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Drought Frequency and Persistence in the Upper River Tana Basin in Kenya

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Drought is an abnormal low rainfall condition over an extended period of time in the Upper River Tana basin in Kenya as distinct from aridity, which is a condition of spatial low average moisture availability, is the focal area of study. This study evaluated drought frequency and its persistence using local farmer's information, daily rainfall data and mean river discharges. The drought was analyzed using data on agricultural activities, daily rainfall and mean daily discharges. The data analysed using a number of tools and these were cross-tabulation, frequency analysis, Cramer's V and Phi statistics, Control chart, and Time Series techniques in order to determine drought periods, frequency and persistence. The results indicate that drought is a meteorological phenomenon of Upper River Tana basin hydro-climate conditions as well as its socio-economic set up. The definition of drought and therefore meanings of drought, however, vary by agro-climatic zones, socio-economic activities, rainfall conditions, and hydrological characteristics. The frequency of drought in all cases tends not to have a definite pattern and therefore less predictable while persistence tends to be restricted to a water year. Most drought episodes identified are widespread and thus confirming the fact that drought is an issue in the study area. Drought episodes tend to

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occur at the beginning and at the end of a decadal period and in some cases tend to portray persistence beyond the calendar year but not beyond a water year. These results have implications for planning farming activities.

Keywords: Drought frequency; persistence; Cramer's V and Phi statistics; time series.

1. BACKGROUND

Drought occurrence is part of the general circulation of the earth-atmosphere system [1,2], (Gregory 1986), and [3,4]. Variations in drought episodes are examined in terms of severity, persistence, and frequency of occurrence. There is no universal definition of drought and, lack of precision in measuring drought frequency in a geographical area, makes drought difficult to determine accurately its beginning and or the end hence determining its frequency and persistence (UNDP, 1977) [5]. It is an extended drought episode into following water year that creates a condition of desiccation which degenerates in to an ecological imbalance [2,6]. In Africa, drought has always been associated with disaster, and more particularly famine, social disruptions, refugees' problem and environmental degradation in the available literature.

It is common to link drought frequency to the 11-year solar cycle, the El Niño-Southern Oscillation (ENSO), and or climatic variations [7,8,9] (Gregory, 1986; etc.). However the link of frequency and persistence of drought to events such as solar cycle, *El Niño*, Southern Oscillation, and climatic change are still subject of scientific discussions [1,10,11,12]. Attempt to identify the variations in drought frequency and persistence in the Upper Tana catchment in the various climatic regimes focus on the meteorological conditions and crop agriculture. One of the limitations of the paper is the determination of onset and end of a drought episode due to the creeping nature of the phenomenon (Zewde, 1976, Baker, 1977,) [13,3]. Daily data records have been used to determine the beginning and end of drought.

2. METHODS OF DATA COLLECTION

The field survey in Upper Tana catchment, and Department of Kenya Meteorological Service (KMS) provided mean daily rainfall and river discharge data. A sample of 480 administrative units was used in a three-stage process of making field observations; executing questionnaires and carrying out validity tests. The sampled units were used for gathering hydro-meteorological data of at least 30-year period. Information from local farmers, agricultural field officers, hydrologists and Kenya Power Generation (KENGEN) field officers. Rainfall and river discharges were obtained from meteorological and river gauging stations with consistent records ≥ 30 years. The stations used in this study include 4AB05, 4AC04, 4AD01, 4BB01, 4BC04, 4BD06, and 4BE01.

The results of the descriptive data analyses are the bases for higher statistical techniques of drought analysis. Most of the field data on drought are measured at the nominal and ordinal level thus the use of Cramer's V as measure of association based on χ^2 (chi-square) distribution and φ (Phi) also based on χ^2 distribution.

Let a sample of size *n* of the simultaneously distributed variables A and B for $i = 1, \ldots, r; j = 1, \ldots, k$ be given by the frequencies $n_{ij} =$ Number of times the values (A_i, B_j) were observed.

The chi-squared statistic then is:

$$\chi^2 = \sum_{i,j} \frac{(n_{ij} - \frac{n_{i.} n_{.j}}{n})^2}{\frac{n_{i.} n_{.j}}{n}} \quad (1)$$

Cramer's V is computed by taking the square root of the chi-squared statistic divided by the sample size and the minimum dimension minus 1:

$$V = \sqrt{\frac{\varphi^2}{\min(k-1, r-1)}} = \sqrt{\frac{\chi^2/n}{\min(k-1, r-1)}} \quad (2)$$

Where:

- φ^2 is the phi coefficient.
- X^2 is derived from Pearson's chi-squared test
- *n* is the grand total of observations and
- *k* being the number of columns.
- *r* being the number of rows.

$$\varphi = [\chi 2/n]^{0.5} . \quad (3)$$

Sometimes phi squared is used as a measure of association, and phi squared is defined as

$$\varphi^{2} = [\chi 2/ n]^{0.5}. \quad (4)$$

Field information on rainfall periods, rainfall adequacy and exceptional low rainfall which are ordinal measures are subjected to χ^2 test as a measure of difference between different agro-climatic zones of Upper Tana at α _ 0.05.

2.1 Drought Analysis

The drought were parameterised according to deciles range techniques, weighted rainfall standardised anomalies index and the standardised rainfall anomalies techniques, The control chart technique used as a measure of deviation from the expected daily rainfall and river discharges. The lower limit of the control charts at 2 sigma marks the lower index for both the mean and standard deviations, and below which a drought condition is indicated. The computed lower limits of both mean and the standard deviation define the lower thresholds of rainfall and river discharge.

Time series analysis technique has been computed to determine the components of the rainfall and river discharges. Spectral analysis has been used for frequency and persistence of an extended abnormal low rainfall and low river flow. Periodograms for daily rainfall data and mean river flows at all the stations were generated in which low-frequency variation is characterised by a smooth series while a random effect (white noise) is characterised by variation spread evenly across all frequencies. A spectral density plot is then generated by smoothing (moving average and exponential) the respective periodograms basing the process on the Holt model that assumes linear trend and no seasonal variation for daily rainfall. In the case of river flows, autoregressive smoothing is used to estimate linear regression model with the first order autoregressive errors based on the ARIMA model.

River flow data is also subjected to difference smoothing with the degree of differencing in all cases being 1 but experimental analysis at 3 are also used to test the limits of differencing applicable. The isolate the main drought periods in the daily rainfall series and the daily river flow series, cluster analysis techniques is used. An integrated meaning of drought that makes sense in terms of drought management and adaptation would require that locals indicate their experiences of exceptional low rainfall and river flow periods Exceptional low rainfall conditions impacts on human activities and water deficiency The human activities include crop agriculture, livestock and pasture availability, drying up of vegetation, and lack of water supply both for human beings and livestock.

3. RESULTS AND DISCUSSION

3.1 Local Perception of Drought Frequency

Only 54% of the respondents are aware of the occurrence of exceptional low rainfall while 33.5% and 16.1% are not aware and sometimes aware respectively. There is variation in drought experiences observed in various agro-climatic zones. The high rainfall areas to the west such as Nyeri and Thika are less likely to have experienced drought than the low rainfall potential areas to the east such as Meru and Tharaka Nithi, probably due to the influence of altitude and direction of prevailing moisture-laden winds. The results of phi and Cramer’s V statistical analyses confirmed the strong association between drought occurrence and geography.

The local knowledge on drought occurrence was assessed using calendar periods of exceptional low rainfall conditions. Except for the 1980’s and 1990’s, the recorded highest incidences of drought occurrences were between 1983-1984 and 1993-1994 periods. The characterisation of drought conditions tended to vary with agro-climatic zones as well as by the main agricultural activities although reference to maize crop tended to be universal. The effects associated with exceptional low rainfall periods in the Upper Tana include poor harvest, crops failure, death of livestock/famines, dropping of river levels, lack of pasture, total lack of rainfall, vegetation drying up, scarcity of water and no rainfall seasonality. Fig. 1 shows the periods of exceptional low maize harvests due to exceptional low rainfall periods in Meru.

3.2 Drought Frequency and Persistence

3.2.1 Local perception on drought frequency and persistence

Most local farmers have no idea on the frequency of drought (63.5%). This result means that most locals in upper Tana may not be

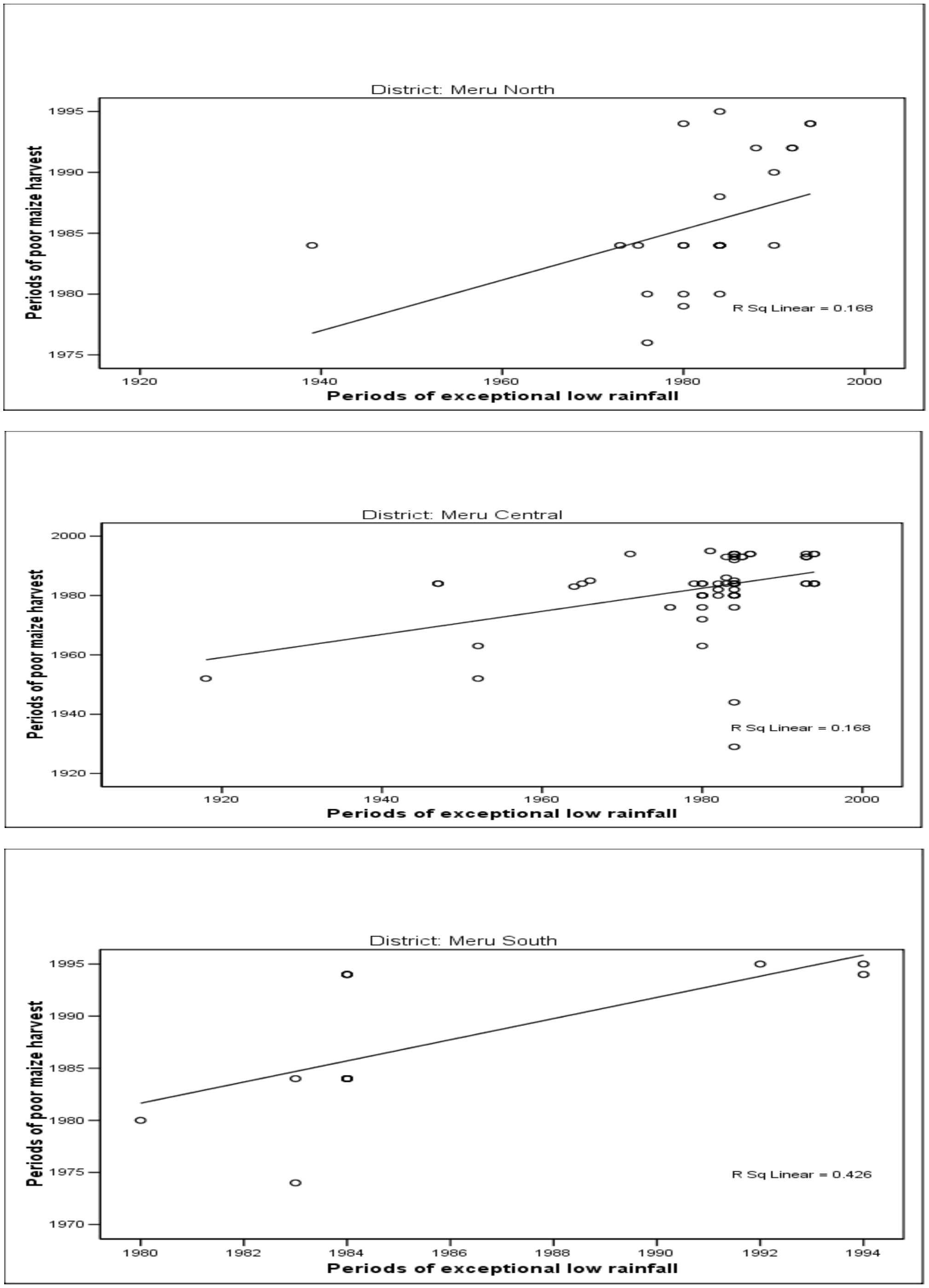


Fig. 1. Periods of exceptional low maize harvests by exceptional low rainfall periods in Meru North, Central and South

expected to respond adequately to drought effects and drought management initiatives. 94% of the respondents had no knowledge of the frequency of periods of exceptional low rainfall periods while 35% had the awareness. The respondents gave a wide variety of answers on the frequency although majority tend to give a return period of 10 years but cumulatively the 2-5 years return period dominates. The wide variations in the answers indicate that drought frequency is not a well-established local knowledge and spatial variability of drought episodes. The link between drought frequency with global phenomena such as the 11 year solar cycle, the Southern Oscillation, El Niño, and Climatic variations [7,8,9], (Gregory, 1986) are not direct The lack of definite rhythm in drought cycles makes drought frequency to be more of a probable event.

The idea that drought tends to be more frequent and has a higher probability of occurrence in the semi-arid and sub-humid lands [12] have led to the perception that drought is a problem of the semi-arid and sub-humid lands. This study presents variations of drought frequency and persistence in diverse agro-climatic zones. In Upper Tana, the drought persistence cannot be established with certainty as the general response to the question of duration of drought episodes that have indicated. Droughts tend to last from 1 year to two years conforming to the general observations in Eastern Africa [14,15,16]; (Flohn, 1964) [10,11].

3.2.2 Meteorological drought frequency and persistence

To establish the normal rainfall conditions for each station used in the study, control plots at 2 standard deviations from the expected are generated using daily rainfall records for the period 1957-1987 (30 years of record). Daily rainfall variations within the lower and upper rainfall intervals are considered normal while conditions outside the intervals were treated as outliers and therefore abnormal. If a condition is below the lower control limit at 95% confidence level, then that condition in this study is considered as a drought episode.

Fig. 2 shows that January-February period is generally the driest period with rainfall data, mean rainfall ranging from 1.8 mm at Kiritiri Chief's Camp (9037039) to 11.46 mm at 9036271 (Kiandongoro Gate, Aberdares National Park). The mean rainfall in February ranged from 2.53 mm at Nyakio Estate (9037010) to 14.28 at 9036271 (Kiandongoro Gate, Aberdares National Park). The March-May period is normally the long rains time with the daily rainfall mean ranging from 6.55 mm at Lare (Meru, 9037041) to 20.45 mm at 9036271 (Kiandongoro Gate, Aberdares National Park).

The long term daily mean rainfall for all stations in the region (Fig. 3) are used in establishing the upper and lower limits within which rainfall conditions are considered normal and outside which the conditions are abnormal. It is the lower limit at 2 sigma which is used to identify drought conditions in the Upper Tana Catchment. The identified periods of drought are then be used to generate drought frequency and persistence measure.

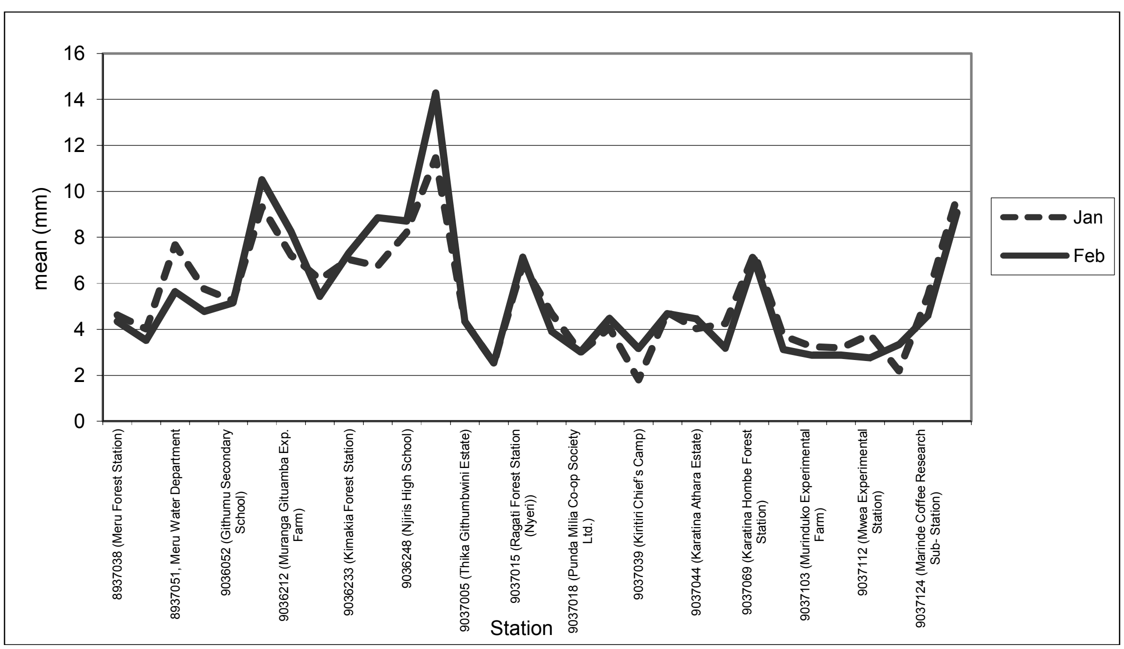


Fig. 2. Long term daily mean rainfall in January-February at Stations in Upper Tana Catchment

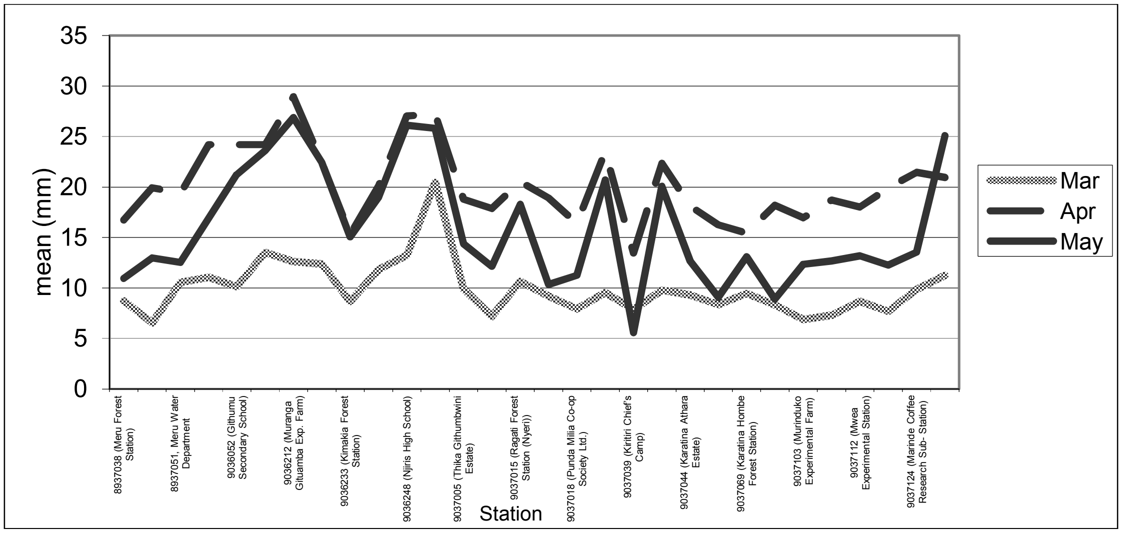


Fig. 3. Long term daily mean rainfall in March-May at Stations in Upper Tana Catchment

Fig. 4 show that there are two rainfall periods and a third possible rainfall period in the August-September period. The third rainfall period is best shown by the results of the lower control limits of the daily rainfall standard deviations, probably due to a localised effect associated with systems generated by Mount Kenya and other relief features. This not well defined rainfall period is crucial in land preparation as well as in the planting of legume crops in Upper Tana catchment. The standard deviation captures the daily rainfall variations that may define meteorological drought in the catchment. Other indices of meteorological drought have been used before [17].

Distributions within the control limits are treated as normal and those outside the limits were treated as outliers and therefore abnormal. Rainfall distributions above the upper limit of the

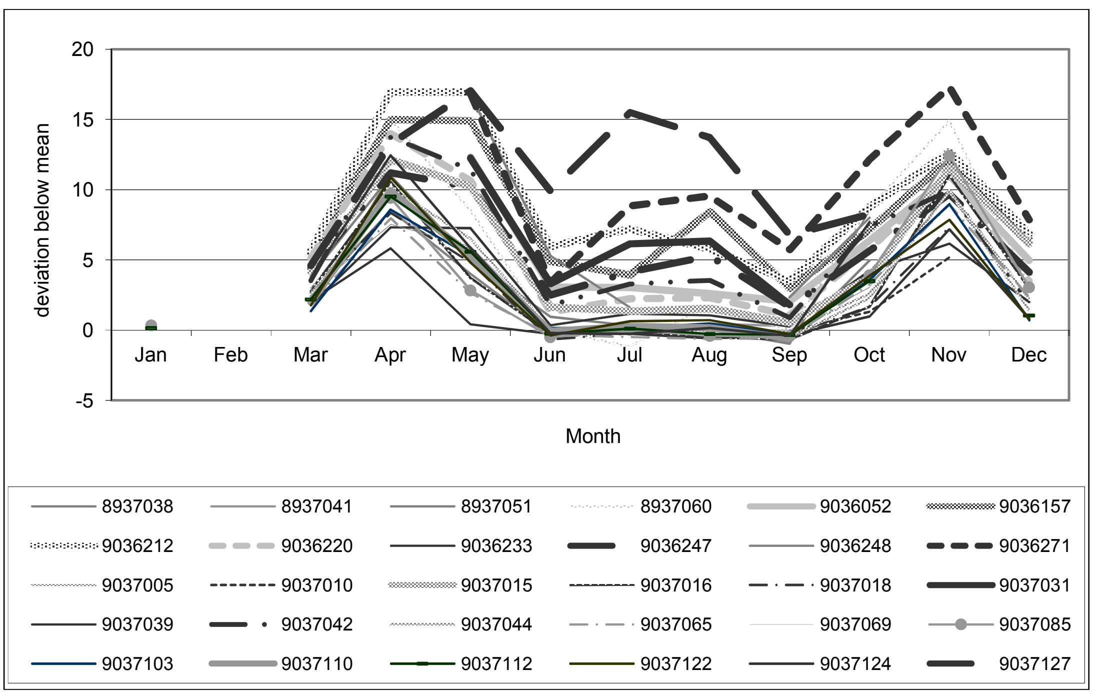


Fig. 4. Deviations below the lower limit of the long term mean (at 95% confidence level)

control plot can lead to flooding either in situ or in the lower reaches of the catchment outputs.

A two way cluster analysis of the periods of drought occurrence by month in Upper Tana Catchment results in 5 clusters being identified of which the below lower limit of the mean centred about 1961, 1971, and 1974 while periods 1950-1951 and the below lower limit of the standard deviation centred around 1951, 1966, 1967, 1969, and 1970. When the below lower limits are combined, the period around 1970 and 1974 accounts for most of the drought episodes in Upper Tana Catchment during the period of study.

Clusters when ranked by attributes indicated that cluster 3 is the most occurring followed by cluster 5. The pie chart below represents the cluster frequencies or size in a two-step analysis (Lower limit of the mean and lower limit of the standard deviation). However, clusters when considered in terms of drought episodes by stations (within cluster percentage) indicates that most contributing stations are in the relatively dry lower areas of Upper Tana Catchment but there is no clear separation. The meaning of this is that most drought episodes identified in the study are widespread and thus confirming the fact that drought is an issue in the Upper Tana Catchment as has previously been observed from the field data analysis results. By months, cluster 3 is mostly accounted for by the month of March, January and August, which are months of planting and land preparation in the Upper Tana Catchment. When the confidence intervals of the lower limits of the mean are taken into account, the results are that most drought episodes tend to occur within three years (±) lower limits from 1971.

Ranking of clusters by stations is measured by using the Bonferroni adjustment and this indicates that many of the stations recording drought conditions in 1961(lower limit of the mean) and 1951 (lower limit of the standard deviation). A difference test (Student's t-test) indicated cluster 1 and cluster 3 as the most significant clusters in drought episodes identified by both the mean and the standard deviation lower limits.

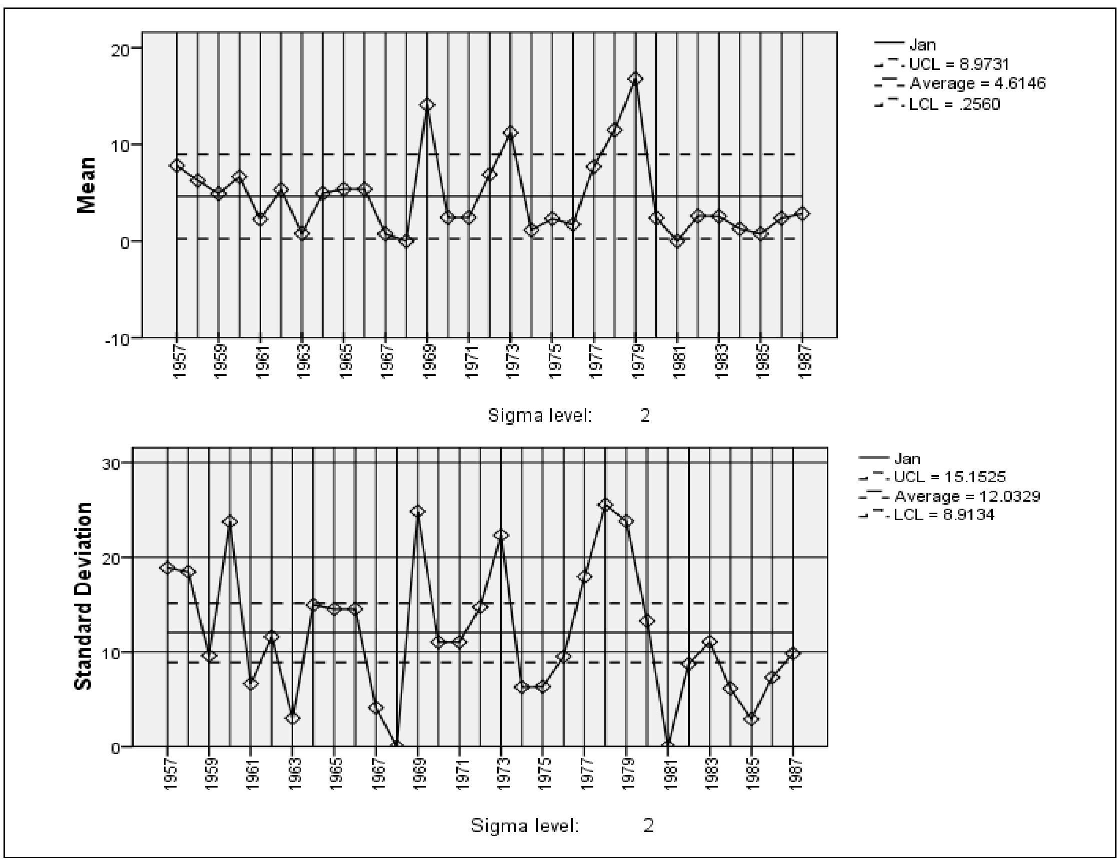


Fig. 5. Control plot of the daily rainfall in January at station 8937038

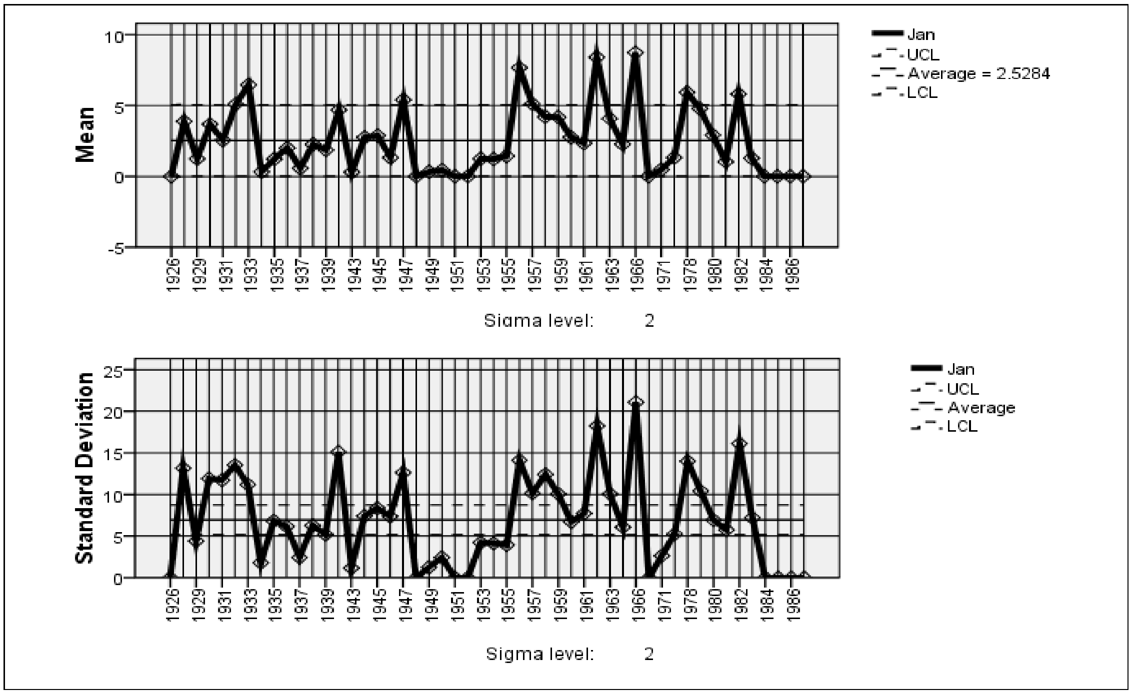


Fig. 6. Control Plot of the Daily Rainfall in January at station 9037010 (Nyakio Tea Estate; a control station in the study)

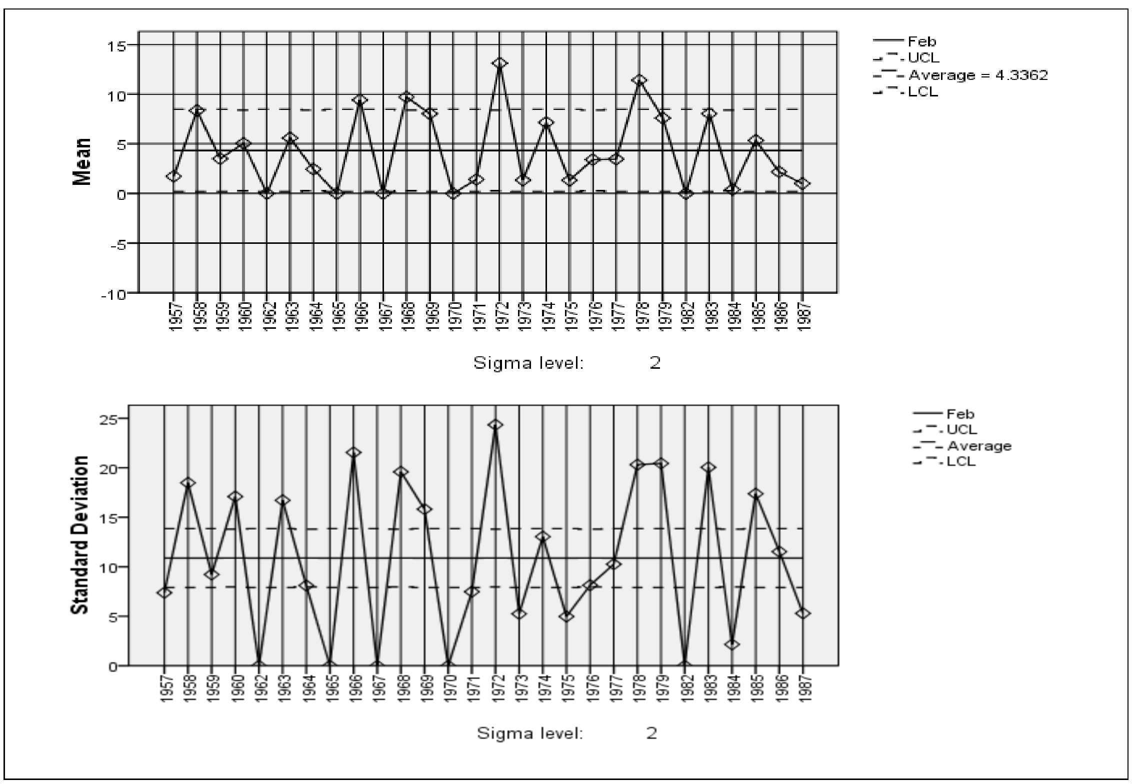


Fig. 7. Control Plot of the Daily Rainfall in February at station 8937010 (Nyakio Tea Estate; a control station in the study)

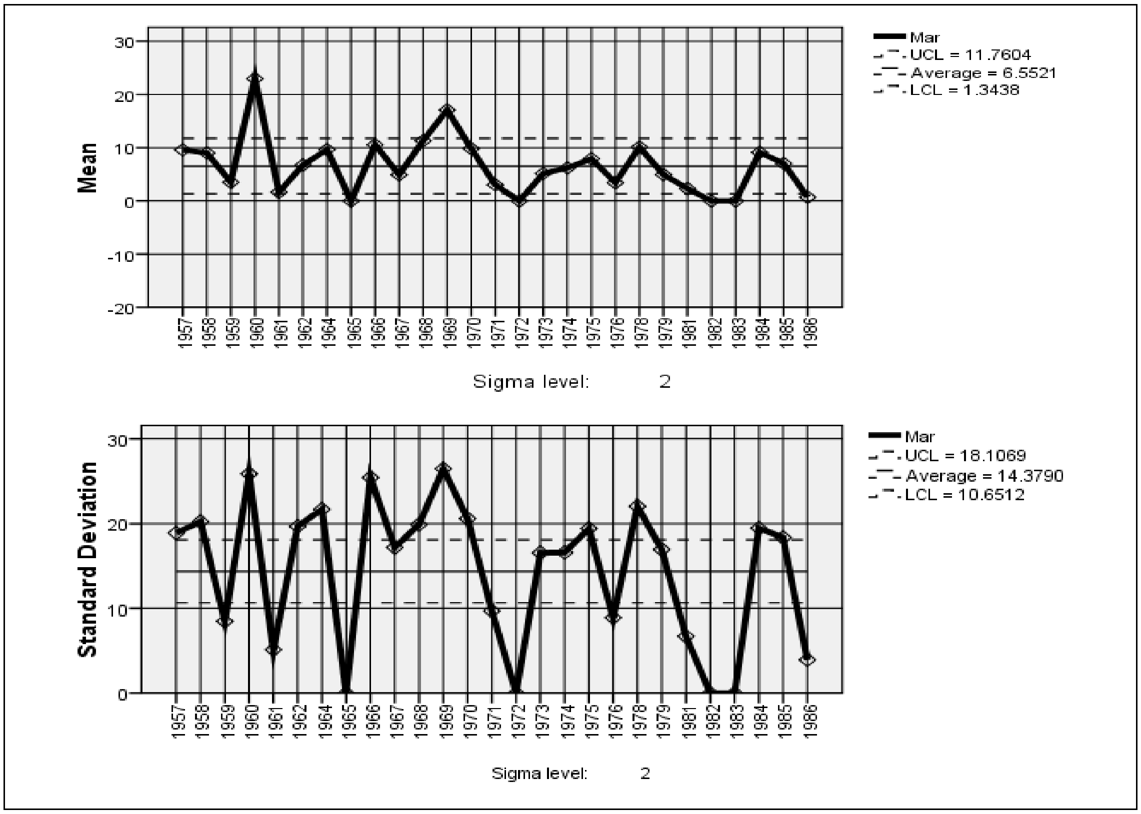


Fig. 8. Control plot of the daily rainfall in March at station 8937041 (Meru Muchiimukuru)

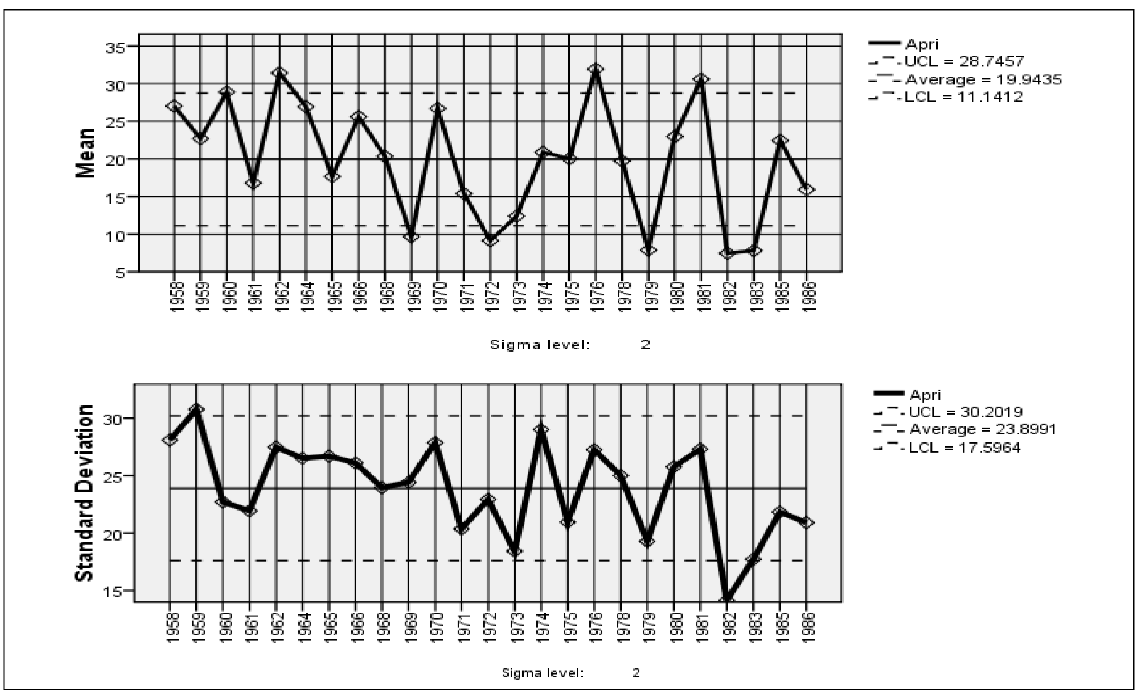


Fig. 9. Control plot of the daily rainfall in April at station 8937041 (Meru Muchiimukuru)

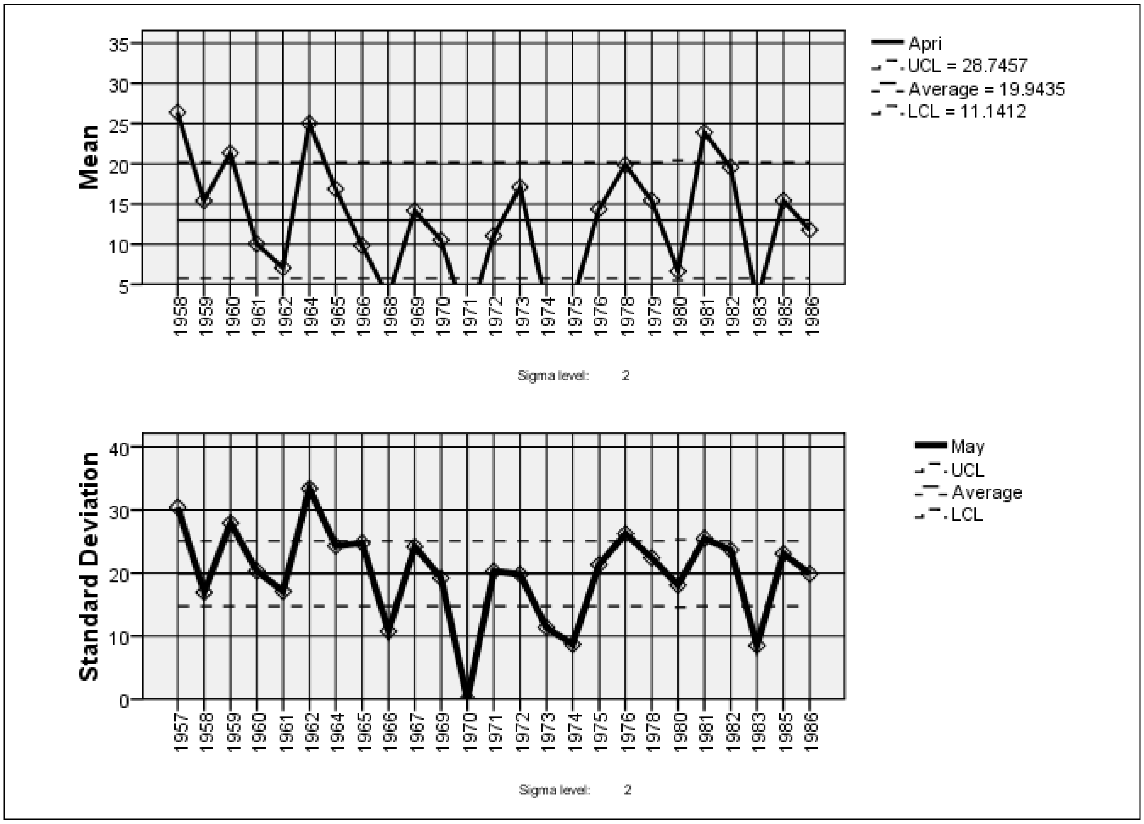


Fig. 10. Control plot of the daily rainfall in May at station 8937041 (Lare, Meru)

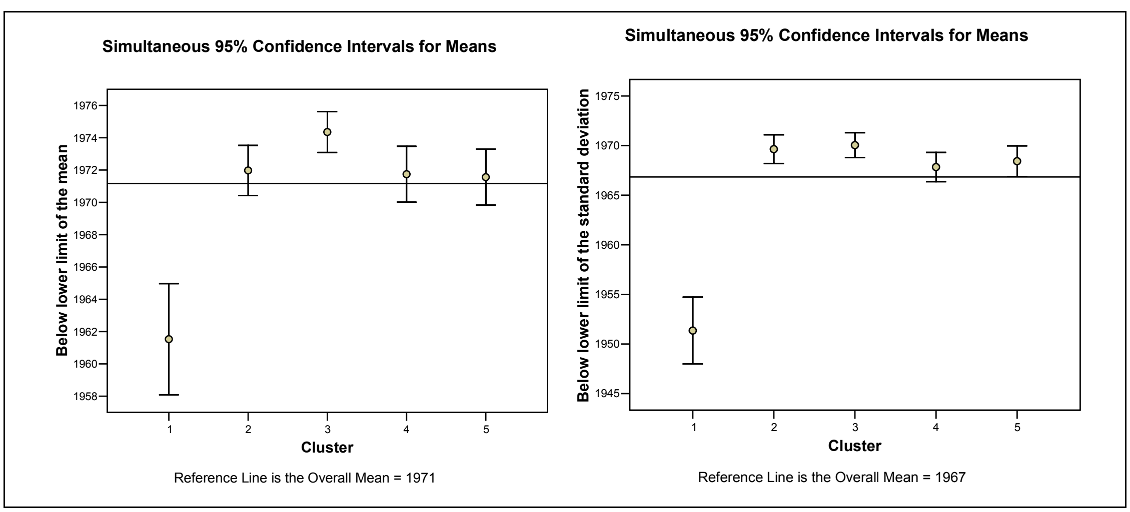


Fig. 11. Confidence Intervals for lower limits of the mean and standard deviation

3.2.3 Hydrological drought frequency and persistence

After establishing the meteorological drought periods and frequency, attempt is made to identify periods of hydrological drought in the Upper Tana as the region accounts for about 70% of the hydropower generation in Kenya. The time series plots of daily river volume discharges for January to December (natural log transform plots) indicate irregular flow discharges but with signs of periods of low flows alternating with periods of high flows as has already been indicated in the meteorological drought analysis and in the general descriptive analysis of river discharges in Upper Tana above. The early 1950s, early and late 1960s, early 1970s, early 1980s and the 1990s all showed signs of low river discharge flows which could have been hydrological drought conditions.

Characteristic of both low flow discharges and high flow discharges is indication of persistent in either a downward or upward flows within which there can be variations. That is, if there is an indication of low flow discharges, this tends to continue for some times but with irregular up flow discharges in the general depressed flow conditions and the inverse is true of high flow discharges conditions. The implications of this was that at times of low flow discharges, there were some indications of irregular relative high flows and the inverse is true of high flow indications. This can in effect lead to easing off emergency measures taken in response to low or high river discharges and it can be in these periods of irregular "soundings" that disastrous effects of drought or floods can occur.

The series plots above indicate irregular variations in the daily mean flow at several stations in Upper Tana. To smoothen the irregular variations, the study first use a running median (not the mean due to extremes) to create new variables. The effect of running median (lag time being 10 days) indicate more pronounced below mean conditions than above mean conditions. The overall picture is that the duration of low flows below the expected tend to last longer than the above average but the above average tend to be more severe as demonstrated in the Fig 15.

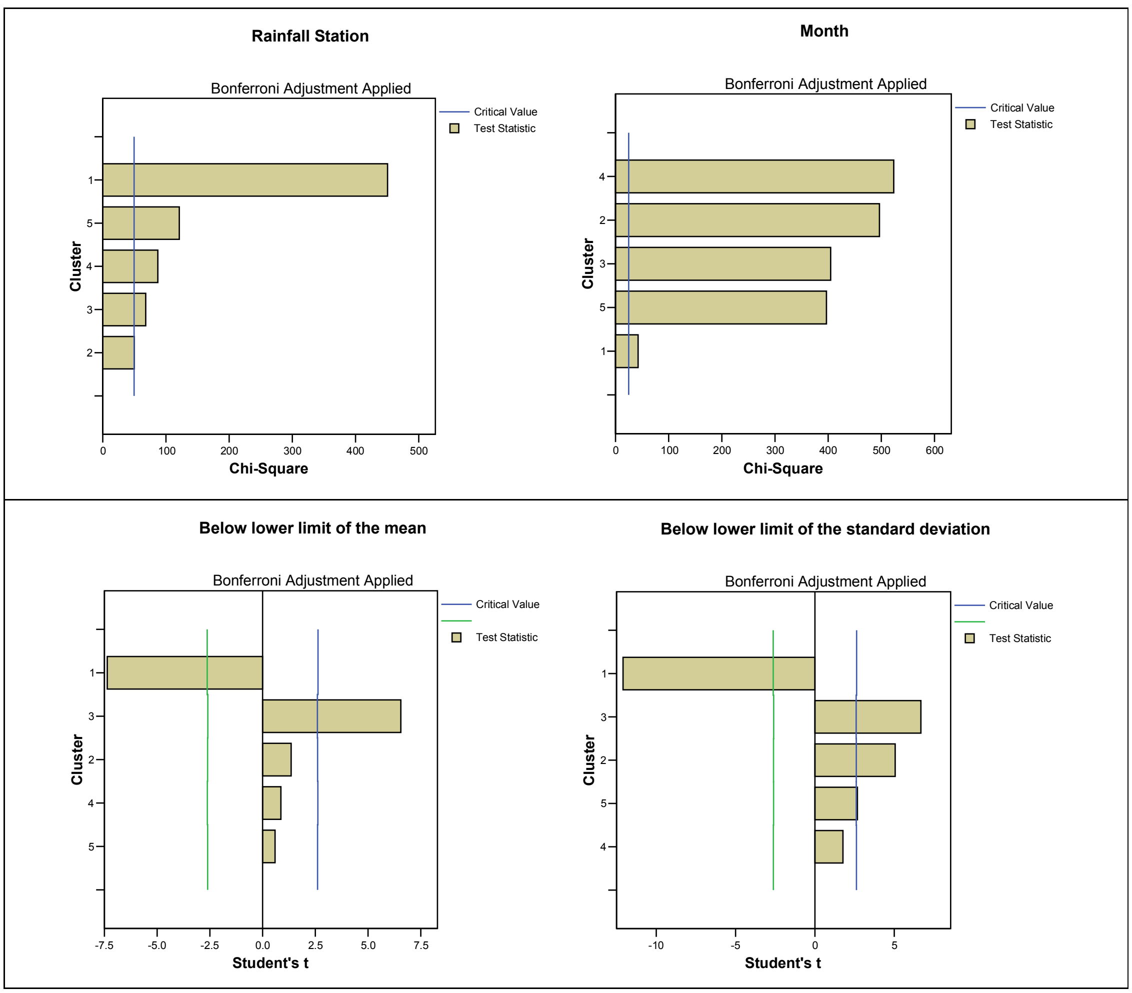
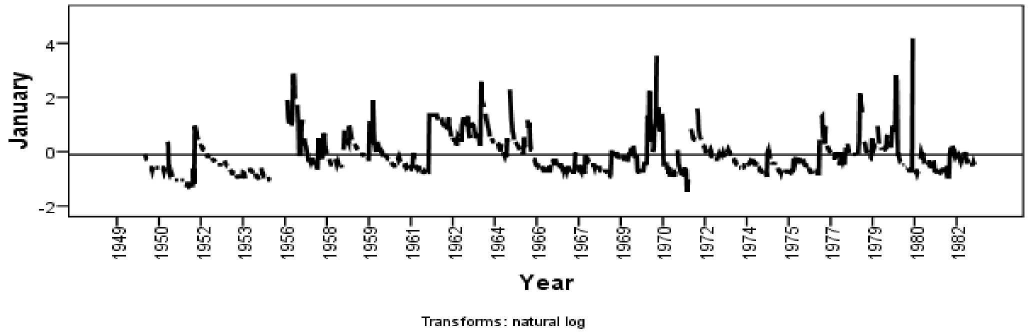
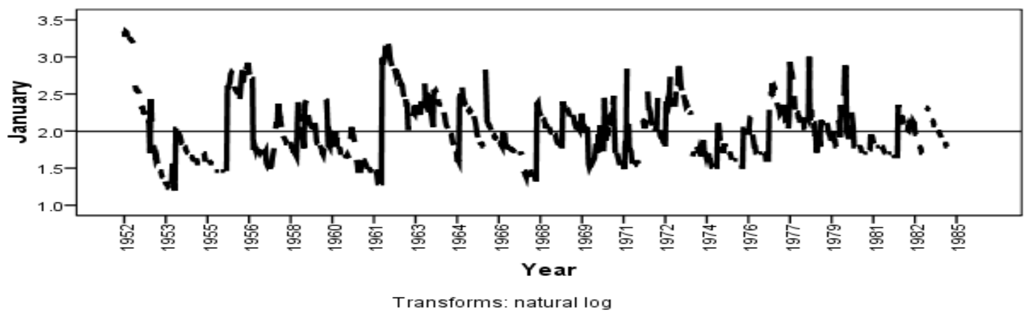


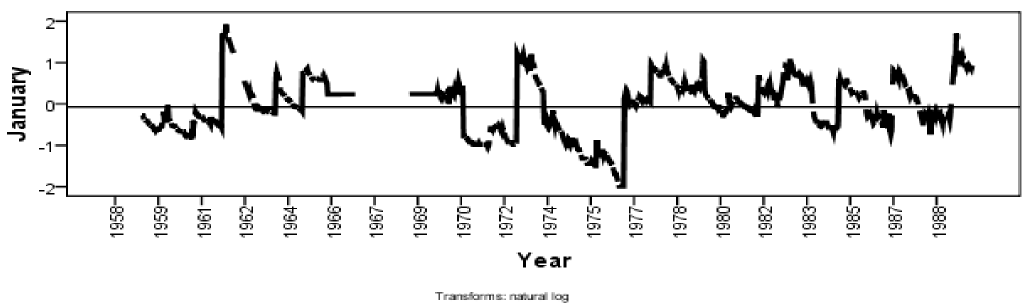
Fig. 12. Clusterwise Importance



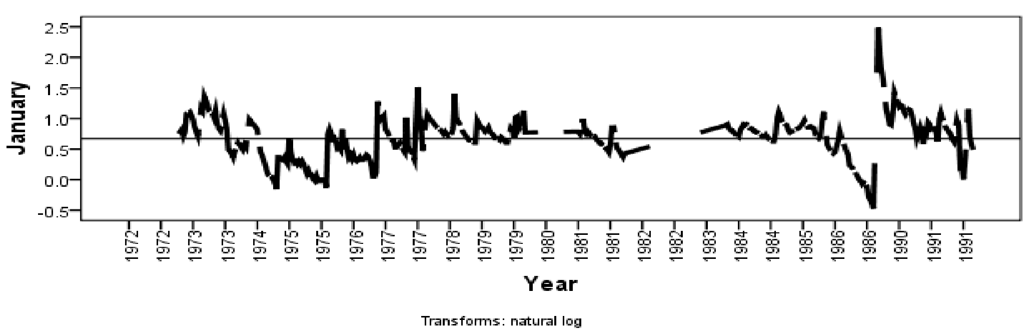
4AB05



4AG01



4BC05



4BD06

Fig. 13. January Time Series Plots of daily river discharges (volume) at stations 1950-1990

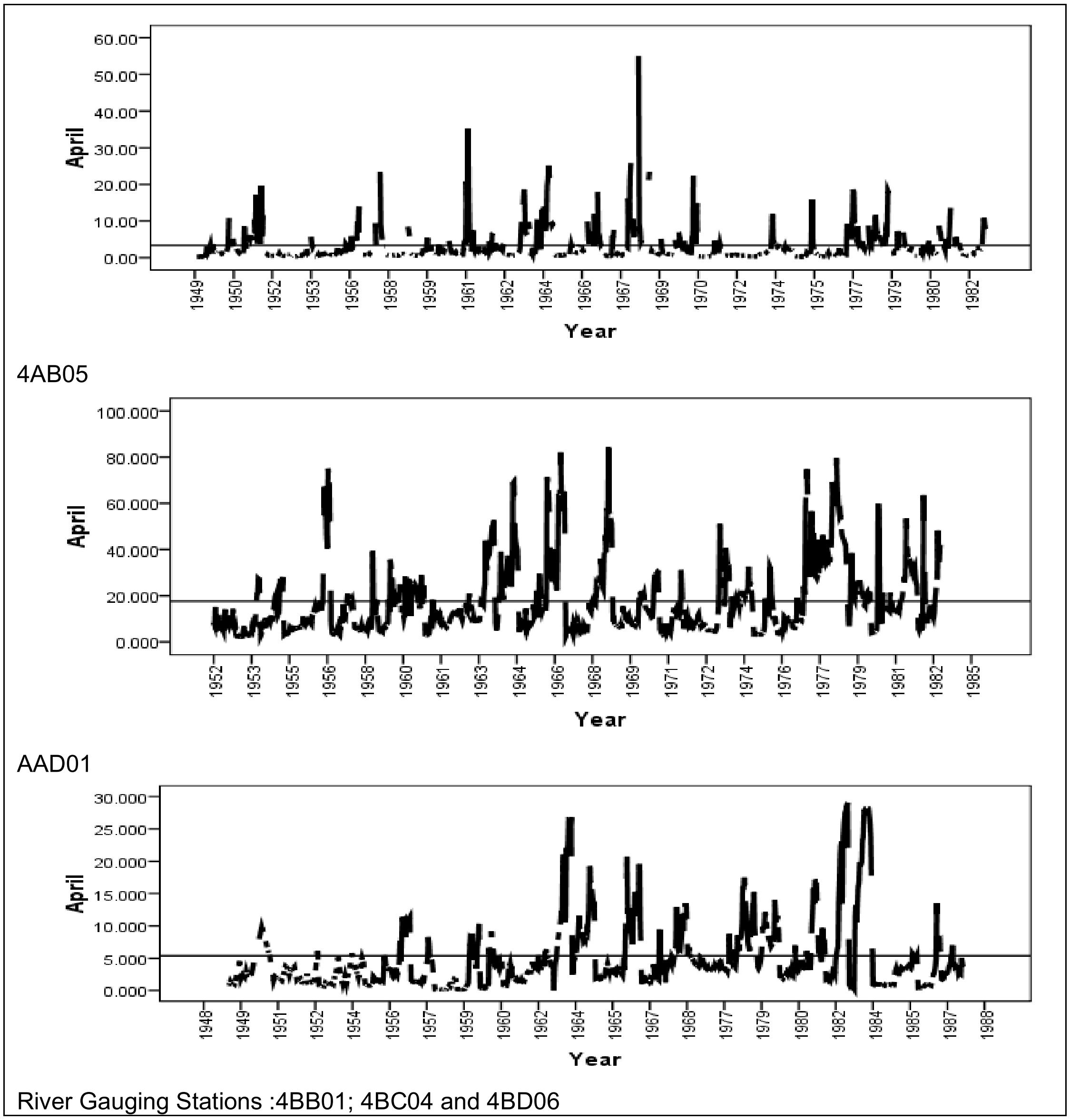


Fig. 14. April Time Series Plots of daily river discharges (volume) at stations 1950-1990

The result of the running median smoothing does not effectively remove the irregular variations. This requires other time series smoothing techniques to be applied. Since the river volume flow is a continuous variable and multiplicative due to the effect of subsurface storage, exponential smoothing is applied. Exponential smoothing results in well-defined periods of low flows and high flows. The low flows tends to be more pronounced and persistence than the high flows in the river flow series results.

The exponential smoothing used is given by the formula:

$$s_t = \alpha \cdot x_t + (1 - \alpha) \cdot s_{t-1} \quad (5)$$

Where

α is the smoothing factor, and $0<\alpha<1$.

In other words, the smoothed statistic s_t is a simple weighted average of the current observation x_t and the previous smoothed statistic s_{t-1}. The term smoothing factor applied to α here is something of a misnomer, as larger values of α actually reduce the level of smoothing, and in the limiting case with α = 1 the output series is just the same as the original series. Simple exponential smoothing is easily applied, and it produces a smoothed statistic as soon as two observations are available.

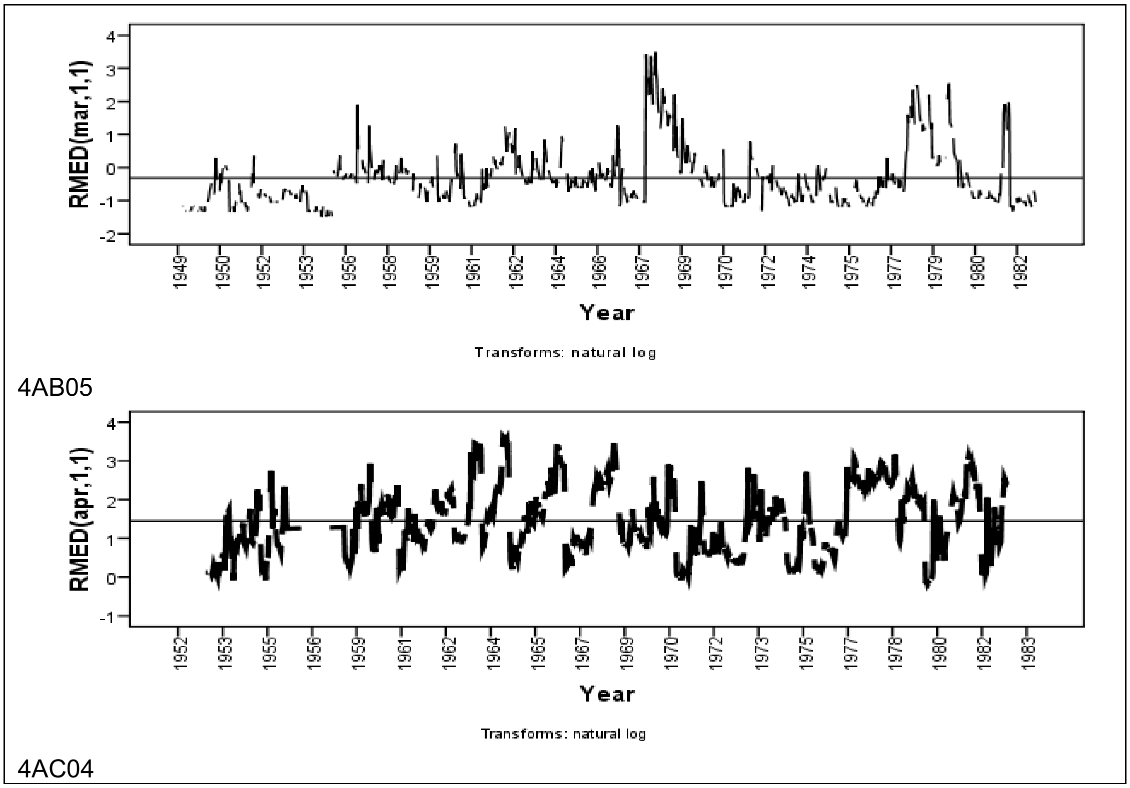


Fig. 15 Running median time series plots of daily river discharges at stations AB05 IN March and at 4AC04 in April (1950-1990)

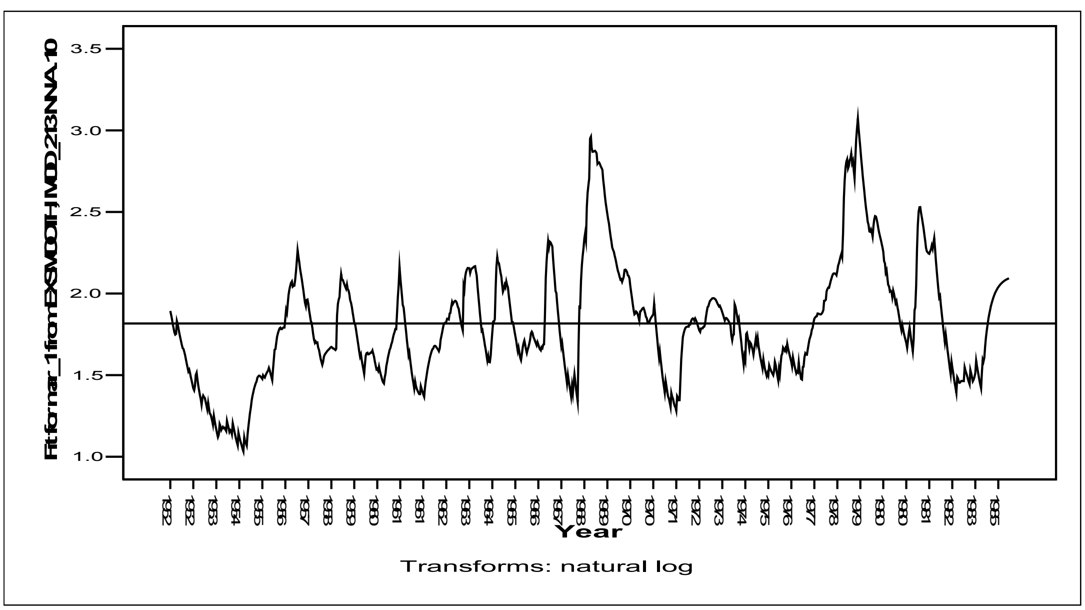


Fig. 16. Exponential smoothing time series of Daily River discharges in March at stations 4AD01 1950-1990

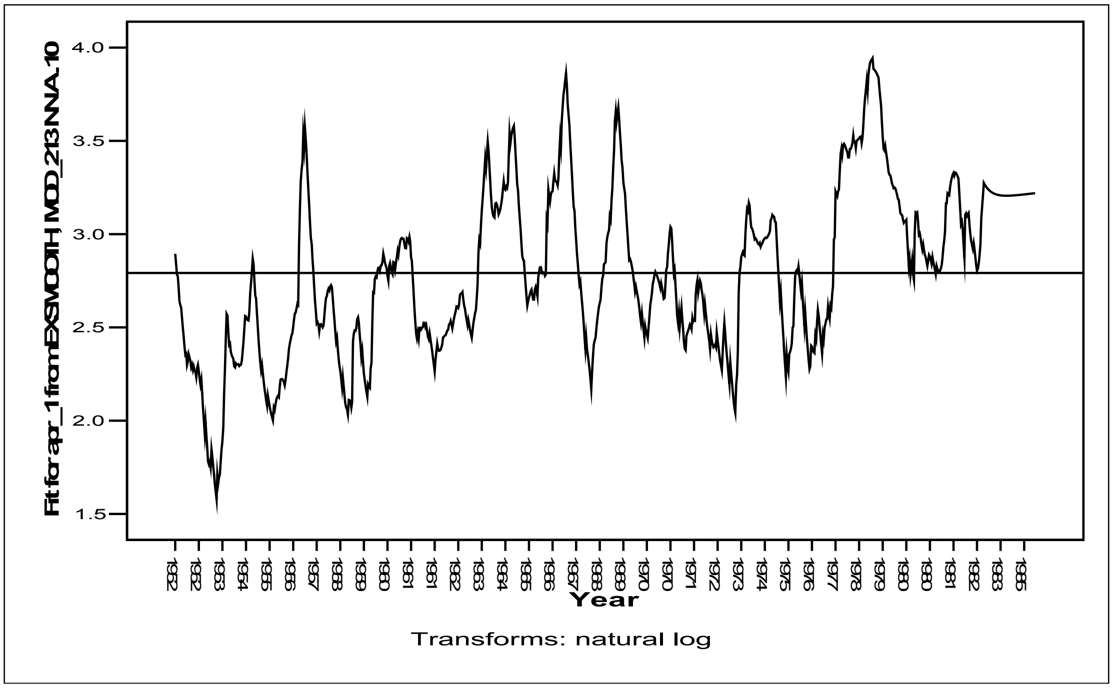


Fig. 17. Exponential Smoothing Time Series of daily river discharges (volume) in April at stations 4AD01 1950-1990

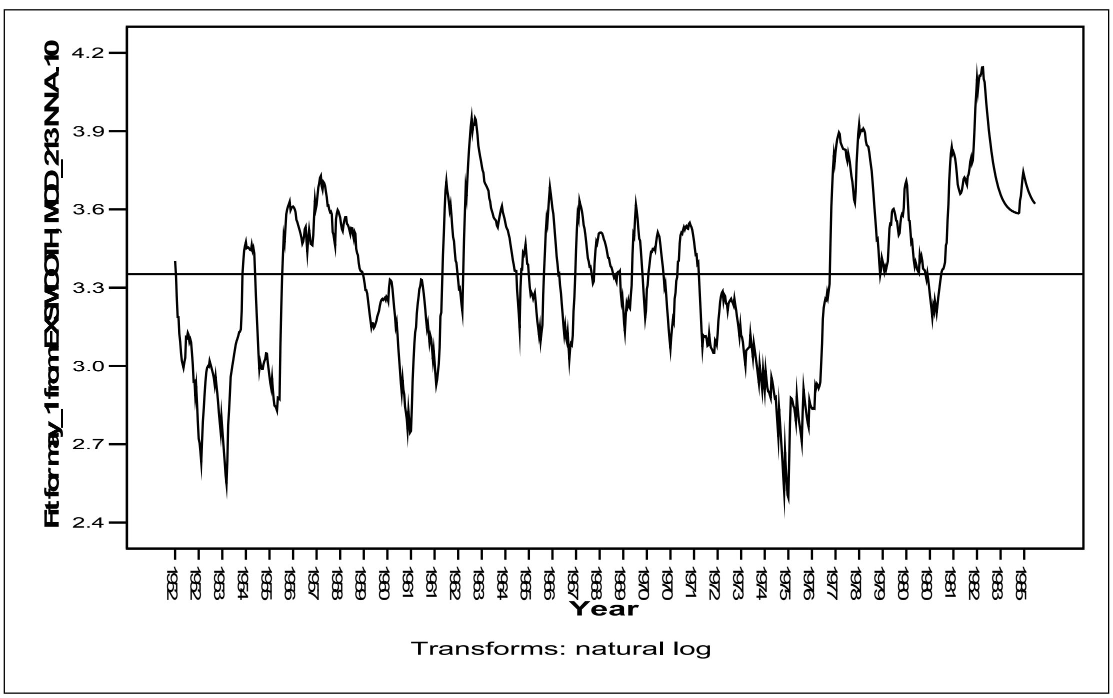


Fig. 18. Exponential smoothing time series of daily river discharges (volume) in May at stations 4AD01 1950-1990

It is considered necessary to have some measure of the trend in daily river discharges in the Upper Tana Catchment. Having solved for the missing data using running median (low filter pass) and the linear trend at the point of missing data, a trend analysis is then carried out. Results indicate a general crest and trough trend where a major high flow is always followed by an extended low flow as shown in Figs.19,20,21.

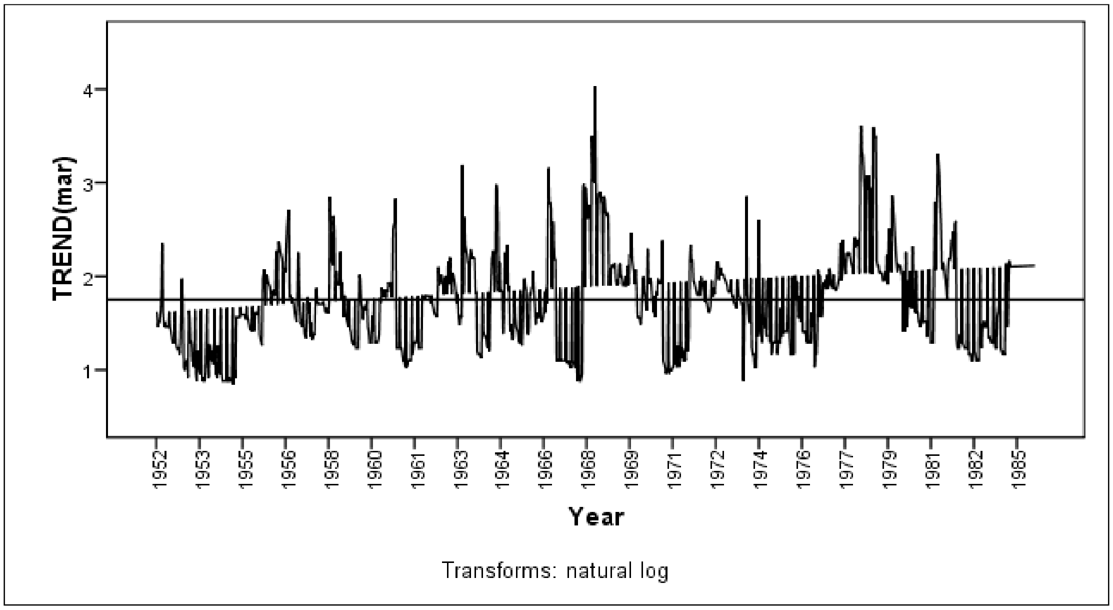


Fig. 19. Daily river discharges (volume) trend in March at Station 4AD01 1950-1990

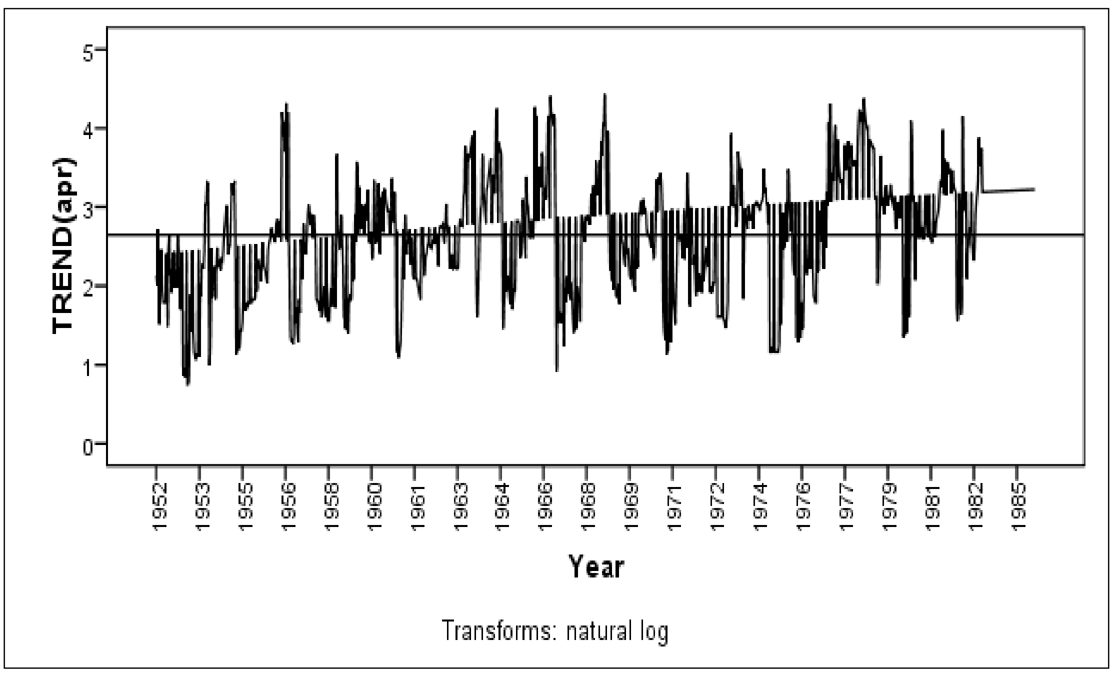


Fig. 20. Daily river discharges (volume) trend in April at Station 4AD01 1950-1990

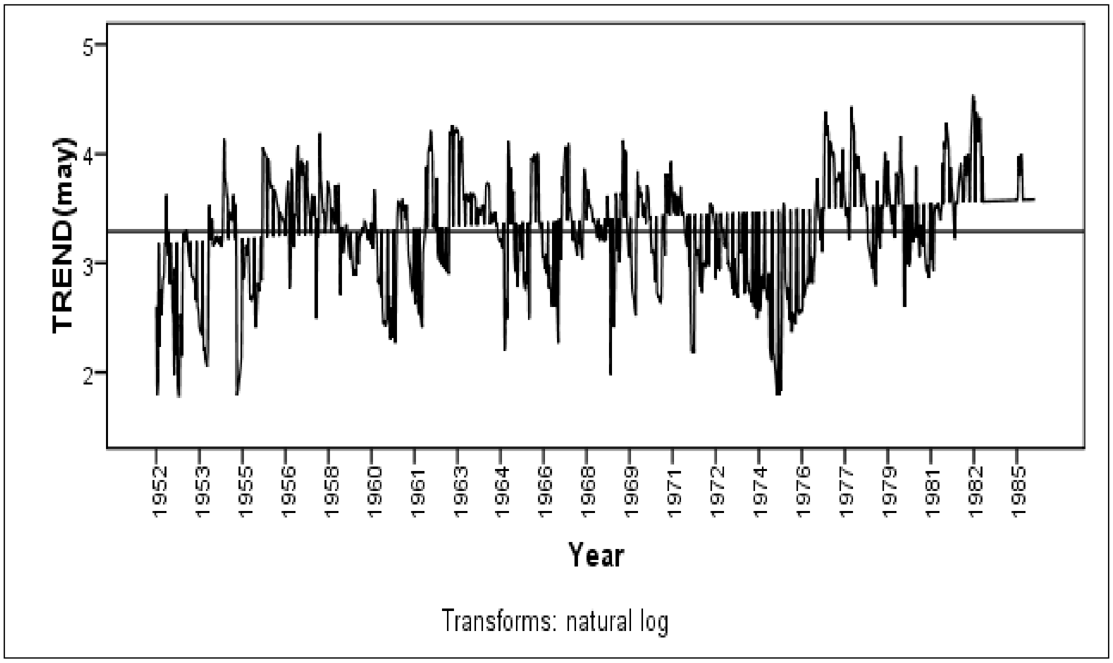


Fig. 21. Daily river discharges (volume) trend in May at Station 4AD01 1950-1990

The observed daily river discharge characteristics as indicated by times series plots of daily discharges, daily running medians, exponential smoothing and trends require statistical statements. The spectral analysis is employed using Bartlett's Window with a span of 7 days to produce spectral density and periodgram estimates. The Fast Fourier Transformation requires an even length series and some series have odd lengths necessitating first cases to be truncated so as to make the series even. Plots of the spectral density and periodgrams result in series that are spread throughout the plots indicating random characteristics and persistence largely restricted to within water years.

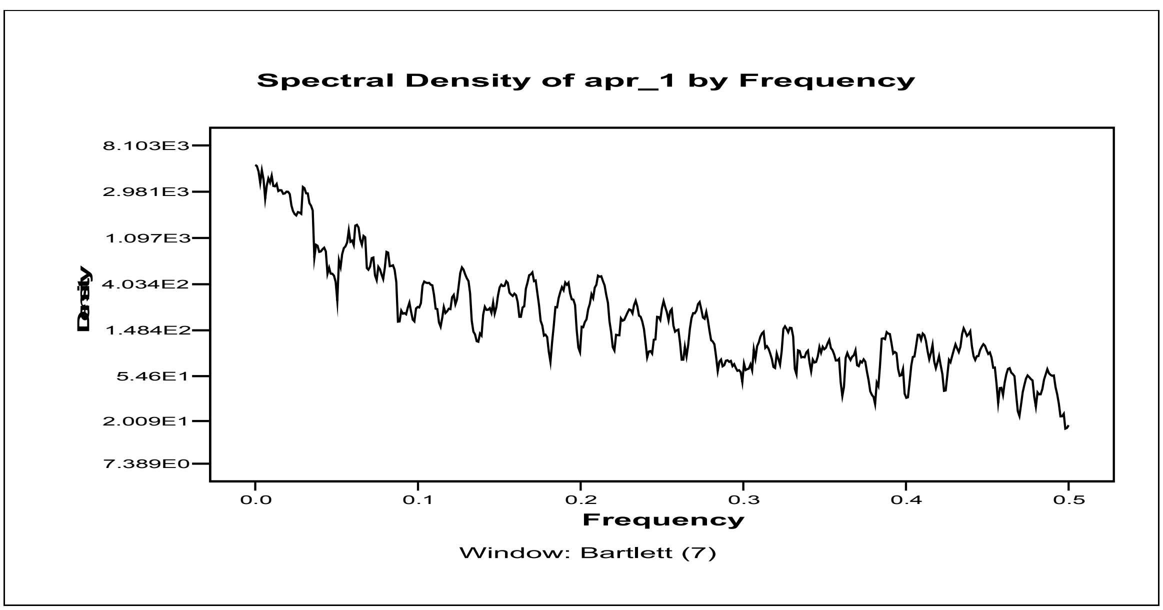


Fig. 22. Spectral density Daily River Discharges in April at Station 4BC04 1950-1990

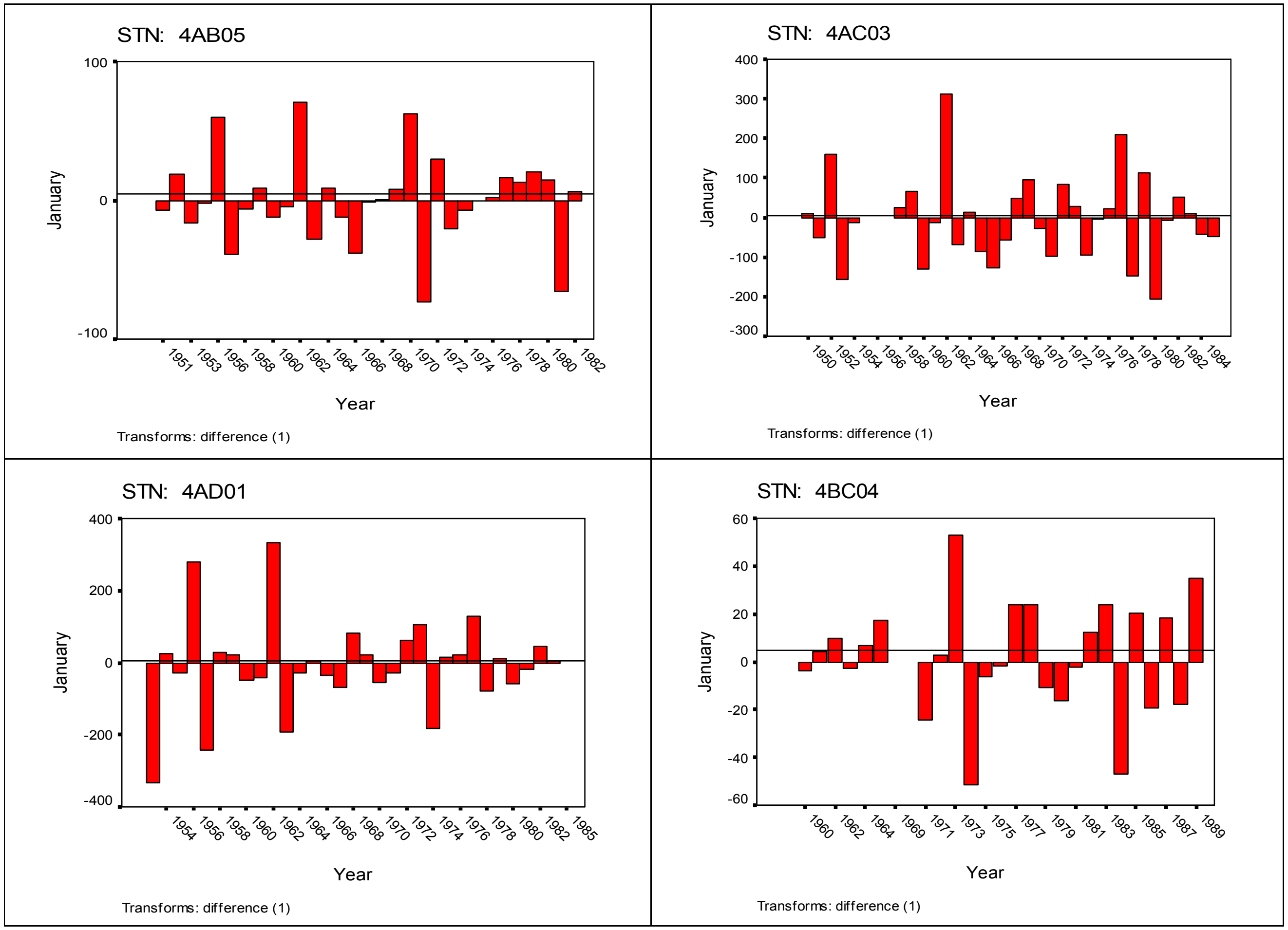


Fig. 23. January Time Series differencing of Daily River Discharges (volume) at Station 4AB05, 4AC03, 4AD01 and 4BC04 in Upper Tana Catchment (1950-1990)

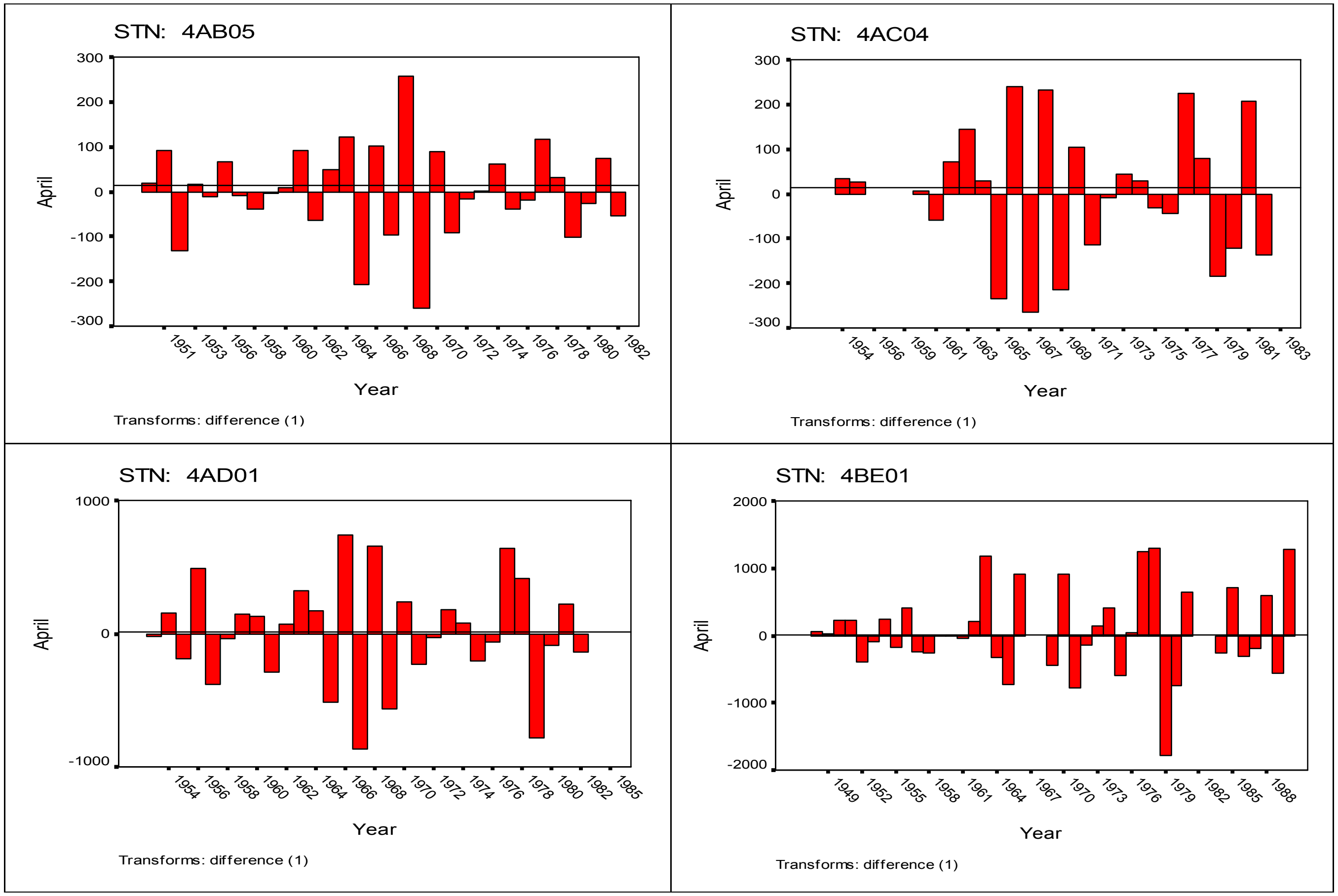


Fig. 24. April Time Series differencing of Daily River Discharges (volume) at Station 4AD01, 4AB05, 4AC04, and 4BE01 in Upper Tana Catchment (1950-1990)

To identify periods of hydrological droughts in Upper Tana, the daily river discharges data to time series differential analysis based on one year span. The differential time series plots indicate incidences of low flows that qualifies as hydrological drought periods. The seasonal differencing plot of daily river discharges indicated period that could be considered drought periods but not in a well-defined structure. It was necessary to consider the seasonal differencing based on monthly totals and thus providing a clearer picture of the periods of exceptional low river flows that could be considered hydrological drought periods as illustrated in Figs. 23, 24, and 25.

Setting the confidence level at 95%, the control chart is used to identify river flow periods that indicate extended low daily river discharges that can be described as hydrological droughts (Fig. 25).

Typical of the results in is the tendency to have short crests (possibly floods) followed by relatively extended lows (possibly droughts). The lows below the lower confidence limits (2 sigma)

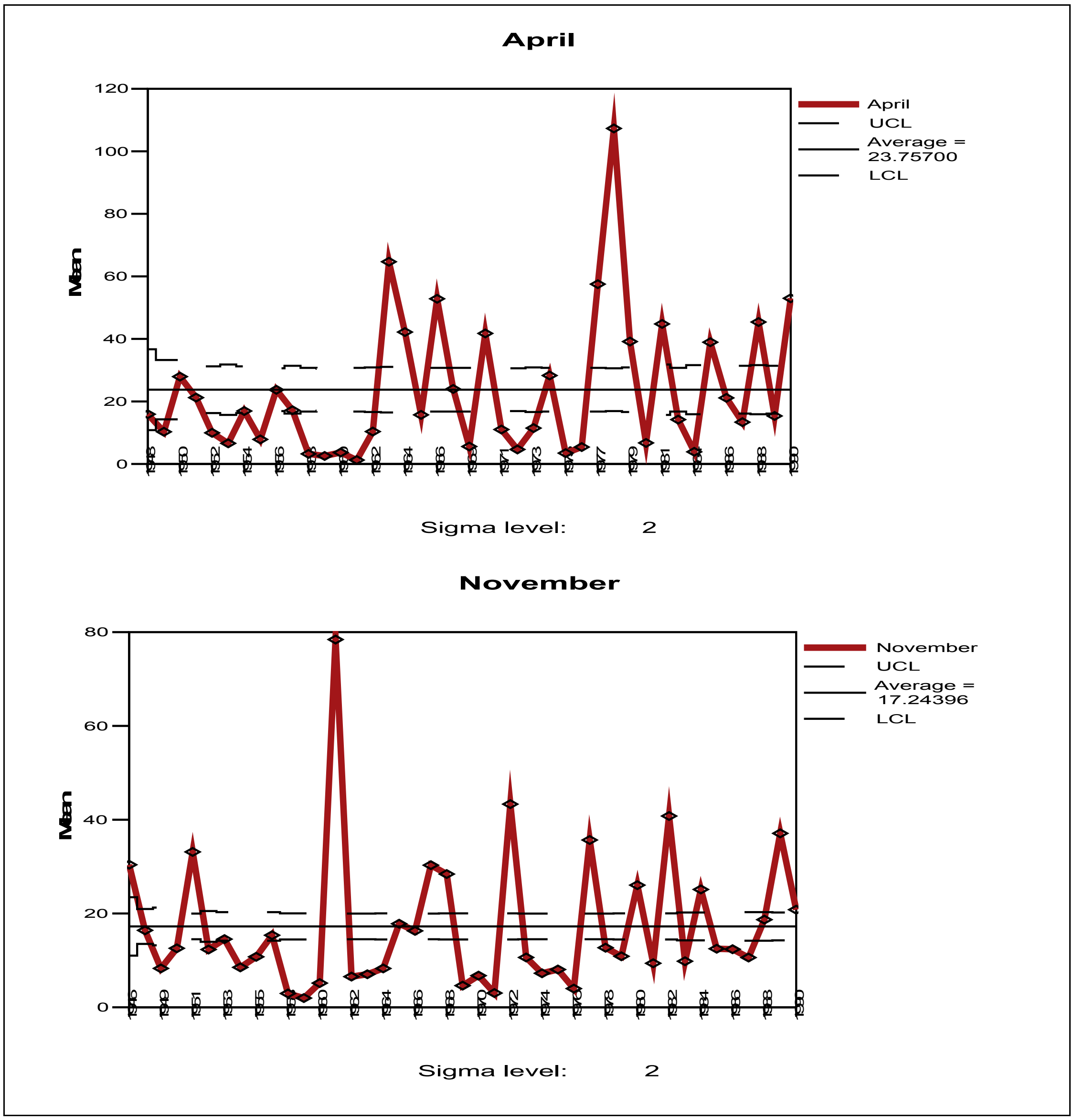


Fig. 25. Control plots for April and November Daily River discharges at 4BE01 in Upper Tana

of daily discharges, in all cases are treated as drought episodes. The episodes tended to last for 1 to 2 water years but in most cases 2 and above. The tendency to have hydrological droughts persisting for more than 1 water year can be explained in terms of the ground water storage recharge lag term. This study assumes that if in a water year there is extreme low rainfall conditions in a sub basin of upper Tana that results in depletion of the ground storage, the following rainfall is used to recharge the ground storage and therefore cannot all be available for channel flows.

Using the explore data analysis techniques, the identified drought periods are analysed in terms of representative drought episodes that can be used to generalise hydrological drought measurements in the Upper Tana Catchment. Results indicate that the most typical representative data for hydrological drought measurements are to be found in the early 1960s daily river discharges as defined by the boundaries of the confidence levels (95%). The January-February drought periods occurred mostly in the 1960s and 1970s early and it is the position of this study that hydrological drought definitions in Upper Tana during the months of January and February should use the either the early 1960s data extending into late 1950s or the early 1970s data extending to mid 1970s.

4. CONCLUSIONS

Drought is a meteorological phenomenon in the Upper Tana Catchment climate whose definition varies with socio-economic activities practised there, rainfall conditions, and hydrological characteristics. Water deficiency is defined in terms of abnormal low rainfall conditions the thresholds of which vary with socio-economic activities, lower limits of mean and standard deviations of daily rainfall and river discharge conditions, and dam levels in the reservoirs. Drought frequency and persistence are largely random but drought episode tends to follow an abnormal high rainfall period. Drought persistence is largely a one rainfall calendar event but with a general tendency to occur at the beginning and end of a decadal period thus the impression of extended drought episodes. Mid decadal droughts tend to be severer than other periods of drought. Locally in Upper Tana catchment, drought impacts are more meaningful in terms of agricultural crop performance and/or yields, food availability, pasture, and water for livestock. From meteorological perspective, drought in Upper Tana tends to be more universal when the amount of deviation from the expected rainfall conditions is analysed than on the actual amount of rainfall received. Hydrological droughts on the other hand tend to be more meaningful in terms of amount of rainfall received and its impact on channel flows.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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