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Analysis of Hydrological Drought Events in the Upper Tana Basin of Kenya

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Abstract
Drought is a major environmental hazard which has serious implications for water management and environmental protection. This is especially so when unsustainable water management, as well as predicted climate change effects in droughts, could result in severe impacts on nature and society. Inefficient management of drought and water resources could put aquatic ecosystems under serious severe stress. The lack of adequate water availability in rivers during drought episodes leads to heavy overexploitation of the rivers and reservoirs, which significantly affects the survival of associated biological diversity. It is therefore essential to know the occurrence of drought events in river basins with a view to establishing and developing measures to minimize the socioeconomic and environmental impacts of its effects in these areas. In this paper, drought duration and severity were examined in four homogenous regions of the upper Tana basin. The homogenous regions were established using principal component analysis results of discharge data from twenty two river gauge stations in basin. The runs analysis technique was then applied to examine the drought duration and severity at the homogenous regions of the basin. Results indicated that the mean drought duration varied from 4 to 11 months across the regions whilst the standardized mean severity ranged from 0.63 to 3.89. Two of the regions experienced nearly the same standardized mean severity. Drought events occurred at times when the basin experienced rainfall deficits an indication that low rainfall affects discharge in the rivers of the basin. The variations in the number and frequency of the drought events in the homogenous regions would possibly be related to the semi-arid and arid nature of the climate in most of the southern and eastern parts of the basin. To minimize the impacts of drought in the basin, it is recommended that capacity building of the local communities in the basin be done focusing on water conservation and alternative livelihoods systems to minimize overdependence on water resources in the basin.
Keywords: Drought, hydrological drought, runs analysis, water management

1.0 Introduction

Mankind has always been faced with extreme hydrological events and problems related to either too much or too little water. Water related disasters have been more devastating as far as deaths, suffering and economic damages are concerned. 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.

Despite advances in research, mankind is still very much vulnerable to extreme hydrological events, and the heavy expenditures on both structural and non structural measures for their control, the extreme events continue to present a hazard in both developed and developing countries, although comparatively the effects are far deeper and more serious in terms of human losses and societal impacts in developing countries compared to developed countries. Understanding the characteristics of these events is therefore crucial for their management, and for assessment and allocation of water resources and in the design and management of water resource systems.

Drought is an extreme hydrological event that recurs and is a normal part of climate but it differs from other hazards like floods in that its effects accumulate slowly and lingers for long even after the event is over, its onset and termination dates are difficult to determine and it does not have a universal definition. Moreover, 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 (Smakhtin, 2001).

Some of the effects of drought include reduced agricultural production, plant and animal damage and increased demand for water and the ensuing conflicts among various water dependent activities. Drought also causes disruptions in the performance of water supply systems, leads in the decline of hydropower production and depletion of groundwater aquifers. The drought of 1999/2000 in Kenya, for instance, led to 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 (UNEP/GoK, 2000).

Drought does not have a concise, precise, commonly and universally accepted definition. This is because it means different things to different people and is region, impact and discipline specific. The available definitions are therefore either conceptual or operational in nature. Conceptual definitions specify boundaries of drought and are generic in their description while operational definitions focus on the onset, termination and severity of drought and are useful in analysing frequency, severity and duration of drought events. The lack of a universally acceptable definition of drought means that several drought types exist. The common types of drought include agricultural, meteorological, hydrological, water management, urban and socio-economic. Agricultural drought is largely due to soil moisture deficiency and links various characteristics of meteorological and hydrological droughts to agricultural impacts as a result of precipitation shortages, differences between actual and potential evapo-transpiration and soil moisture deficits. Meteorological drought occurs as a result of precipitation deficits and is expressed mainly on the basis of the degree of dryness and the duration of dry periods whilst urban drought occurs when actual water supply is insufficient to meet municipal water demand under the normal operation of the water supply system (Rossi *et al*., 1992). Socio-economic drought manifests itself when the demand for particular goods and services exceeds supply due to a weather related supply shortfall and links the supply and demand of some economic good with elements of the other drought types. Hydrological drought is said to be in progress when actual stream flow in a river for a selected period falls below a given threshold or truncation level, and can therefore be defined as periods when stream flow falls below a specified level of concern or water demand level. It is related to the effects of precipitation shortfalls on surface and sub-surface water supply and usually lags meteorological and agricultural droughts. A detailed account of drought types, impacts and their management is available in Wilhite and Glantz (1985); UNEP (1992); Kundzewicz *et al* (1993) and WMO (1997).

Although various studies on extreme hydrologic events have tended to focus on floods and other drought types such as agricultural and meteorological, hydrological drought has not received as much emphasis despite its effects on water resources as manifested in the reductions of river flows, dam levels, urban and rural water supplies, deterioration of water quality and competition over available water resources. Hydrological drought also causes serious socio-economic and human losses particularly where rivers act as water supply systems or as inflows to hydropower, and faunal habitats. Knowledge of hydrological drought in streams is therefore important in the planning and design of water supply, allocation of waste loads, design of reservoir storage and maintenance of quantity and quality of water for irrigation, recreation and wildlife conservation.

In this study, hydrological drought was examined using annual mean daily discharge from twenty-two river gauge stations (RGSs) in the River Tana basin of Kenya. Discharge data was used since a few flow records provide an integrated and reliable view of the runoff conditions in a basin and their spatial variation is small. Besides, discharge is easily amenable to human manipulation in terms of flow control, diversion and storage. The fact that river catchments are known to integrate the effects of rainfall over large areas means that hydrological drought analysis using flow data can advance the knowledge of droughts and provide critical information to various users than other drought types. Discharge records have also the important advantage of integrating spatial variability much better than rainfall within a basin and it is much easier to detect hydrologic extremes in discharge records compared to rainfall since changes in rainfall are amplified in stream flow (Hastenrath, 1990; Marengo, 1995 and Pearson, 1995).

Various major river basins in Kenya including the Tana experience marked fluctuations in water levels in the rivers. The fluctuations in the water levels lead to hydrological drought if water levels decline below a particular water demand level. The flow deficits in these rivers are of great concern because of continued increase in demand for water from the rivers for various activities including urban and rural water supply, water based recreation, agricultural and hydropower production. Previous studies in the Tana basin have focused on general aspects of the basin's resource management (Bobotti, 1996), flooding (Mutua, 1993), sedimentation and soil erosion (Otieno and Maingi, 1993) and except for (Sharma, 1994) who used rainfall records to examine general aspects of drought in the basin, no detailed studies have been done focusing on hydrological drought in the basin. In this study, hydrological drought events in the the upper areas of the Tana basin and their empirical relationships determined based on the delimitations of the basin into homogenous hydrological regions.

2.0 Study Area, Data and Methodology

2.1 Study Area

The study was conducted in several catchments of the upper Tana basin which lies at an altitude of 1 000 metres above the mean sea level (**Figure 1**). The topography, climate and hydrology, geology, soils and agro-ecological zones of the area are briefly described in the following subsections.

2.1.1 Location and Topography

The study area forms part of the Tana basin which lies between 5 200 metres above mean sea level on Mt. Kenya and 915 metres at the *Kiambere* area. Mt. Kenya and the Aberdare Ranges lie to the North and Northwest, respectively while the central parts of the basin consist of undulating to rolling topography (**Figure 1**). The topographic units of the area are shown in **Figure 2**.

2.1.2 Climate, Hydrology and Geological Characteristics

The basin experiences two rainy seasons with the long rainy season starting from March to May and the short rainy season beginning in October and ending in December. Areas below 1 100 metres above mean sea level receive low and unevenly distributed rainfall while those with altitudes of 900 to 1 400 metres above mean sea level receive comparatively higher rainfall amounts ranging. Precipitation decreases with an increase in temperature and decrease in altitude from the summits to the southeast lowlands. Areas lying within 1 400 and 1 800 metres above mean sea level receive higher amounts of annual rainfall.

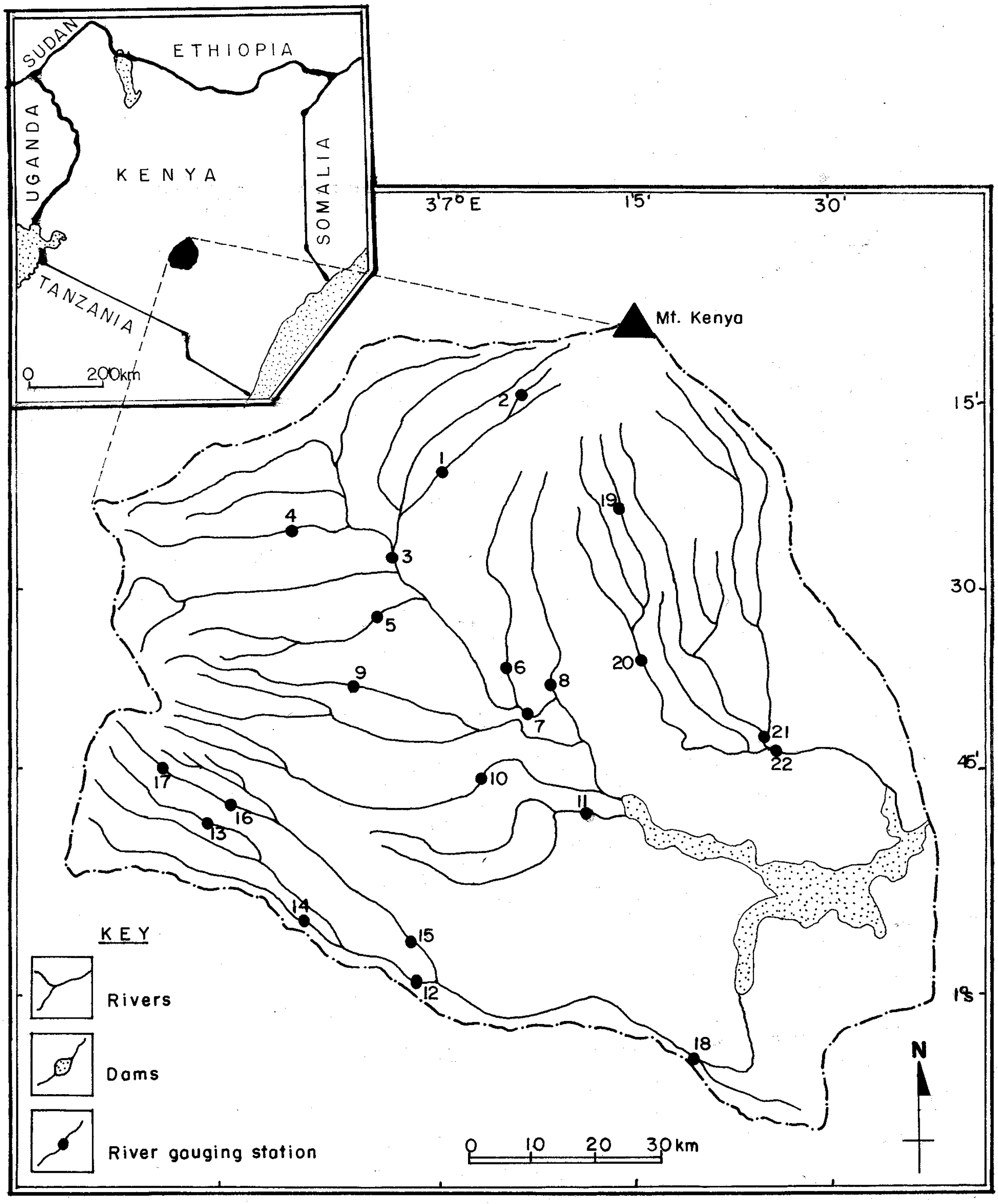

Figure 1: Location of the Upper Tana Basin Showing the River Gauge Stations Used

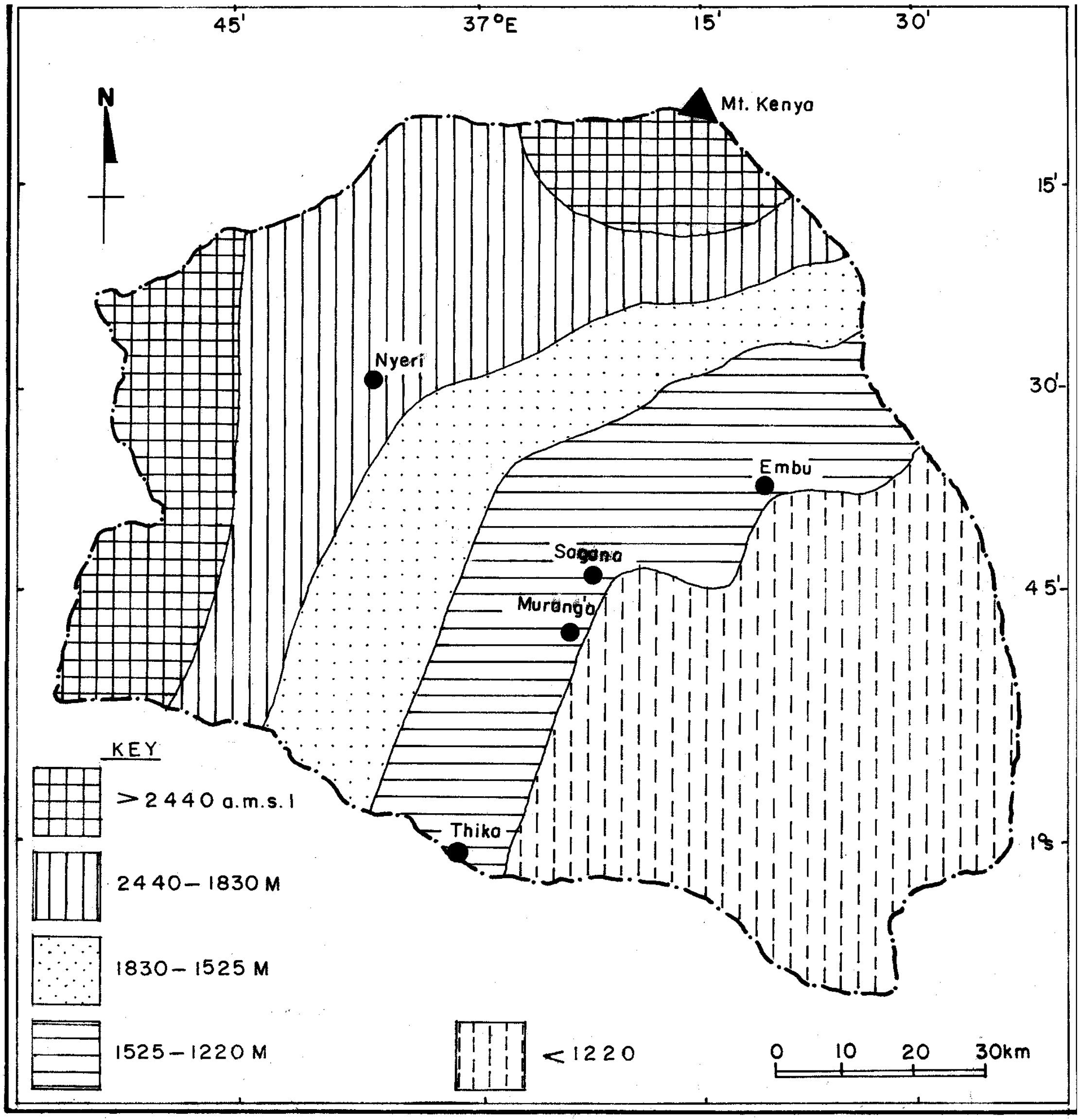

Figure 2: Topography of the Upper Tana Basin *(Source: Omari, 1992)*

The annual mean minimum and maximum temperatures are 10 °C and 20 °C respectively whilst monthly minimum and maximum temperatures are 5 °C and 15 °C in January and March, respectively. The annual mean temperature in the basin is about 22 °C while relative humidity varies from about 70% in the morning to about 45% in the afternoon with an average daily evaporation of about 6 mm. The mean wind speed ranges from just over 140 km per day between February and March, to almost 100 km per day from May to July but on average daily sunshine hours varies from about 4 hours in July, to around 9 hours in February. The corresponding radiation is about 440 cal/cm^2/day in July and about 680 cal/cm^2/day in February (Jaetzold and Schmidt, 1983).

The basin is drained by several perennial streams with some of the main rivers as shown in Figure 1 and listed in Table 1 being *Chania*, *Thika*, *Maragua*, *Sabasaba*, *Rwamuthambi*, *Sagana*, *Thiba*, *Tanasagana*, *Ragati*, *Gura*, *Mathioya* and *Rupingazi*. These streams originate from Mt. Kenya and the Aberdare Ranges, flow in a predominantly south-easterly direction and display an almost parallel drainage pattern. Besides, the flows in the rivers show a marked variation in seasonal and annual runoff that pose a serious problem to proper management of water in the basin. The high flows generally occur from March to June and during October, November and December while low flows or dry season flows are generally experienced during the months of January and February, and between July and September (Bobotti, 1996).

The basin's surface geology (**Figure 3**) comprises mainly of the Precambrian metamorphic and volcanic rock formations with nearly half of the basin covered by Tertiary and Quaternary volcanic rocks such as basalt, Phonolites and Trachytes. However, some sedimentary rocks occur within the main river valleys while glacial deposits form the main rock type below the peaks of Mt. Kenya. The volcanic rock formation originates in Mt. Kenya and the Aberdare Ranges. Areas below 1 000 metres above mean sea level contain rocks consisting of gneisses, schists and calcareous rocks that originate from sediments that have undergone geological changes as a result of shearing, folding and faulting. The youngest rocks are quaternary and tertiary volcanic rocks that originate from the Mt. Kenya and volcanoes in the Aberdare Ranges. Examples of these rocks include basalts and Phonolites (Hughes, 1984).

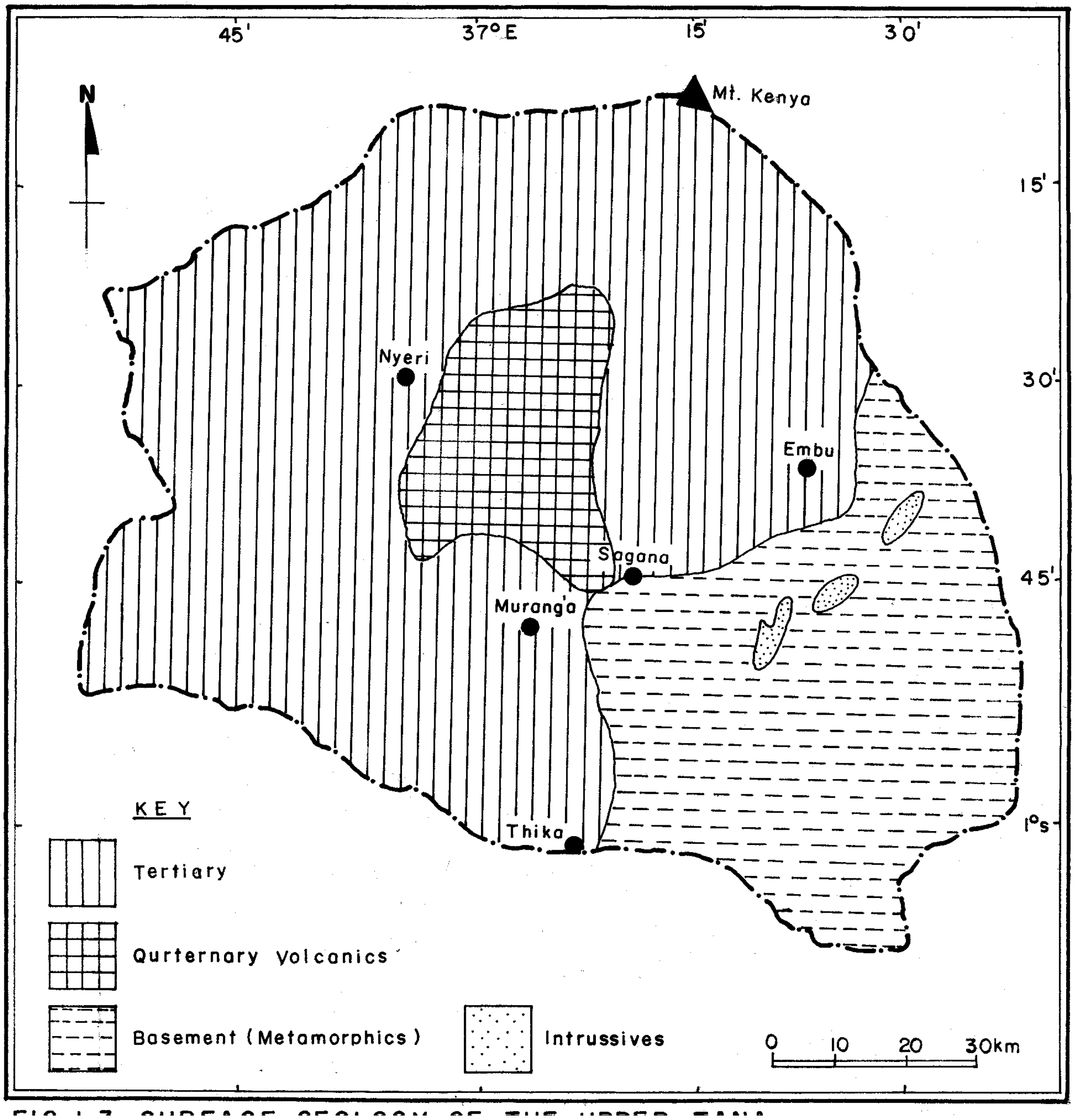

Figure 3: Surface Geology of the Upper Tana Basin *(Source: Baker, 1967)*

Most of Tana River's flood plains consist of recent alluvial sediments although some parts overlie volcanic rocks, the Mozambique Belt and Metamorphics. The volcanics overlie the Mozambique Belt Metamorphics that were deposited about 2 300 million years ago. These were affected by the Mozambique orogeny about 650 million years ago. Throughout the years, these rocks have been transformed to reach high grades of metamorphism and examples include gneisses and schists. The basement rock system is geologically older compared to the tertiary and quaternary volcanic system due to longer processes of erosion. Detailed geological descriptions of the basin are available in Baker (1967).

2.1.3 Soils and Agro-ecological Zones

The basin has various soil types and agro-ecological zones that influence land use patterns. Most of the soils in the basin are volcanic in nature and have high infiltration rates besides being highly permeable and resistant to erosion. The other parts of the basin comprise of soils originating from Precambrian rock formations. The higher parts of the region such as mountains and major escarpments comprise Histosols, humic Andosols and Lithic Leptosols that are imperfectly drained and developed on Olivine basalts and ashes of major older volcanoes. On the northeast and southeast hills and minor scarps are Regosols, Lithic Leptosols, Cambisols and Ferralsols type of soils that are of moderate to high fertility. On the level structural plains of the southern and eastern uplands, low fertility non-volcanic soils such as Ferralsols and ferric Acrisols exist while on the plateaus, Nitisols and Vertisols occur. In the north-eastern, south-eastern and the southern boundary of the area are Nitisols, Vertisols and Fluvisols that are of moderate to high fertility, respectively. The soils are developed on undifferentiated Basement system rocks such as gneisses.

On the plateaus, high structural plains and on the volcanic foot ridges are soils based on Tertiary basic igneous rocks such as Olivine basalts, Nepheline Phonolites and basic Tufts. These soils include Nitisols, Andosols, Cambisols, chromic Acrisols, Luvisols and Phaeozems and older basic tuffs. On the lower topographical sites such as valleys, soils that have developed in minor valleys are found. On the higher parts of Mt. Kenya, mountain soils such as Histosols, Lithic Leptosols and Andosols of moderate fertility are found while on the volcanic foot hills; soils such as Nitisols, Andosols, Cambisols and Acrisols are predominant (Jaetzold and Schmidt, 1983).

The soils have a moderately high to low natural fertility. Hill soils of low natural fertility such as Regosols, Lithic Leptosols, Cambisols and Ferralsols are found on insel-bergs in which the volcanic bedrock gives way to the Basement rock system consisting mainly of gneisses. The lower plateaus of Mt. Kenya comprise of Ferralsols, Nitisols and Nitisols that range from well drained to imperfectly drained vertisols. On the uplands, soils of low fertility such as rhodic and orthic Ferralsols and Acrisols occur. Mountain soils occur in broad zones from west to east, changing from medium texture in the highest parts over a medium to heavy texture in the middle and the lower parts. Soils in the southern part of the region occur in varied patches and show a heavy texture (Jaetzold and Schmidt, 1983).

The various agro-ecological zones in the basin give rise to several land use patterns depending on rainfall, temperature and altitude variations. From the highest to lowest altitudes, the main zones are Tropical Alpine, Forest, Sheep-Dairy, Tea-Dairy, Coffee-Tea and Coffee zones. Other agro-ecological zones include Rocks and Glaziers and National park, the Forest zone, Pyrethrum-Wheat, Wheat-Barley, Wheat/Maize/Pyrethrum and the Wheat/Maize/Barley zones. Others are the Cattle/Sheep/Barley, Ranging, Coffee and Sunflower/Maize zones on the lower highlands. Various land use activities occur in the various agro-ecological zones and are related to different soil types in the basin. These activities are dependent on the availability of water in the basin for their sustenance and development and in view of decreasing quantities of water in the rivers of the basin and the resultant hydrological drought; there is need that these activities be planned in a proper and sustainable manner.

2.1.4 Data Used in the Study

Mean discharge data from twenty river gauging stations (RGSs) were collected from the Ministry of Environment, Water and Natural Resources in Nairobi. The gaps in the records were filled using the correlation analysis methods and the then the quality of the data checked using the mass curves analysis. The data was then subjected to principal component analysis to establish the homogenous regions in the basin. Four representative river gauge stations (RGSs) were then selected based on communality analysis results and drought events of duration and severity in each of the homogenous regions examined. The four representative RGSs used in the study are given in **Table 1**.

Table 1: Communality Values of Representative River Gauge Stations in the Homogenous Regions

Homogenous Region	River Gauge Station	Name of Station	Communality value
R1	4AC4	Chania Old	0.89
R2	4BE1	Maragua	0.83
R3	4CB4	Thika	0.93
R4	4DA10	Thiba	0.83

The drought events were examined using the runs analysis technique as described in the following section.

2.1.5 Runs Analysis Method

Various approaches are available for determining drought events from a hydrological time series (Rossi *et al.*, 1992; Panu and Sharma, 2002). The most common and widely used approaches are the runs analysis and use of low flows using the mean annual minimum flow of fixed duration. Whereas the latter method is only suitable when drought magnitude for a given drought duration is of main interest (Pearson, 1995); the runs analysis method (Yevjevich, 1972) is suitable when drought events of duration and severity are of interest and has practical applications for designing reservoirs to supply river flows and when permissions for river abstractions are considered (Clausen and Pearson, 1995). The technique was therefore used in this study.

Duration and severity constitute two fundamental descriptors of hydrological drought in a river or stream (Tallaksen *et al*., 1997) and so the two events were determined using discharge series at the four homogenous regions in the basin using the runs analysis method. A run was defined as an uninterrupted sequence of time when discharge values were less than the mean flow, q_0 used as the truncation level. The two hydrological drought events were defined as shown in **Figure 3** indicating that each run was characterized by duration d with flow values $q < q_0$, and drought severity s_d, for duration d with $q < q_0$. The mean was used as the truncation level as it has been found to be more sensitive to the extreme values of frequency distributions and it also standardizes the severity of maximum and minimum flows, and provides valuable information on the duration and intensity of periods without significant river flood events. It is also indicative of normal hydrological conditions since it lends itself well to revealing the occurrence of hydrological drought (Dracup *et al*., 1980; Capra, 1994; Clausen and Pearson, 1995).

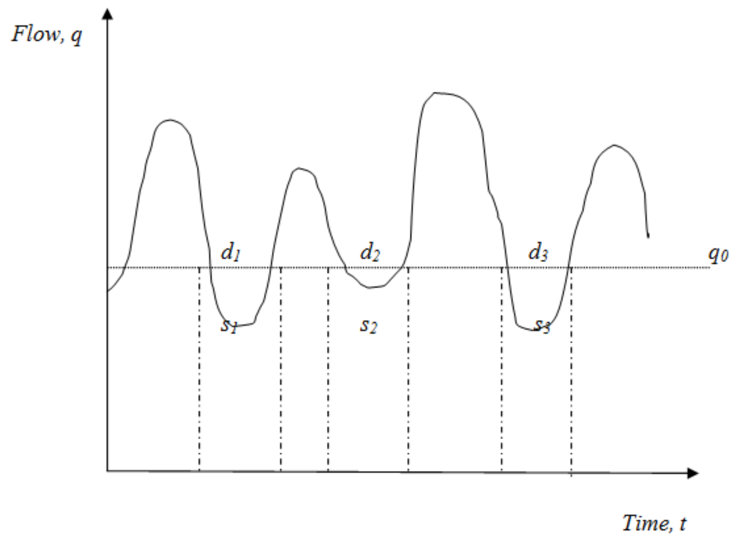

Figure 3: Schematic Definition of Hydrological Drought (*Source*: Tallaksen *et al*., 1997)

Consequently, the long term mean discharge at representative gauging stations in the homogeneous regions obtained from Principal Component Analysis (PCA) results was used to isolate drought duration and severity by taking the historical record of discharge and dividing it according to the respective long term mean discharge, and all adjacent periods for which the annual discharge was below the long term mean and then combined into drought events of duration and severity. The standardized discharge values were then used in the analysis.

3. Results and Discussion

The characteristics of the monthly drought events are summarized in **Table 2**. Mean monthly flow values at each of the representative gauge stations in the homogenous regions were used as truncation levels. The duration and severity were extracted based on discharge data series of 40 years period at each of the representative river gauge stations in the respective homogenous regions **R1**, **R2**, **R3** and **R4**.

Table 4: Characteristics of Drought Events in the Homogenous Regions in the Upper Tana Basin

Drought Event	***R1***	***R2***	***R3***	***R4***
Mean *duration* in months	4	11	9	5
Standardized mean *severity*	1.78	3.89	3.82	0.63

From **Table 4**, the four homogenous regions experienced drought events with the mean duration varying from 4 to 11 months across the regions whilst the standardized mean severity ranged from 0.63 to 3.89 with regions R2 and R3 experiencing nearly the same standardized mean severity. The drought events were experienced in the four homogenous regions of the basin with majority of the events concentrated from mid 1960s to early 1970, early to mid 1980s and early to mid 1990s and in the early to mid 2000s in the four regions of the basin. The results further show a higher frequency of drought events occurrences in some two regions but nearly a similar frequency of drought occurrences in the other two remaining regions.

The period when the drought events occurred generally correspond to times when the basin generally experienced serious rainfall deficits. This shows a connection between low rainfall and deficits in discharge. The variations in the number and frequency of the drought events in the homogenous regions would possibly be related to the semi-arid and arid nature of the climate in most of the southern and eastern parts of the basin. The recent episodes of forest loss within and around the Mt. Kenya region and Aberdare ranges would also be contributing to water deficits in the surrounding rivers which obtain their waters from the two mountain catchments of the basin.

The variations in the duration and severity of drought events in the basin would be due to the fact that the basin is not homogeneous but has several catchments with different characteristics in terms of geology, topography, soils and land use activities. The various forms of land degradation in the basin also influence stream flow in different ways. It should be noted that most parts of R3 and R4 are located near the semi arid and arid parts of the basin and there rainfall deficits experienced in the two regions cause extended periods of stream flow deficits for most times of the year. The influence of the arid climate in the southern end portions of R3 would be a contributing factor to stream flow deficits in the adjacent catchment areas. The stream flow deficits experienced in regions R1, R2 and R3 could be possibly be as a result of continued loss of forest cover and other forms of land degradation within Mt. Kenya and the Aberdare water catchment areas (UNEP/GoK, 2000).

The periods during which the drought events were experienced in the various regions of the basin generally correspond with those when most parts of the country was under extended rainfall deficits. This indicates that rainfall deficits are a precursor to stream flow deficits in rivers that lead to hydrological drought events (Downing *et al*. 1987). The information on drought occurrences in the homogeneous regions of the basin may be used in planning for water withdrawals for purposes of domestic and agricultural production in the different parts of the basin. The results also show that the four regions in the basin have different drought characteristics in terms of duration and severity but the drought events lasted longer and were severe in regions located in the semi arid and arid regions of the basin.

The drought events have implications on various activities that depend on water from the rivers. These activities include irrigation, domestic water use, hydropower production and waste disposal, among others. The lower parts of R2 are under the influence of the semi arid climate in the basin and hence the high number of drought event experienced in the hydrological region. Lower portions of R3 may be influenced by the semi arid climate in the Athi basin to the south and southwest of the basin and so stream flow deficits in the rivers of the basin are more frequent in any given year. The periods during which extended stream flow deficits occurred generally correspond with the times when the country faced rainfall deficits leading to meteorological drought (Ogallo and Nassib, 1984; Ininda, 1987 and UNEP/GoK, 2000).

This confirms the fact that deficiency of rainfall is a precursor to stream flow deficits in rivers that lead to the occurrence of hydrological drought. The differences in the stream flow deficits in the regions would be due to the location of the regions within the basin: R1 and large portions of R2 are situated within the wet and humid Mt. Kenya and the Aberdare forest zones that ensure the streams in the regions are constantly well supplied with water while lower portions of R3 and R4 are both located within the arid and semi arid portions of the basin. The two regions are mainly influenced by the adjacent dry portions of the Athi and Ewaso Ngiro basins to the south and east of the basin, respectively. The fact that R2 is located in the semi arid zone of the basin means stream flow deficits in the streams of the basin are frequent and last for longer time compared to the other hydrological regions. In R4 severity of drought would be due to the arid nature of the climate especially in the lower parts of the region and the influence of the dry and arid Ewaso Ng'iro basin to the east of the basin. For R1, drought was also quite severe although the region is located in the Montane Afro-Alphine agro-ecological zone in the basin. This could be due to increased deforestation of the Mt. Kenya forest and the Aberdare Range that are the main water catchment areas for the main rivers originating from the two forests.

According to UNEP/GOK (2000) the massive destruction of the two forests, the water levels in most of the rivers within the forests had declined so much that they could not sustain adequate water flows to the hydropower dams located downstream of the basin during the 1999-2000 drought. With the same amount of rain steep areas or those having soils with low permeability and little underground storage in R1, R2 and R3 may fail to supply vegetative needs and lead to severe stream flow deficits at critical drought periods. On the other hand, highly permeable areas in the hydrological regions with sufficient ground storage may support sizeable stream flows throughout the dry areas, except in more elevated portions of the basin. Anthropogenic changes such as farming activities, drainage works and residential improvements in the different regions of the basin could also aggravate drought conditions by speeding up water runoff and by reducing surface pondage, infiltration and underground storage in the basin. The wide annual variation of rainfall within the region due to differences in topography within the basin contributes to stream flow deficits observed in the basin's rivers. Besides, the proximity of R3 to the arid parts of the *Athi* basin which experiences prolonged dry periods throughout the year may explain the critical cumulative water deficits (severity) in the region. R4 is close to the more arid climate in the *Ewaso Ng'iro* basin to the east of the region explaining the high number of drought events and the severity of the drought in the region.

Conclusions and Recommendations

The study revealed that monthly and annual drought events that have occurred in the various homogenous regions of the upper Tana basin and that the events corresponded to the periods of rainfall deficits that occurred within the basin. The events were found to have various durations and severities. Since drought occurrence is the basin can have serious implications on land use activities, there is need to develop community based sustainable rural livelihood strategies and systems such as the promotion of water harvesting structures and water conservation systems so as to minimize the significant adverse impacts of drought in the basin. It is also important to institute capacity building of the local communities in the basin on strategies for sustainable drought management and alternate livelihoods strategies in view of frequent drought occurrences in the basin.

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