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Spatial Characteristics of Drought Duration and Severity in the Upper Tana Basin, Kenya

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Abstract

Drought is a recurring hazard in many countries of Africa, and Kenya is thus no exception. In the majority of the countries in the continent, drought affects agriculture, since it is predominantly rain-fed and is the mainstay of the economies in these countries. Various socioeconomic activities are highly prone to the impacts of drought. Since drought will always occur, there is and will always be need for understanding its various manifestations to ensure that the effects associated with its occurrence are managed in a sustainable manner. This study examined the spatial characteristics of drought duration and severity in the Upper Tana Basin (UTB) of Kenya using discharge records from twenty two river gauge stations (RGSs) in the basin. Drought duration and severity data were extracted from the discharge records using the runs analysis technique and the data series subjected to principal components analysis (PCA) from which common factors for the two drought events were examined. Results showed that drought duration and severity had distinct spatial patterns in the basin. The two drought events were explained using four significant principal factors that cumulatively explained nearly 59 percent variance for drought duration and 56 percent of variance for drought severity in the basin. The spatial patterns of the factor loadings for drought duration showed large meridional patterns with anomalies confined to the eastern and southeast parts of the basin. For drought severity, the spatial patterns of the factor loadings portrayed a zonal pattern reflecting differences in the relief features between the western and eastern parts of the basin. The spatial characteristics of the drought events may be used to plan for different land use activities in the basin.

Keywords: Drought, duration, severity, upper Tana basin, principal components analysis.

Introduction

Mankind has always faced challenges related to extreme climatic and hydrological events and problems related to either too much or too little water[1]. The variations in water levels in the water courses is mainly as a result of rainfall variability arising from global climate change that causes various direct and indirect impacts on water resources, agricultural production, livelihood systems and natural ecosystems[2-4]. Other effects of climate extremes of drought include livestock production, hydrological balances in rivers, food security and the general economy of an area[5,6]. Water related disasters have been more devastating as far as deaths, suffering and economic damages are concerned, compared to other natural hazards such as earthquakes and volcanoes. Besides the destructive direct effects, extreme hydrological events such as droughts and floods have often been followed by secondary, indirect calamities such as famine, epidemics and fire. Mankind still faces serious challenges arising from extreme hydrological events in spite of continued research on the characteristics of these events. The events lead to heavy expenditures in terms of structural and non structural measures required to control them. Indeed, these events continue to be ever challenging in both developed and developing countries as the impacts associated with them are far deeper and more serious in terms of human losses and societal effects. It is therefore crucial to understand the spatial manifestations of these events to ensure their sustainable management and for effective assessment and allocation of water resources and in the design and management of water resource systems.

Drought is an example of an extreme hydrological event that recurs and is a normal part of climate. It differs from other hazards like floods in that its effects accumulate slowly and lingers for long even after the event is over, and its onset and termination dates are difficult to determine. Besides, it lacks a universal definition, its impacts spread over very large areas making the quantification of the impacts much more difficult, and it differs in duration, severity, magnitude and frequency from one place to another[7].

The effects of drought are diverse and include reduced agricultural production, plant and animal damage, air and water pollution, forest fires and increased demand for water and the ensuing conflicts among various water dependent activities. Other effects include disruption in the performance of water supply systems, decline in hydropower production, dilution capability of rivers and depletion of groundwater aquifers. The various drought episodes that have occurred in Kenya, have caused serious stream flow deficits and water level fluctuations in several rivers, reservoirs and groundwater aquifers in the Tana basin and other basins causing undue pressure on the water sources[8]. To properly manage drought and its associated impacts, it is necessary to know its various characteristics so as to plan for various land use activities in an area.

Material and Methods

Study area: This study was done in the Upper Tana Basin (UTB) which is one of the most important water basins in Kenya as about 75% of the hydroelectric power that is produced in the country comes from the basin. The location of the basin is shown in figure 1.

Data used and Methodology: Mean monthly discharge records from twenty two river gauge stations (RGSs) spread within the upper Tana basin were used in the study. The data was obtained from the Ministry of Environment, Water and Natural Resources Headquarters in Nairobi. The quality of the data was checked and ascertained using mass curves analysis before any analysis commenced. The drought duration and severity series at each of the twenty two river gauge stations were assembled using the runs analysis technique and the two data series subjected to principal components analysis (PCA) technique which is a statistical tool used to analyse spatial patterns of data. The various principal components are derived from empirical orthogonal function solutions based on common factor analysis concepts which identify and classify characteristics that groups together variables with common characteristics. Although the PCA technique is based on the concept of variance and employs either covariance or correlation input matrix of a set of variables, the correlation matrix is, however, preferred since it assigns equal weighting to variables[9] and so it was applied in the study to examine the spatial patterns of drought duration and severity in the basin. The technique was used since it has the ability to reduce the dimensionality of a large data set by replacing inter correlated variables with a smaller number of uncorrelated variables and it offers the possibility of interpreting orthogonal functions in terms of recognisable physical processes. Moreover, its empirical components and their coefficients are orthogonal in time besides the fact that the empirical orthogonal functions do not require equidistant points of observations like most of the other orthogonal functions[10, 11].

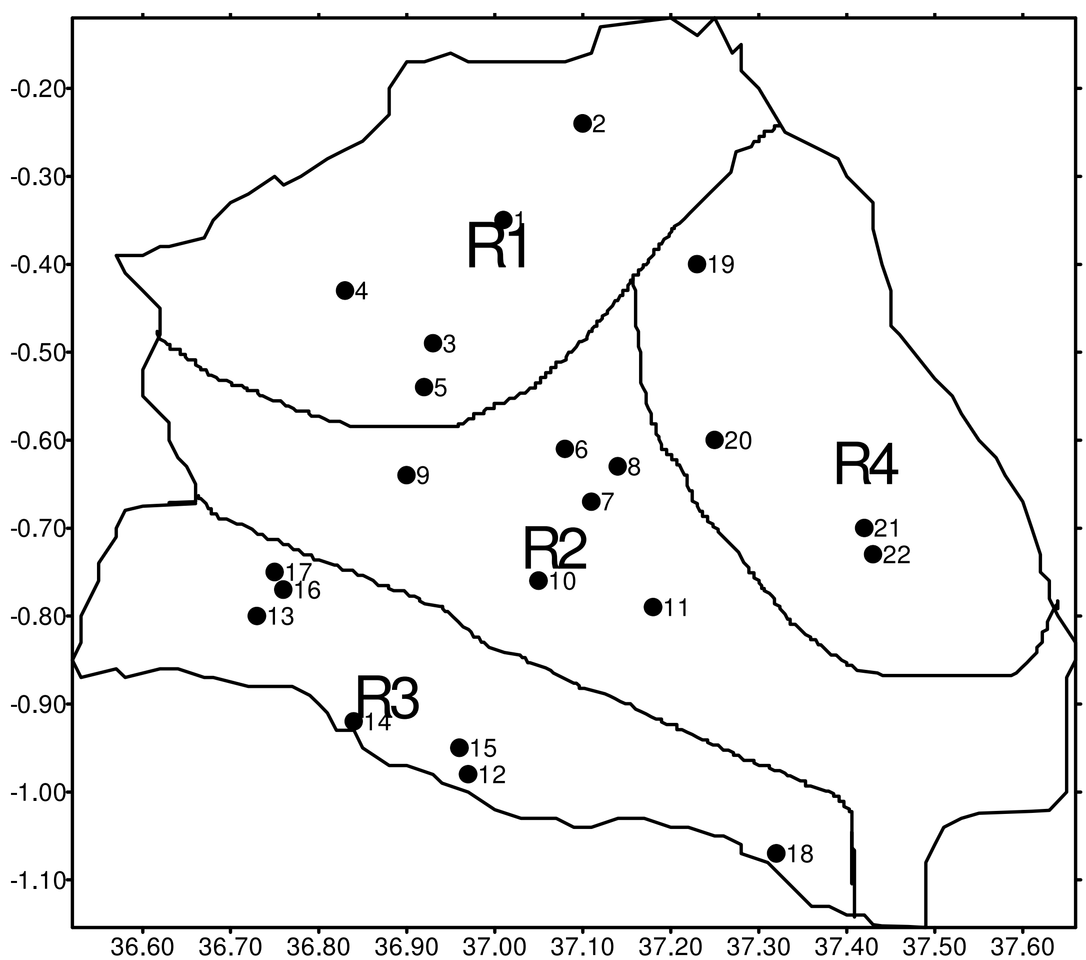

Figure-1
Homogenous Hydrological Regions R1, R2, R3 and R4 derived from Rotated Principal Component Analysis of Discharge Data; the numerals show the numbers of the river gauge stations used in the study

Several key steps are required in using the PCA technique. These steps are formulation of principal components, rotation of the components and selection of the number of significant components in the analysis. The formulation of the principal components of a data set requires that basic measures of association between the variables at various gauging points and the formulation of a linear set of orthogonal vectors be computed. This is done by preparing the correlation matrix and extracting and transforming the initial factors from the drought event variables using either the temporal or the spatial mode of the correlation matrix of the data. In the temporal mode of the analysis, the correlation matrix is generated between periods over a set of locations to yield groups of periods having similar spatial characteristics or patterns for use in composite analysis. The matrix of the data is then transposed such that each individual time is a variable and each station an observation. This leads to the production of components having loadings on the individual times and scores which are then used to indicate the spatial pattern where the factor loadings are used as weights[10]. In the spatial mode, the variables of the correlation matrix are generated between locations over a given period. These variables represent the gauging stations whilst the observations represent individual specific values at each time unit. The principal loading matrix contains the correlation of each component that can be plotted to depict the spatial pattern of each component. While the temporal mode can be used to classify periods for which specific regions experience similar spatial extremes of the drought events, the spatial mode is useful in classifying locations with similar temporal anomalies in hydrological events.

The PCA method linearly transformed spatially correlated time series of discharge data from which drought duration and severity were extracted into two sets of orthogonally uncorrelated functions. For a given flow event j, the PCA model took the form given in equation (1).

$$Z_j = \sum_{k=1}^{m} a_{jk} F_k \; ; j = 1, 2, \ldots, n \qquad (1)$$

Where Z_j is standardized variable j, a_{jk} are the standardized factor loading coefficients of variable j on the k^{th} component, F_k, are the principal factors, m is the number of common factors and n is the number of factors.

The variance of the squared loading in each column of the data is given by the expression in equation (2),

$$V = n \sum_{j=1}^{m} \sum_{k=1}^{n} \left(\frac{a_{jk}}{h_j} \right)^4 - \sum_{j=1}^{m} \left(\frac{\sum_{j=1}^{n} a_{jk}^2}{h_j^2} \right)^2 \qquad (2)$$

Where V is variance, n is number of variables, m *is* number of common factors, a_{jk} is the loading of the variable j on factor k, and h_j is the communality of variable j.

The factor loadings were obtained using the correlation matrix since it gave equal weighting to the various river gauge stations and assigned perfect correlation between the variables and the correlation matrices themselves. On the other hand, the weight coefficients represented the principal components to the original data. One of the advantages of the above model is that a few of the principal components contain most of the variations in the original data series arranged according to the proportion of variance explained by each principal component. This is so because the PCA transforms data into an orthogonal set of principal components in such a way that the amount of variance explained by the components decreases from the first component to the last.

Rotation of Principal Components: The eigenvectors in the correlation matrix are orthogonal or uncorrelated which means that interpretation of the direct solutions or the un-rotated components or factors is ambiguous and it is therefore necessary to adjust the frames of reference of the orthogonal vectors, before they can be interpreted to reduce the ambiguities that usually accompany the direct solutions. This adjustment of frames of reference of the variables is geometrically known as 'rotation' and does not affect the cumulative variance explained by the eigen values. The two common types of rotation are the 'orthogonal' and 'oblique' in which the reference axes are maintained in the orthogonal type of rotation whilst the components are partially correlated in the oblique type of rotation. Examples of the orthogonal rotation include *Varimax*, *Quantimax* and *Equimax* methods whilst the oblique types of rotation methods include the *Oblimax*, *Oblimin* and *Promax*[12]. Rotated solutions have been noted to provide better descriptions of interrelations between variables and do not affect the total variance explained by the factors[13,14]. The Orthogonal Varimax Rotation was applied in the study because it gives clear descriptions of the spatial patterns of drought events[15,16].

Selection of the Number of Principal Components: The number of components to be retained in a given analysis is vital if useful information is to be obtained from the analysis and appropriate methods are used to select the number of factors that explain substantial amounts of variance in the final solutions. The selection of the factors is based on various criteria which include Kaiser's criterion where eigen-values equal to or greater than unity are taken as significant, whilst in the Castell-Scree test[15,17] the eigen-values are plotted against the corresponding ordinate eigenvector numbers. In the random errors test[15] the sampling error is based on the comparison of the sampling errors for the eigen-values and the separation in the neighbouring eigen-values. The other criteria are logarithms of the eigen values (LEV) and the isotropy test where the LEV criterion, logarithms of the eigen-values are plotted as factor numbers of the variables[18]. The Kaiser criterion was preferred in as it is widely used and because of the brevity that characterised the data.

Results and Discussion

The rotated principal component analysis (RPCA) results for drought duration based on standardized values of respective drought events are shown in table 1. The spatial plots for drought duration using the first three significant factor loadings as obtained from the spatial mode solutions are shown in figures 2, 3 and 4.

From table 1, four significant eigenvectors were extracted from the PCA solutions by the Kaiser criterion. The factors explained individual variances in spatial patterns of drought duration decreasing from 27.0% to 7.9% for the first to the fourth factor respectively giving a cumulative variance of drought duration explained by the significant principal factors to be 58.6%. The number of significant principal components shows the number of anomaly centres in terms of duration and hence the four types of map patterns which were obtained from the PCA procedure. The spatial plots of the three factors for drought duration are shown in the illustrations in figures 2, 3 and 4. From figure 2, the spatial variations of the first factor showed a *meriodional* pattern with significant positive factor loadings located mainly in the central, south, southeast and eastern parts of the basin.

The factor describes the mean pattern of drought duration which showed variations between north and south. This is due to climatic differences between those areas located to the north and those in the southern parts of the basin. These areas are mainly in the two hydrologically homogenous regions[19] with long durations of discharge deficits since they are located in the arid and semi arid zones of the basin and are adjacent to the dry Athi and Ewaso Ng'iro drainage basins to the south and north east respectively. The rainfall received in these regions is low and poorly distributed throughout the year and so the rivers in the two regions are stream flow deficient most of the time. The spatial patterns of the second factor (figure 3) accounted for 14% of spatial variance in duration and showed a *zonal* pattern with significant positive loadings occurring mainly on the western and eastern parts of the basin. This factor could be associated with the differences in relief and topography between the western and eastern parts of the basin. The highlands to the western parts of the basin rise above 2 400 metres above mean sea level while those to the eastern parts lie below 1 220 metres above mean sea level. This difference in relief, topography and altitude influences the type, mechanism and occurrence of rainfall and hence stream flow in the basin. The basin is also under the influence of the Inter-Tropical Convergence Zone whose zonal arm affects the progression and distribution of rainfall in various parts of the basin.

Table-1
Eigen values and variances explained for drought duration

Factor	Eigen values	% variance extracted	% cumulative variance extracted
1	5.94	27.0	27.0
2	3.08	14.0	41.0
3	2.13	9.7	50.7
4	1.72	7.9	**58.6**

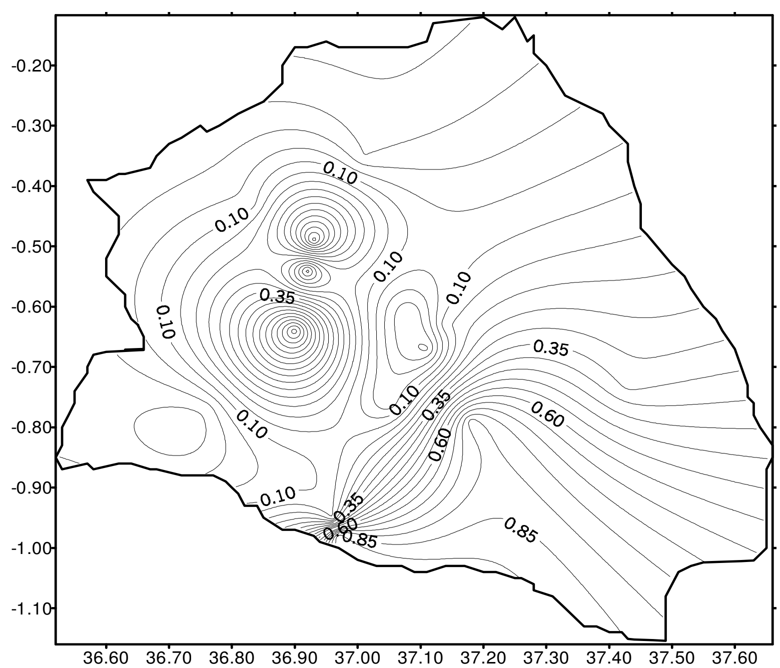

Figure-2
Spatial plots of the factor loadings for drought duration of first rotated principal component

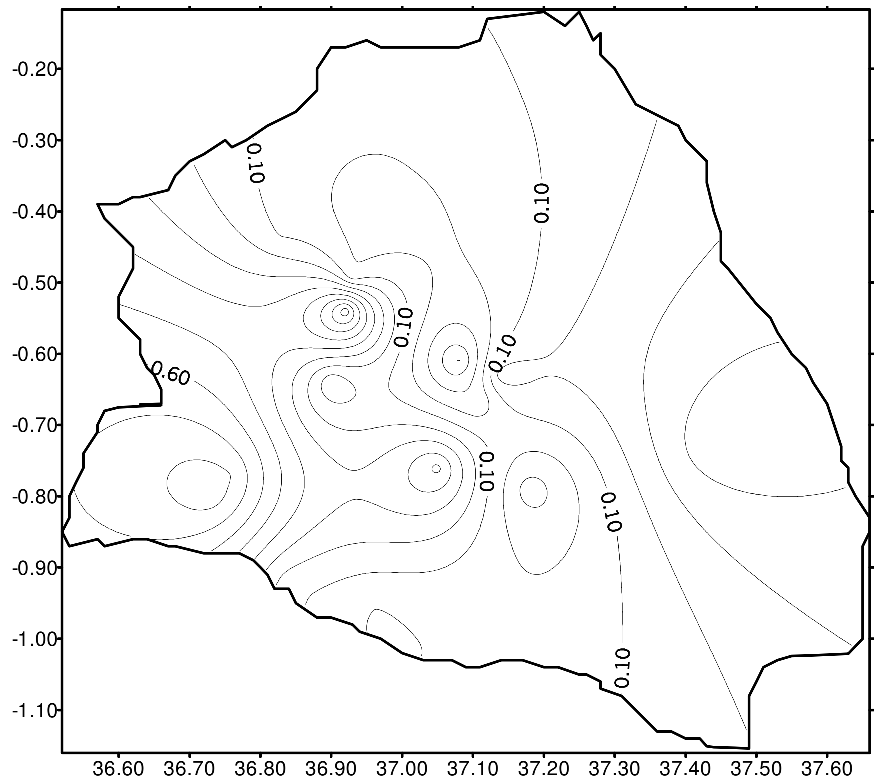

Figure-3
Spatial plots of the factor loadings for drought duration of second rotated principal component

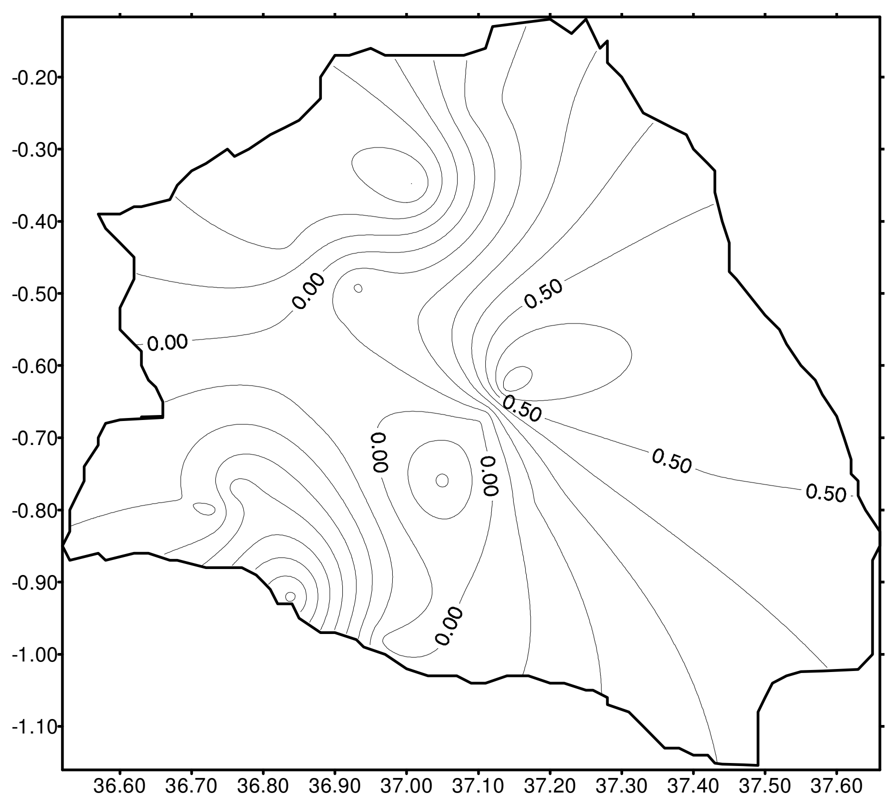

Figure-4
Spatial plots of the factor loadings for drought duration of third rotated principal component

The third principal component explained 9.7% of spatial variance in duration and dominated the northwest, southwest and eastern parts of the basin as is evident from figure 4. The factor showed a *meridional* pattern indicating differences in climate between the north and the south. Most areas to the north especially those around the central portions of the basin and large portions to the south, southeast and eastern are dry most of the time due to influence of the arid Athi basin in the south and the Ewaso Ng'iro basin to the north east of the basin. The meridional (north-south) pattern of the third factor has also been observed in seasonal rainfall and is due to the north-south movement of the zonal arm of the Inter-tropical Convergence Zone[20]. The large anomalies in duration were concentrated to the eastern and south-eastern areas of the basin. This is because the areas are known to have the greatest indication for long durations of long periods of low discharge since they are located within the semi-arid parts of the basin and so they receive low and poorly distributed rainfall and are therefore dry most times of the year.

Table 2 shows the rotated PCA solutions for drought severity from which it is noted that the four significant factors cumulatively accounted for 55.7% of variance in spatial patterns of drought severity in the basin. The variances explained by the individual factors decreased from the first factor to the fourth one and were respectively, 24.6%, 13.8%, 10.3% and 7.0%. The contour plots of the factor loadings for the first three factors are shown in figures 5, 6 and 7**.** The spatial pattern of drought severity in figure 5 shows the first eigenvector to have significant factor loadings in western, northwest, northern and eastern parts of the basin. Low and insignificant loadings were observed in the other parts of the basin.

Table-2
Rotated PCA factors and variances explained for drought severity

Factor	Eigen values	% Variance extracted	Cumulative % variance extracted
1	3.42	24.6	24.6
2	2.03	13.8	38.4
3	1.94	10.3	48.7
4	1.75	7.0	**55.7**

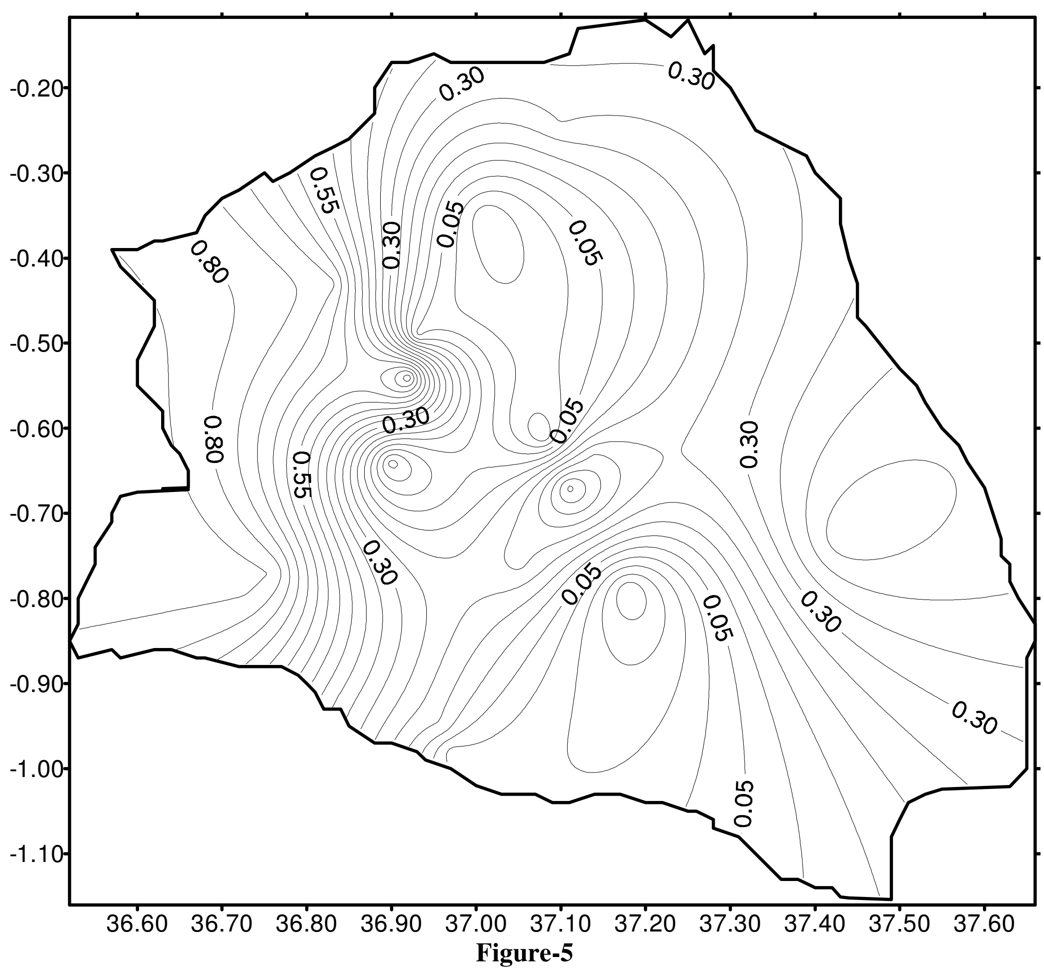

Figure-5
Spatial plots of the factor loadings for severity for the first rotated principal component

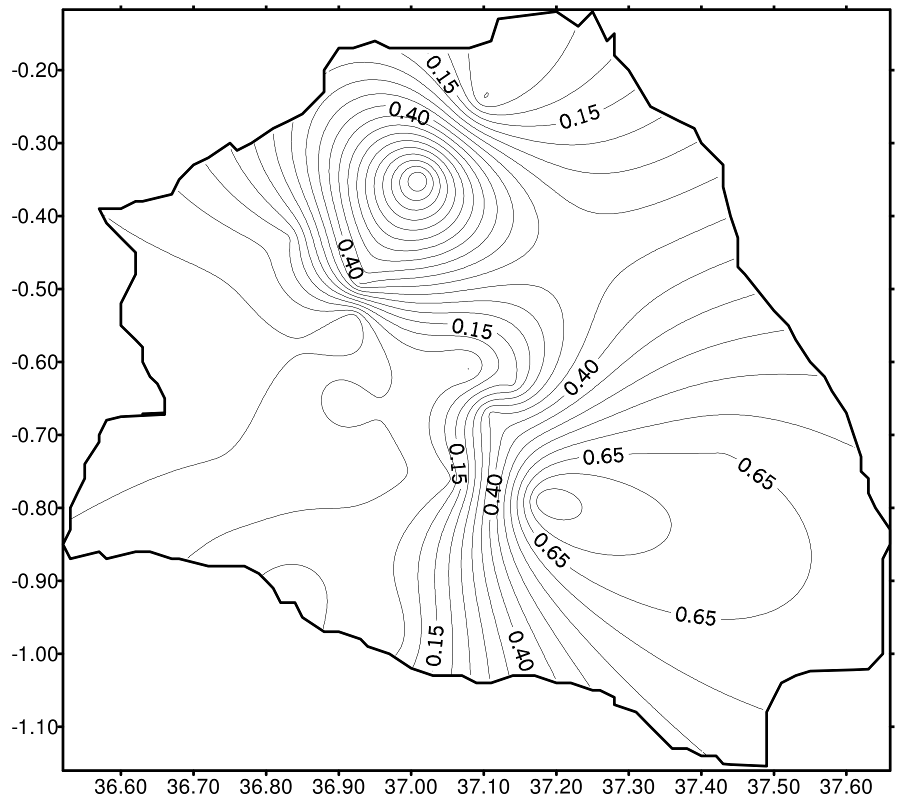

Figure-6
Spatial plots of the factor loadings for severity for the second rotated principal component

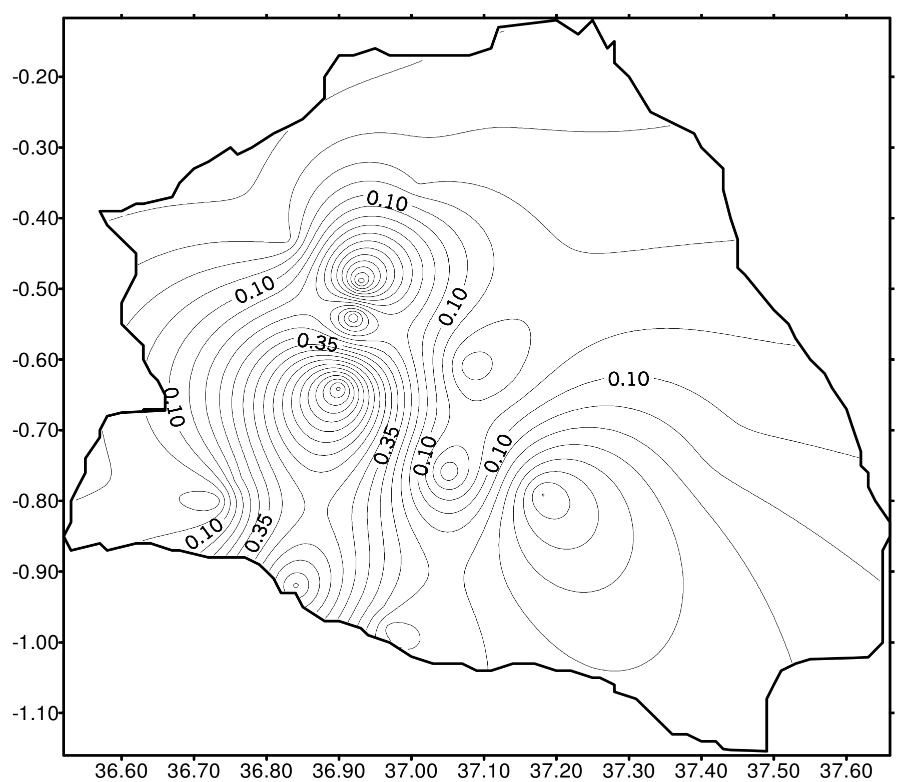

Figure-7
Spatial plots of the factor loadings for severity for the third rotated principal component

The spatial plots of this factor showed a zonal pattern reflecting differences between east and west due to relief features that affect the distribution of rainfall in various parts of the basin. Rainfall is generally high in the western, northwest and northern areas near the Aberdares and the Mt. Kenya zones and in the upper reaches of the central regions of the basin. The remaining regions of the basin especially in the south, south east and eastern receive less and poorly distributed rainfall. The spatial distribution of the factor is also indicative of the onset of rainfall that begins in the western parts and progresses to the east in response to the northward and eastward movements of the Inter Tropical Convergence Zone[21].

The spatial plot of the factor loadings for the second eigenvector in figure 6 shows a *meridional* map pattern with significant positive loadings in the northwest/ southeast and west-east orientation. In the other parts of the basin the factor loadings were not significantly different from zero. The two map patterns reflects differences between the northwest and southeast and east and west would be associated with the influence of climate between areas located to the northwest and southeast and relief features between western and eastern parts of the basin. As was noted earlier, relief features determine the type, mechanism and distribution of rainfall in the basin. From figure 7, the factor loadings of the third eigenvector was dominant in central, southern and southeast portions of the basin and just like results for duration in the previous two sections, this factor showed a north/south dipole pattern in the basin, an indication of the arid and semi arid climate both in the north and south of the basin. The parts of the basin in which significant factor loadings were dominant represent areas of the basin with the greatest potential for sustained stream flow deficits. These areas are close to semi arid and arid regions of the basin where water availability from rainfall is scarce and therefore the stream flow deficits last for longer periods in any given year and are likely to be severe.

Conclusion

Drought duration and severity showed distinct spatial patterns across the four homogenous regions with four significant factors cumulatively explaining about 59% variance for drought duration in the basin. Large *meridional* patterns in drought duration were observed for with the anomalies confined to the eastern and southeast portions of the basin. For severity, the four common factors cumulatively explained nearly 56% of variance while the spatial patterns of the factor loadings portrayed a *zonal* pattern reflecting differences in the relief features between the western and eastern parts of the basin. The spatial characteristics of the drought events may be used to plan for different land use activities within the various areas of the basin.

Acknowledgements

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