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Author's details: *please complete the table below before submitting the abstract.*

Submitting Author	***Prof. Dr.-Ing. Benedict Mwavu Mutua***
Position	*Deputy Vice-Chancellor (Planning, Partnerships, Research and Innovation)*
Department, Institution	*Division of PPRI,* *Kibabii University*
Address	*P.O. Box 1699- 50200, Bungoma, Kenya*
Country	*Kenya*
Email	*bmmutua@kibu.ac.ke*
Phone	*+254 735 968699*
Gender	*Male*

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Drought forecasting under climate change scenarios using artificial neural networks for sustainable water resources management in upper Tana River basin, Kenya

Benedict Mwavu Mutua[1], Raphael Muli Wambua[2] and James Messo Raude[3]

[1]*Division of Planning, partnerships, Research and Innovation, Kibabii University*

bmmutua@kibu.ac.ke

[2]*Department of Agricultural Engineering, Egerton University*

wambuarm@gmail.com

[3]*Department of Soil, Water & Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology*

ramesso@jkuat.ac.ke

Short Abstract

Climate change has continued to impact negatively on water resources globally. For instance, extreme weather conditions especially the drought phenomena have become frequent in Africa. This has prompted water engineers and hydrologists to formulate mitigation and adaptation measures to address these challenges. The frequency of drought event of a defined severity for a defined return period is fundamental in planning, designing, operating and managing water resources systems within a basin. This paper presents an analysis of the hydrological drought frequency for the upper Tana River basin in Kenya using the absolute Stream flow Drought Index (SDI) and modified Gumbel technique. The study used a 41-year (1970-2010) stream flow data and forecasted hydrological droughts for 2, 5, 10, 20, 50, 100, 200, 500 and 1000-year return periods in relation to the selected stream flows. The results provide an overview of drought trends within the river basin and therefore would be very useful in applying drought adaptation policies by water resource managers.

Keywords: Upper Tana River basin, Hydrological drought, Return period, Gumbel technique, Drought frequency

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1. Introduction

Hydrological drought decreases the availability of water resources (Liu *et al*., 2012) in river basins thus, adversely impacting on economic aspects (Carrol *et al*., 2009; Van Vliet *et al*., 2012), social dimensions such as increased human conflicts and mortality rates (Garcia-Herrera *et al*., 2010) and ecological systems. There is need to understand the drought events in order to develop drought mitigation mechanisms in river basins (Wambua *et al*., 2014). Hydrological drought impacts on large areas and large human population and may be triggered by climate change and /or variability (Mondal and Mujumdar, 2015). Like other drought events, hydrological drought is considered to be a 'creeping hazard' because it develops slowly, it is not easily noticed, covers extensive areas and it lasts for long periods of time with adverse impact on ecological systems and socio-economic development (Liu *et al*., 2015; Van-loon, 2015). In addition to hydrological droughts, other types of droughts Include meteorological agricultural/soil moisture droughts and socio-economic drought. However, according to Van-loon and Laaha (2015), hydrological drought has the most significant effects almost across different sector.

The key parameters of droughts are the longest duration and highest severity for a defined return period. Such parameters aid in designing water storage systems capable of withstanding effects of droughts (Kyambia and Mutua, 2014). Since occurrence of drought contributes to adverse socio-economic impacts, they need to be quantified so as to improvise on the coping and/or mitigation mechanise. Thus hydrological drought estimation using stream flow data for a defined range of return period in a river basin is crucial. The commonly used return periods are 2, 5, 10, 20, 50, 100, 200, 500 and 1000 years.

1.2 Hydrological drought process

The occurrence of hydrological droughts can be expressed using the hydrologic water balance Equation 1.

$$R = P - ET - \Delta S - G \quad (1)$$

Where; *R*=Runoff (mm), *P*=precipitation (mm), *ET*=Evapo-transpiration (mm), *ΔS*=Change in soil-water storage (mm), and *G*= Ground water (mm). However, the frequency of occurrence of drought is not well researched and thus not understood for numerous river basins in the world. Therefore, there was need to carry out this study at the Upper Tana River basin in Kenya.

1.3 Objective

The objective of this research was to estimate hydrological drought frequency using absolute Stream flow Drought Index (SDI) and modified Gumbel's technique for the Upper Tana River basin, Kenya.

2. Materials and Methods

The study was carried out in the upper Tana River basin in Kenya where the basin has an area of 17,420 km^2 (Figure 1). The basin plays a critical role in regulating the hydrology of the entire basin (IFAD, 2012) and in the process, it controls the hydro-electric power generation within the Seven-Folk dams downstream of the Tana River. The basin is very critical in Kenya as it drives the socio-economic development through hydro-electric power generation, water supply and agricultural production.

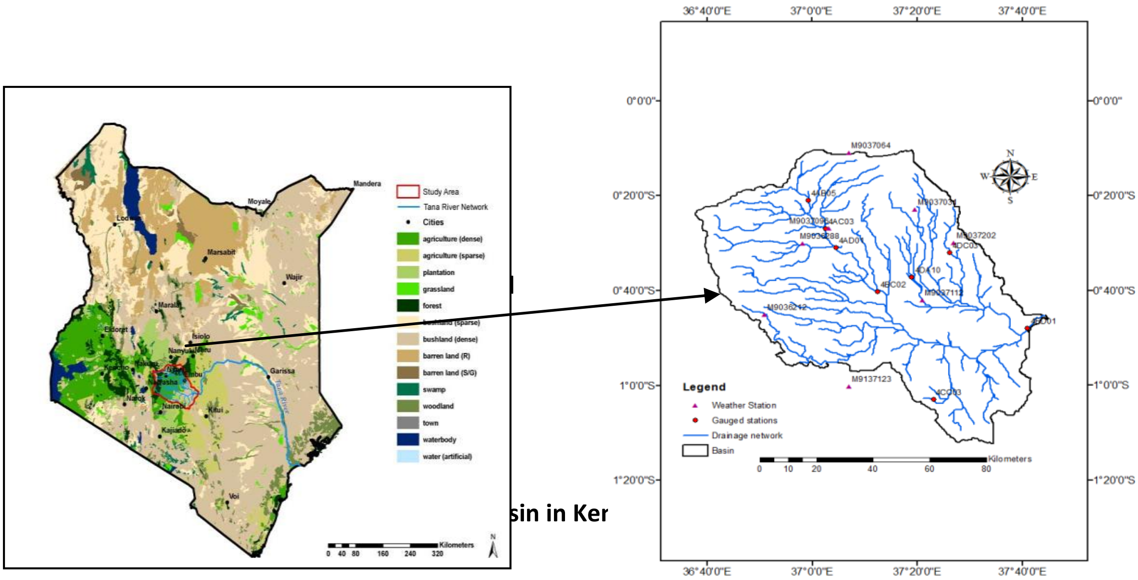

Figure 1: Study area

2.1 Data acquisition

Stream flow data used in the present study was obtained from the Ministry of Water and Irrigation, and Water Resources Management Authority (WRMA) (WRAM, 2010) for eight stations for a period of 41 years (1970-2010). Data from eight stations with consistent records that had less than 20% missing values was selected for the study. The Double mass curve was used to check for the data consistence.

2.2 Gumbel's extreme value (EV1) method

Although the Gumbel's method was originally developed for flood estimation, it was adopted in this study to estimate the hydrological drought using the relation: $Q_T = \overline{Q}(1 + KC_v)$ (2)

Where; Q_T=the probable hydrological drought discharge with a return period of T years, C_v= coefficient of variation, $\overline{Q}$ =The mean hydrological drought discharge (m^3/s) and *K*= frequency factor.

2.3 Stream flow drought index

In this study, the Stream flow drought index (SDI) using the stream flow data was determined. The *SDI* for each gauged station was determined using the relation: $SDI_i = \frac{(Q_i - \overline{Q_k})}{\sigma_k}$ (3)

Where; SDI_i=stream flow drought index for i^{th} hydrological month, Q_i=stream flow for the i^{th} hydrological month, K=length of period of data record/reference period σ_k=the standard deviation of the cumulative stream flow volumes for k^{th} reference period.
The original function was developed by Gumbel (Gumbel, 1958) for extreme flood estimation that used data that exhibit positive values. In this study, the stream flow drought index with negative values as shown in Table 1 represent the period of drought episodes.

Table 1: Definition of states of drought based on SDI

State	Drought description	Criterion
0	Non drought	$SDI \geq 0.0$
1	Mild drought	$-1.0 \leq SDI < 0.0$
2	Moderate drought	$-1.5 \leq SDI < -1.0$
3	Severity drought	$-2.0 \leq SDI < 1.5$
4	Extreme drought	$SDI < -2.0$

These negative values were converted to their corresponding absolute values and fitted to Equation (3). Then the SDI for 2, 5, 10, 20, 50, 100, 200, 500 and 1000-year return periods were computed using Equation (3). The resulting SDI data was arranged into ascending order alongside the corresponding stream flow. The stream flow corresponding to the computed SDI_m of rank m for each specific return period was selected. Those stream flow values without corresponding SDI were interpolated using Equation (4) expressed as:

$$Q_m = Q_o + \frac{Q_1 - Q_o}{SDI_1 - SDI_o} \times (SDI_m - SDI_o) \qquad (4)$$

Where; Q_m= the stream flow of rank m and specific return period (m^3/s), Q_1=higher rank stream flow (m^3/s), Q_o=lower rank stream flow (m^3/s), SDI_1=the higher stream flow drought index, SDI_o= the lower rank stream flow drought index and SDI_m= interpolated value of stream flow drought index.

2.4 Development of the modified mathematical model

The Gumbel method was developed for flood studies. However, there is scanty research as far as its application in drought studies is concerned. In this study, the principles used by Al-Mashindani (1978) in flood assessment were modified and used to estimate hydrological drought for the Upper Tana River basin. Equation (5) was used to compute the stream flow (Q_T) at each selected return period.

$$Q_T = \overline{Q}\left[1 + \frac{c_v(y_T - y_n)}{\sigma_n}\right] \qquad (5)$$

The values of C_v were obtained from the From Gumbel's Tables and the values of y_n were estimated using Equation (6) given as: $y_n = 0.5236 + \frac{1}{2} \times (0.5747 - 0.5236) = 0.54915 \approx 0.55$ (6)

Considering a stream flow drought index (SDI_m) with a rank m corresponding to a particular stream flow Q_m, Equation (5) was modified as:

$$Q_m = \overline{Q}\left[1 + \frac{c_v(y_m - y_n)}{\sigma_n}\right] \qquad (7)$$

The computed values corresponding to hydrological drought event of a particular severity for a given return period were selected from the Gumbel Tables. For a particular stream flow drought index corresponding to stream flow Q_m with a rank m, the value of y_m was determined from Equation (8) given as:

$$y_m = -\ln\ln\left[\left(\frac{N+1}{m}\right) \div \left(\frac{N+1}{m} - 1\right)\right] = -\ln\ln\left[\left(\frac{N+1}{m}\right) \times \left(\frac{m}{N+1-m}\right)\right] \qquad (8)$$

3. Results and discussion

The results show that the absolute SDI increased with the return period in all gauged stations (4AB05, 4BC02, 4AC03 and 4AD01) as given in Figure 2. This means that the stream flow Q_T for any return period can be determined from the mean flows of the annual minimum and the average of the first three minimum mean stream flows for the Upper Tana River basin. This is found to be consistence with the similar results for flood estimation by Al-Mashindani et al. (1978).

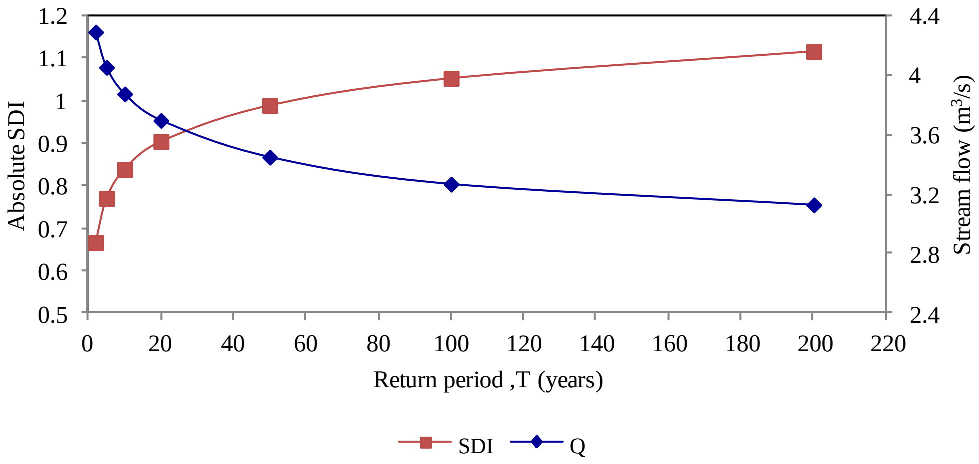

Figure 2: The relationship between the Q_m, *SDI* and return period

4. Conclusion

Stream flows have been explored and their corresponding return periods estimated. It is concluded that the computed absolute SDI values vary across the gauge stations and increase while the corresponding stream flow decline with increase in return period. A simplified mathematical model for estimating hydrological drought event that uses the mean of the annual minimum and average of the first three minimum stream flows as input variables was developed for different return periods in the Upper Tana River basin.

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