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# Drought Indices Assessment for Sustainable Water Resources Management-a Case Review for upper Tana River basin, Kenya

Raphael M. Wambua[1*], Benedict M. Mutua[2] and James M. Raude[3]
[1]Lecturer and PhD Candidate, [2]Associate Professor,
Egerton University Department of Agricultural Engineering, Kenya
[3]Senior lecturer, BEED, Jomo Kenyatta University of agriculture and technology, Kenya

***Abstract:*** **Drought indices as means of assessing drought which is a stochastic natural disaster influencing socio-economic development in the upper Tana River basin are presented. Drought is a condition on land or river basin with intense and or persistence below average precipitation and water scarcity. Drought phenomenon may be characterized in terms of its severity, intensity, duration and magnitude. For the purpose of prospective planning and management of drought, its characterization, analysis of drought severity, impacts and risk assessment is vital. Development and application of drought indices have been used to characterize drought at varying spatial and temporal scales for regional, national and river basin levels. This article review drought indices and explores their applicability in different time scales of drought for 1, 3, 6, 12, 24 and 48 months lead times. A reliable index must be able to quantify drought severity, detect drought beginning and end times for early warning systems, monitoring and prospective water resources planning. Since numerous drought indices have been developed over the years, it is critical to provide their detailed analysis review, indicate their differences and applications. A research direction for drought assessment using indices in upper Tana River basin for water resources management is proposed.**

***Key words: Drought severity, upper Tana River basin, drought characterization, water resources, early warning*** **system**

## 1. INTRODUCTION

On global scale, drought has become more frequent and severe due to climate variability with different regions experiencing droughts at varying scales and times [14]. Consequently, global impacts of drought on environmental, agricultural and socio-economic aspects need to be studied. As such, four distinct types of droughts namely; meteorological, agricultural, hydrological and socio-economic are recognised. These droughts have either direct or indirect impacts on river basins. The former include degradation of water resources in terms of quantity and quality, reduced crop productivity, increased livestock and wildlife mortality rates, increased soil erosion and land degradation, and increased plant diseases and insect attacks [60: 52]. Severe drought impacts have been experienced in other regions of the world leading to food insecurity and general increase in world food prices. For instance, very notable recent droughts of 2009 and 2011 in Kenya adversely affected the agricultural sector where crop yields were drastically reduced. Due to the problems mentioned above, river basin managers often have a challenge of addressing water risks, conflicts and balancing economic development while at the same time maintaining reliable water resources [45].

African countries are among the most vulnerable to impacts of climate variability and drought. The impacts adversely affect the well being of the population. These impacts are compounded by numerous factors such as vast arid and semi-arid lands (ASAL) in the region, poverty, high population density, and human diseases. This is expected to multiply the demand for water, food and forage for livestock within the area in the next decades [45]. In East Africa, it has been projected that water availability will decline due to drought. In addition, there is a likelihood of increased desertification due to decline in seasonal amount of precipitation and alteration of its patterns at different magnitudes for different locations [67; 24].

Droughts in Kenya have impacted adversely on rain fed agriculture, water resources, hydropower generation and ecosystems. The agricultural sector alone which contributes to more than 51% of the gross domestic product (GDP) in Kenya [67] has been critically affected by frequent droughts. Over the past 50 years, Kenya has experienced at least one main drought per decade [11] .In addition; there has been a notable increase of drought in terms of frequency, duration and intensity. Any damage caused by drought on agriculture and water resources leads to famine, humanitarian crisis, rationing of water supply and decline in hydropower generation. Effective drought forecast allow water resource decision makers to develop drought preparedness plans. Such plans are critical for advance formulation of programmes to mitigate drought-related environmental, social and economic impacts. Therefore, accurate drought assessment and forecasting with an adequate lead time is paramount for formulation of mitigation measures in river basins [55].

Drought forecasting has received a new approach especially with the development of the Drought Indices and Artificial Neural Networks (ANNs). An ANN is a computing system made up of a number of simple and highly interconnected information processing elements. Such a system has performance characteristics that resemble biological neural networks of human brain. ANN has numerous merits when used for data processing. The system processes information based on their dynamic state response to external input [39]. ANNs have the capacity to model relationships that are quite dynamic and can capture many kinds of relationships including non-linear functions which are difficult or impossible to determine using other approaches [41]. The ANNs have recently been used in water resources engineering (WRE). WRE comprises the study of hydraulics, hydrology, environment and geological related variables. Such variables are dynamic and exhibit non-linear and stochastic characteristics. These properties make WRE variables complex and difficult to determine due to spatial and temporal variations. Thus due to their advantages, ANNs provides effective analytical techniques in modelling and forecasting non-linear and dynamic time series variables in WRE such as drought [41].

At present, most basins in Kenya have limited or lack of adequate quantifiable information of drought occurrence, frequency and severity. In addition, there is lack of sufficient and appropriate drought assessment and forecasting methods. Drought models can be used to estimate and forecast drought conditions on a spatial and temporal domain. To prepare for effective mitigation of drought risks in Kenya, evaluation and forecasting of drought conditions is vital. Thus, this research presents a review of drought indices for possible drought assessment in upper Tana River basin with a focus to informed decision making on matters relating to water resources management.

*Drought Definition*

Drought is a condition on land characterised by scarcity of water that falls below normal average or defined truncation level. The term drought has been defined differently in numerous applications [61]. However, it is a challenge to quantitatively define the term. Drought is perceived as a stochastic natural disaster that adversely affects water resources within river basins [26]. It may be described as a hydro-meteorological epoch on land characterized by temporary and recurring water scarcity. The magnitude of the drought is measured by the extent with which it falls below a threshold level over an extended period of time [39]. Drought has been identified as the most complex natural hazard since it is difficult to detect, develops slowly and impact on numerous aspects within a region [39]. Success of drought preparedness and mitigation depends upon timely information on its onset, and propagation in terms of temporal and spatial domain. Such information is usually obtained via effective and continuous drought monitoring using drought indices. The study of spatial and temporal drought conditions is fundamental in offering a wide range of solutions for control and management water resource systems. Assessment of drought conditions is critical for planning water supplies, irrigation systems, crop and food security programmes, hydropower generation, water quality management and waste disposal systems [1].
Drought may also be described by two distinct dimensions such as conceptual and operational terms [69]. The former is developed to offer a general understanding and develop a policy for drought management [44]. The latter objectively defines criteria for drought beginning, end and severity of drought for different applications.

*Drought Characteristics*

Droughts are characterized into numerous aspects. These include drought severity, duration, frequency, magnitude and spatial distribution (Figure 1) [3; 63]. These dimensions of drought are described below.

**Drought severity:** This is the extent of precipitation deficit in terms of magnitude or degree of impacts resulting from precipitation deficit [68]. In addition, Drought severity can be mathematically defined as a product of its magnitude and duration (Figure 1).

**Duration**: Drought duration refers to any continuous period of sequence with deficit of water below a defined truncation level.

**Intensity:** It the ratio of the drought magnitude to its duration.

**Drought frequency**: the frequency also called return period of a drought is the mean time period between two consecutive drought events that have the same severity either equal or greater than a defined threshold.

**Magnitude:** It is the accumulated water deficit in terms of precipitation, soil moisture, runoff, stream flow, water reservoir levels and ground water below a certain truncation or threshold level for a given duration

**Spatial distribution**: It is the geographical extend in terms of areal coverage of drought which is variable during a drought event.

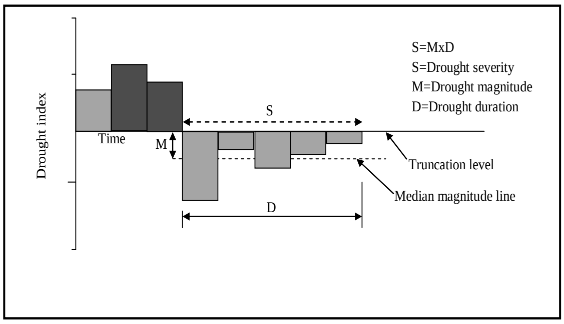


Fig.-1. the characteristics of a drought event

**Impacts of Droughts**

Different droughts have direct or indirect impacts on river basins (Table 1; Figure 2). The former include degradation of water resources in terms of quantity and quality, reduced crop productivity, increased livestock and wildlife mortality rates, increased soil erosion and land degradation, and increased plant diseases and insect attacks [60; 52]. On the other hand, the indirect impacts comprise reduced income, tax revenues increased prices for food, unemployment, and migration of people and animals (Figure 2). Worldwide, more than eleven million persons have died since 1900 as a result of drought related impacts. In addition, two billion persons have been critically affected by the impacts [10]. The main challenges associated with drought are that it causes ill health through water scarcity, malnutrition and famine [60].

Table 1. Historical drought effects in Kenya (E-Eastern,RV-Rift valley, NE-North eastern, C-central,, W-Western, Co-Coast , CW-Countrywide

| Period (years) | Areas | Remarks on the drought effects |
|---|---|---|
| 1960-1961 | E, RV | Caused Cattle deaths |
| 1972 | CW | Water shortage livestock deaths |
| 1973-1974 | CW | Human and livestock deaths |
| 1974-1976 | E, N, and C | Heavy livestock losses, food and water shortages |
| 1980 | C, E, W and Co | Low crop production, water shortages |
| 1981 | E | Famine and water shortage |
| 1983 | CW | Water shortages, human and livestock migration |
| 1984 | C, RV, E, NE | Huge food shortages |
| 1987 | E and C | Severe food shortages |
| 1992-1994 | NE, C and E | Moderate food shortages |
| 1999-2000 | CW | Deficit food supply, interuption of electricity supply, water scarcity |
| 2010-2011 | E, C, C,NE | Food and water deficit |

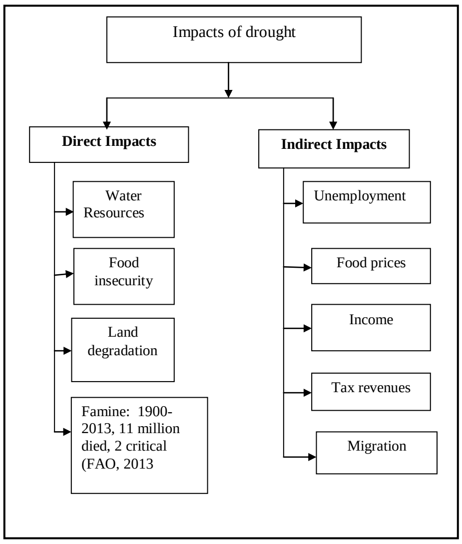


Fig-2. Flow chart showing the impacts of drought in a river basin

*Main Drought types*

There are four main types of droughts as described by [73]. The four types of drought are: the Hydrological, Meteorological, Agricultural and Socio-economic droughts. The hydrological drought characteristics are defined by magnitude, severity, duration and frequency, and can be studied at a basin scale. Hydrological drought may be categorized into surface and ground water droughts. Agricultural drought links meteorological or hydrological drought to agricultural impact. Agricultural droughts impact negatively on farming systems whenever they occur. Their impacts are normally two-fold; environmental and economic impacts. The agricultural drought is a type associated with low agricultural production, decline in output from agro-processing industries and unemployment incidents in the agricultural sector.

*Fundamental dimensions of drought indices*

Numerous approaches for drought characterization have been used. However, drought indices are the most preferred methods. A drought index is single numeric value calculated by integration of drought indicators. A drought index gives a distinct representation of drought and guide decision-making in a more effective way than the drought indicators that are presented by the raw data sets of drought [19]. The following are the basic dimensions of the drought indices that make it more effective in drought characterization than the drought indicators.

i) Drought indices can define the drought beginning and end times
ii) The indices provide detection and real time drought monitoring
iii) The indices provide reliable means for drought evaluation
iv) It's possible to represent drought conditions for a given region using drought indices
v) Drought indices provide correlation of drought with drought impacts over geographical time scales
vi) It is possible to express drought conditions in different levels and communicate the implications to various stakeholders

*Drought indices*

Drought indices or models are used for assessment of occurrence and severity of droughts. The Drought Indices (DIs) were developed for specific regions using specific structures and forms of data input. Drought indices may be categorized into two broad categories; remote-sensing based and the data driven drought indices [2]. The remote-sensing based indices are presented from data obtained from remote sensors to map the conditions of land. Data driven indices are those calculated using ground based data recorded over time [40; 51].

Different perceptions pertaining drought may be presented using drought indices. The indices are used to identify the three main physical droughts such as meteorological, agricultural and hydrological droughts. All the three types of droughts are triggered by precipitation deficiency on a river basin. A decrease in precipitation below a truncation level may cause low moisture content leading to fundamental agricultural drought. This in turn may cause reduced water flows in surface, sub-surface and ground water resources contributing to the hydrological drought. Thus the propagation of three main droughts originate from discrepancies in the hydrologic cycle caused by climate variability (Figure 3).

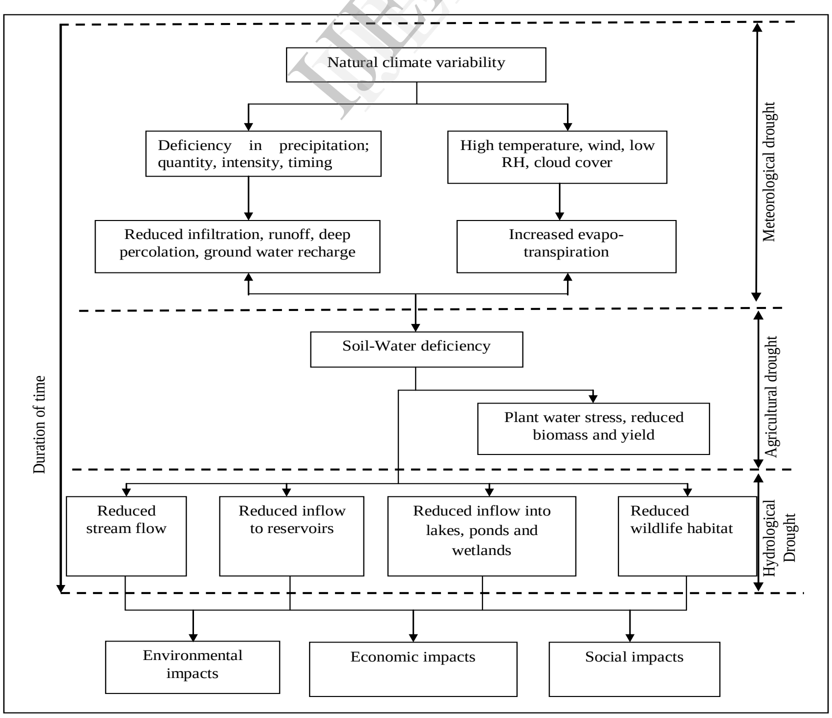


Fig- 1. Propagation of drought via hydrological cycle

The drought indices are used to compute drought conditions for different time scales. Typical time scales for drought forecasting include 1, 3, 6, 12, 24 and 48 months lead time. Each time scale has its corresponding effects [44]. as described using the standardized precipitation index (SPI) in table 1.

**Table 1. The Structure and Scope of Drought Forecasting**

| SPI Input | Phenomena reflected | Application of the output |
|---|---|---|
| SPI-$LT_1$ | One-month lead time drought conditions | For detection of short-term agricultural drought during growing period |
| SPI-$LT_3$ | Three-month lead time drought conditions | For short-term and seasonal metorological drought esmimation |
| SPI-$LT_6$ | Six-month lead time drought conditions | Medium-term trends in precipitation over seasons detected |
| SPI-$LT_9$ | Nine-month lead time drought conditions | Detects any significant medium effects of drought on agriculture |
| SPI-$LT_{12}$ | Twelve-month lead time drought conditions | For detecting drought effects on stream flows, researvoir and ground water levels |
| SPI-$LT_{24}$ | Twenty four- month lead time drought conditions | For detecting long-term drought effects on stream flows, researvoir and ground water levels |

Table 2. Summary of different drought indices for (Hydrological (H), Meteorological (M), Agricultural (A) and Remote Sensing (RS))

| **Drought index/Developed by** | **Type of drought** | **Key notes** , |
|---|---|---|
| Surface Water Supply Iindex (SWSI) /[53] | H | Calculates the weighted average of the standardized anomarlies for precipitation,reservoir storage, runoff and snowpack |
| Drought Severity Index (PDSI) /[47] | H | Analysies precipitation and temperature in a water balance model. It compares meteorological and hydrological drought on spatial and temporal domain |
| Aggregated Drought Index (ADI) / [28] | MHA | It is a multivariate, aggregate drought index with five to six hydrological inputs such as precipiattion, streamflow, reservoir storage, evapotranspiration, soil moisture and snow water content. Its fist priciple component(PC1) is normalized by the standard deviation |
| Standardized Precipitation Index (SPI) / [36] , Duosken, N. J. and Kleist, J. 1993 | M | It is a simple index,has reliable spatial consistency, its probablistic in nature and useful in risk and decision analysis. It is adjustable to user defined time periods and can be used to determine three main dimensions of drought; intensity, duration and spatial extend |
| Crop Moisture Index (CMI) / [48] | A | It analyses precipitation and temperature in a water balance model |
| Normalized Difference Drought Index (NDVI) | A | It uses visible red and near infrared bands for calculation of vegetation conditions. An adnanced radiometer is used to capture ad reflect the bands. |
| Regional Stream flow Defiiciency Index (RSDI)/ [55] | H | It is used to characterize drought within a homogeneous region. It uses flow duration curve for for discharges that exceed 90% of the time defined as Q90. A RSDI is computed for each homogeneous region using time series stream flow |
| Soil moisture deficit index (SMDI)/ [43] | A | It considers spatial variability of hydrological parameters of soil type, land cover and meteorological variables. |
| Palmer Modified Drought Index (PMDI)/ [47] | M | It is used to calculate the beginning and end time of drought and wet periods which may otherwise be impossible to detect using the PHDI. |
| Z-Index /[47] | M | a monthly standrdized anormally of the available moisture; its an intermediate term within the oroginal PDSI and used for short term drought forecasting |
| Effective Drought Index (EDI)/ [3] | | Used to detect drought beginning and ending and accumulated stress while ignoring the effect of runoff and ET |
| Reclamation Drought Index (RDI)/ [66] | H | Similar to SWSI and incorporates temperaure-variable and duration into basin-wise index computation |
| Crop Water Stress Index (CWSI)/ [21; 24] | RS | The CWSI is calculated from the expression: $CWSI = 1 - \frac{AET}{PET}$ where aet is the actual ET, PET is the potential ET. The index is mainly used for irrigation scheduling |
| Vegetation Condition Index (VCI)/ [32] | RS | It is used to determine the departure of amount of NDVI from long term NDVI as a measure of the health of the vegetation |
| Crop Specific Drought Index (CSDI)/Meyer *et al.*, 1993 | A | It uses the crop and soil phenology and climatological data to estimate soil water availability for different zones and soil types |
| Keetch-Byram Drought Index (KBDI) /[31] | M | M for analysinsg precipitation and soil moisture in a water budget model. It is used to monitor forest fires and is for fire control and management |
| Temperature Condition Index (TCI) /[33] | RS | It uses te brightness temperature to determine the deviation of month from recorded maximum temperature.in general, the highre the temperature the higher the drought. It is computed from: $TCI = \left( \frac{BT_{max} - BT_j}{BT_{max} - BT_{min}} \right) \times 100$ Btmax=maximum brightness temperature,Btmin=minimum brightness temperaturebtj=the jth month brightness temperature |

| | | |
|---|---|---|
| Normalized Difference Water Index (NDWI)/ [12] | RS | Used to determine volumetric water content based on physical principles |
| Vetetaion Health Index (VHI)/ [33] | RS | It combines vci and tci with some weight factor a for the contribution of vci and tci. The factos amay be set to 0.5 where information is lacking . the following relation applies: $VHI = a \times VCI + TCI \times (1 - a)$ |
| Evapo-transpiration Drought Index (ETDI) [43]. | A | It combines the hydrological parameters of soil and land use material in a spatial domain. The ETDI considers water stress ratio as expressed in the form: $ETDI = \frac{PET - AET}{PET}$ weekly values reflect short-term droughts |
| Standardized precipitation index (SPI)/ [64] | M | Used to fatcor in the impact of cliamte change on drought characteristics which could not be detected by the original spi. It uses both the precipitation and the temperature data sets. It considers water balance and evapotranspiration |
| Hybrid Drought Index (HDI)/ [27] | M,H,A Integrated | It combines the SPI, PDSI, and SWSI to represent various drought impacts |
| Vegetation Drought Response Index (VegDRI)/ [4] | M.A,RS | Used to characterize specific droughts and combines indices SPI,PDSI and NDVI |
| Modified Perpendicular Drought Index (MPDI)/ [13] | RS | It is best used to accurately differentiate between the surfaces that are bare soils and densely vegetated agricultural or forest areas. A vegetation fraction that considers soil moisture and vegetation growth is used for undulating topography and variable soil types, the mpdi performs better than PDI. |
| Recconnaissance Drought Index (RDI)/ [59] | M | It uses the precipitation and potential evapotranspiration. It is a more comprehensive DI than SPI. It is a physically based and calculates the deficit between the evaporative demand of atmosphere and precipitation. It is a simple index in computation of drought. |
| Normalized Multi-band Drought Index (NMDI)/ [65] | RS | It is an index used to improve sensitivity od ndwi and ndii by using inrformation from nir and swi bands. It extracts both vegetation and soil water content. |
| Relative Soil Moisture (RSM) Index/[58] | A | It is a water component calculated from water balance. It considers climate, soil physical properties, potentail ET ,precipitation, and crop charcetristics and managemnet pracices variables |
| Agricultural Drought Index /[35] | | Uses water balance model and crop transpiration to calculate an integrated transpiration deficit |
| Rainfall Anormally Index (RAI)/ [62] | M | An average precipitation based on weekly, monthly and annual time periods is used to characterize relative drought. The resulting drought is then ranked with respect to fisrt ten severe droughts in a long-term record. The drought is then asigned a magnitude based on resulting values |
| Drought Severity Index (DSI)/ [5] | M | Accumulated monthly deficit of precipitation, temperature and ground water conditions data |
| National Rainfall Index (NRI)/ [15] | M | The total annual precipitation agianst its long term average are correlated. It reveals patterns and abnormalities of yearly precipitation on continental scale. |
| Drought frequency index (DFI)/ [16] | M | The index uses the mean frequency of of reccurrence for assessing the magnitude of drought in an area. |
| Ground water resource index (GRI)/ [37] | H | A simplified distributed water balance model is applied. It considers river basin geo-physical characteristics that affect hyrological response to precipitation |
| Water balance drought derived index (Vasiliades *et al*., 2011) | H | A water balance model is used to simulate runoff and the index is created by developed by normalizing and standardizing the generarted runoff to the mean runoff |
| Vegetation outlook (VegOut)/ [56] | Aggregate | It combines the cliamte information and RS data of current vegetation conditions with oceanic index data and environmental information including land cover type, irrigation status, soils and ecological settings to predict future outlook of vegetation condition |
| Ration Vegetation Index (RVI)/ [49] | RS | The index is computed from the relation: $RVI = \frac{NIR}{R}$ where the NIR is near infra red and R is red bands repsectively |
| Weighted Diffrence Vegetation Index (WDVI)/ [7] | RS | The index is a function of near infra-red (NIR), rainfall (R) and slope of soil line $\gamma$ as expressed in the relation: $WDVI = NIR - \gamma R$ |
| Perpendicular Vegetation Index (PVI)/ [50] | RS | this index is calculated for the function: $PVI = Sin(a)NIR - Cos(a)R$ where a is the angle between the soil line and the NIR |
| Difference Vegetation Index (DVI)/ [34; ]; Ray 1994 | RS | The index is a function of near infra red band and the rainfall computed from the relation: $DVI = NIR - R$ |
| Soil Adjusted Vegetation Index (SAVI)/ [20] | RS | It is a function of near infrared band, red band and soil adjustiment fcator as per the expression: $SAVI = \frac{NIR - R(1 + L)}{(NIR + R + L)}$ where L is the soil adjustment factor to account for soil variation |
| Infrared Percentage Vegetation Index (IPVI)/ [8] | RS | It is calculated from the following function: $IPVI = \frac{NIR}{NIR + R} = \frac{NDVI + 1}{2}$ |

| | | |
|---|---|---|
| Atmospherically Resistant Vegetation Index (ARVI)/ [30] | RS | It based on atmoshperic variables as per the relatiion: $RB = R - \gamma(B - R) = \frac{NIR - RB}{NIR + RB}$ where $\gamma$ is a correlation parameter which is optimum at $\gamma$ =1 |
| Anormally Vegetation Index (AVI)/ [6] | RS | It uses the annual ndvi to assess vegetation dynamics and surface dryness of land |
| Cubed Ratio Vegetation Index (CRVI)/ [57] | RS | The $CRVI = \left(\frac{NIR}{MIR}\right)^3$ MIR is the landsat-5 thematic mapper mid infrared |
| Simple Ratio Water Index (SRWI)/ [72] | RS | Uses NDVI applied in MODIS with feedback loops to minimize atmospheric and soil bias that is present in ndvi and other Vis |
| Vegetation Tempertaure Condition Index (VTCI)/ [65]. | RS | Uses NDVI and LST and is computes from: $VTCI = \frac{LST_{NDVi\max} - LST_{NDVi}}{LST_{NDVi\max} - LST_{NDVi\min}}$ where $LST_{NDVIimax}$ and $LST_{NDVIimin}$ are the maximum and minimum land surface temperature of the pixels in the study region and lstndvii is the land surface temperature of the pixel |

*Effect of Global Warming on Drought*

Global warming is caused by two main aspects; first is the climate variability which slows down the global circulation of ocean currents due to moderated differences in temperature between tropical and temperate sea water bodies. Secondly, the ice melting in the Polar Regions implying cold water entering the oceans and drifting into the tropics affect global warming. The ice melting flowing and flowing leads into cooling of tropical oceans whose effect is picking significantly of low moisture by the prevailing winds [23]. The wind takes with it the little moisture picked along its course. Global warming influences the rate and timing of evapo-transpiration. Due to global warming, some regions in the world are likely to get wetter while those that are already under dry conditions likely getting drier. Thus, global warming is likely to increase drought occurrence and expansion of the dry areas [9]. For instance, the regions in southern Africa, the Sahel region of Africa, southern Asia, south west of United States of America have generally been getting drier over the years [10]. In addition, water resources are expected to decline by up to 30% in the affected areas. These notable changes will occur partly because of an expanding atmospheric circulation pattern. This pattern is called Hadley cell in which warm air in the tropics rise, losses moisture to the thunderstorms, and descends in the sub-tropics as dry air. During this process, jet streams shift to the higher latitudes, and storm patterns shift along with them leading to expansion of arid and semi-arid lands [9].

*Stochastic drought forecasting models*

The term stochastic refers to the spatial and temporal variation of hydrological parameters. Numerous approaches have been developed for analysing stochastic characteristics of time series hydrological variables [18]. Development in forecasting and early warning of the drought phenomena is increasingly being applied in many regions in the world. This is being done to help mitigate consequences of drought on vulnerable river basins. Different drought modeling and forecasting techniques are in use today. Some of the common stochastic drought forecasting models include; autoregressive integrated moving average model (ARIMA), Adaptive Neuro-fuzzy inference system, Markov chain model, Log-linear model and Artificial Neural Network (ANN) model. Some of the hydrological models may use probabilistic approaches [67].

*Autoregressive integrated moving average (ARIMA) model*

One of the most widely used approaches in stochastic hydrological modelling is the Autoregressive Integrated Moving Average Model (ARIMA). It is used for both the non-seasonal and multiplicative seasonal modelling of hydrological parameters. For a non-seasonal ARIMA modelling, a differencing operator represented in the following equation is used:

$$\nabla = 1 - B$$

Where $\nabla$ is the differencing operator, *B* is a backward shift operator. For the purpose of seasonal differencing, an operator which is expressed in the following relation is used:

$$\nabla^d = (1 - B)^d$$

Where $\nabla^d$ is the seasonal differencing operator while d is the differencing parameter which is used to make the series stationary. The complete function of a non-seasonal ARIMA is defined by the relation:

$$\phi(B)Z_t = \phi(B)(1 - B)^d Z_t = \theta(B)a_t$$

Where zt is the observed data series, $\phi(B)$ is a polynomial of order p, $\theta(B)$ is a polynomial of order q, p is a non-seasonal autoregressive average parameter and q is a moving average parameter.

On the other hand, the multiplicative model that accounts for seasonal time series data with cyclic characteristics of the order $(p,d,q)\times(P,D,Q)$ is expressed as:

$$\phi_p(B)\Phi_p(B^s)\nabla^d\nabla_s^D(Z_t-\bar{Z})=\theta_q(B)\Theta_Q(B^s)a_t$$

Where $\Phi_p$ is a seasonal polynomial of order *P*, $\Theta_Q$ a seasonal polynomial of order *Q*.

*Causes of Droughts in Kenya's river basins*

Climate variability and global warming that affect atmospheric circulation play a fundamental role in influencing drought occurrences in Kenya. When the Indian Ocean surface water temperature is abnormally low, it leads to the cooling of South-East and North-East trade winds. These two air masses converge near the equator within a region called Inter-Tropical Convergence Zone (ITCZ). When the winds are cool, they do not pick up enough moisture from the ocean water surface and thus lead to erratic rainfall patterns in eastern parts of Kenya [17]. On the western parts of Kenya, the Atlantic and Congo prevailing winds bring the same drought conditions in case they are abnormally too cool to pick sufficient moisture. Other factors leading to increase in drought frequency and severity include poor land use practices and deforestation, destruction of catchment areas. Some of land use patterns combined with certain cultivation methods contributes to the global warming through atmospheric carbon changes. Most farmers in Kenya are not properly controlling on-site soil detachment and therefore most farmland is exposed to soil erosion. The fertile top-soil is continuously being eroded due to agents of erosion mainly water and wind. Due to the erosion, most of the rain water does not infiltrate into the soil and instead flows as excess runoff. This leads to depletion of soil moisture and plant nutrients.

Destruction of catchment areas and deforestation is another critical contributor of drought in Kenya. Generally the forest cover has decreased by 72% between the years 2000 and 2007 [17] to 6.1% of the total land mass in 2011 [70]. Among the five main water towers in Kenya, the Mau Complex lost the highest with 70% of the forest cover destroyed within the period. The chief causes of deforestation are the need to expand agricultural land, uncontrolled exploitation of forest resources, overgrazing and establishment of new settlements on forest land as accelerated by increasing population pressure.

*Description of upper Tana River basin*

The upper Tana River basin has an area of 17,420 km$^2$ and is part of the larger Tana River basin, which is the largest river system in Kenya with an area of 100,000 km$^2$ [25; 71] Its forest land resources located along the eastern slopes of Mount Kenya and Aberdares range have a critical role in regulating the hydrology and hydro-power generation within the entire basin [22]. The upper Tana River basin lies between latitudes 00$^0$ 05' and 01$^0$ 30' south and longitudes 36$^0$ 20' and 37$^0$ 60' east (Figure 4). The basin is fundamental in influencing the ecosystem downstream.



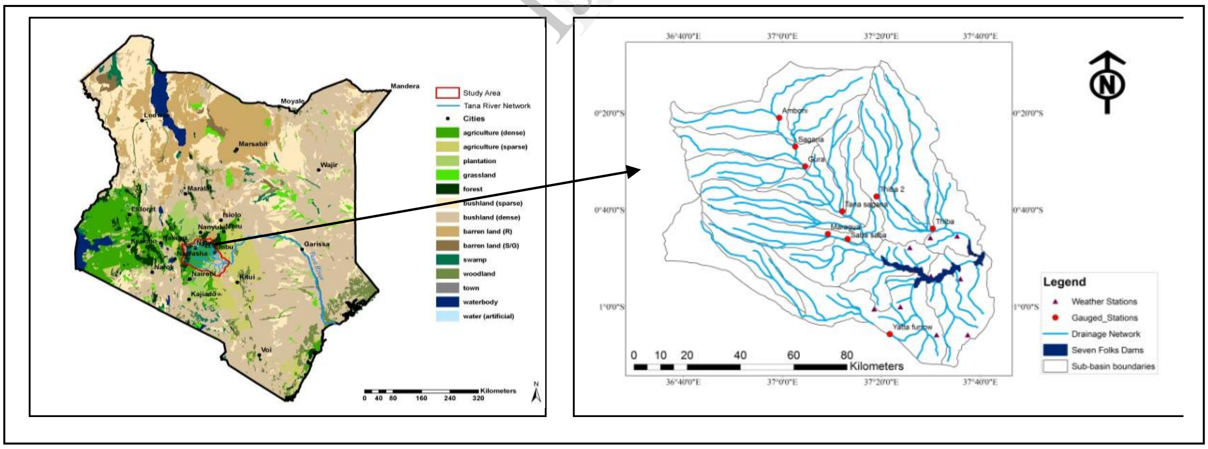


Fig.- 4: The location and drainage network of the upper Tana River basin

*Impacts of Droughts in upper Tana River basin*

Drought has impacted in numerous aspects within the past period. It has led to degradation of water resources in terms of quality and quantity. Due to increased evepo-transpiration and reduced runoff as a result of decreased precipitation, the quantity of surface and sub-surface water has declined. The upper Tana River basin has been negatively affected by notable droughts such as the La Niña of 1999 to 2000, and 2008 to 2009 [46]. These led to severe water scarcity. Concentrations of sediment and chemicals have increased as there is low quantity water that can dilute these substances originating within the basin. Agricultural production and forest resources have reduced since most farming is rain-fed. Due to low stream flow, hydropower generation declined and power rationing especially during specific seasons when drought severity affects water levels in Seven-Folk dams within the basin. The indirect impacts of drought are immense and adversely affect socio-Economic Development within the basin.

*Water resources management in upper Tana River basin*

Water is a critical natural resource which is fundamental for a health ecosystem functioning and socio-economic development. A sound water resources management in the upper Tana River basin is crucial in reduction of poverty, acceleration of socio-economic growth and equitable distribution of resources. Water resources planning in the basin call for planning, development, distribution and optimization in the water resource utilization. Proper water management should focus in optimizing the use of surface and ground water flows for sustainable socio-economic development. All stakeholders should participate in an integrated manner to contribute to the aspects of river basin planning, pollution control, water allocation, monitoring of water flows, financial management and information dissemination.

## CONCLUSION AND RECOMMENDATIONS

This article aimed at exploring drought definition, effects of drought, and the available drought indices used in evaluation of drought and gaps in drought studies with a special focus of upper Tana River basin. This gives direction to further studies of drought assessment and with a view to guiding decision making in water resources management. Such information is vital in quantifying water available for different allocations such as hydropower generation, domestic water supply, irrigation and operation of hydraulic structures. It has been noted that comprehensive drought evaluation have been reported for upper Tana River basin and yet it is a key and largest water resource system in Kenya. From the study it is recommended that:

a) assessment of spatial and temporal drought conditions using available data driven and remote-sensing based drought indices be explored for proper water resources planning and management within the upper Tana River basin

b) an integrated drought evaluation index with multiple lead times (short, medium and long-term lead times), be formulated based on available hydro-meteorological and remote-sensing data sets to guide in planning mitigation programmes within the basin



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