot days (WMO, 2021). Precipitation patterns have also changed with both positive and negative anomalies being observed in different parts of the continent. In the year 2021, for instance, most regions in Africa, experienced remarkable rainfall deficits often marked with late rainfall onsets and early cessation of the same (WMO, 2021, FEWSNET, 2022). Although the continent has contributed the least to global warming with the lowest emissions, it is the most vulnerable and faces exponential collateral damage in all sectors particularly agriculture, which supports most of the population (Gornall, *et al*., 2010, ADB, 2022).

In Kenya, the diverse topography results in a wide range of climates, with the coastal area being hot and humid and the inland areas more temperate. While temperatures vary across the country, a distinct warming trend has been evident since the 1960s with annual mean temperature increase rising by approximately 1^{0}C at an estimated rate of 0.21^{0}C per decade. The temperatures are projected to continue rising by 1.7^{0}C by the 2050s and approximately 3.5^{0}C at the end of the century (MENR, 2016). Hot days and nights are expected to increase more quickly with cold days and nights becoming increasingly rare (NEMA, 2015). There has been a significant geographical diversity in observed rainfall trends in the country with the northern areas becoming wetter and southern areas becoming drier since the 1960s, though with high degrees of variability (WBG, 2021). It is projected that these rainfall patterns will remain highly variable and uncertain though average rainfall especially during the short rains is expected to increase by mid-century. Rainfall in the arid zones is expected to decrease (WBG, 2020).

Makueni county, an arid and semi-arid area in Kenya has experienced a 10^{0}C increase in mean temperature since 1981 with some days having temperatures of over 35^{0}C. Similarly, rainfall patterns have become increasingly erratic and unreliable with increasing drought conditions across the county over the past three decades (MoALF, 2016, Muema *et al*., 2018). These changes have significantly affected agriculture which is the main economic activity in the county often resulting into frequent crop failures and low agricultural productivity. In the face of a changing climate, the understanding of temperature and rainfall patterns (the two key indicators that characterize the state of the climate of a place) is essential for long term planning and effective response through adaptation and mitigation (Ongoma *et al*., 2017, WMO, 2020). This study sought to determine temperature and rainfall trends in Makueni County for the period 1990-2020 using the Mann-Kendall non-parametric trend test for better climate change management in the county.

2. Methodology

2.1 Description of the study area

Makueni county, in eastern Kenya comprises an area of approximately 8,034.7 square kilometers, most of which is arid and semi-arid (GoK, 2014, GoMC, 2019). It is located between latitudes 10 35’ and 30 00’ South and longitudes 370 10’ and 380 30’ East (**Figure 1**). Except for the hilly areas of Kilungu, Mbooni and Chyulu Hills, the county’s terrain is mostly low-lying. There are two distinct rainy seasons in the area: long rains (March, April, and May), and short rains (October, November, and December). The rains are however, unevenly distributed, with the hilly areas receiving approximately 800-1200mm of rainfall (above normal) and the lower regions receiving about 300mm (below normal). The temperatures range from 20.2^{0}C to 35.80^{0}C, with the hilly regions being colder than the low-lying areas (GoK, 2013, MoALF, 2016).

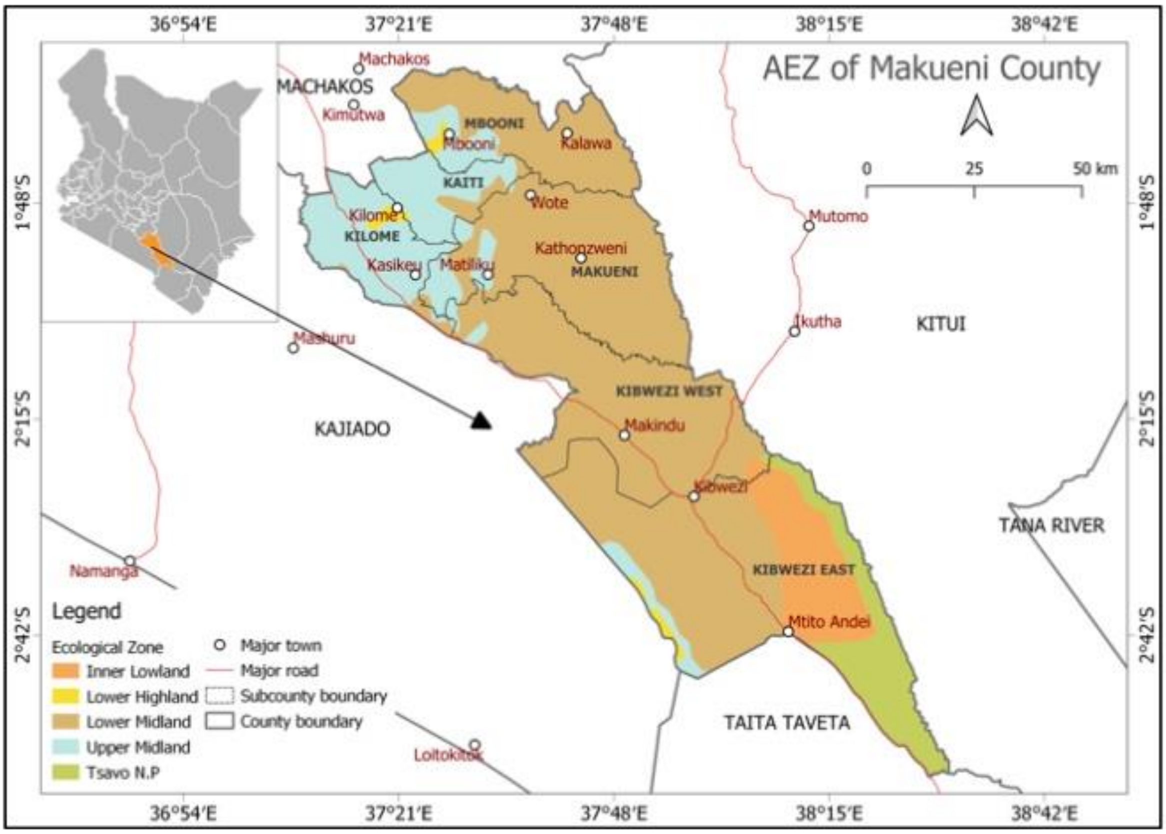

Figure 1: Map of Makueni County showing the different agroecological zones

2.2 Data collection

Trend analysis requires lengthy time-series data in order to reliably detect trends in rainfall and temperature. This study relied on secondary data for rainfall and temperature from the Kenya Meteorological Department for the period 1991-2020.

2.3 Data analysis

The Mann-Kendall (MK) non-parametric trend test (Mann, 1945, Kendall, 1975) was used to detect monotonic trends in temperature and rainfall (identify the presence of a trend), and Sen's estimate (Sen, 1968) was used to assess the magnitude of the trend. The results were deemed significant at the 95% confidence level.

2.3.1 Mann-Kendall Test (MK1)

The Mann-Kendall (MK) test is a robust test that determines whether a time series data has a substantial monotonic upward or downward trend. Since it is a non-parametric test, data does not need to meet the assumption of normality. The test is also less sensitive to sudden breaks instigated by non-homogenous time series. This test is based on two hypotheses: the null hypothesis (H_0) which indicates no trend (no change in the series mean) and the alternative hypothesis (H_1) which indicates the presence of a monotonic trend (a rise or decrease in the mean over time).

The Mann-Kendall test uses the time series of n data points and considers xi and xj as two data subsets where i = 1,2, 3, ..., n-1 and j = i + 1, i + 2, i + 3, ..., n. Data values are evaluated as an ordered time series. Each data value is compared to the subsequent data values. If the data value of a subsequent period exceeds that of the previous period, the S statistic is increased by one. In contrast, S is reduced by one if the data value of a subsequent period of time is less than a previously sampled data value. The total of all these increments and decrements yields the final value of S (Drapela and Drapelova, 2011). The Mann-Kendall test statistic (S) is thus, calculated as follows:

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} sign(x_j - x_i) \qquad \textbf{Eqn. 1}$$

Where, n is the total number of data points, x_i and x_j are the data values in time series i and j (j>i), and sign(x_j-x_i) is the sign function calculated as:

$$sign(x_j - x_i) = \begin{Bmatrix} 1, & if\ x_j - x_i > 0 \\ 0, & if\ x_j - x_i = 0 \\ -1, & if\ x_j - x_i < 0 \end{Bmatrix} \qquad \textbf{Eqn. 2}$$

A positive value of S implies an upward trend, while a negative value signifies a downward trend (Silva, *et al*., 2015). If the time series is sufficiently long (number of data values, n≥10), the S statistics behave essentially normally, and the test is done using a normal distribution with the mean E(S) and variance V(S) as indicated in **Eqns. 3 and 4**.

$$E(S) = 0 \qquad \textbf{Eqn. 3}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \qquad \textbf{Eqn. 4}$$

Where n is the number of data points, m is the number of tied groups and t_i is the number of ties to the extent of i. The standard normal test statistic ZS is computed as:

$$Z_s = \begin{Bmatrix} \frac{S-1}{\sqrt{V(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & if\ S < 0 \end{Bmatrix} \qquad \textbf{Eqn. 5}$$

Positive ZS values imply increasing trends, whilst negative ZS values suggest decreasing trends. The test statistic Z provides significance levels (SL) for rejecting the null hypothesis. The confidence level (CL) for rejecting the null hypothesis is stated as:

$$CL = 1 - SL \qquad \textbf{Eqn. 6}$$

This study adopted a 5% significance level where the null hypothesis of no trend was rejected when $|Z_s| > 1.96$.

2.3.2 Serial correlation effect

The MK test requires data to be serially independent. However, this is not always the case because time series data is frequently autocorrelated. The presence of serial correlation in time series data affects trend detection and may result in the rejection of the null hypothesis in the event of a positive autocorrelation leading to type 1 error. Type 2 error, on the other hand, might occur when the null hypothesis is not rejected in the presence of a negative autocorrelation (Kumar *et al*., 2009). If serial correlation is detected in a time series, it should be removed in order to appropriately assess the significance of trends. Otherwise, the MK test is applied to the original data values without subjecting them to pre-whitening. Several methods have been proposed in literature to account for the effect of auto-correlation in natural time series data. This study used the 'pre-whitening" technique to reduce the impact of serial correlation on the MK test.

2.3.3 Mann-Kendall Trend Test with Trend-Free Pre-whitening (MK2)

Pre-whitening is a filtering technique that is used to turn an autocorrelated series into an uncorrelated one ("white noise" hence the term whitening) before applying a trend test (von Storch, 1995, Yue *et al*., 2002, Hamed, 2009). The Trend-Free Pre-whitening procedure was used in this study, in which lag-1 serial correlation components were eliminated from the series before the MK test. The lag-one autocorrelation coefficient (r_1) was computed using the following equation:

$$r_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}(x_i-\bar{x})(x_{i+1}-\bar{x})}{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad \textbf{Eqn. 7}$$

Where xi represented a value of an observation in a time series, $\bar{x}$ denoted the mean of the time series data sample, and n denoted the sample size. The autocorrelation coefficient values were tested using the following equation:

$$r_1 = \frac{-1 \pm 1.96\sqrt{(\mathrm{n}-2)}}{\mathrm{n}-1} \quad \textbf{Eqn. 8}$$

When r_1 was between the upper and lower boundaries of the confidence interval, the time series data were deemed to be serially correlated. As a result, the Trend-Free Pre-Whitening method, which is a modified MK test, was applied. **Eqn.9** was used to eliminate the trend and obtain a detrended time series data:

$$x'_i = x_i - (\beta * i) \quad \textbf{Eqn. 9}$$

Where,

$$\beta = median\left[\frac{x_j - x_i}{j-i}\right] \; for\ all\ i < j \quad \textbf{Eqn. 10}$$

Lag-1 autocorrelations for detrended time series given by x'_i were calculated using **Eqn. 7**. To obtain a residual series, **Eqn. 11** was used to eliminate the lag-1 autoregressive component (AR (1)) from the detrended series.

$$y'_i = x'_i - r_1 * x'_{i-1}$$ **Eqn.11**

The (β*i) value is added to the residual series once more, as illustrated in **Eqn. 12** and then the MK test is applied to the blended series y_i to ascertain the significance of the trend.

$$y_i = y'_i + (\beta * i)$$ **Eqn.12**

2.3.4 Sen's slope estimator

The MK test detects the presence of a trend, whereas the Sen's slope estimator assesses its magnitude. Sen's slope test assumes a linear trend and represents the quantification of temporal change. Because of its robustness against the effect of outliers, this test is preferred over linear regression in hydro-meteorological investigations (Zhang *et al*., 2005). Sen's slope equation for trend slope estimate (Q) in a sample of N pairs of data is as follows:

$$Q_i = \frac{x_{j-}x_k}{j-k} \; for \; i = 1,2,3 \ldots N$$ **Eqn. 13**

Where x_j and x_k represent data values at times j and k (j>k) respectively, and N represents the total number of slope observations. Sen's estimated slope is the median of the N values associated with Q_i. Based on the slopes value of N, the median of all slopes is ranked from lowest to the highest Q_i as follows:

$$Q = \begin{bmatrix} Q\frac{N+1}{2} \quad if \; N \; is \; odd \\ \frac{1}{2}\left(Q\frac{N}{2} + Q\frac{N+1}{2}\right) \quad if \; N \; is \; even \end{bmatrix}$$ **Eqn. 14**

Where,

$$N = \frac{n(n-1)}{2}$$ **Eqn. 15**

3. Results and Discussion

Before performing the MK test on the temperature and rainfall data, the data sets were evaluated for serial correlation using lag-1 autocorrelation at the 5% significance level to ensure that the data was random. To counteract the effect of serial correlation, the pre-whitening approach was used.

3.1 Trend Analysis of Rainfall in Makueni County from 1991 to 2020

The Mann–Kendall trend test and Theil-Sen's slope estimator were used to analyze the monthly, annual, and seasonal rainfall trends in Makueni County between 1991 and 2020. **Table 1** summarizes the findings. The results of the monthly rainfall analysis revealed a declining trend in nine of the twelve months (January, April, May, June, July, August, October, November and December), with a significant decline in June. The results also revealed an increase in rainfall in two months (February and March), albeit not statistically significant. However, there was no trend in September. Seasonally, rainfall declined in both the long (October, November and December) and short (March, April and May) rain seasons, however this was not statistically significant. Similarly, the county's annual rainfall exhibited a statistically insignificant downward trend. **Figure 2** shows a graphical representation of

Makueni County's annual precipitation pattern from 1991 to 2020. A spark is observed in the year 1998, when the county received ELNINO rains. **Figures 3 and 4** show seasonal (short and long rain seasons) rainfall trends in Makueni County over the study period.

Table 1: MK Trend Test results of Mean Monthly, Seasonal and Annual Rainfall in Makueni County from 1991 to 2020

Period	ACF	Zs	Qmed
January	-0.1712	-0.5178	-0.1080
February	-0.1234	1.1063	0.1000
March	-0.3067	0.3269	0.3210
April	0.0081	-1.2804	-1.0151
May	-0.1620	-0.5312	-0.1461
June	0.1132	-1.7292*	-0.0073
July	-0.1449	-1.6341	0.0000
August	-0.1520	-0.7940	0.0000
September	-0.1183	0.0000	0.0000
October	-0.0529	-0.8596	-0.0450
November	-0.0199	-1.0218	-1.3092
December	-0.2995	-0.7491	-0.9865
Short Rain Season (MAM)	-0.1497	-0.3950	-0.1974
Long Rain Season (OND)	-0.1619	-1.1578	-0.7686
Annual	0.1291	-0.5709	-0.1534

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; and * = significant at 10%; MAM = March, April, & May; OND = October, November, & December

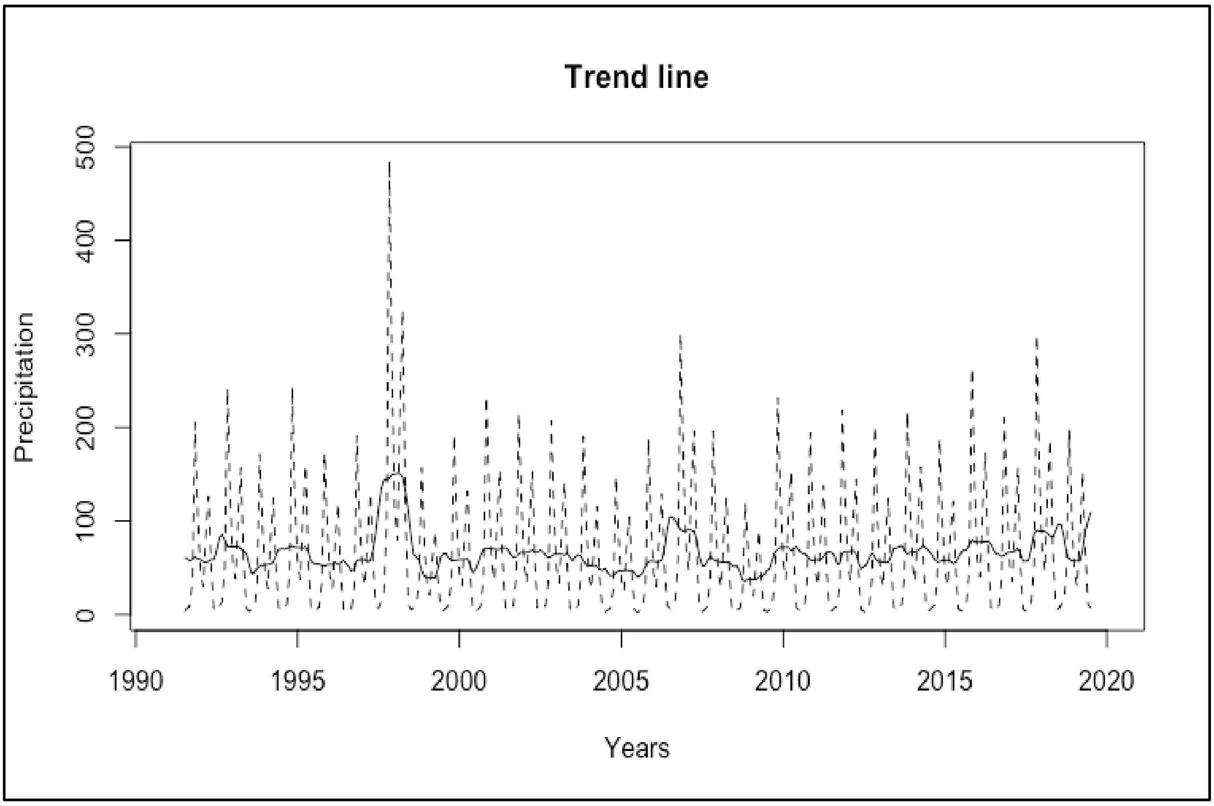

Figure 2: Annual rainfall trend in Makueni County from 1991-2020

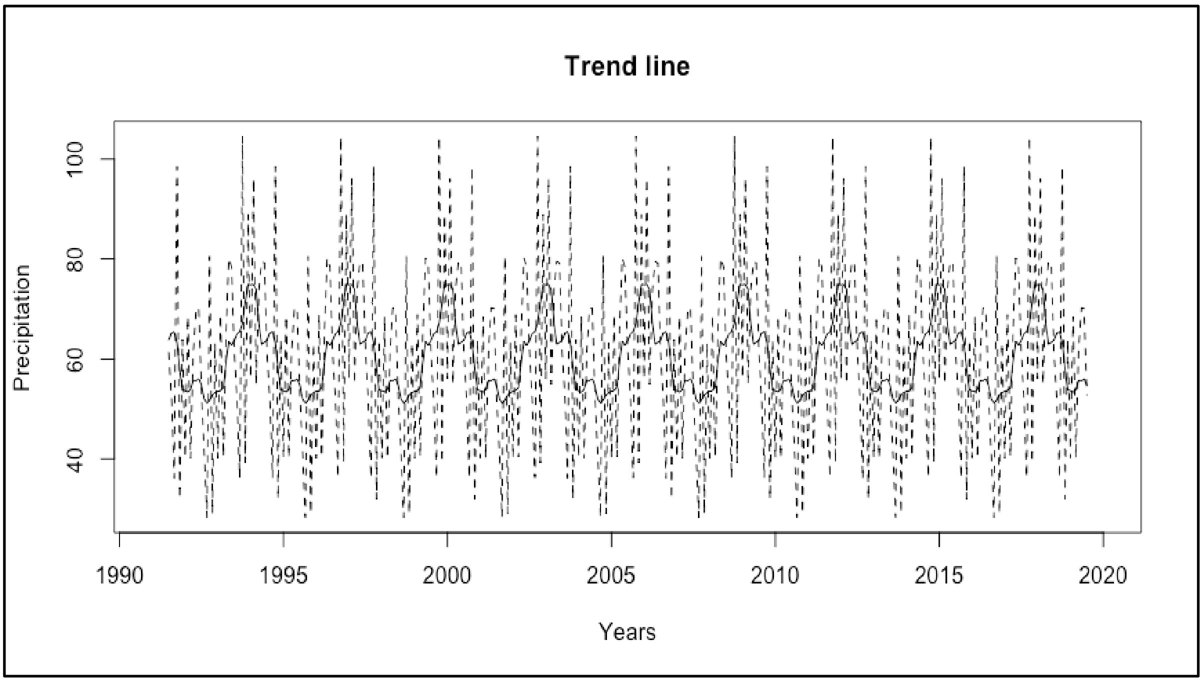

Figure 3: Precipitation Trend for the Short Rain Season (March, April, and May) in Makueni County from 1991 to 2020

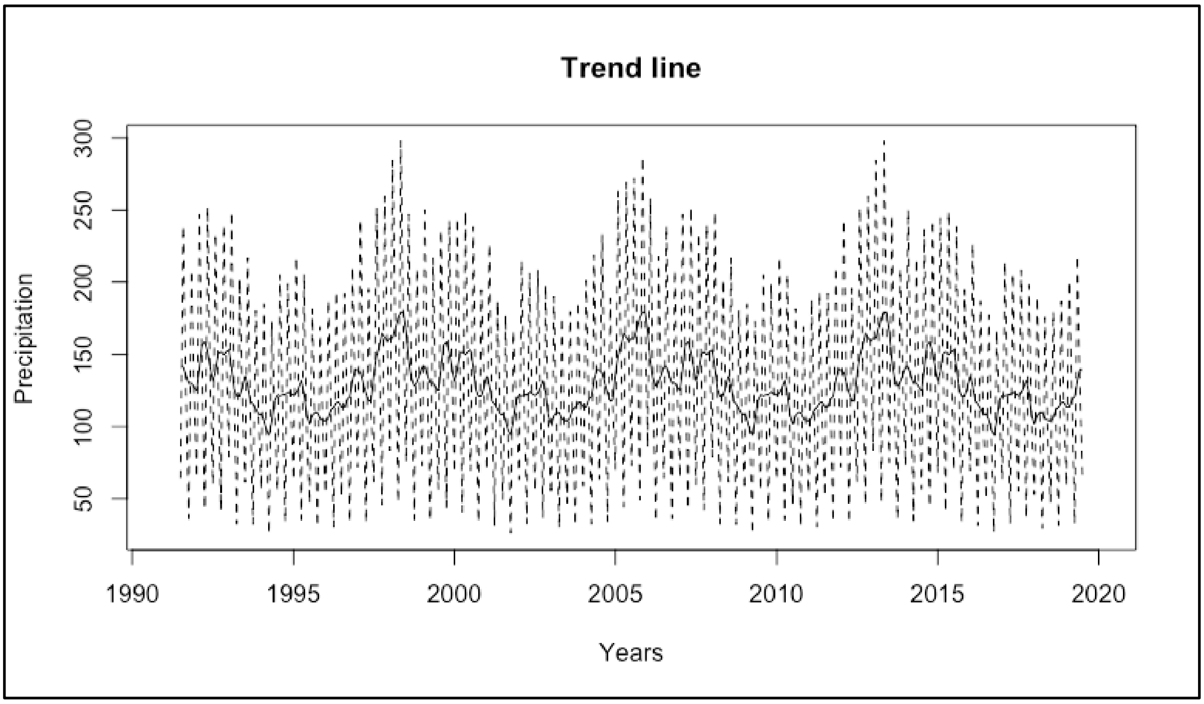

Figure 4: Precipitation Trend for the Long Rain Season (March, April, and May) in Makueni County from 1991 to 2020

3.2 Trend Analysis of Temperature in Makueni County from 1991 to 2020

The MK test and Sen's slope estimator results for average monthly, seasonal, and annual temperature are presented in **Table 2**. The monthly analysis results indicate an upward trend in both maximum and minimum temperatures over the study period. This trend was statistically significant for the majority of the months. Maximum temperature trends from April through December, for instance, were statistically significant at the 1% level whereas the January trend was statistically significant at the 5% level. Similarly, the upward trend in minimum temperature was statistically significant at 1% for the months of February, August, October, and November and 5% for March, April, September and December. In terms of seasonal temperature variations, the results showed a statistically significant (1%) upward trend in both minimum and maximum temperatures throughout both the short (March, April, and May) and long (October, November, and December) rain seasons. Similarly, the findings for annual temperature analysis revealed statistically significant rising trends for both minimum and maximum temperatures (5% and 1% significance levels respectively).

Table 2: Trend Analysis results of Mean Monthly, Seasonal and Annual Temperature (Minimum and Maximum) in Makueni County from 1991 to 2020

Period	**Tmax**			**Tmin**		
	ACF	**Zs**	**Qmed**	**ACF**	**Zs**	**Qmed**
January	0.1157	2.3053**	0.0563	-0.0996	1.5802	0.0200
February	-0.3343	0.8673	0.0154	-0.0750	2.4626***	0.0333
March	-0.2055	1.2511	0.0333	0.1268	2.1355**	0.0231
April	0.0121	2.4459***	0.0500	0.1603	2.3702**	0.0214
May	**0.4023**	2.6684***	0.0701	-0.1746	0.8411	0.0100
June	0.3118	3.8165***	0.0481	-0.0819	0.6977	0.0080
July	0.2767	3.2458***	0.0429	-0.1549	1.0675	0.0125
August	**0.4155**	2.6684***	0.0701	0.1295	3.0048***	0.0250
September	0.1693	3.0646***	0.0407	0.1218	2.0697**	0.0143
October	0.1115	2.5626***	0.0400	0.1634	2.5616***	0.0273
November	0.0124	2.9869***	0.0500	0.3043	3.8822***	0.0273
December	0.1137	2.5752***	0.0666	-0.1366	2.1653**	0.0161
Short Rain Season (MAM)	0.0366	2.7569***	0.0455	0.1426	2.7309***	0.0185
Long Rain Season (OND)	0.2976	3.7932***	0.0533	0.2744	3.4261***	0.0244
Annual	**0.5450**	3.2910**	0.0348	**0.3614**	2.8252***	0.0214

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; Tmax= maximum temperature; Tmin= Minimum temperature; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully removed

3.3 Trend analysis of rainfall in the nine sub-counties in Makueni County for the period 1991 to 2020

Trend analysis results for mean monthly, seasonal and annual rainfall for the nine sub counties in Makueni county are presented in **Tables 3 and 4**. The monthly trend analysis results were varied with some indicating upward trends and others indicating downward trends. Most of these trends were, however not statistically significant.

As far as Kathonzweni sub-county is concerned, mean monthly rainfall exhibited an upward trend in eight (February, March, April, May, June, August, September, and October) of the twelve months. This trend was however, significant only in September (5%). On the other hand, a statistically insignificant downward trend was observed in the months of January, July, November and December. In Kibwezi sub-county, an upward trend in mean monthly rainfall was observed in the months of February through October with significant increases in the months of June (5%), July (5%), October (1%) and September (1%). A decreasing trend was on the other hand observed in the months of January, November, and December, albeit insignificant. Ten of the twelve months in Kilungu sub-county exhibited an upward trend in mean rainfall with this increase being significant only in the month of

April (5%). The negative trends observed in May and December were not statistically significant. In Makindu sub-county, an upward insignificant trend was observed in the months of January, February, March, April, June, July, and September and a similarly insignificant downward trend in the months of May, August, October, November, and December. In Makueni sub-county, all the months exhibited an upward trend in mean rainfall which was only statistically significant in August (5%) and September (1%). Except for December, all months in Mbooni East sub-county showed an upward trend, which was only significant in April (5%), June (10%), and September (1%). Ten (February through November) of the twelve months in Mbooni West sub-county exhibited an increasing trend with the rise being statistically significant in April (1%) and September (10%). In January and December, the observed downward trend was statistically insignificant. In Mukaa sub-county, only two months (May and December) showed a declining trend, albeit statistically insignificant. The remaining months exhibited an upward trend that was only significant in the months of April (1%) and September (10%). In Nzaui sub-county, the months of February and July showed a statistically significant downward trend. The remaining months exhibited an upward trend that was only significant in April (10%) and September (5%).

The seasonal trend analysis results revealed an upward rainfall trend throughout the short rain season in all the sub counties, with a statistically significant increase in five sub counties: Mukaa (1%), Mbooni West (5%), Mbooni East (10%), Makueni (10%), and Nzaui (10%). The long rain season trend results revealed a negative rainfall trend in five of the nine sub counties (Kathonzweni, Kibwezi, Makindu, Mbooni East, and Mbooni West) with a statistically significant decline in Kibwezi (5%). The remaining four sub counties (Kilungu, Makueni, Mukaa, and Nzaui) exhibited an increasing rainfall trend which was significant in Nzaui sub-county (10%). In terms of mean annual rainfall, only two sub-counties (Kibwezi and Makindu) exhibited a declining trend, albeit statistically insignificant. Other sub-counties showed an upward trend, with the rise being statistically significant in Makueni (10%), Nzaui (10%), and Mukaa (5%) sub-counties. It is also worth noting that these three sub-counties are neighbours (border each other).

Table 3: Trend analysis of mean seasonal and annual rainfall in Makueni County sub counties from 1991 to 2020

Region	Annual			Short Rain Season (MAM)			Long Rain Season (OND)		
	ACF	Zs	Qmed	ACF	Zs	Qmed	ACF	Zs	Qmed
Kathonzweni	0.2362	0.2141	0.1354	0.0702	1.2856	0.7282	-0.1386	-0.6066	-0.4770
Kibwezi	0.0005	-0.3211	-0.2011	-0.1031	1.4273	0.8444	**-0.4318**	-0.9696**	-1.8056
Kilungu	**0.3810**	0.7316	0.4107	0.0366	1.4272	1.4320	-0.0593	0.3211	0.4263
Makindu	0.2002	-1.0348	-0.3884	-0.1547	0.3925	0.3279	-0.2038	-1.4986	-1.5701
Makueni	0.0688	1.6771*	0.7183	0.0433	1.7484*	1.3557	-0.1871	0.9990	1.0489
Mbooni East	0.0543	0.8921	0.2928	-0.0095	1.7127*	1.2664	-0.3540	-0.2855	-0.3036
Mbooni West	0.1588	0.9991	0.4055	0.1536	2.3193**	2.0492	-0.2600	-0.2498	-0.4695
Mukaa	0.2437	2.2837**	1.0598	0.0307	2.6048***	2.2530	-0.1025	0.8207	0.8999
Nzaui	0.1153	1.9268*	1.1969	0.1695	1.6771*	1.8221	-0.1736	1.6771*	2.2616

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully eliminated

Table 4: Trend Analysis of Monthly Mean Precipitation in Makueni County sub-counties from 1991 to 2020

Sub-county	Tests	January	February	March	April	May	June	July	August	September	October	November	December
Kathonzweni	ACF	-0.1354	-0.2576	-0.2606	0.2464	0.0220	0.1193	0.0084	0.0196	0.0058	-0.1609	0.0082	-0.1791
	Zs	-0.1070	0.3211	0.7136	1.3202	0.3211	1.3202	-1.2489	0.9277	2.2837**	0.7136	-0.4282	-0.2141
	Qmed	-0.0590	0.0804	0.7475	1.7126	0.1458	0.0765	-0.0422	0.0476	0.2533	0.3295	-0.7458	-0.2038
Kibwezi	ACF	-0.1392	-0.0603	-0.3136	0.0358	-0.0730	0.0783	0.1021	-0.0186	-0.0462	-0.1700	-0.3260	-0.2442
	Zs	-0.4639	0.7136	0.7136	1.4272	1.1418	2.3028**	2.8210***	2.7374***	3.0288***	1.1061	-0.7493	-0.9277
	Qmed	-0.3888	0.1228	0.6264	1.6234	0.3173	0.0258	0.0224	0.0404	0.0897	0.2691	-1.8330	-1.6256
Kilungu	ACF	-0.1805	-0.2734	-0.3134	0.1918	0.0149	0.1425	-0.2092	0.0968	-0.0795	-0.0777	0.0744	-0.2072
	Zs	0.4282	0.2855	0.4639	2.3193**	-1.3559	1.3559	0.0000	0.8921	1.2846	0.3925	0.4282	-0.3568
	Qmed	0.3210	0.1465	1.0875	6.2392	-1.8722	0.1906	0.0085	0.1480	0.2491	0.5361	1.2655	-0.5470
Makindu	ACF	-0.2117	-0.1066	-0.3163	0.0605	-0.0343	0.2196	**0.4759**	-0.0811	-0.0637	-0.0464	-0.0009	-0.3227
	Zs	0.2855	0.8921	0.6780	0.6423	-0.1427	1.0171	-0.1688	-0.5352	0.7850	-0.2855	-1.6414	-0.9991
	Qmed	0.1230	0.0724	0.7390	0.4773	-0.0811	0.0220	-0.0688	-0.0079	0.0190	-0.0767	-2.3478	-2.1413
Makueni	ACF	-0.0291	-0.2984	-0.2146	0.1810	-0.1285	0.0345	-0.0942	0.0565	0.0552	-0.0438	0.0377	-0.2098
	Zs	1.3202	0.3211	1.1775	1.6057	0.7136	1.6057	0.3568	2.2480**	3.2297***	1.5700	0.7850	0.0357
	Qmed	0.6633	0.2054	1.0055	2.8898	0.4580	0.1930	0.0230	0.2625	0.4226	0.9800	1.3740	0.1624
Mbooni East	ACF	-0.1572	-0.3227	-0.2372	0.3072	-0.0241	0.0470	-0.1468	0.0999	0.1381	-0.1352	-0.1101	-0.3469
	Zs	0.7493	0.6780	0.7850	2.2480**	0.6066	1.6771*	0.4461	1.5343	2.6405***	0.6423	0.1427	-0.8564
	Qmed	0.4145	0.2903	1.3019	2.8760	0.3347	0.1187	0.0156	0.0908	0.2230	0.3944	0.4283	-1.0435
Mbooni West	ACF	-0.1925	-0.1001	-0.1724	0.1871	-0.0734	0.0741	-0.2013	0.0434	-0.1994	-0.0125	-0.2124	-0.3300
	Zs	-0.0357	0.2855	1.2489	2.7118***	0.3211	1.1061	0.1784	1.2846	1.8911*	0.2141	0.8921	-0.6780
	Qmed	-0.0225	0.1057	1.6379	4.5419	0.1633	0.1470	0.0065	0.1355	0.1553	0.2062	1.1905	-1.3241
Mukaa	ACF	-0.1409	-0.2613	-0.2325	0.1877	-0.2282	0.0834	-0.1906	0.0466	-0.1511	0.0398	0.0086	-0.1856
	Zs	0.9277	0.3925	1.0705	3.1757***	-0.8921	1.3559	0.2855	1.0348	1.6771*	0.8921	0.8207	-0.1070
	Qmed	0.4214	0.2412	2.0041	6.2547	-0.8574	0.2747	0.0155	0.1313	0.2438	0.8804	1.9771	-0.3465
Nzaui	ACF	-0.2252	-0.3023	-0.2772	0.2105	0.0470	0.1877	-0.0447	-0.0207	0.0240	-0.0437	-0.0411	-0.1261
	Zs	0.6423	-0.3211	0.6066	1.8555*	0.1070	1.3916	-0.8921	0.3925	2.3193**	1.4986	0.9991	0.0714
	Qmed	0.3186	-0.2564	0.7948	4.4704	0.1618	0.3731	-0.0976	0.1091	0.4171	1.4418	2.6721	0.4448

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully eliminated

3.4 Trend Analysis of Temperature in the nine sub-counties in Makueni County for the period 1991-2020

Temperature data between 1991 and 2020 was analyzed to determine the trends in annual, seasonal, and monthly minimum and maximum temperature. The results for the average monthly minimum temperature and those of the average monthly maximum temperature are presented in Tables 5 and 6 respectively. **Table 7** presents results for mean annual and mean seasonal temperature trends. Regarding mean monthly minimum temperature, eight (Kathonzweni, Kibwezi, Kilungu, Makueni, Mbooni East, Mbooni West, Mukaa, and Nzaui) of the nine sub counties exhibited an upward trend in all the twelve months with the increase being statistically significant in majority of the months (**Table 5**). Kibwezi, Kilungu, Mbooni West, and Mukaa sub counties for instance, showed a significant upward trend in all the twelve months. With the exception of Makindu sub county, all other sub counties exhibited a statistically significant upward trend in the months of January, February, August, September, and October. In the month of April, there was a significant upward trend in each of the nine sub-counties. Seasonally, all the nine sub-counties exhibited an upward trend in minimum temperature over the short rain season. This rise was statistically significant in seven of the nine sub counties (Kathonzweni, Kibwezi, Kilungu, Makueni, Mbooni West, Mukaa, and Nzaui). Similarly, all sub counties except Makindu showed a statistically significant increase in minimum temperature over the long rain season (**Table 7**). In terms of mean annual minimum temperature, seven (Kathonzweni, Kibwezi, Kilungu, Makueni, Mbooni West, Mukaa, and Nzaui) of the nine sub counties exhibited a statistically significant (1%) upward trend over the study period. The remaining two sub counties (Makindu and Mbooni East) also showed an upward trend that was however, not statistically significant. These results are a clear indication of rising temperatures in the regions of Makueni county.

Regarding maximum temperature, all the nine sub counties exhibited an increasing trend in all the months with the rise being statistically significant in various months as shown in **Table 6**. Eight (Kathonzweni, Kibwezi, Kilungu, Makindu, Makueni, Mbooni East, Mbooni West, and Nzaui) of the nine sub counties for instance, showed a significant upward trend in at least six of the twelve months. The months of January, November, and December were notably hot months across all the nine sub counties as they exhibited a statistically significant upward trend in these months. In December alone, the rise in temperature was significant at 1% level in all the sub counties while the trend in November was significant at 1% in seven of the nine sub counties (with the remaining two sub counties having an upward trend that was significant at 5% level). The month of July was also notably hot as eight of the nine sub counties showed a significant temperature increase in this month. In terms of seasons, mean maximum temperature during the short rain season showed an upward trend in all the sub counties. This trend was statistically significant in five (Kathonzweni, Kibwezi, Kilungu, Makueni, and Nzaui) of the nine sub counties. All the sub-counties exhibited a statistically significant upward trend in mean maximum temperature over the long rain season. Annually, all the sub counties showed a statistically significant upward trend in mean maximum temperature. This trend was significant at 1% level in eight sub counties (Kathonzweni, Kibwezi, Kilungu, Makindu, Makueni, Mbooni East, Mbooni West, and Nzaui), and at 10% level in one sub county (Mukaa). These results point to a significant hotter Makueni county with likely consequences of more severe droughts and reduced food productivity in a region that is already grappling with food insecurity issues.

Table 5: MK trend test result of the monthly minimum temperature of the sub-counties in Makueni County from 1991 to 2020

Sub-county	Tests	January	February	March	April	May	June	July	August	September	October	November	December
Kathonzweni	ACF	0.0260	-0.0340	0.0861	0.1021	-0.1910	0.0100	-0.1753	1.1082	0.2881	0.2098	0.3230	0.1137
	Zs	2.5334***	2.0696**	2.1052**	2.7832***	1.5700	1.2669	0.7136	2.3375**	2.3550**	2.5334**	3.6753***	2.5752**
	Qmed	0.0338	0.0300	0.0229	0.0345	0.0168	0.0172	0.0072	0.0266	0.0189	0.0353	0.0327	0.0666
Kibwezi	ACF	0.1504	0.0543	0.2869	0.1036	**-0.3743**	0.0499	0.0727	**0.5639**	**0.4316**	**0.4890**	**0.5200**	0.2259
	Zs	2.7832***	1.9982**	2.8372***	3.0870***	1.8195*	2.2305**	3.1757***	3.5078***	2.7950***	3.3952***	4.6332***	3.6753***
	Qmed	0.0419	0.0348	0.0436	0.0311	0.0251	0.0252	0.0263	0.0378	0.0287	0.0575	0.0477	0.0455
Kilungu	ACF	**0.3807**	**0.3797**	**0.3707**	**0.4059**	0.3486	0.0499	**0.4991**	**0.4552**	**0.6389**	**0.6364**	**0.6564**	0.3290
	Zs	2.0821**	3.9580***	2.7574***	3.5453***	3.3898***	2.2305**	2.9075***	4.4832***	4.5957***	4.5207***	3.5828***	3.7109***
	Qmed	0.0410	0.0803	0.0433	0.0521	0.0495	0.0252	0.0495	0.0759	0.0790	0.0749	0.0459	0.0602
Makindu	ACF	-0.1215	-0.0347	0.1283	-0.0177	-0.2958	-.0.1223	-0.1441	-0.1530	0.1813	0.1289	0.2897	-0.2014
	Zs	1.2132	0.8207	1.0528	1.6595*	-0.7850	-0.4282	-0.3925	0.3033	-0.7493	1.1418	2.2480**	0.8923
	Qmed	0.0207	0.0151	0.0141	0.0204	-0.0101	-0.0062	-0.0048	0.0022	-0.0079	0.0185	0.0225	0.0098
Makueni	ACF	0.0743	0.0188	0.0930	0.2099	0.0049	0.1535	-0.0607	0.1779	**0.3621**	0.2406	**0.3596**	-0.0840
	Zs	2.9442***	2.5691***	2.3019**	2.9259***	1.6771*	1.3202	0.9277	2.2123**	2.0071**	2.8372***	2.0071**	1.4273
	Qmed	0.0346	0.0362	0.0248	0.0377	0.0247	0.0230	0.0095	0.0298	0.0211	0.0401	0.2111	0.0194
Mbooni East	ACF	0.0379	0.0442	0.0784	0.1994	0.1039	0.1931	0.0461	0.2066	0.3523	0.2113	**0.3637**	0.0202
	Zs	2.1766**	1.9625**	1.4986	2.4264**	1.0348	1.3202	0.6245	1.7484*	2.1052**	2.1052**	1.1442	0.9277
	Qmed	0.0252	0.0338	0.0165	0.0302	0.0137	0.0180	0.0083	0.0277	0.0251	0.0355	0.0117	0.0152
Mbooni West	ACF	0.2913	0.3196	0.2208	**0.4043**	0.3458	0.3540	0.1843	0.2160	**0.5086**	**0.4933**	**0.5636**	0.0976
	Zs	3.0687***	4.4074***	4.1034***	3.5453***	3.1400***	2.1409**	2.0696**	2.9259***	5.5711***	4.3806***	5.0084***	2.3193**
	Qmed	0.0567	0.0715	0.0499	0.0445	0.0423	0.0420	0.0306	0.0477	0.0804	0.0693	0.0537	0.0315
Mukaa	ACF	0.2191	0.2172	0.2248	0.3365	0.2375	0.2704	0.1379	0.2253	**0.5041**	**0.4764**	**0.5176**	0.0054
	Zs	3.4439***	3.9964***	3.6753***	3.8893***	2.9973***	2.0696**	2.4264**	2.8546***	5.7212***	4.4457***	5.7212***	5.3166***
	Qmed	0.0532	0.0643	0.0487	0.0466	0.0383	0.0378	0.0309	0.0468	0.0758	0.0747	0.0674	0.0510
Nzaui	ACF	0.1043	0.0421	0.1092	0.2327	0.0268	0.1655	-0.0453	0.1740	**0.3684**	0.2723	**0.3746**	-0.0905
	Zs	3.0330***	2.9973***	2.6048***	3.1400***	2.1052**	1.4273	1.0348	2.2480**	2.6075***	2.9259***	2.9075***	1.6057
	Qmed	0.0408	0.0404	0.0296	0.0398	0.0260	0.0234	0.0107	0.0305	0.0262	0.0434	0.0319	0.0210

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully eliminated

Table 6: MK trend test result of the monthly maximum temperature of the sub-counties in Makueni County from 1991 to 2020

Sub-county	Tests	January	February	March	April	May	June	July	August	September	October	November	December
Kathonzweni	ACF	0.2082	-0.3147	-0.1327	-0.2621	0.1782	0.1146	0.0497	-0.1350	0.0770	-0.0117	0.1730	0.1130
	Zs	2.2837**	0.1427	1.3916	1.6771*	1.4097	1.8555*	2.7832***	2.3907**	2.0696**	1.6057	3.2114***	3.1941***
	Qmed	0.0589	0.0029	0.0379	0.0428	0.0226	0.0228	0.0450	0.0456	0.0249	0.0436	0.0628	0.0783
Kibwezi	ACF	0.2384	-0.1945	-0.1956	-0.3265	**0.3999**	**0.4742**	0.3247	0.2711	0.2958	0.2167	0.0516	0.3035
	Zs	3.6753***	1.2489	1.2489	1.5343	4.0330***	4.0330***	3.0870***	4.2462***	3.1043***	2.3907**	1.9625**	4.1391***
	Qmed	0.1053	0.0238	0.0340	0.0302	0.1300	0.1330	0.0545	0.0592	0.0403	0.0479	0.0478	0.0927
Kilungu	ACF	0.1338	-0.2224	-0.1627	-0.2378	0.1794	-0.0670	-0.0362	0.3575	0.2958	0.0955	0.3422	0.0737
	Zs	2.3193**	0.5709	1.2489	1.3916	2.5691***	1.0705	2.6405***	0.8921	3.1043***	1.4630	3.8180***	3.2471***
	Qmed	0.0513	0.0146	0.0403	0.0329	0.0401	0.0200	0.0521	0.0235	0.0403	0.0303	0.0682	0.0663
Makindu	ACF	0.1179	-0.2951	-0.1675	**-0.4384**	0.1093	0.3133	0.1324	0.0277	0.1012	0.0965	0.1062	0.1992
	Zs	1.8198*	0.4995	1.4273	1.8195*	0.7493	2.8546***	2.5334	2.8902***	2.0163**	2.4264**	2.9259***	3.0687***
	Qmed	0.0628	0.0113	0.0459	0.0643	0.0190	0.0389	0.0461	0.0537	0.0271	0.0488	0.0557	0.0859
Makueni	ACF	0.2175	-0.3028	-0.1635	-0.2348	0.2069	0.0841	0.1023	-0.0533	0.0862	0.0060	0.2054	0.2160
	Zs	2.6405***	0.3568	1.2846	1.5700	1.9625**	2.1766**	3.2471***	2.8189***	2.1052**	1.6057	3.3898***	3.6753***
	Qmed	0.0587	0.0092	0.0400	0.0418	0.0339	0.0304	0.0515	0.0513	0.0316	0.0455	0.0704	0.0804
Mbooni East	ACF	0.1407	-0.2923	-0.1064	-0.2803	0.2633	0.0778	0.0446	0.1224	0.0753	0.0534	0.1899	0.2214
	Zs	2.7118***	0.0000	1.1061	0.9277	1.1955	1.7127*	2.9259***	3.2471***	1.9625**	1.4630	2.9616***	3.5325***
	Qmed	0.0570	-0.0005	0.0394	0.0235	0.0174	0.0260	0.0513	0.0614	0.0320	0.0383	0.0645	0.0800
Mbooni West	ACF	0.1560	-0.2115	-0.1279	-0.3045	0.1320	-0.1506	-0.0881	0.0019	0.0315	0.1163	**0.3970**	0.0296
	Zs	2.3550**	0.3211	1.0348	0.6066	1.9268**	0.7850	2.7475***	1.8911*	1.3920	1.5343	2.1947**	3.2114***
	Qmed	0.0505	0.0111	0.0401	0.0209	0.0259	0.0143	0.0561	0.03473	0.0167	0.0339	0.0536	0.0602
Mukaa	ACF	0.1352	-0.1871	-0.1212	-0.2468	0.1434	-0.0477	-0.1189	0.0191	0.1446	0.1552	0.2996	0.0645
	Zs	1.9625**	0.2498	0.9277	1.0348	1.6314*	0.2498	2.0339**	1.0348	0.1427	0.9991	3.2471***	3.0687***
	Qmed	0.0470	0.0072	0.0322	0.0286	0.0327	0.0075	0.0454	0.0231	0.0044	0.0240	0.0561	0.0625
Nzaui	ACF	0.2159	-0.2940	-0.1621	-02200	0.1892	0.0433	0.0447	-0.1153	0.0666	0.0131	0.2047	0.1864
	Zs	2.5334***	0.4282	1.1599	1.4986	1.7484*	1.6414*	3.0330***	2.4977***	1.7841*	1.6771*	3.3898***	3.5682***
	Qmed	0.0524	0.0080	0.0444	0.0442	0.0300	0.0255	0.0492	0.0459	0.0241	0.0396	0.0701	0.0833

ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully eliminated

Table 7: Trend Analysis of Mean Seasonal and Annual Temperature in Makueni County sub counties from 1991 to 2020

Temperature	Tests	Kathonzweni	Kibwezi	Kilungu	Makindu	Makueni	Mbooni East	Mbooni West	Mukaa	Nzaui
					Annual					
Tmax	ACF	**0.4787**	**0.6304**	**0.3729**	**0.4840**	**0.5147**	**0.4729**	**0.4460**	**0.4038**	**0.4859**
	Zs	3.8079***	4.9334***	3.0200***	2.8325***	4.7833***	3.8829***	2.7574***	1.7820*	4.2206***
	Qmed	0.0474	0.0582	0.0387	0.0363	0.0569	0.4441	0.0356	0.0234	0.0498
Tmin	ACF	**0.4597**	**0.5458**	**0.7297**	0.1413	**0.5787**	**0.5687**	**0.7182**	**0.6988**	**0.5896**
	Zs	3.6578***	4.2956***	3.5828***	1.0348	2.7950***	0.3564	4.4457***	5.4211***	3.3577***
	Qmed	0.0274	0.0317	0.0275	0.0090	0.0216	0.0017	0.0410	0.0533	0.0278
					Short Rain Season (MAM)					
Tmax	ACF	-0.0178	0.0470	-0.0629	-0.0864	-0.0391	-0.0586	-0.0974	-0.0250	-0.0284
	Zs	1.8555*	2.0696**	1.8198*	1.5700	1.7484*	1.2846	0.9277	1.4273	1.8198*
	Qmed	0.0370	0.0464	0.0361	0.0315	0.0420	0.0276	0.0185	0.0288	0.0414
Tmin	ACF	0.1913	-0.0101	0.4996	-0.0094	**0.3785**	**0.4285**	**0.6050**	**0.5022**	**0.3871**
	Zs	3.1043***	3.5152***	3.4227***	1.3559	2.7950**	0.2063	4.2206***	4.7458***	3.4702***
	Qmed	0.0268	0.0322	0.0400	0.0114	0.0225	0.0016	0.0447	0.0525	0.0300
					Long Rain Season (OND)					
Tmax	ACF	0.1583	0.3286	0.2285	0.2028	0.2128	0.1732	0.2456	0.2151	0.2009
	Zs	3.4255***	3.7109***	3.6396***	3.7109***	3.7466***	3.4255***	3.3898***	2.9616***	3.7109***
	Qmed	0.0571	0.0552	0.0572	0.0508	0.0636	0.0550	0.0564	0.0459	0.0623
Tmin	ACF	0.1074	0.4771	0.5978	0.0703	0.1728	0.1944	**0.4302**	**0.3814**	0.1930
	Zs	3.0330***	4.7458***	4.5957***	1.5700	2.8546***	1.8911*	4.4081***	5.3836***	3.0687***
	Qmed	0.0303	0.0588	0.0652	0.0163	0.0300	0.0264	0.0595	0.0742	0.0313

Tmax = maximum temperature; Tmin = minimum temperature; ACF = Autocorrelation Coefficient; Zs = Mann-Kendall trend test; Qmed = Theil-Sen's slope; MAM = March, April, & May; OND = October, November, & December; * = significant at 10%; ** = significant at 5%; and *** = significant at 1%. Bold numbers indicate presence of serial correlation, but it was successfully eliminated

3.5 Discussion

Though statistically insignificant, mean annual rainfall in Makueni county exhibited a declining trend. Similarly, monthly mean precipitation was found to be on a downward trend in most of the months, albeit statistically insignificant. Rainfall trend in both the short and long rain seasons showed a gradual reduction. These findings are consistent with existing literature. A study by Recha, *et al*., (2016), for example, showed a declining rainfall pattern in the county over the preceding five decades. Similarly, a study by Abuya, (2021) reported declining rainfall in the county for the period between 1985 and 2015. The current study through household surveys and key informant interviews also established that the frequency of drought occurrence in the county has increased over the last ten years. This observation corresponds with that of Mutua et al., (2016) and GoMC, (2018) who reported an increase in the frequency of drought over the last three decades with rainfall patterns falling far below normal.

Although mean annual rainfall in the entire Makueni County exhibited a declining trend, some sub counties (Mukaa, Nzaui and Makueni) within the county experienced a statistically significant upward trend. This variation can be explained by the ecological zonation of these sub counties. The terrain in these sub counties which border each other consist of several forested hills including Makuli, Nzaui, Mbitini, and Kilungu among others, that play a key role in climate regulation. These findings are consistent with existing literature (GoMC, 2012, GoMC, 2019) as these regions which form part of the upper regions of Makueni county receive more rainfall than the low-lying areas of the county. A rather intriguing observation was made regarding seasonal rainfall trends in the sub counties, as all of the sub counties exhibited an increasing rainfall trend over the short rain season, with the increase being statistically significant in five (Makueni, Mbooni East, Mbooni West, Mukaa and Nzaui) of the nine sub counties. Further investigation through household surveys and interviews confirmed these findings, as participants claimed that they no longer relied on the long rain seasons as they had in the past, since rainfall during this period reduced significantly while increasing during the short rain seasons. A report by the Kenya Forestry Research Institute points out that the short rain seasons in Makueni County are more reliable since 60% of the annual rainfall in the area is experienced during this season (KEFRI, 2023). These findings indicate that climate variability and change are a reality in Makueni County, and needful adjustments are inevitable if the effects of climate change are to be effectively mitigated.

Regarding temperature (minimum and maximum) patterns, this study revealed a statistically significant upward trend in mean annual and seasonal (both short and long rain seasons) temperatures for Makueni County over the study period. Mean monthly temperature patterns also exhibited an increasing trend that was statistically significant in most of the months. Similarly, mean annual, seasonal and monthly minimum and maximum temperature trends were on a rising trajectory in all sub counties with the trend being statistically significant in most of the observations. These findings indicate a warming Makueni county. The findings are consistent with existing literature as temperatures in the county have been reported to be on a rising trend over the last few decades (MoALF, 2016, GoMC, 2022). These patterns have led to heat stress, reduction in crop cycle time, and emergence of new plant species, pests and diseases, all leading to reduced agricultural productivity and associated food insecurity, loss of livelihoods and heightened poverty levels (MoALF, 2016).

Conclusion

This study examined the annual, seasonal, and monthly trends of rainfall, minimum temperature, and maximum temperature in Makueni County from 1991 to 2020. The findings of the study provide solid evidence of an increase in temperature and a decline in rainfall in the entire Makueni county and some variabilities in seasonal rains in the sub counties. This is a clear indication of a changing climate in Makueni County. These findings can be used as a reference in policy decisions that relate to climate change mitigation and adaptation especially in the field of agriculture, and water use and management. Interventions like climate-smart technologies and innovative water harvesting techniques should be fronted and adopted in order to increase resilience of the population in the arid and semi-arid regions of Makueni county. Provision of alternative livelihoods outside rainfed agriculture should also be enhanced in order to reduce households' vulnerability to climate change effects.

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