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Understanding the Hydrology of the Nyando River Basin using Hydrological Modelling

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Abstract: ***The Nyando River is the main water source to all water users in the Nyando River Basin. Low river flows during dry periods affect socio-economic development in the upstream and downstream part of the river basin. Hence in this study input and output water balance components were assessed using the SWAT model and existing hydrogeological surveys investigated in the river basin. Scarce input climatic data in the catchment areas of the river basin were improved using inverse distance weighting and temperature lapse rate techniques. In addition, the SWAT model was parameterized using water withdrawals and existing hydrogeological information. During calibration of the model simulated and observed river flows corresponded well with achieved values of R^2 and NSE ranging from 0.51 to 0.90. The output water balance components are actual evaporation and transpiration, deep aquifer recharge and river runoff at the outlet of the study area with mean annual values of 1279 mm/a, 62 mm/a and 228 mm/a respectively. Rainfall is the main input water balance component with mean annual value of 1572 mm/a and annual change in water storage range between ±160 mm/a. Results showed that about 80% of the surface water in the catchment is lost through evaporation and transpiration while about 3% recharges groundwater. In addition, approximately 17% is available annually in the catchment for use. Therefore, proper planning and management of water resources in the river basin is required to reduce water shortage during prolonged droughts and also to meet increasing water demands.***

Keywords: Nyando, Kipchorian, Ainapng'etuny, water balance, SWAT model and hydrogeological survey

1. Introduction

Fresh water is a basic need to human life and its demand increases as the world's population increases. Kenya is one of the countries in the world where water scarcity is pronounced with renewable water resources of 647 cubic metres per capita as estimated by United Nations - World Water Assessment Programme (UN-WATER/WWAP, 2006). According to United Nations Development Program (UNDP, 2006) the per capita daily water withdrawal in the country has been decreasing due to population increase. In comparison to per capita daily water use in USA and Europe of about 200 - 600 litres Kenya is a country under water stress (UNDP, 2006). Possible effects of climate change such as droughts and floods had interfered with socio-economic development in western Kenya. A previous drought assessment indicated that about 75% of the population living in the western Kenya is vulnerable to drought because they depend majorly on surface water resources (UNISDR, 2008). Surface water abstractions authorized by the Water Resources Management Authority had been claimed to cause low river flows in dry periods and inconvenience to downstream water users (UN-WATER/WWAP, 2006). Groundwater extraction is not visible to majority of the residents in the region because the cost of sinking boreholes is unaffordable. Therefore, there is a need to ensure proper management of surface water resources and equitable distribution of water.

Despite water resources management policies are in place, they have not been successfully implemented due to insufficient water resources information (UN-WATER/WWAP, 2006). Hence surface water assessment is required to provide a better understanding of water balance components and distribution of water in the catchment. Hydrological models such as Soil Water Assessment Tool (SWAT) and Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) had been used in the Nyando Catchment to determine response of hydrologic variables to land use and climate change. However, water balance components have not been successfully simulated in the previous studies due to use of inadequate climatic data and neglecting water abstraction and geological formation of the catchment (Olang and Fürst, 2011; Opere and Okello, 2011; Nyolei, 2012). Therefore, in this study the SWAT model was used to simulate water balance components using interpolated climatic data. In addition, water abstractions and hydrogeological information of the study area were used to parameterize the SWAT model. SWAT model had been used to conduct water resources assessment in small- and large-scale catchments. Flexibility of the SWAT model has enabled the use of data interpolation techniques and remote sensing data to be used in data scarce regions (Arnold and Fohrer, 2005; Neitsch et al., 2005).

Data scarcity especially climatic data has been identified as the main contributor to poor performance of the SWAT model. But interpolation techniques have been used to improve the quality of the input climatic data and proved to enhance model performance (Masih et al., 2011; Vu et al., 2012). An inverse distance weighting (IDW), spline interpolation and Kridging are commonly preferred approaches in spatial interpolation (Keblouti et al., 2012). The SWAT model was discovered to perform better during wet seasons than in dry seasons especially in simulating the actual evaporation and transpiration and soil moisture (Feyereisen et al., 2007; Tobin and Bennett, 2009). Incapability of the SWAT model to simulate the actual evaporation and transpiration accurately has led to model calibration using measured and remote sensing the actual evaporation and transpiration (Gao et al., 2006; Immerzeel and Droogers, 2008; Hong et al., 2010; Githui et al., 2012).

2. Materials and Methods

Study area

The Nyando River Basin (see Figure 1) is situated in Kavirondo Rift Valley located in the western part of Kenya. The river basin is within the latitude of 0º25'S and 0º10'N and

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longitude of 34º50'E and 35º50'E. It covers an area of about 3550 km^2 with an altitude range of 3000 m above mean sea level (amsl) at Tinderet volcano in upstream part of the river basin and 1135 m above mean sea level at Lake Victoria. The river basin has three sub catchments/tributaries i.e. Ainapng'etuny, Kipchorian and Awach-Kano. The total river length is approximately 150 km in length from the upstream part in Londiani to the Lake Victoria at the downstream of the catchment. The river basin has different land covers such as natural forests, grasslands, agricultural fields, wetlands and settlements. The forests which cover 20% of the river basin are situated in Londiani, west Mau, Timboroa and Tinderet. The agricultural fields cover about 70% of the river basin comprised of cash and food crops. The main cash crops are tea, coffee, sugarcane and rice while food crops are corn, millet, sorghum, fruits, beans, vegetables and potatoes. The grasslands, settlements, shrub lands and wetlands cover approximately 10% of the catchment (Olang and Fürst, 2011; Nyolei, 2012). Soils in the highlands of the river basin originated from parent extrusive and intrusive igneous rocks such as phonolites, nephelinites, granites, tuffs, basanites and tephrites. The soils in Kano plains at the downstream part of the catchment are mainly alluvial from Quaternary Holocene deposits (Andriesse and Van der Pow, 1985).

The Nyando River Basin is characterized by a semi-humid tropical climate and is primarily influenced by the Inter-Tropical Convergence Zone (ITCZ). Long rains start from early April till August and short rains begin in September till early or mid-January (Olang and Fürst, 2011). Air temperatures are high in dry months from February to March and low in June and July as depicted in Figure 2. The months of June and July are normally characterized by cool and cloudy weather while in February and March the weather is usually cloudless and warm. Mean annual rainfall at the upstream part of the river basin is approximately 1600 mm/a and it ranges from 1400 mm/a to 1500 mm/a for the entire catchment (DHV consulting engineers, 1987; Karicho, 2010; Olang and Fürst, 2011). According to IPCC (2007) rainfall extremes within the tropics are increasing due to global warming that increases sea surface temperatures. The population of the catchment was approximately 1 million with the population density of 288 persons per km^2 in 2009 (Kenya National Bureau of Statistics (KNBS), 2009).

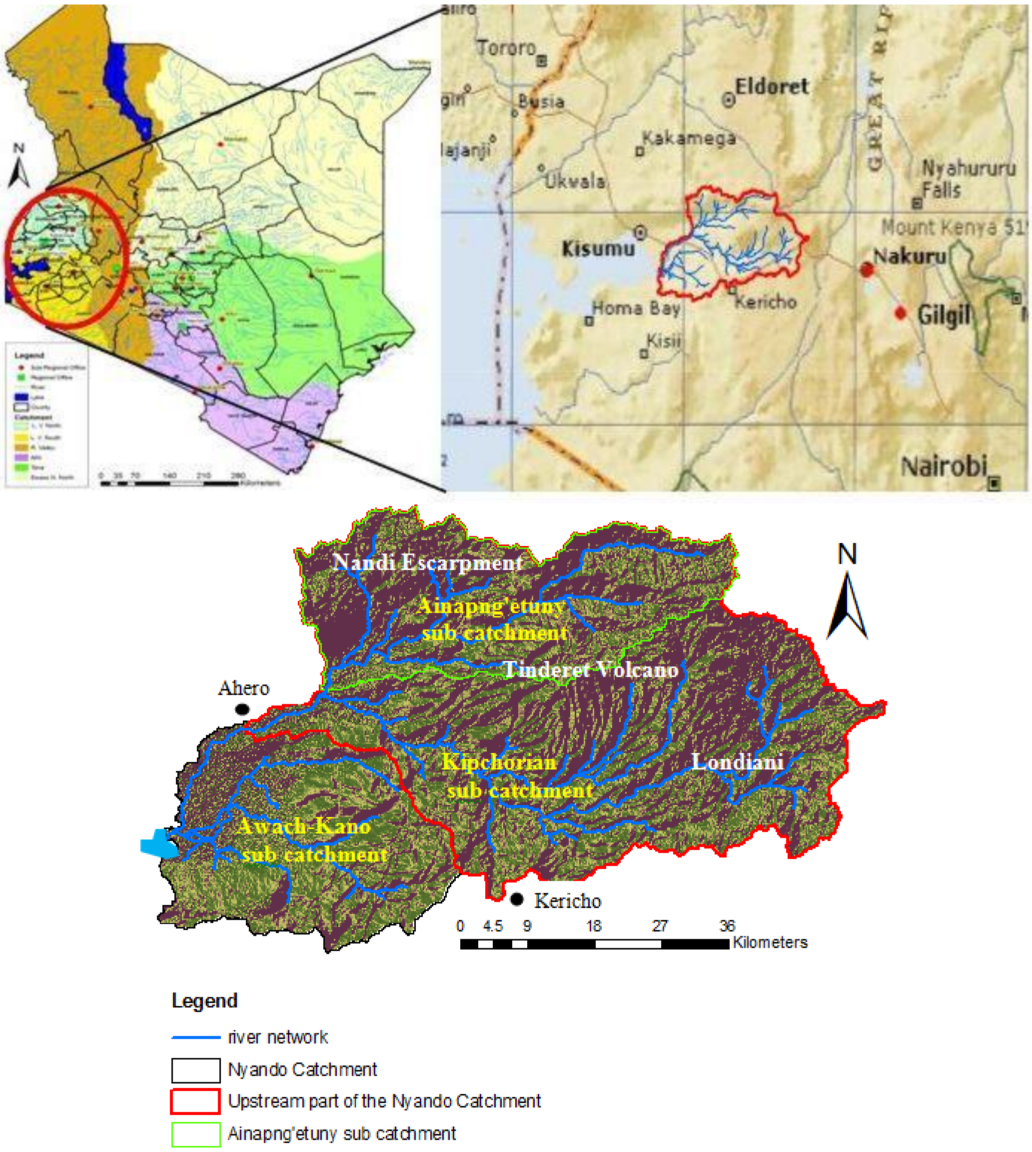

Figure 1: Map of the Nyando River Basin and its location in Kenya

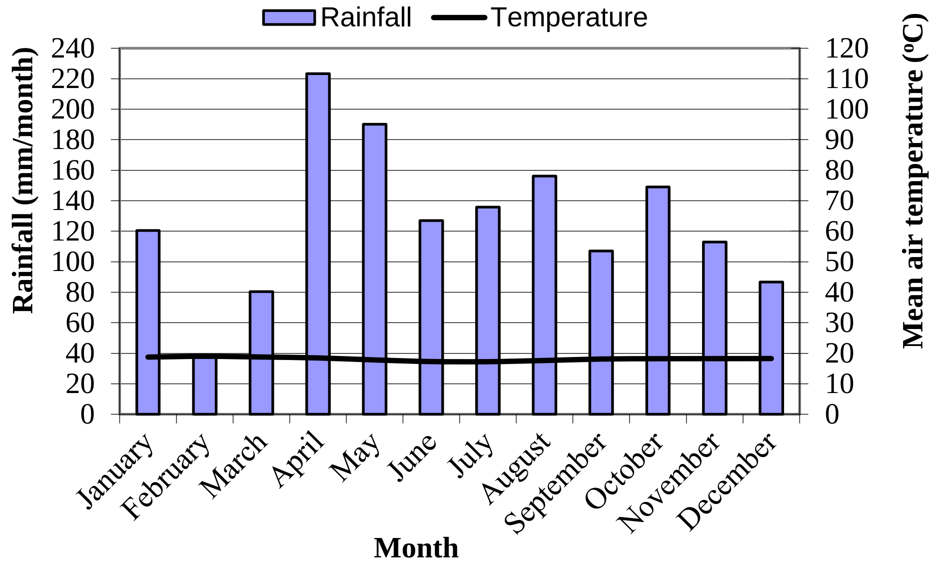

Figure 2: Mean monthly rainfall and air temperature of the Nyando River Basin
[Source: Kenya Meteorological Department]

Geological setting

Geological formation of the Nyando River Basin consists of Precambrian basement and intrusive rocks, Tertiary Miocene and Pliocene volcanic rocks, Quaternary Pleistocene and Holocene deposits (Pickford and Andrews, 1981; DHV consulting engineers, 1987). The river basin has a southern and a northern plateau with a basement of Archean Nyanzian system that is overlain by Precambrian intrusive igneous granite and granitoid gneisses (Schoeman, 1947; Binge, 1949; Pickford and Andrews, 1981). The Precambrian granite and granitoid gneisses outcropped in areas of Muhoroni, Koru, Songhor, Nandi and Nyabondo escarpment are slightly weathered compared to granite capped by Tertiary lavas (Binge, 1949; Pickford and Andrews, 1981; DHV consulting engineers, 1988). The southern plateau covers the Kipchorian sub catchment while northern plateau is in the Ainapng'etuny sub catchment as depicted in Figure 3 (Binge, 1949; Pickford and Andrews, 1981; Karicho, 2010).

The Kipchorian sub catchment in the southern plateau borders Sondu River Basin. The southern plateau is dominated by phonolitic lavas of Tertiary Middle Miocene originated from Tinderet, Londiani, Nakuru and Menengai volcanoes. Kericho phonolites of upto 65 m thick are underlain by Precambrian granite in the Kipchorian sub catchment and the Sondu River Basin (Gevaerts, 1964; DHV consulting engineers, 1987). Phonolitic nephelinites in the Kipchorian sub catchment were described as "deeply weathered along joints and fractures" (Shipman et al., 1981). Geological investigations indicated that tectonic movements which resulted in formation of the Kavirondo Rift Valley caused fractures in the Kericho phonolites at fault zone due to down movement of western Nyanzian plate (Binge, 1949; Pickford and Andrews, 1981; Shipman et al., 1981; Mathu and Davies, 1996). Vertical electrical sounding method was used to determine the depth of fractures in the Kericho phonolites and it was discovered that they are "highly broken" upto a depth of 15 m and slightly fractured at the base (DHV consulting engineers, 1987). The Precambrian granite in the southern plateau was described as chemically weathered to a depth of 20 m and 75 m at fractured fault due to water percolation through permeable phonolites (DHV consulting engineers, 1987).

The Northern plateau was formed by the Precambrian Nyanzian basement and granite intrusive igneous rock. The Early Miocene tuffs with biotite and agglomerates which are located in Soba, Songhor and Kapurtay in Meteitei originated from volcanic eruption that occurred in the Tinderet volcano over 19 million years ago. The thickness of tuffs and agglomerates is upto 200 m (Pickford and Andrews, 1981; Shipman et al., 1981). Agglomerates and analcite basanites and tephrites in the upstream part of the Ainapng'etuny sub catchment are covered by impermeable clay layer (DHV consulting engineers, 1988; Mathu and Davies, 1996).

Hydrogeology

Hydrogeology of the Nyando River Basin was investigated using geophysical surveys and MODFLOW model (DHV consulting engineers, 1987 and 1988; Karicho, 2010). Field investigations conducted by DHV consulting engineers (1988) in the northern part of Muhoroni revealed that groundwater recharge from streams, surface and sub surface runoffs in the upstream part of the Ainapng'etuny sub catchment are minimal due to impervious clay soils which overlay tuffs and basanites.

The Ainapng'etuny River and its downstream tributaries such as Nyangore, Kapchure, Kundos and Lumaiywo flow through a transition zone at the foot of the Nandi escarpment. The transition zone consists of major rift faults and fractured faults running from east to west and north to south as depicted in Figure 3. The fractured faults were described to be permeable and allow percolation of surface water into shallow and deep aquifers in the sub catchment. In addition, surface and sub surface runoffs were discovered to be infiltrating and percolating through permeable talus screes and boulders at the foot of the escarpment (DHV consulting engineers, 1988; Katsurada et al., 2007). Therefore, it was concluded that significant groundwater recharge occurs at talus screes and fractured zones (DHV consulting engineers, 1988). However, this recharge was not quantified during that investigation.

The Kericho phonolites in the southern plateau were investigated using geophysical survey to determine groundwater potential and it was discovered that weathered granite and fractured phonolites are water bearing rocks. However, groundwater in these rocks flows downstream towards the Kano plains and the Lake Victoria. The groundwater flowing towards the Kano plains from the upstream part of the Nyando catchment areas recharges shallow and deep aquifer at the fractured faults (DHV consulting engineers, 1987). Groundwater inflow from the upstream part of the Nyando catchment areas into the shallow groundwater aquifer at the Kano plains was quantified using the MODFLOW model. Boundary inflow used in the MODFLOW model set up covered areas of Muhoroni, Kibigori and Chemelil which are near to the confluence of the Kipchorian and Ainapng'etuny rivers. The estimated groundwater inflow at the boundary recharging shallow groundwater aquifer at the plains was 55.7 mm/a (Karicho, 2010).

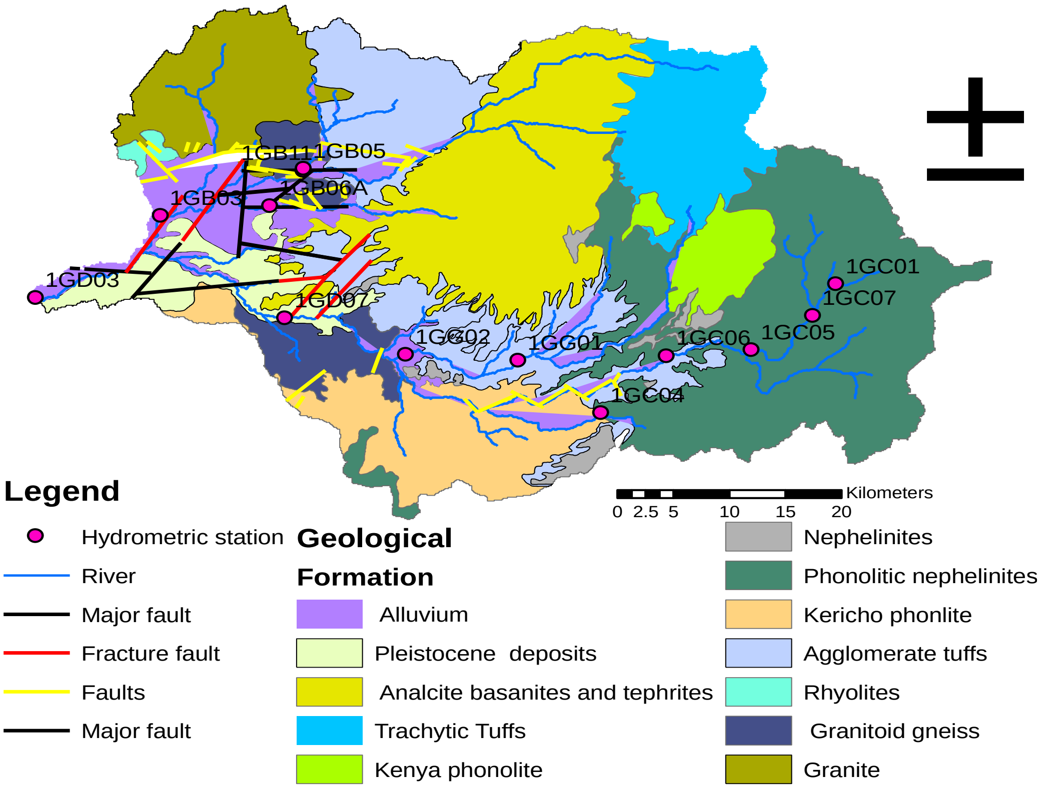

Figure 3: Geological map with fault lines and fractured zones in Nyando River Basin

Hydrological concept in SWAT model

The United States Department of Agriculture developed the SWAT model to generate scenarios related to water resources management, pollutants, plant growth and sediments. The model had been used in understanding hydrological processes in previous research studies (e.g. Arnold et al., 2005; Gassman et al., 2007; Cibin et al., 2010; Mango et al., 2011; Masih et al., 2011; Jinggang et al., 2012). The model subdivides the catchment into sub basins and further into hydrologic response units (HRUs) using input land use, soil and topography information (Arnold and Fohrer, 2005).

Water balance components in the SWAT model are precipitation (R), evaporation and transpiration (ET), surface runoff and subsurface lateral flow (Q), percolation (P), return flow (QR) and soil moisture (SW). The water balance equation used in the model is presented in Equation (1) (Arnold et al., 1998).

$$SW_t = SW_0 + \sum_{i=1}^{t} (\mathrm{R} - \mathrm{Q} - \mathrm{ET} - \mathrm{P} - \mathrm{QR}) \qquad (1)$$

where SW_t is the soil moisture at time t (mm), SW_0 is the initial soil moisture (mm) and t is period (days).

Data used in the study

Historical climatic data acquired were screened to identify data gaps and outliers. The climatic data was improved using regression, interpolation and lapse rate techniques. Daily measured rainfall data for 20 gauging stations was obtained from the Water Resources Management Authority - Lake Victoria South Regional Office (WRMA - LVSRO). Seven rainfall stations in the Nyando River Basin and 13 rainfall stations in neighbouring catchments were used in this study. Data screening was carried out to identify data gaps and outliers. Missing data was first filled with data from Kenya Meteorological Department. Then rainfall stations which were having less than 15 days data gaps in a month were filled using a regression approach. The data that was used in this study covers the time period from 1970 to 2010. Rain gauge density in the Nyando River Basin is low and led to poor performance of the SWAT model in simulating the water balance components in previous studies (Muiruri, 2011; Opere and Okello, 2011; Nyolei, 2012). Therefore, in order to increase the rain gauge density in the study area, spatial interpolation of the daily rainfall data was conducted using an inverse distance weighting (IDW) technique (Jinggang et al., 2012). Additional 8 gauging stations were created to enable spatial distribution of rain gauges used in setting the SWAT model.

Temperature data for the study period from 1970 to 2010 was not available in the Nyando River Basin. Hence daily temperature data for neighbouring meteorological stations in the Kericho and Kisumu was transferred to 15 created stations in the catchment using the temperature lapse rate method with a standard temperature gradient of -6.5 °C/km (Stahl et al., 2006; Minder et al., 2010).

Existing hydrogeological surveys information revealed that geological formations in some parts of the study area transmit water from surface, sub surface and shallow aquifers to deep aquifers (Pickford and Andrews, 1981; Shipman et al., 1981; DHV consultants, 1987; DHV Consultants, 1988). For example, areas of Lumbwa, Londiani, Tugunon and Ainamoi in the Kipchorian sub catchment have weathered phonolitic nephelinites, agglomerates and Kericho phonolites which transmit water from surface and shallow aquifers to deep aquifers. Also fractured fault and permeable Baraget phonolites in Baraget Valley allows deep aquifer recharges. In the Ainapng'etuny sub catchment upstream areas are covered by impervious layers while the downstream is characterized by fractured zone at the foot of the Nandi escarpment that allow water losses from river beds, land surfaces and shallow aquifers to deep aquifers (Binge, 1949; Shipman et al., 1981; DHV consultants, 1987; DHV Consultants, 1988). The study conducted in the downstream of the Nyando River Basin using MODFLOW model revealed that some of the water losses from shallow aquifers in the Ainapng'etuny and Kipchorian sub catchments were recharging downstream aquifers in Kano plains and Lake Victoria (Karicho, 2010). Therefore, these hydrogeological surveys information were used in this study to select groundwater parameters to calibrate groundwater section of the SWAT model.

Remote sensing data of actual evaporation and transpiration with a spatial resolution of 8 km and a monthly temporal resolution for the time period from 1983 to 2006 was downloaded from University of Montana website. A total of 41 pixels were obtained in the study area and used to determine remote sensing mean annual actual evaporation and transpiration. The remote sensing mean annual actual evaporation and transpiration for the study was 1248 mm/a was compared with simulated mean annual actual evaporation and transpiration by the SWAT model.

Model set up

The SWAT model set up was carried out after processing all input data. A 90 m spatial resolution digital elevation model (DEM) was used to delineate the study area and sub basins. The study area of 2723 km^2 was delineated and a threshold area of 75 km^2 was used in definition of stream network and sub basin outlets. The study area was divided into 21 sub basins. In the generation of the HRUs, land cover and soil maps were added into the model. The land cover map obtained from Ministry of Forestry and Wildlife, Kenya was prepared by FAO under the Africover project. The land cover was generated from 1999 LANDSAT TM images (Bands 4, 3, 2) and verified by fieldwork. The soil map used was prepared by International Co-operation Administration of the United States of America through field investigations from April to August 1958 and available in Kenya Soil Survey Department, Kenya. A threshold of 10% of the land cover, slope and soil classes was selected for the generation of the HRUs in order to avoid generation of minor HRUs and enhances model computation efficiency (Arnold et al., 1998; Masih et al., 2011).

Daily rainfall data and daily minimum and maximum temperature data for a period of 41 years from 1st January 1970 to 31st December 2010 were used as input for the SWAT model weather database. The SWAT model was calibrated using 31 years of climatic data from 1st January 1970 to 31st December 2000. Then 10 years from 1st January 2001 to 31st December 2010 climatic data were used in validating the SWAT model. Also, monthly water use data was added to the water use database in the model to enhance simulation of actual evaporation and transpiration. The SWAT model simulation was set up with two years of warm up period (1970 and 1971).

The SWAT model was calibrated using observed river flow for the nine hydrometric stations (see Figure 3) data from 1972 to 2000. Discharge data was acquired from the Ministry of Water, Sanitation and Irrigation (MWSI) and the WRMA – LVSRO. During calibration parameters were varied and coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) Equations (2 and 3) were used to determine the best parameter value (Nash and Sutcliffe, 1970). The parameter value with the highest R^2 and NSE was considered the best. In addition, a good balance between simulated and observed mean flow was used to optimize parameters. After calibrating the SWAT model, the observed discharge data of ten years period from 2001 to 2010 was to validate the model.

$$NSE = 1 - \frac{\Sigma(Q_m - Q_s)^2}{\Sigma(Q_m - \overline{Q_m})^2} \tag{2}$$

$$R^2 = \frac{[\Sigma(Q_m - \bar{Q}_m)(Q_s - \bar{Q}_s)]^2}{\Sigma(Q_m - \bar{Q}_m)^2\,\Sigma(Q_s - \bar{Q}_s)^2} \tag{3}$$

where Q_m is observed flow (m^3/s), $\bar{Q}_m$ is mean observed flow (m^3/s), Q_s is simulated flow by the SWAT model (m^3/s) and $\bar{Q}_s$ is mean simulated flow (m^3/s) (Nash and Sutcliffe, 1970).

In this study the Hargreaves method in the SWAT model was used to calculate the potential evaporation and transpiration due to lack of relative humidity, solar radiation and wind speed data (Hargreaves, 2003).

Water balance of the study area and sub basins was determined using Equation (4) (Arnold et al., 1998).

$$P - AET - Q_{out} - R_{DA} = \frac{\Delta S}{\Delta t} \tag{4}$$

where, P is precipitation (mm), AET is actual evaporation and transpiration (sum of transpiration, soil and water evaporation) (mm), Q_{out} is river runoff leaving the study area (mm), R_{DA} is groundwater recharge to deep aquifer (mm) and $\frac{\Delta S}{\Delta t}$ is change in water storage over time step (mm) (Arnold et al., 1998).

3. Results and Discussion

Model calibration

The SWAT model was calibrated using historical observed river flow data from nine river gauging stations. Parameters used in the calibration step are presented in Table 1.

Table 1: Model parameters used in the calibration step

Sub catchment	Parameter	Range	Default	Fitted value
Kipchorian	Rchrg_Dp	(0-1)	0.05	0.40 - 0.49
Ainapng'etuny	Rchrg_Dp	(0-1)	0.05	0.48
Both sub catchments	GW_Revap	0-0.2	0.01	0.08
	GW_Delay (days)	(0-500)	31	72
	Esco	0-1	0	0.08
	Canmx	0-1	0	0.3

The simulated and observed flow values were compared at daily and monthly time steps for the study period of 30 years (1972 to 2000). The coefficient of determination (R^2), NSE and a balance between simulated and observed mean flows were used to determine the performance of the SWAT model in simulating the river flow component. The coefficient of determination (R^2) and NSE obtained at monthly time step ranged between 0.51 and 0.90 and from 0.46 to 0.76 on daily time step respectively. The simulated and observed mean river flows corresponded well in the Ainapng'etuny sub catchment compared to the Kipchorian sub catchment as shown in Table 2. However, R^2 and NSE values for all stations at daily and monthly time step after calibration indicated good performance of the model in simulating long term stream flows despite rainfall fluctuation from time to time. The coefficient of determination (R^2) and NSE values for daily time step were lower than values for monthly time step in some stations. In comparison to low values of R^2 and NSE ranging from 0.2 to 0.50 for stations 1GD03 and 1GB03 reported in previous research studies (Muiruri, 2011; Opere and Okello, 2011), the results obtained in this study showed that interpolation of input climatic data and increase of station density in the study area for the model set up enhanced performance of the SWAT model in simulating stream flows.

Table 2: Summary of observed and simulated river flows in the Nyando River Basin for the calibration period

Nyando River Basin		Mean flow (m^3/s)		Time step			
				Monthly		Daily	
Sub catchment	Station ID	Simulated	Observed	R^2	NSE	R^2	NSE
Kipchorian	1GC04	0.95	0.97	0.90	0.87	0.73	0.67
	1GC06	0.91	1.78	0.82	0.51	0.70	0.46
	1GC05	0.92	0.84	0.79	0.77	0.62	0.60
	1GD07	11.76	11.66	0.84	0.76	0.67	0.53
Ainapng'etuny	1GB11	1.10	1.10	0.85	0.82	0.65	0.59
	1GB06A	0.50	0.60	0.76	0.85	0.67	0.54
	1GB05	3.69	3.81	0.88	0.90	0.76	0.68
	1GB03	6.72	6.57	0.84	0.78	0.65	0.59
Outlet of the study area	1GD03	18.87	19.99	0.80	0.68	0.72	0.64

The simulated and observed stream flows were also compared using time series as depicted from Figures 4 to 6. Visual inspection of the time series for Kipchorian sub catchment in Figure 4 revealed that the model estimated relatively well normal and low flows than peak flows. In the Ainapng'etuny sub catchment, the time series in Figure 5 revealed that the peak flows in upstream station 1GB05 and downstream station 1GB03 were underestimated in almost similar periods that is from 1981 to 1982. Comparing with stations in the Kipchorian sub catchment and the outlet station 1GD03 (see Figure 6) it indicated that the underestimation of the peak flows in the Ainapng'etuny sub catchment stations between 1981 and 1982 could be due to errors related to field data collection and processing and filling of data gaps. Generally, overestimation and underestimation of the simulated flows in the study area could be due to uncertainty of the SWAT model, calibration parameters and interpolation techniques used and errors of the discharge data used.

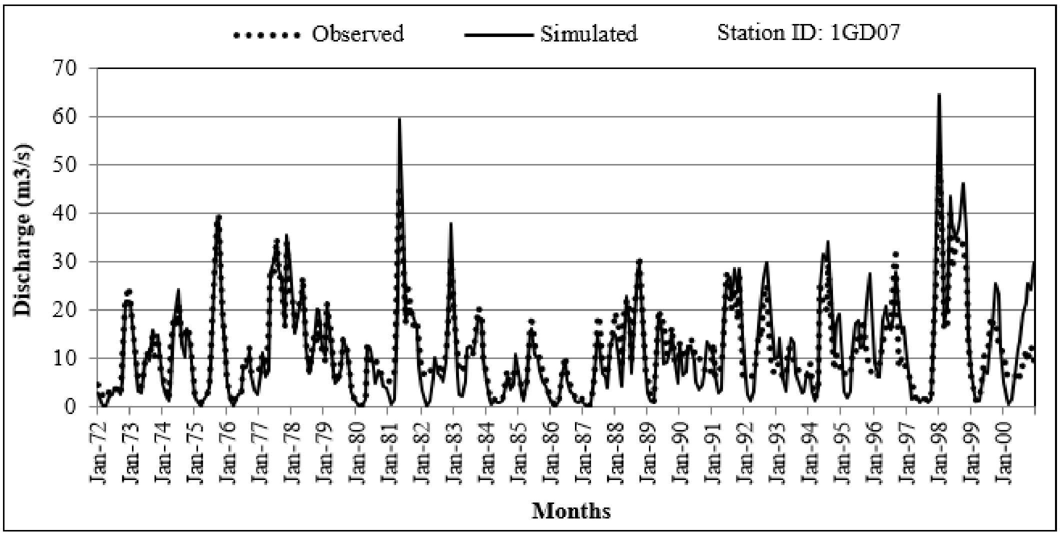

Figure 4: Monthly observed and simulated river flows in the Kipchorian sub catchment for the calibration period

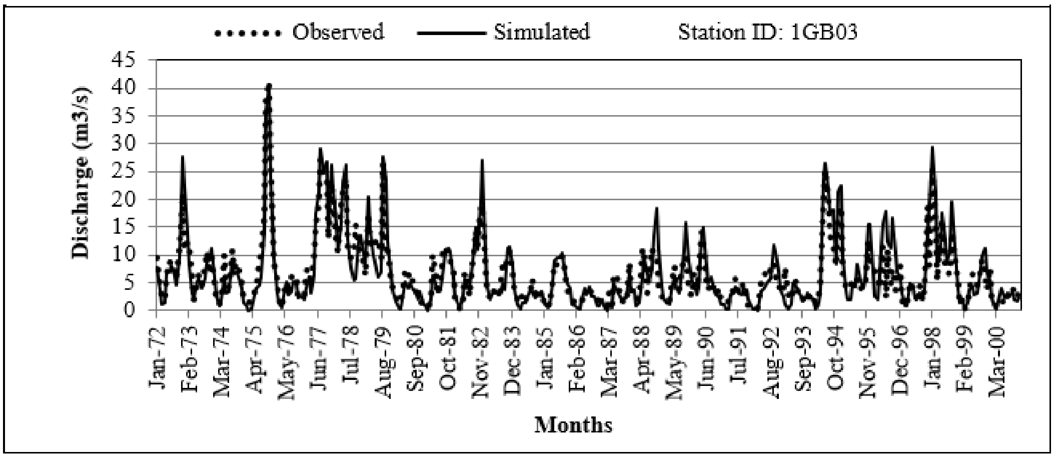

Figure 4: Monthly observed and simulated river flows in the Ainapng'etuny sub catchment for the calibration period

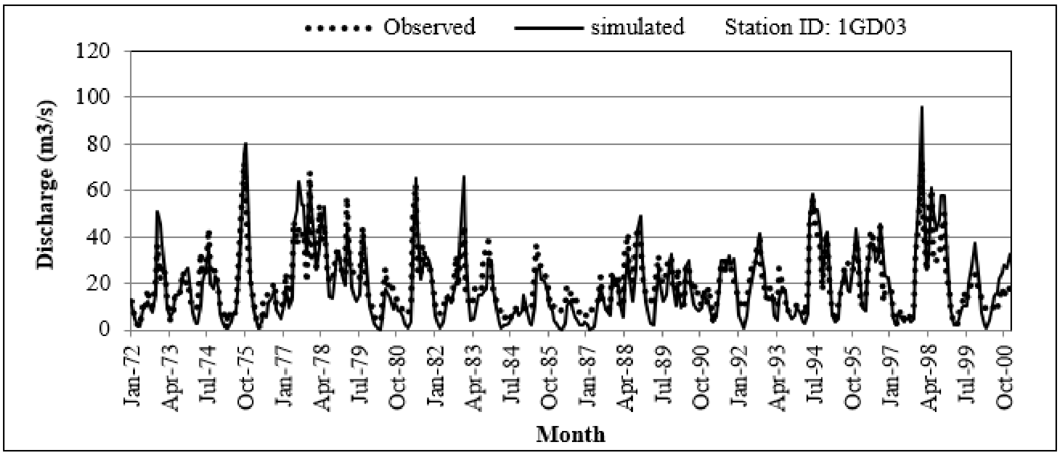

Figure 5: Monthly observed and simulated river flows at the outlet station of the study area for the calibration period

Model validation

After the SWAT model was calibrated using 30 years climatic data, it was validated using data period of ten years (see Figures 7, 8 and 9). The results obtained shows that the SWAT model used to simulate water balance components for the Nyando River Basin performs well. For example, R^2 and NSE for monthly time step in both sub catchments ranges between 0.94 and 0.4. The previous studies conducted in the Nyando River Basin using the SWAT model without considering its geological formation and existing hydrogeological information found results of NSE and R^2 below 0.4 (Muiruri, 2011; Opere and Okello, 2011). Therefore, hydrogeological information plays an important role in the estimation of water balance of the Nyando River Basin.

Table 3: Summary of observed and simulated river flow results in the Nyando River Basin for the validation period

Validation							
Nyando River Basin		Mean flow (m³/s)		Time step			
				Monthly		Daily	
Sub catchment	Station ID	Simulated	Observed	R^2	NSE	R^2	NSE
Kipchorian	1GC04	0.75	0.86	0.58	0.40	0.51	0.32
	1GC06	3.25	2.79	0.94	0.83	0.63	0.53
	1GC05	1.56	1.45	0.75	0.62	0.59	0.56
	1GD07	16.52	16.68	0.81	0.79	0.63	0.58
Ainapng'etuny	1GB11	1.20	1.30	0.74	0.56	0.54	0.41
	1GB06A	0.70	0.70	0.76	0.61	0.62	0.51
	1GB05	2.80	3.40	0.78	0.84	0.65	0.50
	1GB03	6.14	6.06	0.83	0.68	0.64	0.52
Outlet of the study area	1GD03	23.13	22.06	0.77	0.65	0.52	0.43

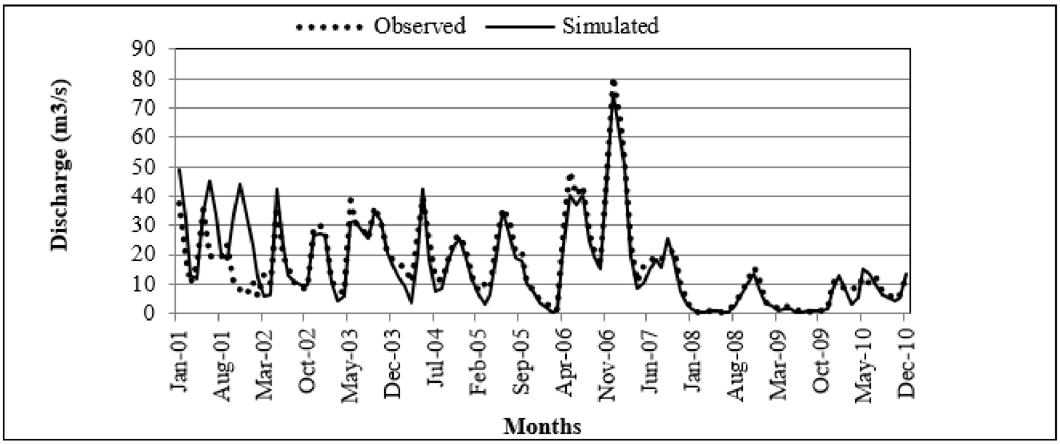

Figure 6: Monthly observed and simulated river flows at the outlet station of the Kipchorian Sub catchment for the validation period

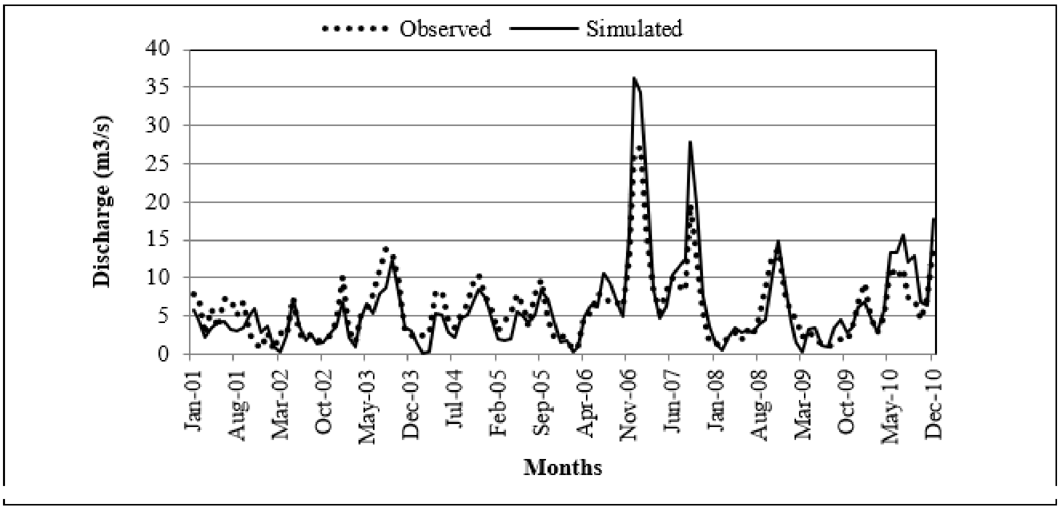

Figure 7: Monthly observed and simulated river flows at the outlet station of the Ainapng'etuny Sub catchment for the validation period

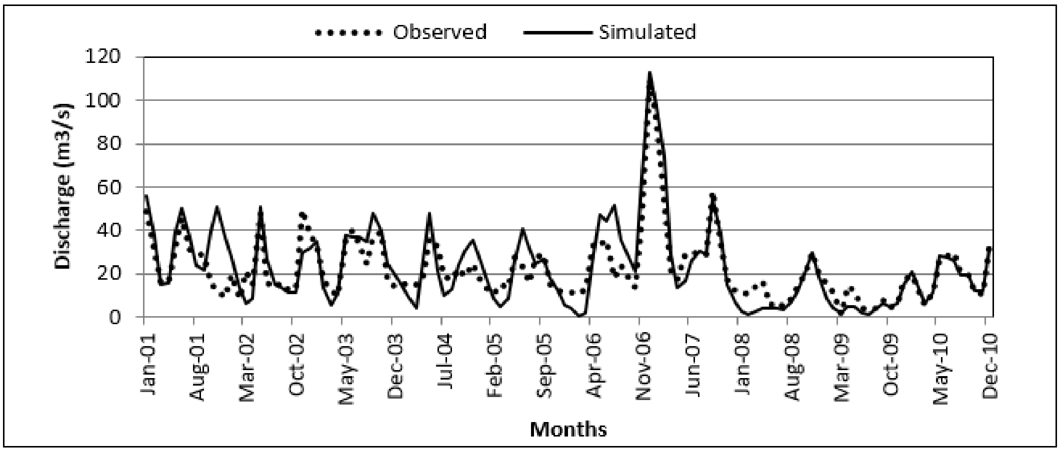

Figure 8: Monthly observed and simulated river flows at the outlet station of the study area for the validation period

Water balance analysis

Water balance computations were carried out using rainfall as input and actual evaporation and transpiration, deep aquifer recharge and river runoff at the outlet as output components.

Rainfall time series from 1972 to 2000 (see Figure 10) showed that the rainfall observed in the study area ranges between 2062 mm/a in 1977 and 1141 mm/a in 1984. These high and low rainfall events occurred due to increase and decrease in normal sea surface temperatures which led to unusual southern oscillations (Cadet, 1985; IPCC, 2007). Rainfall that occurred in 1977 and 1998 caused floods in Nyando division and the low annual rainfall amount in1984 and 1986 caused water shortage in the study area (Kenya Ministry of State for Special Programmes-Office of the President, 2009). High annual rainfall amounts like those of 1977 and 1998 are likely to occur more frequently in the future because rainfall extremes within the tropics were projected to increase in the 21st century (Meehl et al., 2007).

The annual Actual Evaporation and Transpiration (AET) depicted similar fluctuations with annual Potential

Evaporation and Transpiration (PET) (see Figure 10). Estimated annual AET in the study area ranged between 1032 mm/a and 1340 mm/a from 1973 to 2000. Potential evaporation and transpiration are controlled by parameters such as solar radiation, wind speed, relative humidity and air temperature. Time series in Figure 10 showed that an increase in rainfall reduced PET and AET for example from 1990 to 2000. Based on the data used in the model it revealed that during wet seasons air temperature was reduced due to cloud cover that intercepts incoming short-wave radiation.

Annual river runoff values at the outlet of the study area varied from 60 mm/a to 580 mm/a (see Figure 10). The maximum value of annual river runoff in 1998 was due to an El Niño event which caused an increased rainfall input from October 1997 until early 1998 and led to flood events which displaced about 3000 persons in the Kano plains. The low river runoff of 1984 and 1986 caused water shortage in the downstream of the study area (Kenya Ministry of State for Special Programmes-Office of the President, 2009).

Annual Deep Aquifer Recharge (DAR) values as depicted in Figure 10 ranged between 3 mm/a and 260 mm/a. High rainfall amounts increase the shallow and deep aquifer recharge through infiltration and percolation for example in 1977 and 1994. In 1976, 1984, 1986, 1993 and 1999 deep aquifer recharge was less than 15 mm/a due to the low rainfall received. The deep aquifer recharge in the Baraget Valley was attributed to the Baraget phonolites and agglomerates which were described as faulted, fractured and permeable (Shipman et al., 1981). In the Londiani and Lumbwa area deep aquifer recharge was believed to occur through weathered and permeable phonolitic nephelinites which overlay the Lower Miocene tuffs and agglomerates (Shipman et al., 1981). The Kericho phonolites which overlay the Precambrian granite in Ainamoi, Kapkiam and Kipchorian were discovered as fractured and permeable hence transmitting the shallow groundwater to deep aquifer (DHV consulting engineers, 1987). In the downstream part of the Ainapng'etuny sub catchment unconsolidated talus screes at the foot of the Nandi escarpment and fractured faults which run from east to west and north to south through Chemelil, Kibigori, Kundos, Mbogo and Nyangore were discovered as deep aquifer recharge zones (DHV consulting engineers, 1988).

Rivers and tributaries in the study area flow across and along colluviums, talus screes, fractured joints, faults and valleys and it was discovered that the groundwater recharge occurs on the river beds and banks (Shipman et al., 1981; DHV consulting engineers, 1987 and 1988). These river beds and banks consist of weathered and fractured volcanic rocks, boulders and pebbles which allow percolation of river water into groundwater aquifers. Further it was discovered that groundwater in shallow aquifers flow downstream of the study area towards Nyando wetlands and the Lake Victoria (DHV consulting engineers, 1987; Karicho, 2010). These observations revealed that water loss occurs from the river system to shallow aquifers and the shallow groundwater recharges deep and downstream aquifers. Due to limitation of the SWAT model to estimate these water losses independently they were considered as deep aquifer recharges and therefore in this study deep aquifer recharge is an output water balance component.

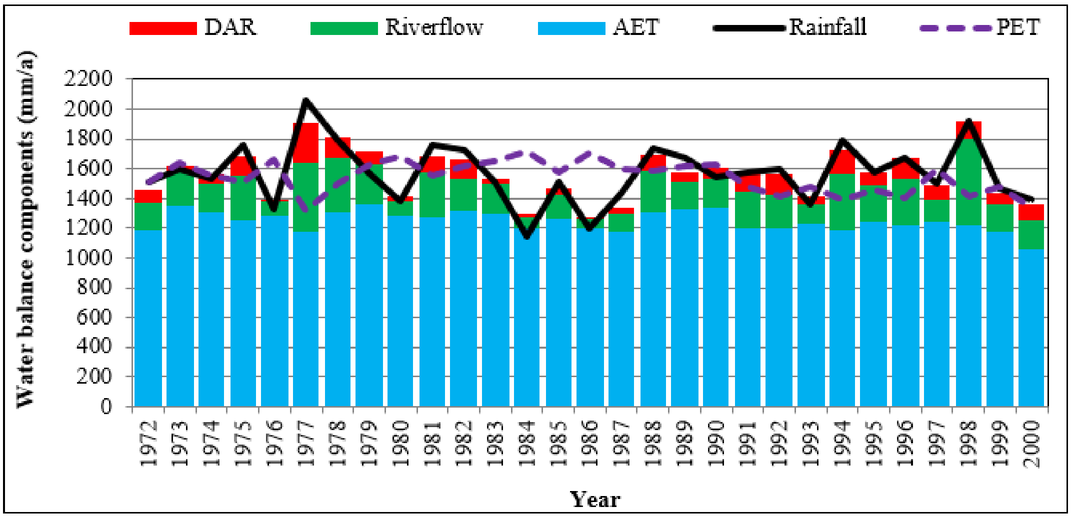

Figure 9: Time series of water balance components

Annual water balance calculations are useful for planning and management of water resources and equation (4) was used in determining water storage changes. The change in water storage ranged between ± 160 mm/a in 30 years. In 1977 a surplus of 160 mm/a was due to high rainfall and low actual evaporation and transpiration as depicted in Figure 10. On the contrary a shortfall of -160 mm/a that occurred in 1979 was as a result of an increased total water output and a low total rainfall amount (see Figure 11). Cumulative annual change in water storage revealed that in 1970s and 1980s the rainfall received was low compared to the total water output and led to reduction in the water storage for the two decades. In 1990s and 2000s the rainfall received was higher than the total water output resulting in increment of the water storage.

The mean annual change in water storage was 3 mm/a and insignificant compared to the rainfall input of 1572 mm/a. The actual evaporation and transpiration were the main output water balance component with a mean annual value of 1279 mm/a and it represented about 80% of the total water output. The mean annual actual evaporation and transpiration obtained was comparable with remote sensing mean annual value of 1248 mm/a estimated by Zhang et al. (2010). The simulated mean annual river runoff was about 228 mm/a and the mean annual deep aquifer recharge (DAR) was 62 mm/a. In comparison with the MODFLOW model results reported by Karicho (2010) it revealed that about 78% of the estimated mean annual DAR in this study flows toward Kano plains recharging the downstream shallow aquifer and 22% recharges the deep aquifers through fractured volcanic rocks and fault zones (DHV consulting engineers, 1987).

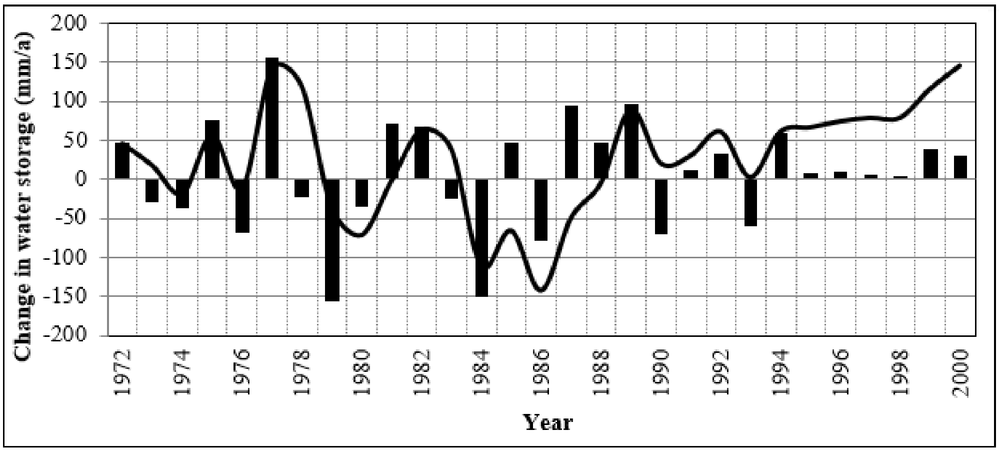

Figure 10: Annual (bar) and cumulative annual (line) change in water storage

4. Conclusions and Recommendations

Studies suggested that the effects of climate change such as floods and droughts are expected to increase due to global warming. In the Nyando River Basin, water demand is increasing and water users are vulnerable to water shortage as a result of prolonged droughts which had led to low river flows (UNISDR, 2008). Therefore, this study provided more understanding on water resources situation in the river basin. The findings of this study showed that the reliable and accurate climatic data enhanced performance of the SWAT model obtaining values of R^2 and NSE ranging from 0.51 to 0.90. It was established that 83% of the annual precipitation received in the river basin is lost through evapotranspiration and seepage. Hence 17% of received rainfall is available as accessible surface water. Despite the fact that the SWAT model to estimate the upstream water loss to groundwater aquifers through geological formation of the river basin, field investigation using geophysical surveys is recommended to verify the model findings. Also, integration of the SWAT-MODFLOW model could be used for further study in the Nyando River Basin to simulate water loss along the river system to shallow aquifer, deep aquifer recharge and groundwater flow. This will enable the MODFLOW model to use HRUs generated by the SWAT model in estimating the shallow and deep aquifer recharges in each sub basin.

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