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Response of Stream Flow peak to Climate Change in Kainji and Shiroro Hydroelectric Power Generations, Niger State, Nigeria

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Abstract

Climate changes impact hydrological processes and control stream flow at the basin scale. This study was carried out to examine the potential influence of climate change on stream flow peaks in Kainji and Shiroro Hydropower Projects, Niger State for the period 1967-2017. The study uses long term historical data on rainfall, minimum and maximum air temperature, runoff peak discharge and evapotranspiration to investigate observed hydro-climatic variability and climate change. The Mann–Kendall and Sen's slope estimator tests were used to detect monotonic trends in the hydro-climatic variables and their magnitude with MAKESENS_1_0 software. The contribution of climate changes to stream flow was revealed by climate elasticity model. The results showed an increasing trend in minimum and mean temperature, rainfall and stream flow while evapotranspiration and maximum temperature showed decreasing trend. Mean annual rainfall and runoff changes in Kainji and Shiroro showed an increasing trend that is statistically insignificant. The precipitation elasticity of stream flow was 1.0 in Shiroro and 0.99 in Kainji indicating that 1 percent change in precipitation caused a corresponding 1 percent increase in runoff and revealed that stream flow increases with increasing precipitation, whereas the evapotranspiration elasticity of stream flow is -0.12191in Kainji indicating that a 1 percent increase in potential evapotranspiration produces -0.122decrease in stream flow and -0.533 for Shiroro indicating a 1 percent increase in evapotranspiration results in 0.5 percent decrease in stream flow Peak due to rainfall events are increasing in both stations.

Keywords: Climate Change, Shiroro Hydropower Station, Kainji Hydropower Station, Mann-Kendall test, Climate elasticity and Stream Flow Peak

Introduction

Climate change is one of the significant challenges facing human development (Pilesjo and Al-Juboori, 2016). The increased concentrations of the so-called greenhouse gases in the

atmosphere are causing the air temperature to rise and this in turn is having many other effects such as changes in the rates of evapotranspiration and in the amounts and distribution of precipitation. Historical trends and observation show that the global temperature is increasing on a global scale while precipitation is experiencing a decrease or increase in many regions of the world. The IPCC (2013) states that the average global surface temperature increased by 0.85°C over the period 1880 to 2012. This is expected to increase by 1.4ºC to 5.8ºC by 2100 relative to 1990 and globally averaged sea level is projected to rise by 0.09 to 0.88m by 2100. Renewable energy offers a mitigation measure for climate change since it releases lower carbon dioxide than fossil fuel and can be replenished (Kumar, Schei, Ahenkorah, Rodriguez, Devernay, Freitas, Hall, Killingtveit and Liu, 2011). Hamududu and Killingtveit (2012) and Berga (2016) projected hydropower as the leading renewable source for electricity generation globally accounting for 16.4 percent of global electricity production in 2016 and 86 percent of global renewable energy production (Hamududu and Killingtveit, 2012; 2017; IEA, 2017). In 2010, hydropower was generated in 150 countries. Figures published by International Energy Association (IEA), International Hydropower Association (IHA) and World Watch Institute and Kumar (2012) showed that the global hydropower generation has increased by 50 percent since 1990. In 2008, the generation of electricity from hydroelectric plants was 3,288 TW-h/year (11.8 EJ) compared to 1,295 TW-h/year (4.7 EJ) in 1973 (IEA, 2010), which represented an increase of roughly 25 percent in this period. The worldwide installed hydropower capacity reached 985 GW in 2012 and 1267 GW in 2017. World Economic Council (2016) observed that the total installed capacity has grown by 39 percent from 2005 to 2015, with an average growth rate of nearly 4 percent per year. Installed hydropower capacity is projected to reach 1,947 GW by 2050, i.e., about double current levels (IEA 2012). Hydropower generation will almost double to 7,100 TWh per year. Hydropower generations are vulnerable to climate

change, The production and use of electricity from hydropower depends on stream flow which is greatly influenced by weather in a great variety (Beniston et al., 2013).

Nigerian's hydropower potential is high and hydropower currently accounts for about 32 percent of the total installed commercial electric power capacity. In 2018, the total installed energy capacity in Nigeria is 12,522 MW, of which 2,062 MW is hydropower (IHA, 2018). The total exploitable potential of hydropower is estimated at over 14,120 MW, amounting to more than 50,800 GWh of electricity annually. Despite this huge potential, only about forty-five percent of the population of over one hundred and ninety-four million has access to electricity. The roughly 85 per cent of hydropower yet to be developed therefore offers solutions to address existing power shortages. (IHA, 2018; UNIDO, 2019). Nigeria's power sector is heavily dependent on hydropower, which accounts for approximately 30 percent of its installed capacity (National Bureau of Statistics, 2021). The three major hydropower plants in Nigeria are Kainji, Jebba, and Shiroro (NERC, 2021). Unfortunately, the Nigerian hydropower has been challenged with hydrological shortfalls (Anieheobi, 2008). Olofintoye and Adeyemo (2011); Adegbihin, Yusuf, Iguisi and Zubairu (2016) observed that the reservoir inflow pattern showed a decreasing trend and this could be attributed to climate change. Gradual alterations in precipitation patterns are affecting the resource base of hydropower, thereby leading to changes in the volume and timing of water availability. In the right of this, this study was conducted to evaluate the response of stream flow peak to climate change.

2. Materials and Methods

2.1 Study Area

The study covers the Shiroro and Kainji hydropower projects. The Shiroro Hydropower Project is a 600MW hydropower project located on latitude $9^{0}57^{1}25^{11}1$N and longitude $6^{0}49^{1}55^{11}$E (Figure 1). It is located on the Shiroro Gorge on the Kaduna River in Niger State, Nigeria. The project was commissioned in 1989 and began operation in 1990. The climate of the area is

tropical continental with mean annual rainfall of about 1205 mm. The area has two major seasons. The rainy season starts from April to October while the dry season lasts from November to March with about 110 days length of growing season. The mean annual temperature is about 27°c. The North-South Power Company Limited is the concessionaire of the hydropower project after agreement with the Federal Government in 2012 to and became operational in 2013.

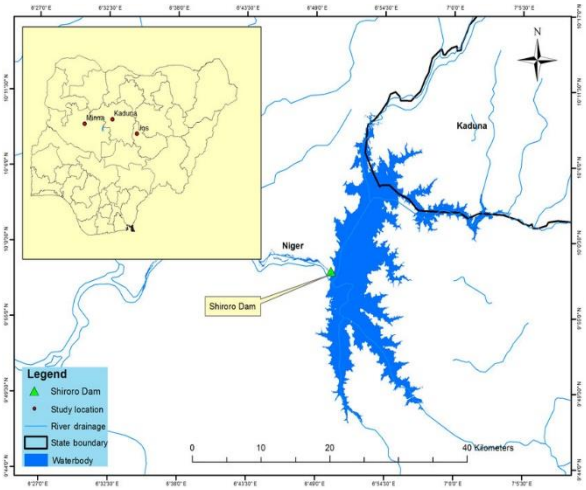

Figure 1: Map of Nigeria and Shiroro Local Government Area showing Shiroro Dam

The Kainji hydropower dam is located in Borgu LGA of Niger State, Nigeria (Figure 2). The Kainji Hydropower Station was acquired by Mainstream Energy Solutions Limited (MESL) who specializes in hydroelectric power generation. The company is the concessionaire of the Kainji Hydroelectric Company, comprising the Kainji Hydroelectric plant with a total installed capacity of 760 MW of electricity. The climate is described as tropical continental with high maximum temperatures and an average daily maximum of 33.5 ^{0}C in the warmest month while the mean annual temperature is about 30 ^{0}C.

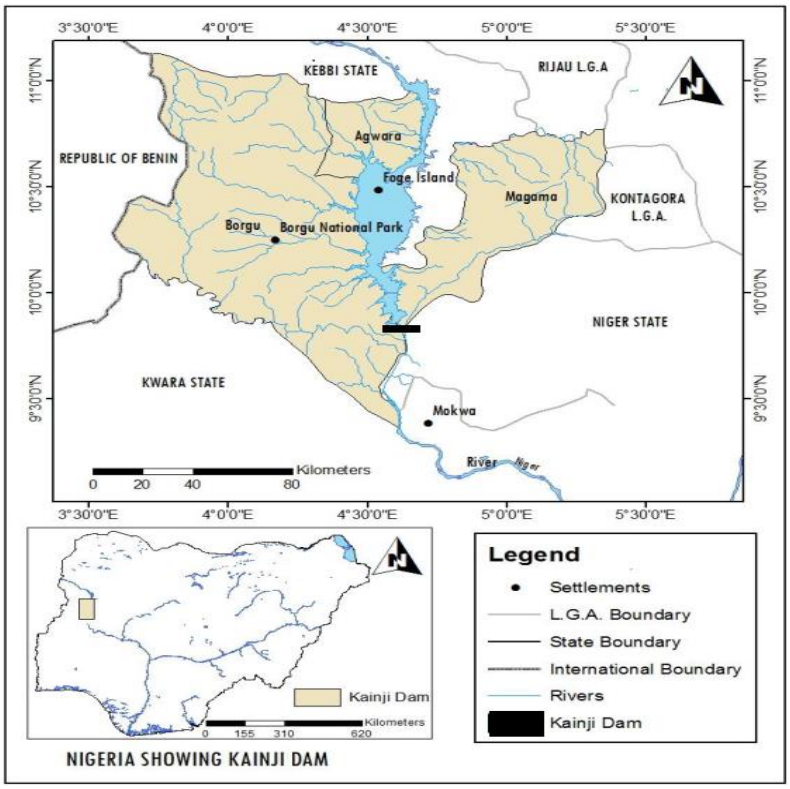

Figure 2: Map of Borgu Local Government Area showing Kainji Dam

2.2 Methods

The data required for the research include a 51-year hydro-climatological data from Kainji and Shiroro hydropower stations. The data include mean monthly minimum and maximum air temperature, rainfall, evapotranspiration and runoff peak discharge for Shiroro and Kainji hydropower stations from 1967 to 2017. The data was collected from Nigeria Meteorological Agency (NIMET) Data Management Unit, Abuja. The changes in the annual hydro-climatological data values at the study area were investigated using trend and climate elasticity of stream flow to identify the cause and consequence of a shift in climate pattern. These are valuable tools for evaluating climate change (Dani and Pal (2017; (Auffhammer et al., 2011).

2.2.1 Trend analysis

The non-parametric Mann–Kendall test was applied to detect the trend and significance of the hydro-climatic variables in Kainji and Shiroro hydropower dams. The trends were analyzed on an annual and location basis. Sen's slope test was applied to detect the magnitude of increase

or decrease of the trend of climatic variables over the period for this study. The Mann-Kendall test statistic S is calculated using the formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1} \text{sign } (xj - xk) \quad \ldots\ldots\ldots\

Where ΔQ represents the stream flow runoff Q the (millimeters), while ΔX represents the dominant climate factors on the hydrological cycle (the precipitation and potential evapotranspiration) and $\bar{Q}$ and $\bar{X}$ are the mean of both variables. Sankarasubramanian et al. (2001) introduced the non-parametric estimator, expressed as:

$$\epsilon_p = Median\left(\frac{Q_t - \bar{Q}\bar{P}}{P_t - \bar{P}\bar{Q}}\right) \text{ ---------- (6)}$$

Where εp is a climate elasticity, $\bar{P}$and $\bar{Q}$ are mean annual precipitation and stream flow for the whole period, Pt and Qt are annual precipitation and stream flow for the t-th year. To estimate εP, a value of $(\frac{Q_t - \overline{\bar{Q}\bar{P}}}{P_t - \bar{P}\bar{Q}})$ is calculated for each pair of P_t and Q_t in the annual time series, and the median of these values is the nonparametric estimate of εP. Chiew (2006) also showed that there is a high correlation between εP values estimated using this non-parametric estimator and modelling approaches for catchments in the USA and Australia, respectively, although the hydrological modelling approach gives slightly higher εP values, and has low bias compared to a broad range of hydrological models. The εP estimates generally range from 1.0 to 3.0, that is, a 1% change in mean annual precipitation results in a 1–3% change in mean annual stream flow. Sankarasubramanian, Vogel and Limburner, (2001); Kim, Hong and Lee (2017) used rainfall elasticity of stream flow estimate to quantify the effects of climate change on river basins in United States and Korea Republic respectively.

Results and Discussion

Trends Analysis of Hydro-Climatic Variables

A time series analysis of the hydro-climatic variables in Kainji and Shiroro reservoirs showed that the variables have fluctuated throughout the study period. The result of the Mann-Kendall trend and Sen's slope analysis on MAKESENS_1_0 software is shown in table 1.

Table 1: Mann-Kendal Trend Statistics for Kainji and Shiroro Hydropower Stations

Kainji Hydropower Station

Time series	First year	Last Year	n	Test Z	Signific.	Q
Mean R	*1967*	*2017*	*51*	0.88		1.543
ET	*1967*	*2017*	*51*	-3.02	**	-0.075
Min T	*1967*	*2017*	*51*	4.73	***	0.021
Max T	*1967*	*2017*	*51*	-0.49		-0.002
Mean T	*1967*	*2017*	*51*	3.34	***	0.011
QMax	*1967*	*2017*	*51*	2.41	*	1.350

Shiroro Hydropower STATION

Time series	First year	Last Year	n	Test Z	Signific.	Sen's slope estimate Q
Max T	*1967*	*2017*	*51*	5.16	***	0.022
Min T	*1967*	*2017*	*51*	3.62	***	0.013
Mean R	*1967*	*2017*	*51*	0.21		0.048
Qmax	*1967*	*2017*	*51*	0.21		0.006
ET	*1967*	*2017*	*51*	0.00		0.000
Mean T	*1967*	*2017*	*51*	5.06	***	0.018

**Max T=Maximum temperature; Min T = Minimum temperature; Mean T = mean temperature; Mean R= mean annual rainfall; Sum R = total annual rainfall; ET = evaporation; mean Qmax = mean annual runoff peak*

Trend of Temperature

The result of the Mann-Kendall trend analysis indicates that temperature has been increasing in Kainji. The analysis indicates that minimum temperature has increased with a Sen's slope of 1.543. The value of Z is 4.73 (greater than $Z_{0.025}$) where with $Z_{0.025} = 1.96$ at 5 % level of significance; maximum temperature decreased with Z score of -0.49 and a Sen's slope of -0.002 that is not significant at 5 percent while the mean temperature increased with a Z score of 3.34 and a Sen's slope of 0.11 and is statistically significant. This indicates that the minimum and mean temperature has been increasing at the rate of 0.1^0 C per year and 1^0 C per decade. This increases due to climate change. An increase in mean temperature is capable of increasing evaporation rate and precipitation which might lead to flooding thereby causing destruction and break down of equipment required for electricity generation. In Shiroro, the MK test indicate that minimum temperature has increased with a Sen's slope of 3.62 which is greater than $Z_{0.025}$) at 1 %, which makes it statistically significant. The maximum temperature showed an increasing trend with Z score of and 5.16 and a Sen's slope of 0.022 that is significant at 5 percent while the mean temperature increased with a Z score of 5.06 and a Sen's slope of 0.18 that is statistically significant. This indicates that the increase in temperature is significant with mean temperature increasing at the rate of 0.02^0 C per year and 0.2^0 C per decade. The result

is supported by the findings of Olofintoye and Adeyemo (2011) and Salami, Sule and Okeola (2011).

Trend of Mean Annual Rainfall

The Mann-Kendall trend analysis for Kainji indicates that rainfall has increased with a Sen's slope of 1.543. The value of Z is 0.88 (less than $Z_{0.025}$) where with $Z_{0.025} = 1.96$ at 5 percent, which makes it statistically insignificant, indicating that the increase in rainfall may not be noticeable. The result also indicates that rainfall has been increasing at the rate of 1.5 mm per year and 15 mm per decade. In Shiroro, the mean annual rainfall has increased with a Sen's slope of 0.048. The Z-score is 0.21 and is less than $Z_{0.025}$ ($Z_{0.025} = 1.96$ at 5 percent) which makes it statistically insignificant, indicating that the increase in rainfall amount may not be noticeable. The result also indicates that rainfall has been increasing at the rate of 5.73 mm per year and 57.3 mm per decade. The result is supported by the findings of Olofintoye and Adeyemo (2011) and Salami, Sule and Okeola (2011). The MK trend test has been carried out for various hydrological components such as rainfall and stream flow analysis (Oguntunde et al. 2000; Oguntunde et. al.2012; Kumar et al. 2000).

Trend of Evapotranspiration

The Mann-Kendall trend analysis in Kainji indicates that evapotranspiration has decreased. The value of Z is -3.02 (greater than $Z_{0.025}$) where with $Z_{0.025} = 1.96$ at 1 percent, which makes it statistically significant, indicating that the decrease in evapotranspiration is significant with a Sen's slope of -0. 075. This indicates that evapotranspiration has declined by 0.075 mm/year and 0.75 mm per decade. In Shiroro, there is no significant increase in evapotranspiration.

Trend of Runoff Peak Discharge

The Mann-Kendall trend analysis also indicates that runoff has increased. The value of Z is 0.86 (less than $Z_{0.025}$) where with $Z_{0.025} = 1.96$ at 5 percent, which makes it statistically insignificant, indicating that the increase in runoff is not significant with a Sen's slope of 0.412. Annual river discharge has increased by 0.412 m^3/s per year and 4.12 m^3/s per decade. The Mann-Kendall trend analysis for Shiroro indicates that runoff has increased. The value of Z is 0.21 (less than $Z_{0.025}$) where with $Z_{0.025} = 1.96$ at 5 percent with a Sen's slope of 0.006 is statistically insignificant, indicating that the increase in runoff is not significant indicating that river discharge has increased by 0.006 m^3/s per year and 0.06 $m^3/$ decade. The result is

supported by the findings of Olofintoye and Adeyemo (2011) and Salami, Sule and Okeola (2011). The result of the trend analysis of mean annual runoff peak is presented in figure 3.

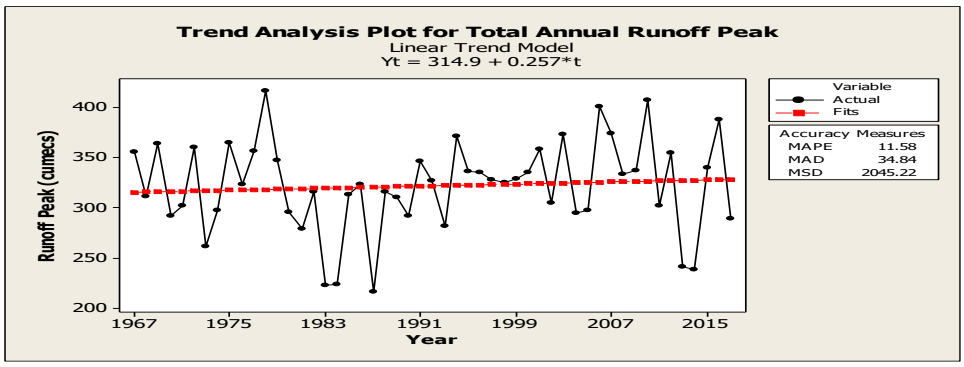

Fig 3. Trend analysis of Runoff Peak in Kainji Hydropower Station from1967 to 2017

The potential causes of the significant trends in runoff were investigated through a correlation analysis with climatic variables to determine whether the trends in stream flows are attributable to climate change/variability (Burn and Hag-Elnur, 2002); Masih, Uhlenbrook, Maskey and Smakhtin, 2009). The correlation between rainfall amount and runoff peak indicates a perfect positive significant relationship between rainfall and runoff peak which implies that an increase in rainfall lead to an increase in runoff peak. Evapotranspiration, minimum, maximum and mean temperature have no significant relationship with rainfall and runoff peak at 0.05 level of significance as the correlation between them is -0.029, -0.083, -0.125 and -0.132 respectively. These findings are in agreement with Jimoh (2008).

Climate Elasticity of Runoff Peak Discharge

The result of the elasticity analysis of runoff elasticity to rainfall and evapotranspiration indicates that the runoff elasticity of rainfall in Kainji is 0.99 which implies that a 10 percent change in rainfall leads to 9.9 percent change in runoff while the runoff elasticity of evapotranspiration was -0.36. This indicates that a 10 per cent change in evapotranspiration leads to decrease of about 3.6 percent in runoff. In Shiroro, the evapotranspiration and precipitation elasticity of stream flow is -0.5 and 1.0 respectively.

Discussion

This study investigated the effects of climate change on runoff in Kainji and Shiroro Hydropower Stations, Niger State from 1967 to 2017. Investigation was conducted using data on rainfall, temperature, evapotranspiration and runoff peak discharge. The result of the research indicated a significant increase of minimum, maximum and mean temperature as well as evapotranspiration in Kainji. Analysis of monthly mean annual rainfall and pattern as well as runoff peak showed increase over the area as a result of changes in climate. The result of the climate elasticity of runoff indicates that rainfall has a positive effect while evapotranspiration has a negative effect on runoff. The Kainji hydropower station has experienced stronger trends and larger peaks than Shiroro. In general, an increase in mean annual stream flow peak in Kainji and Shiroro would be welcome for hydropower generation. This is consistent with the report by Mainstream Energy Limited which shows that Nigeria is witnessing an increase in hydropower generation in recent times (Daily Trust, 2017). According to the publication, over 150MW of electricity is stranded in Kainji Hydropower Station.

Conclusion

The result of trend analysis on climate variables showed that temperature exhibited a statistically significant increasing trend in the area, indicating climate change. Rainfall and runoff showed a statistically insignificant increase. Climate change has led to an increase in temperature of the study area which resulted in an increase in the annual and mean amount of rainfall and runoff. The increase in rainfall also caused an increase in runoff which is necessary for hydropower generation.

Recommendations.

The study reveals that Kainji and Shiroro Hydropower Stations reservoir experience inflow throughout the year. Thus, Nigeria will certainly benefit from the increase in runoff, if the government can increase the water carrying capacity of the reservoir or probably finds a means of storing water, electricity output in the periods of low inflow will increase, as their will be an enough water to produce electricity. The changes in seasonal and inter-annual variability of rainfall can be compensated by improving short term water flow forecasts, building additional storage capacity and enhance turbine capacity efficiency.

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