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Full Length Research Paper

Past Hydrological Drought Characteristics of River Enyau Sub-Catchment, Northern Uganda

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Abstract

River Enyau sub-catchment, the only reliable source of surface water supplying Arua Municipality and its surroundingis experiencing increasing frequency of hydrological drought attributed to climate and landuse/cover change. This rise in the hydrological drought in the sub-catchment threatens 72% of the household's access to safe water and increases their vulnerability to food insecurity, water and sanitation challenges. This study aimed to reconstruct past (1980 – 2009) hydrological drought characteristics in River Enyau sub-catchment to create a better understanding of sustainable water resources planning and management. Historical discharge of the sub-catchment was analyzed for hydrological drought frequency, duration and severity using the Threshold Level Method inR software version 3.5.2. Results showed that the sub-catchment experienced hydrological drought in the past that mainly started in the month of March and ended in the month of April in drought years. There was a significant difference (p<0.001) in the hydrological drought frequency, duration and severity among the different drought years of the past. Therefore, restoration of water towers, best agricultural management practices and proper urban planning are highly recommended in order to reduce the hydrological drought impact on River Enyau sub-catchment.

Keywords: Threshold level method, hydrological drought characteristics, Frequency, Duration, Severity, River Enyau sub-catchment, Northern Uganda.

INTRODUCTION

Hydrological drought is a natural hazard that occurs when the levels of surface and subsurface water resources in rivers, lakes and ground water falls below their long-term average (van Loon, 2015). Hydrological drought is primarily caused by an extended period of rainfall deficit covering a large area (Mtilatila et al., 2020). It's incidence is often intensified by climate change, land use/cover change, human water uses and management (Bhaga et al., 2020; Jiao et al., 2020; Mtilatila et al., 2020; Zhou et al., 2019). Climate change exacerbates hydrological drought through alteration of rainfall and temperature regimes of catchments, resulting into increase in the frequency and severity of extreme weather events (Bhaga et al., 2020; Zhou et al., 2019). Furthermore, land use/cover change affects the propagation process through runoff generation, water infiltration, evapotranspi-

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ration rates and base flow of the catchment (Zhou et al., 2019). According to Wang et al. (2020), human activities such as deforestation result into longer drought durations and reduced drought termination rates in selected Chinese river catchments.

Drought is the most devastating of all climate related disasters with a coverage of 66% of the earth surface (McCabe & Wolock, 2015). Although drought is divided into four types that include meteorological, agricultural, hydrological and socio-economic , there are no distinct boundaries between the four types and their impacts (Bhaga et al., 2020; Mtilatila et al., 2020; van Loon, 2015). Drought alone has led to an estimated economic damage of USD 177,694,605, human deaths of 11,711,271 and 2,459,750,391 affected people globally from 1980-2020 with Africa having the highest number of drought events within the same period. The continent accounted for 40.23% (341) of all the drought events (771) that resulted into 847,143 human deaths, 462,084,671 affected people with an estimated damage of USD 5,509,593 (Nnopuechi, 2021). The East African region has experienced the highest number of incidences of drought disasters in Africa in the recent past. The region registered 46.78% (109) of the 233 drought events in Africa that killed 421,992 people, affected 278,538,223 and resulted into an estimated economic loss of USD 2,193,200 (Nnopuechi, 2021).

In Uganda, drought events are a frequent occurrence in the Northern, Eastern and North-Eastern regions (Branch, 2018). With over 80% of the population dependent on agriculture for their livelihood, the impacts of drought are heavily felt on the people, environment and economy of Uganda (UBOS, 2016). These impacts result into water shortages, crop failures and death of livestock hence referred to as the major cause of poverty, famine, malnutrition, conflicts, displacements and human mortality (Branch, 2018). It affects at least 200,000 people each year and in 2010 alone, drought caused an estimated USD 1.2 billion in damages, equivalent to 7.5% of Uganda's GDP (Bhaga et al., 2020). Furthermore, the country registered 268 drought related deaths with 4.9 million people affected from 1993 – 2018, specifically in 1987, 1998, 1999, 2002, 2005 and 2008 (UNDRR, 2019).

A few studies in Uganda have focused on the different types of drought, their occurrence, severity and prevalence in the cattle corridor (Mulinde et al., 2016). Najjuma et al. (2021) characterized meteorological drought in the central Ugandan districts of Bukomansimbi and Mubende using standardized precipitation index and found the years of 2005 and 2007 to have the highest drought duration, magnitude and intensity. Egeru et al. (2020) examined meteorological drought in the Upper Nile Water Management Zone and noted that it started in the month of December despite a few early onsets in November and later in January of preceding years. In another study by Nakalembe (2018), characterization of agricultural drought in the Karamoja region using vegetation index concluded that the main drivers of food insecurity were cultivation of crops on marginal land, lack of irrigation and previous systematic incapacitation of livestock alternatives through government programming. All these studies proved that drought severity and frequency had increased in Uganda.

Other studies on hydrological drought were carried out in River Malaba catchment of Eastern Uganda. Mubialiwo et al. (2021) focused on the performance of rainfall-runoff models in reproducing hydrological extremes, while Barasa et al. (2013) characterized extreme flows in the River Malaba catchment using standardized precipitation and stream flow indices. However, there is generally limited available literature on hydrological drought characterization using the Threshold Level Method in Uganda and specifically in River Enyau sub-catchment. Limited literature on hydrological drought characteristics in Africa is linked to lack of hydrological data (Bhaga et al., 2020) since few rivers are gauged with limited data sets and poorly managed catchments (Masafu et al., 2016). The limited data sets affect analysis of the past drought characteristics, a key requirement for improved water resources planning and management in countries like Uganda. Hence, this study reconstructed the past hydrological drought characteristics of River Enyau sub-catchment for better water resources planning and management, since the sub-catchment is the second most important river and wetland system in Arua district after the Albert Nile. In addition, it is the only safe and reliable source of surface water from which National Water and Sewerage Corporation (NWSC) supplies 72% of the households in Arua Municipality and its surrounding.

MATERIALS AND METHODS

Description of the study area

River Enyau sub-catchment covers an area of 721 km^{2}between latitude 2^{o}55'0'' and 3^o 20' 0''N and longitude 30^o 45' 0'' and 31^o 10' 0'' E and flows in to Albert Nile. Figure 1 shows the location of River Enyau sub-catchment.

The topography of the sub-catchment is generally flat, rising from an altitude of 853 m above sea level at the Anyau gauging station to a maximum of 1,416 m asl near the source in Vurra county (Kansiime et al., 2013). River Enyau sub-catchment experiences a tropical type of climate characterized by both dry (December and March) and wet seasons (April to November). Rainfall in the sub-catchment is bimodal with an annual average total of 1,250 mm (Matua, 2016). The sub-catchment has an average temperature of 21^{o}C and 32^{o}C during the rainy season and dry season respectively (Kansiime et al., 2013). The vegetation of the sub-catchment is dominated by the equatorial type of savanna grass in the flat plain while the top of the hills is covered by natural forests that have been degraded over time. The sub-catchment is

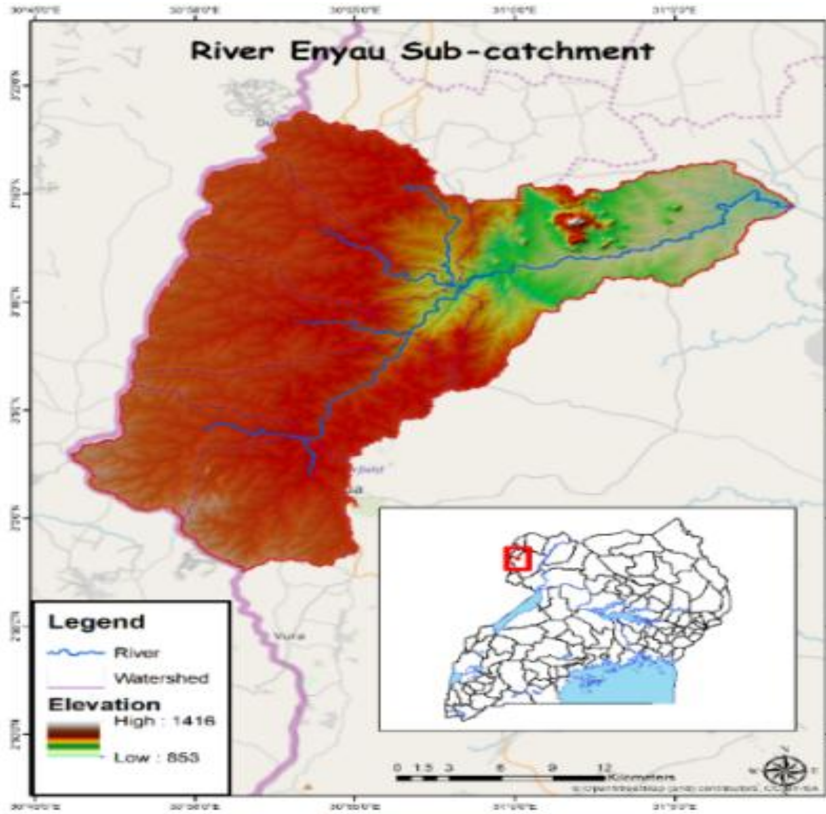

Figure 1. Location of River Enyausub-catchment.

mainly covered by loamy soil with sandy soil dominating along River Enyau banks.

Hydrological modeling

Soil and Water Assessment Tool (SWAT) model description

SWAT is a physically based, semi-distributed model used to assess the impact of human activities on water quantity and quality (Arnold et al., 2012). The model uses a Digital Elevation Model (DEM) to divide the catchment into sub-catchments that are further subdivided in to Hydrological Response Units (HRUs) based on soil type, land use/cover and slope (Neitsch et al., 2011). HRUs are areas of the catchment which respond to rainfall events in the same way due to homogenous soil, land use/cover and slope characteristics. The HRUs form the basic unit of hydrological response in the SWAT model. The simulation of catchment hydrology in the SWAT model is basically divided in to the land and routing phase. The land phase represents the amount of water and pollutants (sediment, nutrient and pesticides) entering the river channel while the routing phase defines the movement of water and pollutants through the river channels to the catchment outlet (Neitsch et al., 2011). The model simulates the hydrological cycle based on the water balance Equation 1.

$$SW_t = SW_o + \sum_{t=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \quad \text{.............1}$$

Where SW_t is the final soil water content and SW_o is the initial soil water content of the day i, t is time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, surface runoff, evapotranspiration, percolation, and return flow respectively all measured in mm.

Input data

Being a physically based model, SWAT requires catchment specific input data for it to run. The inputs used in the SWAT model included; discharge, soil, land use/cover, Digital Elevation Model (DEM) and climate data of River Enyau sub-catchment summarized in Table 1.

SWAT setup

The Digital Elevation Model (DEM) with a 30m resolution was downloaded from the United States Geological survey

Table 1. SWAT model input data.

Input data	Station/Location	Source	Resolution
Rainfall	Arua Met	UNMA	Daily (mm)
Temperature	Arua Met	AgMERRA	Daily (^oC)
Discharge	Anyau	MWE	Daily (m^3/s)
DEM	Uganda	http://gdex.cr.usgs.gov/gdex/	30m*30m
Soil Data	Africa	http://www.fao.org/soils-portal/soil-survey/soil-maps	1:50,000m
Land use/cover	River Enyau sub-catchment	https://earthexplorer.usgs.gov/	30m*30m

website (http://gdex.cr.usgs.gov/gdex/) and used for topographic information. Delineation of the sub-catchment was performed using ArcSWAT 2012 incorporated in ArcGIS interface. The process involved a DEM setup, stream definition, catchment outlet selection and Hydrological Response Unit (HRU) definition and calculation of sub-basin parameters. Anyau gauging station (Coordinates: N3.201145, E31.030384) along Arua-Moyo road was selected as the outlet of River Enyau sub-catchment. The raster maps for soil and land use/cover were over laid on the sub-catchment where the weather data variables were defined.

Model simulation, calibration, validation and performance evaluation

SWAT simulation

SWAT was simulated for the period 1971 to 2009 using the available soil, climate, land use/cover of 2003 and discharge data. The simulated discharge value was used for SWAT model calibration and validation. The calibration and validation were done outside the ArcSWAT software using the Sequential Uncertainty Fitting (SUFI-2) algorithm of the freely available semi-automatic Calibration and Uncertainty Program; SWAT-Calibration Uncertainty Program (SWAT-CUP) package version 5.2.1.1.

Model calibration

Model calibration is the process of changing the discharge parameter values in an attempt to match observed discharge values (Arnold et al., 2012). Model calibration was done using the most sensitive parameters determined in the sensitivity analysis process. The discharge data for River Enyau sub-catchment for the period 1971 to 1977 with three years (1971-1973) warmup period was used in SWAT-CUP during the calibration process.

Model Validation

Model validation is the process of determining whether the model's output behavior has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability (Sargent, 2011). In the SWAT model, it involved using the calibrated model to reproduce data over a period not included in the calibration process. The model was validated using daily discharge data for the period 2000 to 2008 with three years (2000-2002) of warm up period in SWAT-CUP.

Model performance evaluation

The performance of the SWAT model during calibration and validation processes was assessed due to the uncertainties associated with the data, model and differences in the conditions of the periods used in the calibration and validation (Abbaspour et al., 2017). The performance of the SWAT model was assessed using the coefficient of determination (R^2), Nash Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS) (Moriasi et al., 2007). The R^2 is an indicator of strength of linear relationship between the observed and simulated discharge values. It describes the proportion of the variance in observed discharge data explained by the model (Moriasi et al., 2007). The R^2 value ranges from 0 - 1, with higher values indicating less error variance. A model performance review by Moriasi et al. (2015) recommended the use of R^2values >0.6. The $R^2$was determined using Equation 2.

$$R^2 = \frac{\left[\sum_{i=1}^{n}(0_i - \bar{0})(S_i - \bar{S})\right]^2}{\sum_{i=1}^{n}(0_i - \bar{0})^2 \times \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad \text{...........................2}$$

Where 0_i is the observed daily discharge, S_i is the simulated daily discharge, $\bar{0}$ is the average measured discharge, $\bar{S}$ is the average simulated discharge and n is the total number of observations.

The NSE measures how well the plot of daily observed and simulated discharge fits the 1:1 line and its value ranges from – ∞ - 1 with 1 as the optimal value (Moriasi et al., 2007). NSE value of >0.5 is considered satisfactory model performance (Moriasi et al., 2015). The NSE in this study was determined using Equation 3.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(0_i - S_i)^2}{\sum_{i=1}^{n}(0_i - \bar{0})^2} \quad \text{.......................................3}$$

The PBIAS measures the average tendency of the simulated discharge data to be larger or smaller than the observed discharge data with 0 as the optimal value (Moriasi et al., 2007). A PBIAS value ≤ ± 15% is satisfactory for a catchment scale model (Moriasi et al., 2015). The value of PBIAS was determined using Equation 4.

$$PBIAS = \frac{\sum_{i=1}^{n}(0_i - S_i)\times 100}{\sum_{i=1}^{n}(0_i)} \quad \text{.......................................4}$$

Simulation of discharge values from 1980 – 2009

The simulation of discharge values from 1980 - 2009 was done using the calibrated SWAT model. To cater for the effects of land use/cover within the different years, the years 1980 to 2009 were simulated with the land use/cover of 1980, 1989, 2003 and 2009. The simulated value was used in the analysis of hydrological drought in River Enyau sub-catchment.

Determination of hydrological drought

The determination of hydrological drought was done using the threshold level method applied in similar studies by Wang et al. (2020) and Jiang et al. (2019). This method considers drought to occur when flow is below a pre-determined truncation level. The threshold level method is preferred to other methods of drought characterization such as standardized indices because it measures drought duration and severity in absolute terms making its findings applicable in practical terms (Agwata et al., 2015). The steps followed in the determination of the hydrological drought characteristics under the threshold level method are described below;

Discharge threshold value

The flow threshold value was determined using the flow duration curve method (de Medeiros et al., 2019). A flow duration curve is a graph of river discharge recorded over a period of time plotted against its respective exceedance probability. The flow duration curve for this study was constructed using daily discharge values of River Enyau sub-catchment from 1980 to 2009. The daily discharge values (n) for the period considered were sorted in a descending order and each assigned a rank (M) starting with the largest (1,2, 3, …. n). The exceedance probability (P) for each daily flow value was then determined from the Weibull's plotting position using Equation 5.

$$\boldsymbol{P = \left[\frac{M}{n+1}\right] \times 100} \quad \text{...5}$$

Where; P is the exceedance probability (%), M is the ranked position of the discharge on the listing, n is the total number of discharge values for the period of record. A flow duration curve was obtained by plotting each daily discharge value against its respective exceedance probability value. The threshold value was obtained by getting the discharge value that corresponded to the 80% exceedance probability from the flow duration curve(de Medeiros et al., 2019).

Occurrence of hydrological drought

The daily discharge data was analyzed for hydrological drought characteristics in R software version 3.5.2 based on low flow statistics, an R package developed for the World Meteorological Organization (Koffler et al., 2016). Daily discharge for River Enyau sub-catchment from 1980-2009 was plotted against its respective day. The threshold value was then fitted. Hydrological drought occurred when the discharge value fell below the threshold and ended when the threshold was equaled or exceeded. Based on the interevent criterion for removing minor drought events, all drought events whose duration was less than five days were not considered as also used by Cammalleri et al. (2016) and Larsson (2017). Furthermore,, drought events with a deficit volume equal to 0.1 or less of the maximum drought volumes were removed (Koffler et al., 2016). Mutually dependent drought events that occurred less than 6 days apart were pooled together using Equation 6

$$d_{pool} = d_i + d_{i+1} + t_i \quad \text{...6}$$

Where; d_{pool} is the pooled drought duration, d_i and d_{i+1} are the drought duration for drought events one and two respectively, t_i interevent time criterion. While their corresponding deficit volumes were pooled together using Equation 7

$$v_{pool} = v_i + v_{i+1} - z_c \quad \text{...7}$$

Where; v_{pool} is the pooled deficit volume, V_1 and v_{i+1} are the deficit volumes for drought events one and two respectively, Z_c is the interevent volume.

Determination of drought frequency, duration and severity

Drought frequency was obtained as the count of drought events in a year. Drought duration which was the number of days covered by a drought event was determined using Equation 8.

$$T = T_e - T_b + 1 \qquad \text{.......8}$$

Where; T is the drought duration, T_b is the beginning of drought and T_e is the end of drought all in days. While drought severity/deficit volume is the minimum flow below the threshold measured in m^3 obtained by Equation 9.

$$Dv = Q_{80t} - Q_t \qquad \text{.......9}$$

Where; Dv is the deficit volume for a hydrological drought event, Q_{80t} is the threshold value and Q_t is the observed deficit volume.

RESULTS

Past hydrological drought characteristics

The simulated and observed discharge during the calibration and validation processes at the main outlet of River Enyau sub-catchment are presented in Figure 2.

Figure 2 shows a good match between simulated and observed discharge although most of the peaks were not well captured by the model. The model performance is acceptable for the calibration and validation as the statistical indicators were greater than 0.5 during calibration (coefficient of determination, R^2=0.62, Nash-Sutcliffe Efficiency, NSE=0.62, percent bias, PBIAS=0.1) andfor validation (coefficient of determination R^2=0.5, Nash-Sutcliffe Efficiency NSE=0.5 and percent bias, PBIAS 1.9).

Discharge threshold value for hydrological drought

The flow duration curve indicating the discharge threshold value for River Enyau sub-catchment is presented in Figure 3.

Figure 3 shows that the discharge value corresponding to the intersection between 80% exceedance probability and the probability curve was 0.43 m^3 for the sub-catchment. This indicates that the threshold value for droughts to occur in River Enyau sub-catchment was 0.43 m^3/s.

Hydrological drought characteristics

The past hydrological drought frequency, duration and severity for River Enyau sub-catchment from 1980-2009 are presented in Figure 4.

Figure 4 shows that the different hydrological drought characteristics varied from one year to the other in River Enyau sub-catchment during the period of the study. The year 1994 has the highest hydrological drought frequency of four while majority of the years had at least 1 hydrological drought event. The average hydrological drought frequency in River Enyau sub-catchment was two events per year**.** Years like1985, 1993 and 2002 had no recorded drought events. The years 1981 and 1982 had the longest hydrological drought duration of 251 and 197 days, respectively, while the shortest hydrological drought duration was in the years 1983 and 1984 that lasted for six and seven days, respectively. The mean drought duration for the past period (1980-2009) was 78 days (equivalent to two and a half months). The catchment also experienced the largest hydrological drought severity in the years of 1981 and 1982 with drought deficit volumes of 8,135,015 m^3 and 6,452,894 m^3, respectively. Mean hydrological drought severity deficit volumes of 1,698,238 m^3 were recorded in 1999 and 2000 while the year 1996 recorded the lowest deficit volume of 69,742 m^3 among the drought years. One sample t test showed a significant difference (p<0.001) in the hydrological drought frequency, duration and deficit volume among the different drought years of the past.

Other hydrological drought characteristics that included drought start and end months in River Enyau sub-catchment during the period of study from 1980 – 2009 are presented in Figure 5.

Figure 5 shows that hydrological drought in River Enyau sub-catchment mainly started in the month of March with a count of sixteen events. The months of June and September with only single drought start event are the least among the drought start months. Hydrological drought in River Enyau sub-catchment mainly ended in the months of March and April with a frequency of ten and nine respectively. Very few (<4) drought events lasted

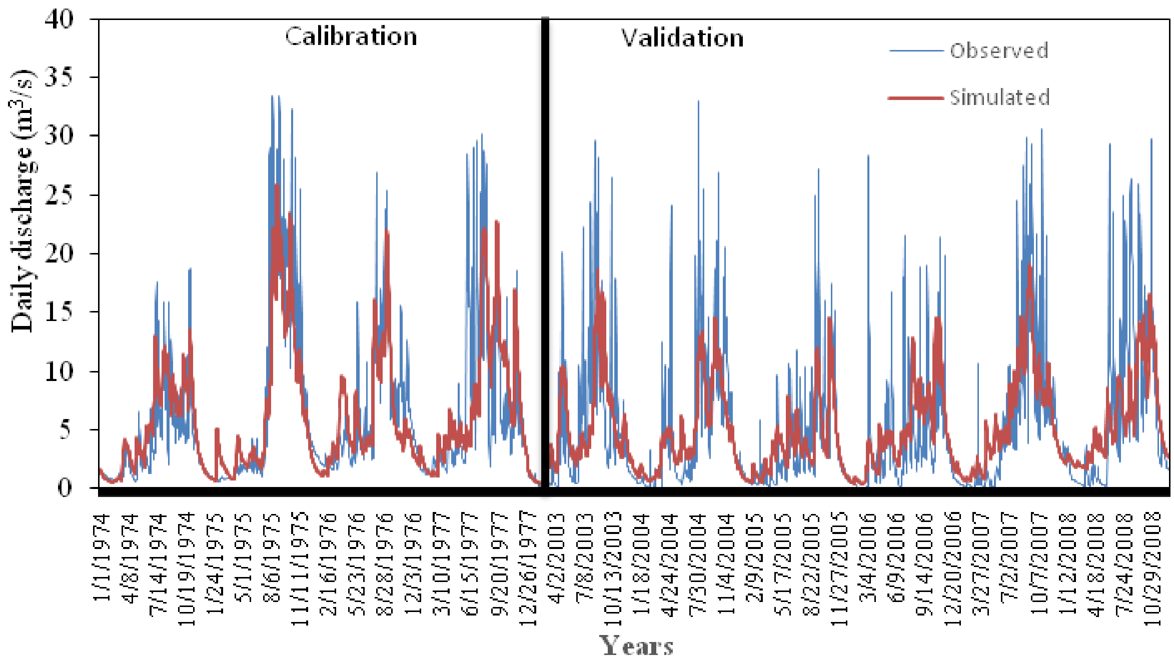

Figure 2. Simulated and observed discharge during calibration (1974 - 1977) and validation (2003 - 2008) periods.

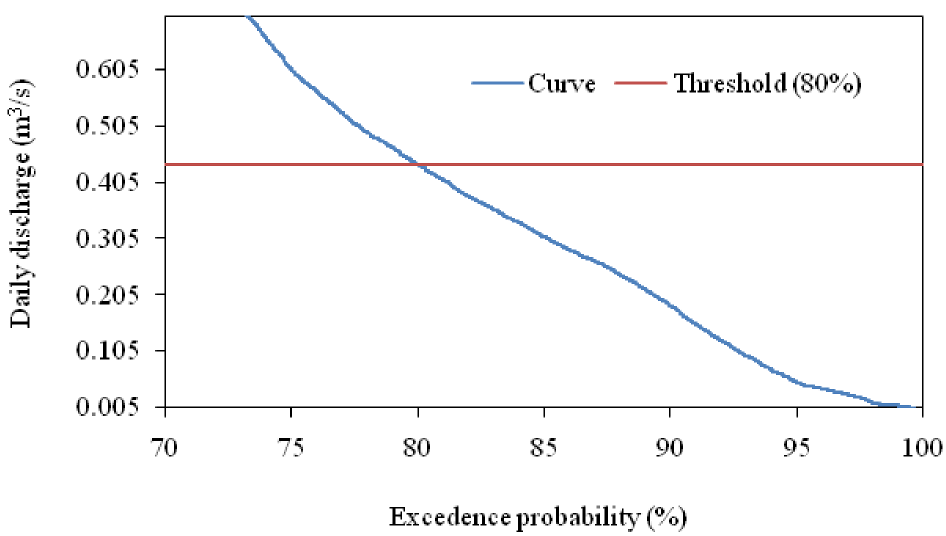

Figure 3. Flow duration curve for River Enyau sub-catchment from 1980-2009.

beyond the month of June while only one drought event lasted up to November.

DISCUSSION

The calibration and validation values showed the ability of the SWAT model to capture hydrological processes in Ugandan catchments as the statistics for model performance during the calibration and validation processes for PBIAS, R^2, and NSE were generally within the acceptable ranges as recommended by Moriasi et al. (2007). The low recorded R^2 and NSE values during validation and failure of the model to capture most of the observed discharge peaks could be attributed to measurement errors in observed discharge and rainfall data, small and shallow depth of the stream network and

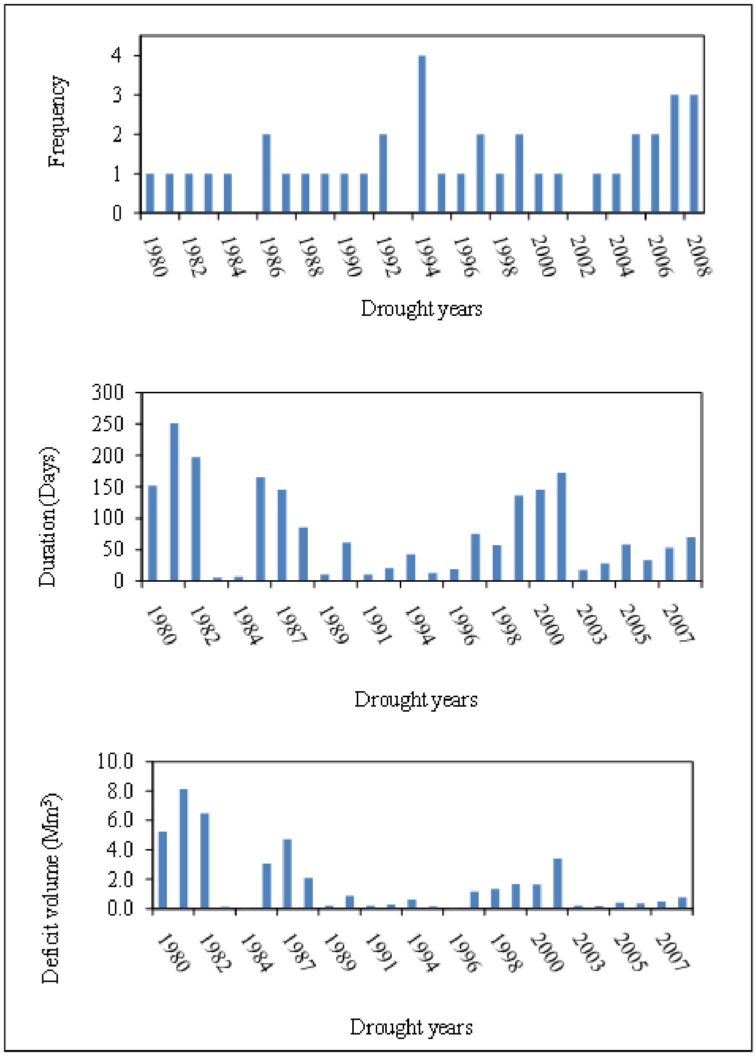

Figure 4. Hydrological drought characteristics of River Enyau sub-catchment from 1980 – 2009.

overbank flow as reported in a similar study by Gabiri et al. (2020). The trend and statistics obtained during the model calibration and validation in this study were within the range as also found by Anaba et al. (2017) in Murchison Bay catchment of Uganda and Ayele et al. (2017) in Upper Blue Nile River basin of Ethiopia.

The discharge of $0.43m^3$ at 80% exceedance probability is an indication that the sub-catchment experiences very low flows in a year. This can be attributed to the flashiness of the sub-catchment where a rainfall event quickly lifts the discharge volume for a short time but quickly returns to low flow as the rainfall event ceases (Koteia et al., 2016). Flashy catchments have less discharge during dry season with negative impacts on water supply for domestic, agricultural and industrial uses.

The significant variations in the annual hydrological drought frequency, duration and deficit volumes for the past years in River Enyau sub-catchment are attributed to land use/cover changes and differences in the quantity, spatial and temporal distribution of rainfall. The hydrological drought frequency of one to four drought events per drought year, with most years registering one drought event, is an indication that most of the drought events occurred in the dry season which is only once a year. This finding agrees with those of Agwata et al. (2015) who found out that most hydrological droughts that occurred in the dry season were in the Upper Tana River catchment of Kenya.

The other drought events usually of shorter length occurred as a result of rainfall anomalies during the rainy season in a year (van Loon, 2015). Similar results were obtained by Barasa et al. (2013) in River Malaba catchment where the drought frequency varied from one to three drought events per drought year. This is in line with findings by Sawatpru and Konyai (2016) who reported

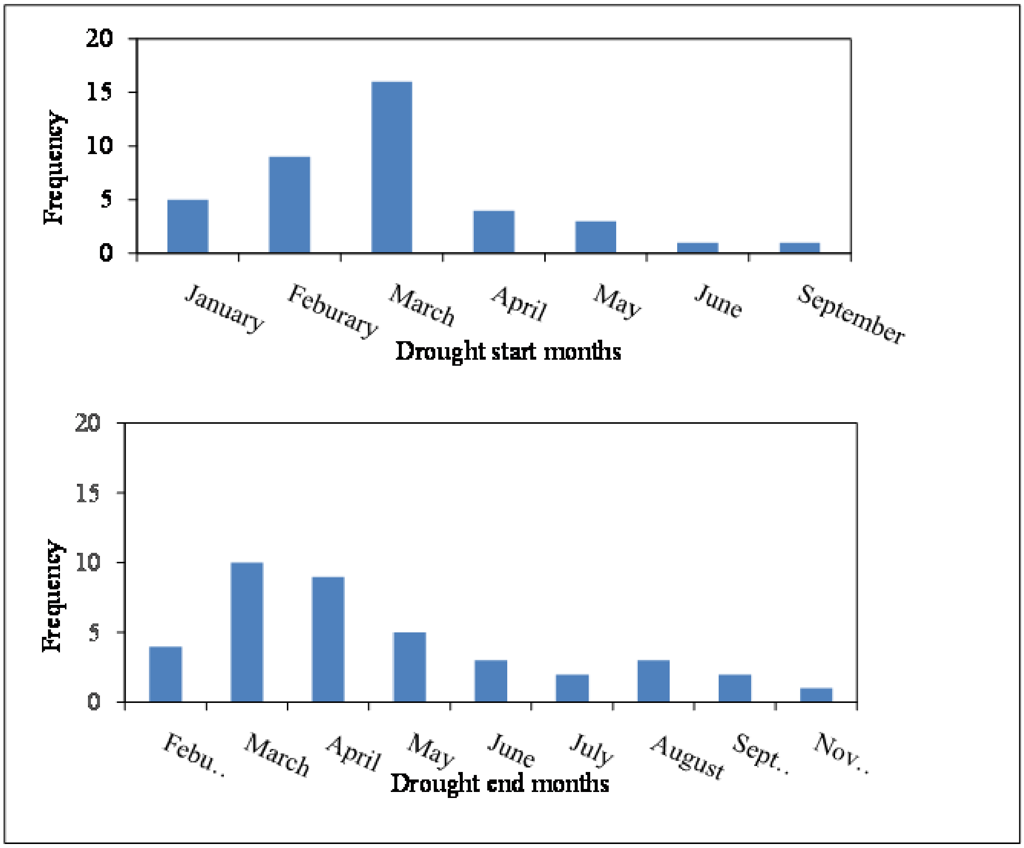

Figure 5. Hydrological drought starts and end months from 1980 – 2009.

a hydrological drought frequency of one drought event per drought year in Yom River catchment of Thailand.
According to Ogwang (2011), the years 1981 and 1982 registered the most severe hydrological drought severity due to low rainfall received as a result of moisture divergence over Uganda. However, Mulinde et al. (2016) reported the period of 1978-1982 as drought years with the highest drought frequency and severity in Uganda.In addition, these years had the longest drought duration meaning there was enough time for the deficit volumes to accumulate. Studies by Sawatpru and Konyai (2016) in Yom River catchment of Thailand, Swetalina and Thomas (2016) in Bearma River catchment of India and de Medeiros et al. (2019) in Piranhas-Açu River catchment in Brazil observed a similar behavior. The high deficit volume recorded resulted into inadequate water supply in the catchments straining domestic water usage, agriculture, health and the industrial sectors.
Past hydrological drought in River Enyau sub-catchment mainly started in the month of March with a count of sixteen events. The starting month is linked to the temporal distribution of rainfall within the sub-catchment. The sub-catchment experienced both wet and dry seasons with the dry season lasting from December to March while the rainy season lasting from April to November (UBOS, 2013). Most hydrological droughts in the sub-catchment do not start immediately at the beginning of the dry season in December due to base flow contribution into the river. However, continued dry season results into baseflow recession from the months of December through to February culminating into hydrological drought in March as the aquifer water becomes depleted. This study confirms that meteorological droughts usually start at the beginning of the dry season in December as reported by Egeru et al. (2020) and is propagated to hydrological drought in March. The findings on propagation of drought from meteorological to hydrological drought have also been reported by (Zhou et al., 2021) and van Loon (2015).
The observed drought end month of April is linked to the onset of rainfall in the sub-catchment. The rainy season in the sub-catchment begins in April or sometimes late march as reported by UBOS (2013). Rainfall contributes water to the river through direct input, surface runoff, subsurface flow and base flow as the shallow aquifers become recharged through percolation (Nsubuga et al., 2014). The ability of the threshold level method to correctly capture months of low flows and the historical droughts of 1981 and 1982 as reported by Ogwang (2011) and Mulinde et al. (2016), and the droughts of 2005 and 2007 as reported by Najjuma et al. (2021)is an indication that the index performed fairly well.

CONCLUSION AND RECOMMENDATION

The study characterized past hydrological drought characteristics of River Enyau sub-catchment to generate information that can be used for improved water resources planning and management. The sub-catchment experienced hydrological drought frequency, duration and deficit volumes that showed a significant difference within the drought years in the past (1980 – 2009). The drought start month in the past was March and end month was April. More research is needed in the projection of future hydrological drought characteristics of River Enyau sub-catchment.

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