Effect of Streamflow on Hydro-Power Generation in the Upper Tana River Basin, Kenya

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ABSTRACT

Hydro-power is one of the Kenya's important energy sources. The main hydro-power project in Kenya is located in the Upper Tana River basin. There has been a fluctuation of power generation due to climate change over the years. The main objective of this research was to assess the effect of streamflow on hydro-power generation under climate change scenarios. Hydro-power generation is estimated by relating the runoff changes to hydro-power generation through the ArcGIS software, in conjunction with ArcSWAT model based on 30-year hydrometric data. Results showed a peak discharge in May, with gradual decrease, the first decade registering a peak flow of 82.74 m^3/s *in Tana-Sagana River followed by 80.65* m^3/s*. The annual average dam inflows declined at the rate of 0.7992* m^3/s *annually. For the 30 years, dam inflow decreased by 23.98* m^3/s*. The minimum inflow rates increased with the years 2000 and 2009 having the lowest inflows of 21.4* m^3/s *and 22.8* m^3/s *respectively. The highest inflow and lowest inflow occurred in 1998 and 2009. A decreasing trend in the amount of hydro-power produced in the scheme from 1990 to 2010. The driest years, which were 1999-2000 and 2009, recorded the lowest levels of hydro-power generation. Decreasing amounts of precipitation and increasing temperatures have led to declining Masinga dam inflow rates. Results from this study are useful in explaining the trend in hydropower generation in the basin. The findings show how the hydro-power generation is correlated to dam inflows, which in turn is linked to the amount of precipitation and can be incorporated for planning of hydro-power supply.*

Key words: stream flow, hydro-power, upper Tana River basin, ArcSWAT, dam inflow

INTRODUCTION

Streamflow of any river basin can directly be influenced by hydro-meteorological variables that are linked to climate change. Climate change is one of the world's greatest challenges of the 21st century. There is unanimous consensus in the scientific community that the world is going to get warmer in the future and the average weather patterns are expected to take a major shift (Godbole, 2014). A more variable climate is expected to be a direct result of increase in atmospheric concentrations of greenhouse gases resulting from human activities (Pilesjo and Al-Juboori, 2016). Unequivocal evidence from in situ observations and ice core records shows that the atmospheric concentrations of important greenhouse gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) have increased over the last few centuries (IPCC, 2014). Carbon dioxide and many other greenhouse gases occur naturally in the atmosphere and are important in keeping the earth warm. Anthropogenic sources of greenhouse gases have increased since the industrial revolution which has resulted into a significant increase in greenhouse gases concentrations in the atmosphere, this trend is expected to continue over the next century which will result into major rise in temperature greater than any time in the past (Pilesjo and Al-Juboori, 2016).

Over the past decade, the assessment of climate change impacts on water resources has been a major research effort. Climate change is expected to affect the hydrological cycle, and consequently, water balances and local water supplies. Predicting water availability under changing climatic conditions and hydrological variations, for both short-term and long-term, are essential for many social, economic and environmental sectors such as agriculture, industry, and biodiversity conservation (Li *et al.,* 2016). Climate change can cause significant impacts on water resources by resulting changes in the hydrological cycle. For instance, the changes in temperature and precipitation can have a direct consequence on the quantity of evapotranspiration and on both quality and quantity of the runoff component. Consequently, the spatial and temporal availability of water resources, or in general the water balance, can be significantly affected which in turn affects agriculture, industry and urban development.

The hydrologic system, which consists of the circulation of water between the oceans and the atmosphere, is an essential part of the global climate system. Changes in global climate are believed to have a significant impact on hydrological regimes and also bring about significant changes in severity and frequency of droughts and floods. For instance, snows and glaciers in Mount Kenya and Mount Kilimanjaro, which act as major water towers in Kenya and Tanzania respectively, are quickly receding due to continued rise in temperatures in the past century. These changing temperatures have been attributed to climate change (Droogers, 2009). Climate change has also led to decreased river flows especially during the dry seasons, which, as a result has severely affected hydropower generation across the country (Bunyasi, 2012).

Hydropower, largely considered as a clean renewable energy source, has provided many economic and social benefits to many countries in the world, such as improving domestic energy supply, providing energy security and services, stimulating national economic development, and increasing economic growth. Hydropower is the main form of renewable source of energy world over and is increasing, the world's hydropower installed capacity and output increased by over 5.3% from the year 2009 to 2010 (Hamududu and Killingtveit, 2012). Hydropower supplies about 50% of electricity in 66 countries and 90% in 24 countries globally. In Africa, it is recorded that the effects of climate change are severely affecting hydropower plants especially in areas that experience low annual rainfall (Bunyasi *et al.*, 2013). Hydropower generation makes a substantial contribution to today's world electricity demands and it is the main form of renewable source of energy over the world. Hydropower accounts for 49% of installed electricity capacity in Kenya with almost all hydropower generated by the seven forks scheme (Droogers *et al.*, 2006).

Hydropower generation is progressively becoming susceptible to climate change related events and resultant processes like reduced reservoir storage capacity due to siltation (Walling, 2008). Climate change has led to more pronounced droughts in the past years, which has led to decreased river flows especially during the dry seasons, which has severely affected hydropower generation across the country. In addition to its impacts on snow and glacier, the continued rise in temperature have also increased the direct evaporation rates from the hydropower water reservoirs which is negatively affecting power generation. (Bunyasi, 2012).

Study objective

The broad objective of this research is to assess the trend of stream flow and its effect on hydro-power generation in the upper Tana basin.

MATERIALS AND METHODS

Study area

The Tana River basin covers nearly 21 % of the total national landmass of Kenya, and has an aerial coverage of about 126,927 km^2 (Agwata, 2006; NEMA, 2013) (Figure 2.1). River Tana is the main river in the basin and it flows for about 1200 meters from the central Kenya highlands to Indian Ocean and it is the lifeline of the seven forks hydro-power project. Five major reservoirs have been built on the upper reaches: Kindaruma in 1968, Kamburu in 1975, Gitaru in 1978, Masinga in 1981, and Kiambere in 1988. Together, these provide three quarters of Kenya's electricity and regulate the river flow. The Upper Tana River basin covers the Aberdares highlands and Mount Kenya and is situated north-west of Nairobi with a surface area of approximately 12,500km^2. The Masinga dam is the largest reservoir of the Seven Forks hydropower project and therefore most important in controlling the Tana River system and the seven forks hydropower project.

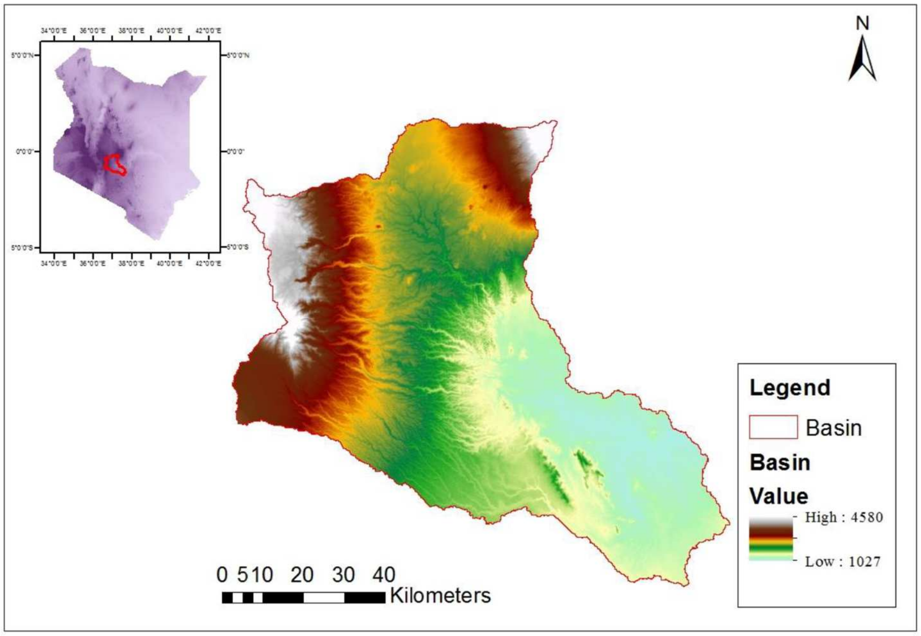


Figure 2.1: study area

Characteristics of the study area

Topography: The main topographic features in the catchment area are the Mount Kenya and the Aberdare ranges. Elevation ranges from 5199m towards the peak of Mt. Kenya to 400m in the east of the catchment. The southern slopes of Mt. Kenya and the eastern slopes of the Aberdare ranges are the main sources of rivers draining into the seven forks dam projects. Towards Mt. Kenya and the Aberdare ranges, the topography is rugged and sloping towards the Tana basin allowing for construction of hydroelectric dams. The slopes in the catchment are characterized by deeply dissected ridges and valleys which vary in altitude between 1,500m up to 2,400m, these dissections are further eroded by the rivers and runoff through erosion forming parallel valleys and ridges (Bunyasi, 2013).

Geology and soils: The geology of the upper Tana can broadly be divided into volcanic rocks in the north and west and pre-cambrian basement complex in the south-east. Other geologic formations of limited extend include igneous intrusions of granite and dolerite and an area of quaternary sandstone between Murang'a and Sagana. The catchment has a broad range of soil types with varying water retention ability. Lithosols and Histosols occur at the highest altitudes in the Aberdare range, with Humic Andosols at slightly lower elevations. Nitosols are found in the mid-elevations and Vertisols in the lower elevations.

Climate: The climate ranges from semi-arid in the east to humid in the west. Generally, the area has a bimodal rainfall pattern with four fairly distinct seasons. The long rains occur between March and May while the short rains during September and November. The long rains and short rains are separated by about three dry months. Rainfall varies between 600mm in the eastern part of the watershed to over 2000mm on the Aberdare mountains. The maximum and minimum mean annual temperature varies between 25.5 – 31.00C and 21.0 – 24.00C respectively (Saenyi, 2012).

Land use: Agricultural activities are being practiced in the western area of the catchment where rainfall is higher, the rest of the area is used for grazing with only scattered cultivation. Maize, sisal, tea and coffee are the major crops grown in the area. Crop husbandry is low with only a few cases where physical conservation measures have been applied.

Data required for study area

Climate data of the study area was obtained from the Kenya Meteorological Department (KMD), the data acquired include precipitation and temperature records for the 1983-2013 period. Water Resources Management Authority, (WRMA), provided data on Tana river flow discharge and stage at different locations along the Tana river, while the Masinga dam reservoir levels were acquired from Kenya electricity generating company, KenGen. Data on soils, land use and topography was downloaded from World Resource Institute (WRI), website.

Filling of missing data

Every data series must be complete before the input to any hydrological model. Data missing can happen due to several reasons like gauge problem, difficulty in reading daily data, personal mistakes in storage, poor storage system and so on. The data series collected from WRMA and Ministry of Water, Kenya had so many missing values and mostly on a long regular series of more than 90 regular days and sometimes a year of missing data. Random missing data were filled by simple interpolation while the long missing series were estimated using data from nearby stations.

Determination of Tana River flow regime

The natural flow of a river varies on time scales of hours, days, seasons, years, decades and longer. To describe the characteristic pattern of the river flow, many years of observation from a streamflow gauge are generally needed. A 30-year stream discharge data for the upper Tana was obtained from the Ministry of Water and the Water Resources Management Authority (WRMA). Flow changes within the 30-year period were analyzed and discharge trends plotted. For determination of the variations in the river flow regime over the 30-year duration, the study period was divided into three 10-year periods starting from the initial study year, 1983 and ending in 2013. The flow regime of different streams in the watershed was established and therefore a general trend of stream flow over the study period established. The mean flow and the minimum peak flow was also determined. The ArcGIS software was used for analyses of catchment characteristics.

Relating river flow regime to hydropower

Data on hydropower generation from 1990 to 2013 was obtained from KPLC and KenGen. The corresponding reservoir levels were established for each specific amount of power generated from the hydropower stations. Hydropower generation over the same period was plotted against time in years and the trend in hydropower generation observed. Water resource availability changes were converted and linked to changes in hydropower generation. The runoff is assumed to be the main determinant of limitation to hydropower generation. On average, runoff can be thought of as the difference between the precipitation and evaporation over long periods of time. The analysis methodology was based on the fact that hydropower generation is a function of flow (Q, in m3/s), Head (H, in m) and efficiencies. Assuming that the changes in water resources will impact hydropower generated in the future, the most varying factor was the streamflow. The approach was based on the fact that the current hydropower generation system may only be limited by water availability. The main assumption was that if water supply reduced, the hydropower systems would likewise reduce generation due to decreased inflow in the reservoirs, and vice versa. With this approach, changes in annual and monthly mean flows were the main predictors of hydropower generation. A relationship was then established between the hydropower generation and stream flow trends using regression method.

Discharge versus hydropower generation analysis

Hydropower technology allows for the transformation of about 90% of kinetic energy of flowing water into electricity. A flow rate of about 4000 liters per second is used to produce one kilowatt of electricity, assuming there is a vertical difference in elevation of 100m. Due to the fact that hydropower generation needs a continuous flow of water with minimum sedimentation, major dam constructions are usually necessary, particularly on rivers with high fluctuations in flow. Reservoirs created by damming of rivers regulate the river flow and also act as sediment settlement tanks. Constructing a dam across a river also causes a change in downstream river flow regime and water quality.

Generally, high amounts of precipitation in an area leads to high stream flow rates and consequently higher hydropower generation since the reservoirs will be constantly full of water, and therefore the channel flow and the power production will be positively correlated. However, deviations from these expectations do occur and are usually attributed changing climate and activities upstream the dam, including land use practices, that lead to poor vegetation cover and hence accelerated runoff or reduced flows due to diversion of water to other point uses such as irrigation.

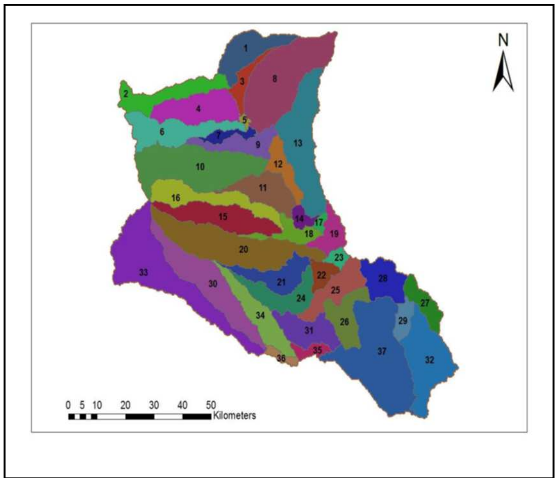
Simulation of river flow regimes and its effect on hydropower generation

The ArcSWAT model was selected as the model for simulation of future stream flow characteristics. Soil, land use and slope characteristics of the study area were processed using the ArcSWAT model. The model was calibrated and validated in order to be representative of the real watershed characteristics. Future river flow scenarios were them simulated based on the predicted climate change scenarios for the upper Tana river catchment. Climate scenarios are used to provide quantitative assessments of climate impacts and can be defined as possible representation of future climate which have been developed to be used exclusively in conjunction with investigating the potential impacts of anthropogenic climate change (IPCC, 2007).

General Circulation Models (GCMs) are currently the most advanced tools available for simulating the response of the global climate system to changing atmospheric composition. In general, the GCM is a numerical representation of the atmosphere and its phenomena over the entire Earth and it incorporates a variety of fluid-dynamical, chemical or even biological equations (IPCC, 2007). The GCM is run using different climate change scenarios and produces outputs of annual and seasonal averages, which enable the determination of the likely changes in precipitation, temperature and runoff as a result of these scenarios taking place.

Model input

The GIS input needed for the ArcSWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers. Data on weather and river discharge were also used for prediction of streamflow and calibration purposes. Topography was defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 90 m by 90 m resolution DEM was downloaded from SRTM (Shuttle Radar Topography Mission) website on 20 February 2016 and projected using Arc GIS 10.2 software package. The DEM is one of the essential spatial inputs which was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. Sub basin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length, and width were derived from the DEM. The surface area of the basin as calculated by the model was 7,026 km^2, SWAT divided the watershed into 37 sub basins and 309 hydrologic response units as shown in the Figure 2.2.



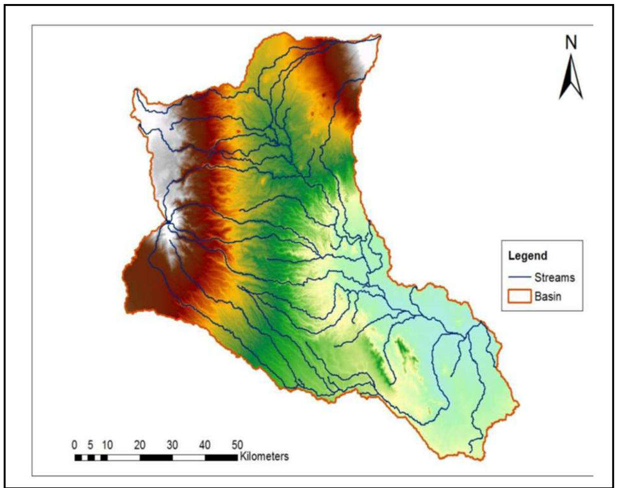


Figure 2.2: Masinga basin (a) sub catchments and (b) stream flow network

Soil data

SWAT model requires different soil textural and physicochemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. Data for soil included the shape file soil map extracted from the soil map of Kenya available from Kenya Soil Survey. For each of the soil units in the study area, the soil physical and chemical properties were determined from the corresponding soil unit identified from the table of the soil properties. Figure 2.3 and Table 3.1 shows some soil types and properties.

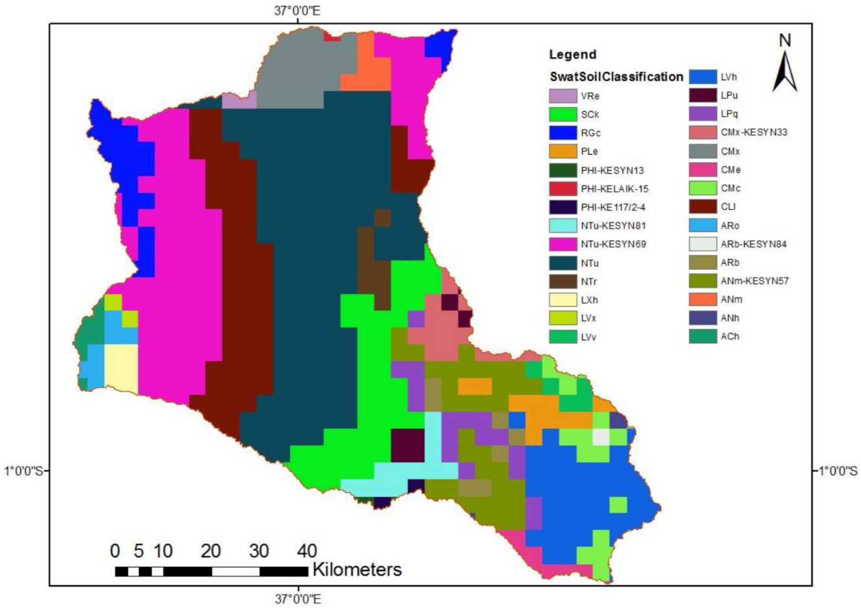


Figure 2.3: Soil map of Masinga dam catchment

Table 3. 1: Soils description

Soil code	Soil name	%sand	%silt	%clay	CEC	Bulk density	TAWC
NTu	Nitosols	7	31	62	21.4	1.10	23
HSs	Histosols	30	56	14	15	0.36	35.0
VRe	Vertisols	30	30	40	40	1.49	12
ANm	Andosols	59	20	21	33	1.13	17.0
PHI	Phaeoze	24	17	59	14	1.10	11.0

m

Land use

Land use is one of the most important factors that affect surface erosion, runoff, and evapotranspiration in a watershed. The land use shapefile of the study area was downloaded from MWI. The reclassification of the land use map was done to represent the land use according to the specific land cover types such as type of crop, pasture and forest Figure 2.4.

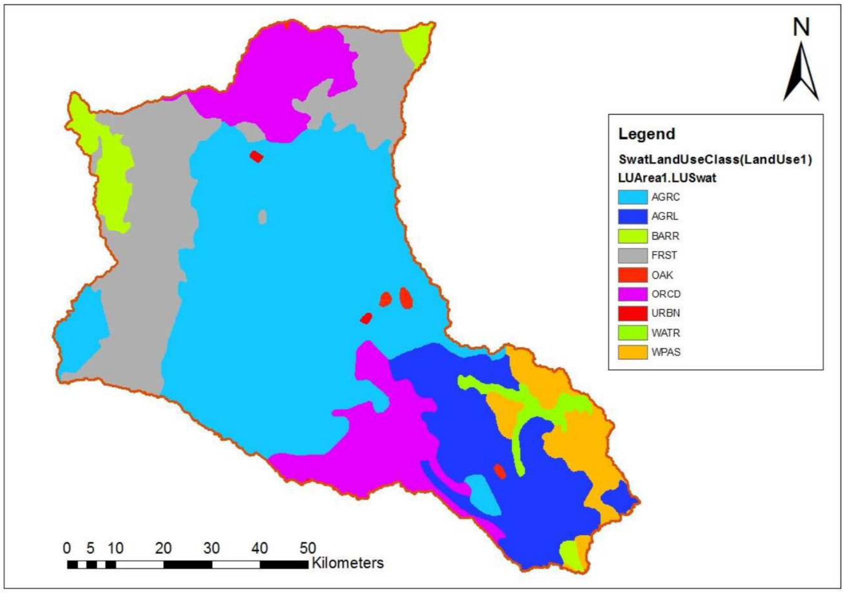


Figure 2.4: Land use map for Masinga dam basin

Discharge data

Daily river discharge values the Masinga catchment were obtained from the WRMA and the Ministry of Water. These daily river discharges were used for model calibration and validation.

Model simulation run

Having successfully loaded the required data, the model was able to run and produce the necessary output information on streamflow on a daily, monthly or yearly basis.

Model Setup

The model setup involved five steps: (1) data preparation; (2) sub basin discretization: (3) HRU definition; (4) parameter sensitivity analysis; (5) calibration and uncertainty analysis. Hydrological modeling using SWAT requires the use of detailed spatially explicit datasets on land morphology or topography, land use or land cover, soil classification and parameters for hydrological characteristics, and climate and hydrological data on a daily time-step (Schuol *et al*., 2007). The DEM, Land cover and soil datasets were projected to Arc 1960 UTM Zone 37S by use of ArcGIS 10.2. Arc 1960 UTM Zone 37S is the Transverse Mercator projection parameters for Kenya. Using the DEM, the watershed was delineated by the use of ArcSWAT extension in the ArcGIS software. The watershed delineation process includes five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub basin parameters.

The model first defines flow direction and accumulation which is then used for stream network and outlets development. Upon selection of preferred basin outlet position, the model was able to delineate the watershed using the DEM and also develop sub basins. The sub basin parameters including area, perimeter and mean elevation were then calculated. In order to be incorporated into the ArcSWAT model, the Land use/Land cover spatial data sets were reclassified into SWAT land cover/plant types. A user look-up table was created to identify the SWAT code for the different categories of land cover/land use on the map as per the required format. The soil map was linked with the user soil database which is a soil database designed to hold data for soils not included in the United States. Subdividing the sub watershed into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrologic conditions for different land covers, soils and slopes.

The soil, land use and slope datasets were imported overlaid and linked with the ArcSWAT databases. To define the distributions of HRUs both single and multiple HRU definition options were tested. For multiple HRU definition the ArcSWAT user's manual suggests that a 20 percent land use, a 10 percent soil and 20 percent slope threshold are adequate for most applications. To identify the most reasonable threshold level in the area the suggested threshold and other land use, soil and slope combinations scenarios were tested. These were 20% - 10% - 20%, 10% - 20% - 10%, 10% - 10% - 20%, 20% - 20% - 10%, and 25% - 30% - 20%. Each scenario was arranged in order of land use percentage over sub basin area, soil class percentage over land use area and slope class percentage over soil area. For example, if a 20% soil area is defined in HRU distribution, only soils that occupy more than 20% of a sub watershed area are considered in HRU distributions. Land uses, soils or slope that cover a percentage of the sub basin area less than the threshold level were eliminated. After the elimination processes the area of the land use, soil or slope is reallocated so that 100 percent of the land area, soil or slope in the sub basin is included in the simulation.

The ArcSWAT model to run, it requires input of meteorological data on daily time step. The weather parameters include precipitation, temperature, relative humidity and solar radiation for the study area over the study period. In absence of consistent daily data, the model is able to simulate the weather data using the weather generator model. The weather generator model requires input of average monthly weather data.

Model calibration and validation

SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or sub watershed. The user determines which variables to adjust based on expert judgment or on sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs.

Sensitivity analysis in practical sense helps determine the predominant processes for the component of interest. Two types of sensitivity analysis are generally performed: local analysis, which entails changing one value at a time, and global sensitivity analysis, which involves allowing all parameter values to change. The two procedures, however, may yield different results. Sensitivity of one parameter often depends on the value of other related parameters; hence, the problem with one-at-a-time analysis is that the correct values of other parameters that are fixed are never known (Arnold *et al.,* 2012). The disadvantage of the global sensitivity analysis is that it needs a large number of simulations. Both procedures provide insight into the sensitivity of the parameters and are necessary steps in model calibration.

The parameter sensitivity analysis was done using the SWATCUP interface for the whole catchment area. Ten hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. Here, the default lower and upper bound parameter values was used. SWATCUP is a freely available computer program, which calibrates the swat model by linking it to several calibration algorithms. It provides user-friendly interface for sensitivity analysis, calibration and validation of the SWAT model output. Parameter sensitivities are determined by calculating a multiple regression system.

RESULTS AND DISCUSSION

Upper Tana River flow regime

The stream flow response to rainfall depends on the catchment attributes that include the physiographic, underlying geology, vegetation cover and rainfall amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and induce complexity, which cannot yet be predicted in hydrology (Berhanu *et al.,* 2015). The complexity of stream flow response in a catchment can be addressed through the process of systematically organizing streams into groups that are most similar with respect to their flow characteristics. The temporal pattern of river flow over a period is the river flow regime, which is a crucial factor sustaining the aquatic and riverine ecosystems. A river flow regime describes an average seasonal behaviour of flow and reflects the climatic and physiographic conditions in a basin. Differences in the regularity of the seasonal patterns reflect different dimensionality of the flow regimes, which can change subject to changes in climate conditions. For analysis of the river flow regime, flow observation period was divided into three classes according to years of flow record, the first class included flow data from 1983 to 1993, the second 1994 to 2003 and the last division was in the period of 2004 to 2013. River flow regime for those periods were analyzed as presented in Figure 3.1.

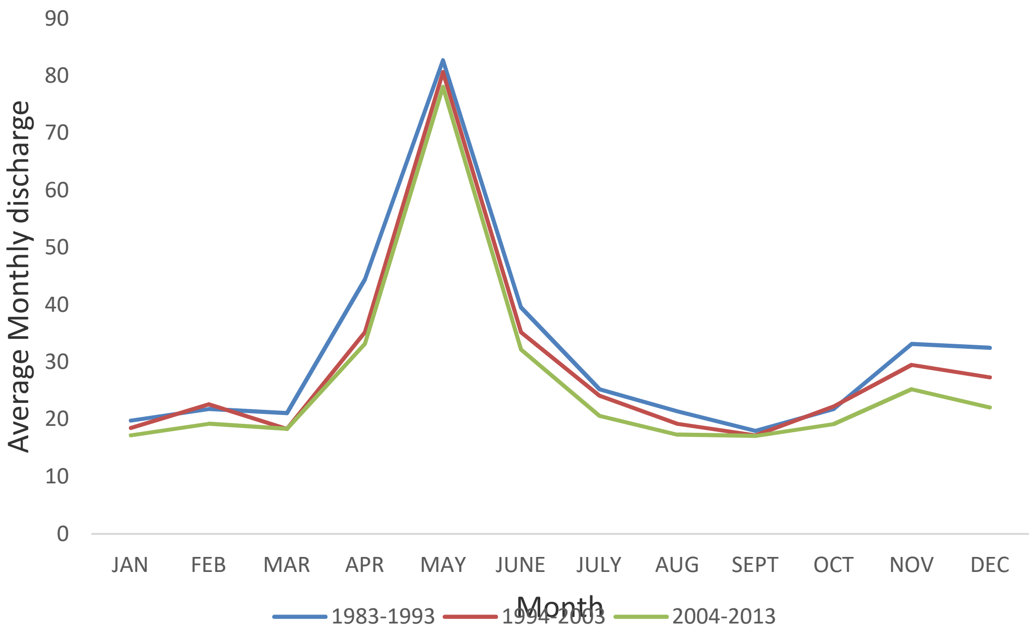


Figure 3.1: Tana-Sagana river flow regime

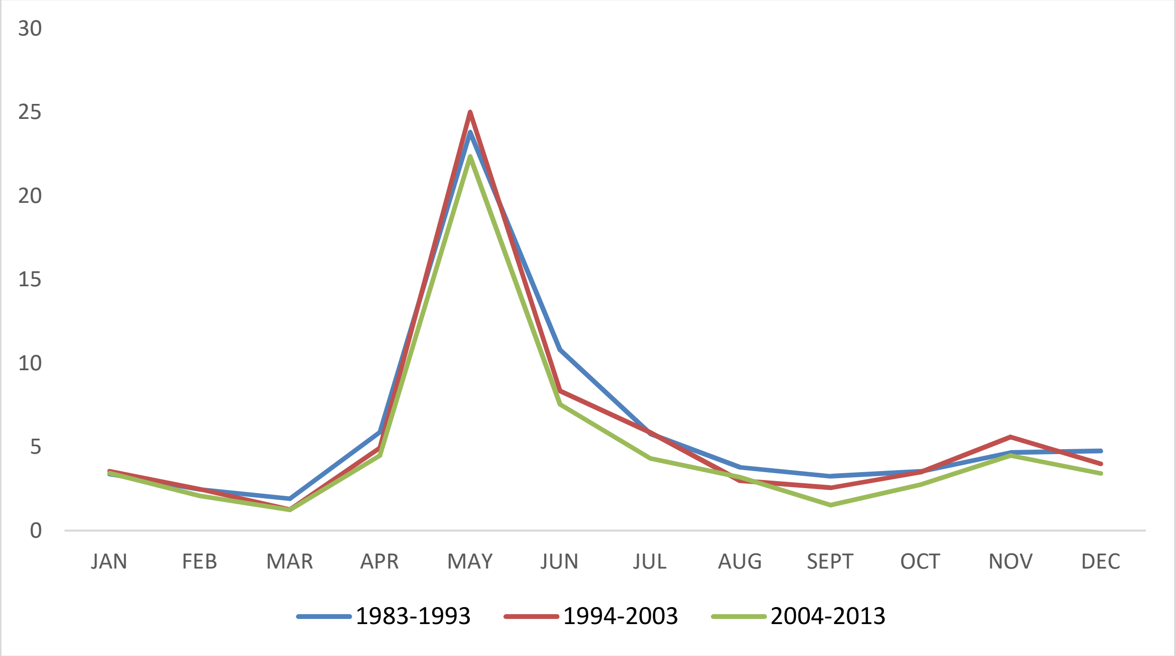


Figure 3.2: River Thiba flow regime

There has been a gradual decrease in the river discharge over the 30-year study period as shown by the Figures 3.1 and 3.2. The highest peak discharge, which occurs in the month of May has shown a gradual decrease over the years, with the first decade registering a high peak flow of 82.74m3/s in the Tana-sagana river followed by 80.65 m3/s in the following decade and finally a high peak flow of 78.1m3/s in the final decade ending in the year 2013. The decline in the streamflow over the years is basically due to decline in the amount of water flowing through the river channels. The reduction in the river flow can be attributed to decreasing amounts of precipitation and also the gradually increasing temperatures from the year 1983 to 2013 as shown in Figures 4.5 and 4.3 respectively, which can be attributed to climate change.

3.2 Effect of river flow regime on hydropower generation

For efficient and sustainable hydropower generation, water availability is an essential component. Changes in the river flow regime in a catchment can affect the amount of water available in the hydropower generating reservoirs which can in turn have an impact on the hydropower plants operation and electricity generation.

Masinga reservoir inflow trends

The data of Masinga reservoir inflow was obtained from KENGEN, the data is based on the dam test flows in cubic meters per second. The inflow rates were determined based on daily dam levels. Based on the trend analysis, the dam inflow rates show a steady decline as given in Figure 3.3

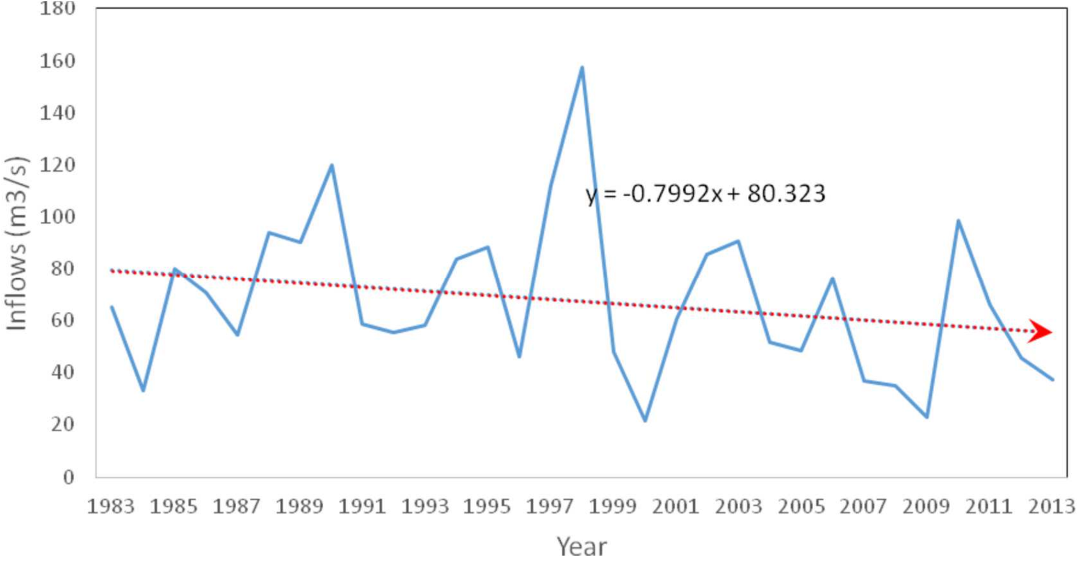


Figure 3.3: Masinga reservoir inflows

Masinga is the largest reservoir of the seven forks project but has the least power output at 40 MW. The main purpose of the dam is to store water, regulate flow during dry season, and control downstream flooding of the Tana River system. Just like the catchments precipitation trends, the Masinga dam reservoir inflows indicate a declining trend. This declining trend can hugely be attributed to the decreasing stream flow in the streams contributing to the reservoir recharge. The annual average dam inflows are declining at the rate of 0.7992 annually based on the trend line equation y=-0.7992x + 80.323. This means that the reservoir inflow is declining by $0.7992m^3/s$ every year, in 30 years, the reservoir inflows have decreased by 23.98 cumecs. Based on Figure 4.8, lowest inflow rates are on the increase with the year 2000 and 2009 recording the lowest inflows of 21.4m3/s and 22.8m3/s respectively.

The highest inflow and the lowest inflow have occurred in the last two decades, in 1998 and 2009 respectively, this indicates an increase in extreme weather events like droughts and floods. During the 30-year period recording the lowest inflows on record at 22.8 m^3 (a year that Masinga plant operation was halted and the reservoir water levels declined to worrying levels). The major cause of variations in inflow is the alternating scarce and abundant rainfall pattern, high evapotranspiration rates and increasing catchment temperatures. Reduction in reservoir inflows unswervingly threatens the operation of the Seven Forks Project, because Masinga reservoir plays regulatory functions for subsequent dams and sediment trapping as a more recent function.

Masinga dam reservoir levels

Daily dam reservoir levels were collected from the Kenya Power Generating company (KENGEN) for the period 1990 to 2013. From the obtained data, the mean annual reservoir levels are about 1054m a.s.l. At this level, the dam operates at its optimum capacity. The minimum water level required for power generation is 1035m a.s.l (Saenyi, 2002). In general, the reservoir levels fluctuate between 1057.56m a.s.l which is the highest level to 1035m a.s.l. The water level, however, dropped to its lowest value ever recorded, 1018.68m a.s.l. in 1999/2000 due to a severe drought Figure 3.4.

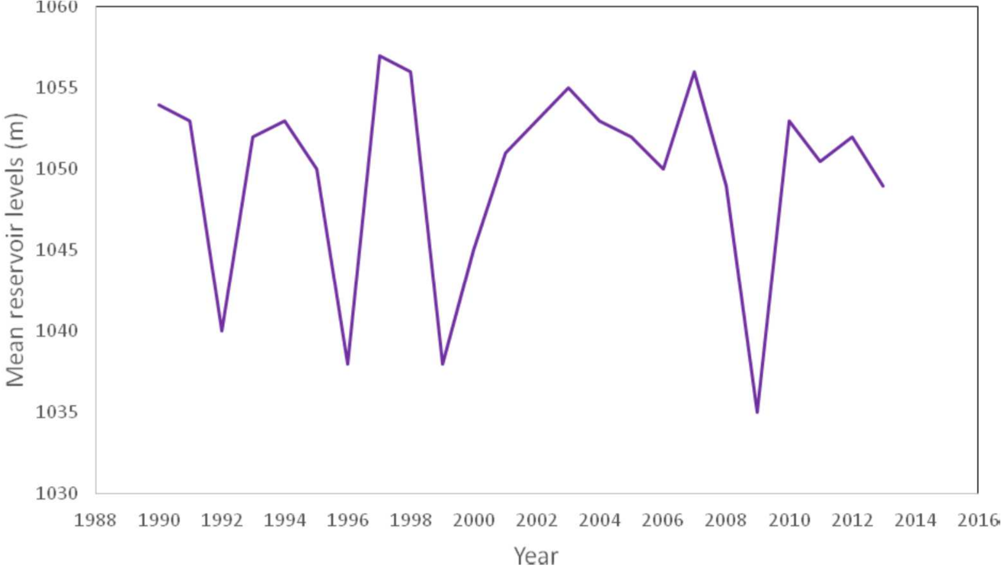


Figure 3.4: Masinga dam reservoir levels

High dam levels result of higher dam head efficiency and therefore less water is required for generating a single unit of energy. The higher the dam levels the greater the reservoir's surface area and thus higher water storage capacity. Subsequently, any drop in the dam levels adversely affect power generation especially during dry seasons where inflows are minimal. A decline in stream flow in the Masinga catchment located in the upper Tana river catchment have resulted to reduced inflows into the Masinga dam reservoir over the 30-year study period which has subsequently led to reduced reservoir levels. As shown in Figure 3.5, the years with the lowest dam inflows also exhibited lowest dam levels.

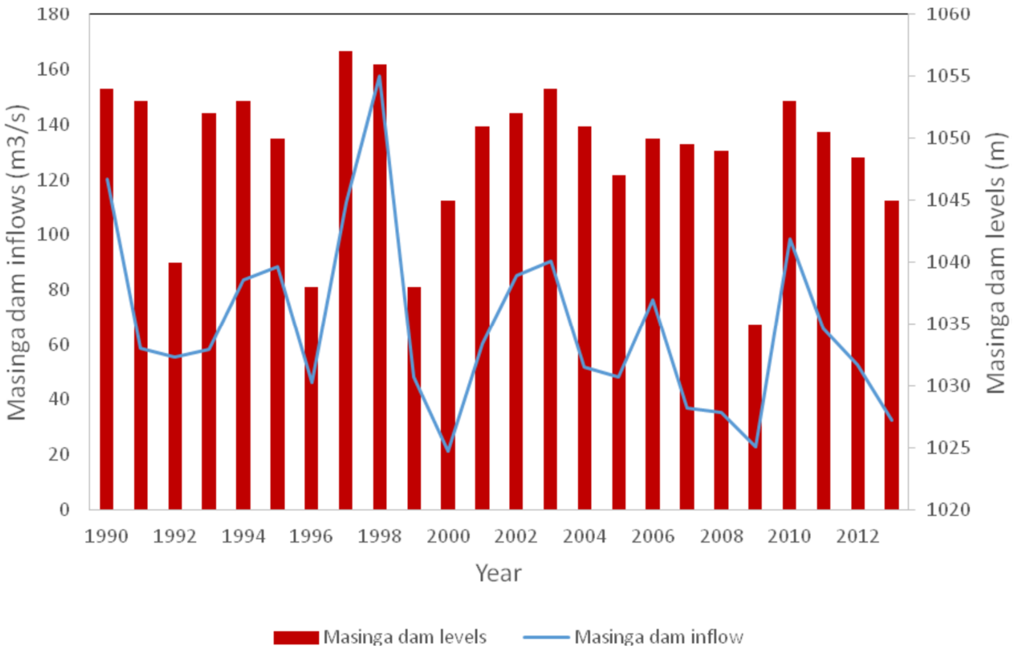


Figure 3.5: Relationship between dam inflows and water levels

Water is essential for hydropower generation; therefore a decrease in dam water levels will directly have an impact on the power output. Masinga dam is important in the seven folks project because it acts as a regulator of water inflows into the other dams. A decrease of water levels in the Masinga dam will therefore be reflected on all the other hydropower generating dams downstream Tana river. Figure 3.5 illustrates the trend of hydropower generation from the seven forks scheme. There has been a decreasing trend in the amount of hydropower produced in the scheme from 1990 to 2010, as shown in the graph. The driest years, which were 1999-2000 and 2009 recorded the lowest levels of hydropower generation. The hydropower generation was even halted for some months in those years because the dam levels declined below the threshold values. The figure also depicts a clear correlation between stream flow, dam water levels and hydropower generation.

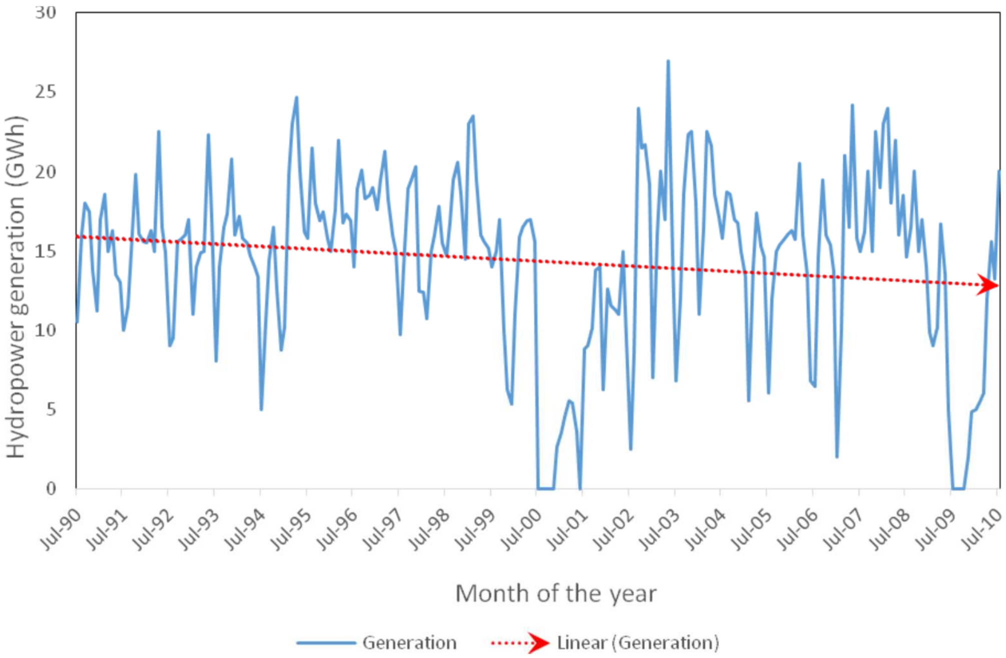


Figure 3.6: Hydro-power generation trend in the seven forks dams

Climate change effects on water resources and subsequently hydropower generation presents an intricate relationship which requires incised analysis to affirm the extent of climate change related events on sustainability of hydropower resources as a significantly reliable source of renewable energy in Kenya (Bunyasi, 2012). Decreasing amounts of precipitation and increasing temperatures have led to declining Masinga dam inflow rates as shown in Figure 3.6 which has led to decreasing hydropower generation over the years. Increasing temperatures will also stress the catchments floral biodiversity which may leave the soil bare and therefore susceptible to agents of erosion. Increased erosion rates in the catchment will lead to sediment deposition in the dams thereby reducing the reservoirs storage volume and also reducing overall dam operation efficiency. Extreme climatic events like droughts and floods have also been experienced in the catchment with two major dry periods in 2000/2001 and 2009/2010. Occurrence of extreme climatic events threatens the sustainability and operation of hydropower generating structures. Figure 3.7 shows the relationship between annual reservoir inflows in million cubic meters with the changes in the energy output in each year during the long rains in the months of April, May and June. There is a clear correlation between the amount of inflows into the dams, which can be linked to amounts of precipitation as shown above, and the changes in power generation. Although the observed reservoir inflows in 2002 and 2003 were comparatively high, the changes in energy output were not very significant. This is because these two years followed a very dry period on which the dam levels had reduced to critical levels and most of the inflow served to fill up the already depleted reservoir. This shows that occurrence of extreme climatic events, especially droughts is negatively impacting hydropower generation.

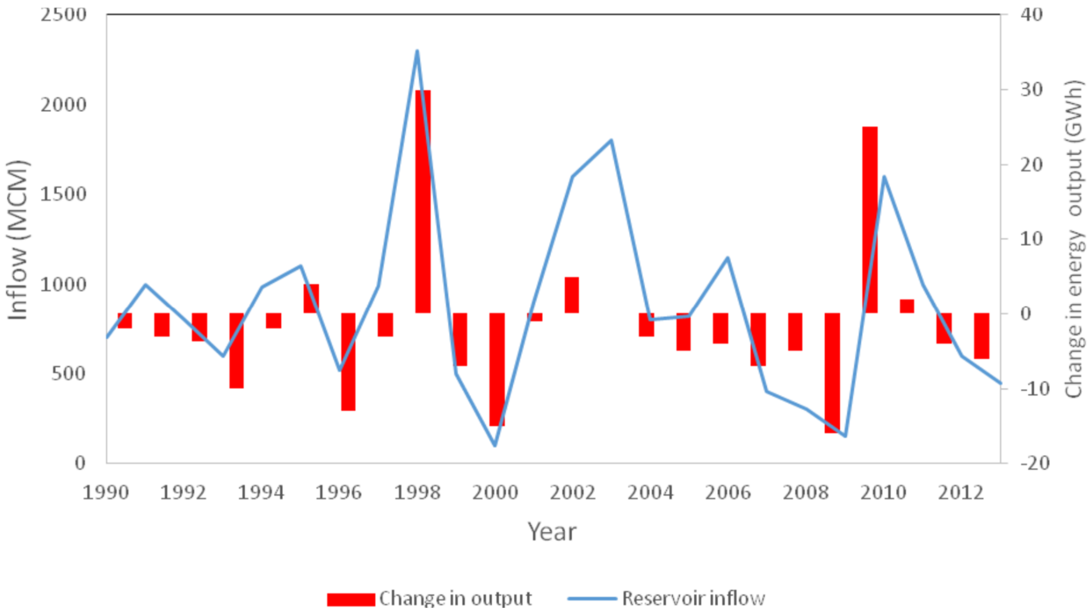


Figure 3.7: Changes in energy output relative to Masinga dam reservoir inflows

Projection of Streamflow using ArcSWAT

The ArcSWAT model database was updated to represent the expected changes in temperature and precipitation as predicted by (Gosling *et al.,* 2011). The model was then run for the reported changes in temperature and precipitation. Figure 3.8 below shows the model results for stream flow in the year 2100 compared to baseline period of 2010-2020.

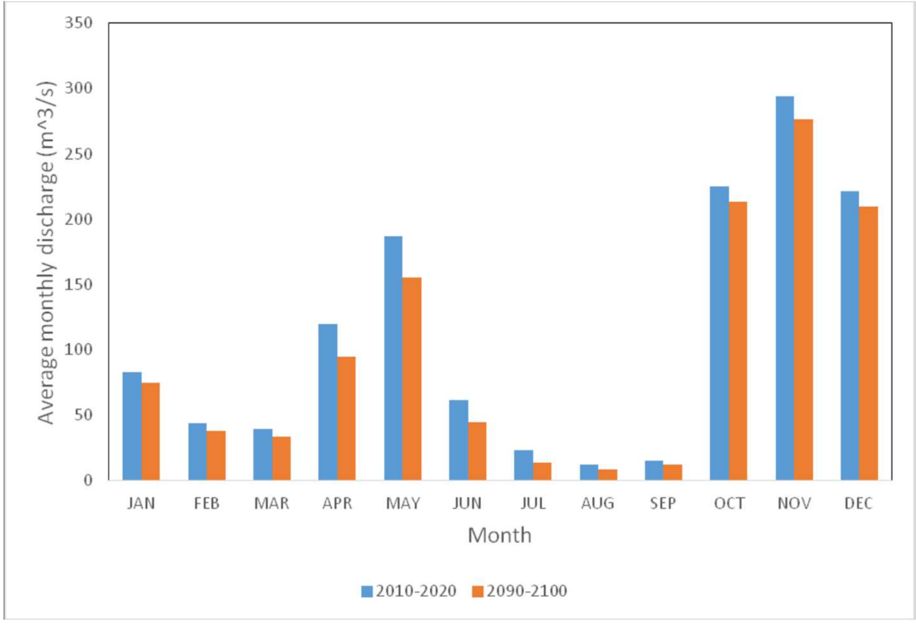


Figure 3.8: Simulated streamflow

From the Figure 3.8, a 3.5 increase in temperature will result in monthly stream flow reduction in every month of the year. The maximum flow reduction of 31.12m3/s was obtained in the month of May, with other wet months also recording major flow reductions. This shows that the climate change scenario will hugely affect the peak discharge of the Masinga dam catchment. The reduction of peak flow discharge can be attributed to the sporadic nature of precipitation together with high evaporation rates due to high temperatures. High flow changes during the wet months can be directly linked to low amounts of precipitation received in the area. The results above imply that in about a century's time, the mean monthly flow of the Masinga sub catchment will decrease by roughly 18 per cent, mostly as a result of temperature rise and changes in rainfall patterns and intensity. Reduction in stream flow directly affects the dam reservoir levels and hence hydropower generation. Hydropower generation basically relies on reservoir water level, which is directly affected by changes in streamflow upstream the dam.

With stream flow expected to continue declining in the future as a result of climate change, hydropower, one of Kenya's major supply of electricity is expected to be impacted by the declining flows. It is evident that hydropower generation from the seven forks dams has been decreasing over the years and that decrease is not expected to stop as future predictions show a further decrease in streamflow in the contributing basins. Climate change therefore remains a threat to the sustainability of hydropower generation in Kenya and in general a setback in sustainable development.

CONCLUSION

The years1999-2000 and 2009, had the lowest streamflows and lowest levels of hydro-power generation. Decreasing amounts of streamflow led to declining Masinga dam inflow rates and subsequently hydro-power generation. The findings show how the hydro-power generation is correlated to dam inflows, which in turn is linked to the amount of precipitation. Results from this study are useful in explaining the trend in hydropower generation in the basin. The projected future streamflows can be incorporated in planning of hydro-power supply in Upper Tana River basin.

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