Vol. 40(1), pp. 50-61, June 2021
ISSN 1821-536X (print)
ISSN 2619-8789 (electronic)

Tanzania Journal of Engineering and Technology

Full Length Research Paper

Assessment of the Impacts of Climate Variability on Hydropower Generation: A case study of the New Pangani Falls, Tanzania

Dativa Byarufu[1*], Jamidu Katima[2], Mahir Said[1]

[1]Department of Chemical and Mining Engineering, University of Dar es Salaam, Tanzania
[2]Kampala International University in Tanzania, Dar es Salaam, Tanzania
*Corresponding Author: dativabonny@yahoo.com

ABSTRACT

Climate change poses potential impacts on hydropower generation either positively by increasing or negatively by decreasing river flow. This study assessed the impacts of climate variability on hydropower with a focus on the New Pangani Falls in Tanzania. Rainfall and temperature time series data from 1980-2014 were analyzed in relation to river discharge and associated impacts to hydropower generation. The Man-Kendall test was used to detect trend in both annual and seasonal time series. The results showed a negative trend in annual rainfall with $Z= -2.41$ at $\alpha = 0.05$ and the slope $Q = -0.964$. Seasonal trend analysis showed that the amount of rainfall received during both dry and wet seasons has been decreasing. Positive trend was observed in both average annual maximum and minimum temperature series at $\alpha = 0.1$ with $Z = 1.73$ and $\alpha = 0.001$ with $Z= 4.04$, respectively and a positive slope for both. Analysis of regime shift at a 5% significant level showed that, rainfall in the New Pangani falls from 1980 to 2014 experienced two decreasing shifts both occurring in the last 15 years of analysis with a percentage of change of more than 10%. This strongly confirms climate variability in the study area. The study shows that hydropower generation depends strongly on the river inflow to the dam ($r = 0.98$) while changes in temperature do not affect the functioning of the hydropower plant as depicted by the weak linear relationship between temperature, rainfall ($r = 0.085$) and power generation ($r = -0.082$). It can be concluded, therefore, that river discharge variability in catchment has an adverse impact on hydropower generation in hydropower plant.

Keywords: *Climate variability, Hydropower generation, New Pangani Falls, Man-Kendall test, Rainfall.*

INTRODUCTION

The world's largest source of renewable energy is hydropower. The World Energy Council (2010) estimated that about 160 countries in the world use hydropower to generate electricity. This is due to the fact that investment in hydropower is cost effective requiring high initial investment but with good maintenance the cost can be as low as 3-5 US cents per kWh (IRENA, 2012) . However, its total contribution to the world energy supply is still low contributing only 16% of the primary global energy supply in 2009 (Kaunda *et al.*, 2012). This is mainly due to underdevelopment especially in Africa where only 8% of its potential hydropower potential is utilized (U.S. Energy Information Administration, 2017). Hydropower is also widely used, because it plays an important role in climate change mitigation (Hoegh-Guldberg, 2010). It is predicted that climate change will have severe impacts to human society in many aspects including agriculture and food production, water supply and energy (Obahoundje *et al*., 2017). The United Nations Conference on Trade and Development (UNCTAD) declared that Climate Change continues to rank high on the international policy agenda in both developed and developing countries (UNCTAD, 2013).

The main technique for avoiding the worst extremes of climate change is to limit the increase in greenhouse gas concentrations in the atmosphere by reducing emissions. As electricity production from fossil non-renewable sources such as fossil fuels is responsible for a significant portion of the greenhouse gas emissions, much of the world efforts to minimise GHG emission focus on the energy sector. Possible measures include increasing reliance on renewable energy sources, including hydropower, to mitigate GHG emissions from fossil fuels (Harrison *et al*., 1998).

Hydropower Generation in Tanzania

Hydropower is a major renewable source of electricity in Tanzania. Not only is it useful in electricity production, but also has benefits in water management for other socio-economical activities. Dams and reservoirs in hydropower plants provide fresh water storage for fishing, water supply and irrigation schemes. With increasing population and drive for industrialization, Tanzania needs sustainable energy solutions. Hydropower has been singled out as a major solution for the energy crisis in the country (Kichonge, 2018). In 2002, 55% of the total energy supplied in the country came from hydropower (Ministry of Energy and Minerals, 2013). However, in 2003, Tanzania experienced significantly reduced precipitation, consequently river flows reduced by one third of the average flow experienced over the past 25 years (World Bank, 2007). This occurrence had significant adverse effect on Tanzania’s hydropower generation. The country experienced frequent load shedding as a result. This forced Tanzania to switch to fossil fuel based power sources mainly from independent power producers.. The incremental cost of power generation due to drought was about 67 million US dollars from January 2004 to February 2005 (Ibid). It was also reported two years later that rationing due to shortage of electricity for supply caused huge loss in a number of sectors estimated to be $1.7 million per day (World Bank, 2007). Currently, hydropower contributes 45% of the total electricity supplied in the country, where 80% of this is generated from Rufiji Basin and the rest is produced from other basins including the Pangani River Basin in the northern Tanzania (Kichonge, 2018).

Water levels in hydropower dams have been fluctuating in recent years. There has been an increase in flooding as well as drought in some parts of Tanzania, which have negative impacts in the operation efficiency and generation of hydroelectricity. This problem is projected to continue for a long time due to current climate variability trend in the country. Pangani basin is the second largest basin in Tanzania and it has three operating hydropower plants, Nyumba ya Mungu, Hale and the New Pangani Falls. Hydrological and climatic studies conducted for the period between 1940 to 1979 on the simulation of firm power production showed that the Pangani River was more reliable than the Great Ruaha River for sustainable power supply (IUCN Eastern and Sounthern africa Programme, 2009). However, due to climate change and competing water uses, hydropower plants in the Basin do not function to their highest design potential (Andersson *et al*., 2006).

New Pangani falls was designed with the capacity to produce 68 MW which is 12.12% of the total hydropower supplied in the country. The plant started operation in 1994 (Andersson *et al*., 2006; FAO, 1969). In the first ten years of its operation, the plant's production capacity showed variations, the lowest being 53.15% of its annual average generation design (PBWB/IUCN, 2009).

The production of hydropower depends strongly on the hydrological circumstances. Although there are researches conducted on the impacts of climate change in the basin, most of these studies have focused on the rainfall variability of the region (Andersson *et al*., 2006; IUCN, 2011), there is no study that has looked on the impact of climate change on hydropower generation in New Pangani falls. This study provides an integrated analysis on the factors that contribute to the variability in production capacity and reduced efficiency of the New Pangani Falls power plant.

MATERIALS AND METHODS

Description of the Study Area

New Pangani Hydropower plant is part of the Pangani Hydro Systems in Tanzania. The plant is located at Koani Village in the District of Muheza, Tanga Region. It is located 12 kilometers from the Segera-Tanga highway and 8 km south of Hale Hydropower Plant (King *et al*., 2010).

The Pangani River Basin covers an area of 43,192.54 km^2, out of which 2,333.90 km^2 lies in Kenya. In Tanzania, the Basin covers four regions, Kilimanjaro, Arusha, Manyara and Tanga, as shown in Figure 1. The basin is divided into 3 major zones;

a) Upper Zone (above Nyumba ya Mungu dam);
b) Middle Zone (between Nyumba ya Mungu dam and the Pangani River/Mkomazi River confluence).
c) Lower Zone (between Pangani/Mkomazi confluences to Pangani Falls).

The plant construction begun in December 1991 and started its commercial operations in 1994 with the capacity of about four times greater than the Old Pangani Falls which by then was designed to generate 17.5 MW (Andersson *et al*., 2006; FAO, 1969).. The plant has an underground powerhouse with 1600 m^3 rock excavation (gneiss). Access to the power plant is through access and auxiliary tunnels 700 m long with a cross section area of 22-30 m^2, water from the power house is discharged through a tailrace tunnel, which is 2500 m long and has a cross section area of 40 m^2.

Data Collection

The 12-month accumulation data on precipitation, temperature and discharge for the case study were obtained from the Centre for Climate Change Studies (CCCS) at the University of Dar es Salaam and from the New Pangani Falls Hydropower plant. Data for the river flow and electricity generation were collected as shown in Table 1.

Table 1: Hydro-meteorological and Generation data collected.

Variable	Period
Rainfall (mm)	1980-2014
Temperature (^{0}C)	1980-2014
Power generation (kWh)	2007-2018
Water inflow (m^3/sec)	2007-2018
Water discharge (m^3/sec)	2007-2018
Dam water level (m.a.s.l)	2007-2018

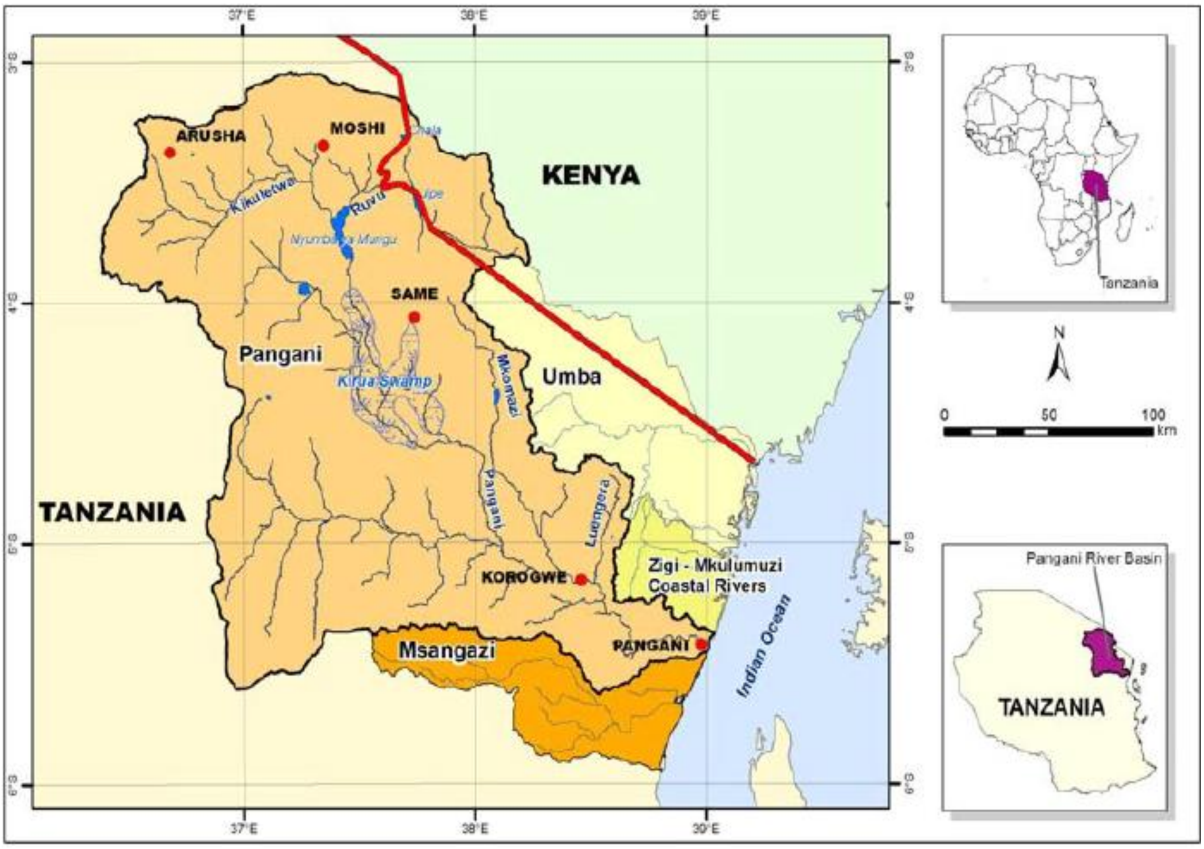

Figure 1: Pangani Basin (Andersson *et al.*, 2006)

Data Analysis

The data analysis was done by using Microsoft excel. Rainfall and temperature data analyses were done in both annual and seasonal timescales, since there dry seasons and rainy season, where the seasons were divided as:

i. October-November-December (OND) (early rainy season),
ii. January-February (JF) (mid-rainy season),
iii. March-April-May (MAM) (main rainy season), and
iv. June-July-August-September (JJAS) (dry season).

Mann–Kendall Test

Mann-Kendall test is a statistical test used in the analysis of trend in climatologic and in hydrologic time series (Helsel and Hirsch, 2002). This procedure was conducted in two phases, first the presence of monotonic increase or decrease in trend (the Mann-Kendall test) and secondly the slope of a linear trend (Sen's slope estimator). The MK test was used to analyse precipitation and temperature data under the null hypothesis (H_O) (i.e. there is no trend in the data) and the alternative hypothesis (H_1) (i.e. there is an increasing or decreasing trend over time). The mathematical computations for the MK test statistics S, Variance and the standard test statistics Z were calculated using equation (1):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(X_j - X_i \right) \qquad \ldots\ldots\ldots\ldots(1)$$

X_j and X_i are the annual data values in years j and i, such that (j > i) and where the sgn function is given in equation (2);

$$\operatorname{sgn}(Xj - Xi = 1if \begin{cases} 1if\,(Xj - Xi)\ \phi\ 0 \\ 0if\,(Xj - Xi) = 0 \\ -1if\,(Xj - Xi)\ \pi\ 0 \end{cases} . \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

The variance Var(S_{mk}) for the S-statistic is defined by equation (3):

$$Var(Smk) = \frac{N(N-1)(2N+5) - \sum_{i=1}^{m} Ui(i)(i-1)(2i+5)}{18} \quad \text{………………………….. (3)}$$

Where N is the number of tied groups and U_i is the size of the Nth group. And the standard normal test statistics Zs was computed using equation (4):

$$Z = \begin{cases} \frac{S-1}{\delta} ifS \ \phi \ 0 \\ 0 ifS = 0 \\ \frac{S+1}{\delta} ifS \ \pi \ 0 \end{cases} \quad \text{…………………….. (4)}$$

Z follows normal distribution and was used to measure the significance of trend. The negative and positive values show increase or decrease in trend (Rajabu, 2007).

Sen’s Method

To establish the magnitude of the true slope in the data the Sen’s slope estimator test was used. This non-parametric test is used when the trend can be assumed to be linear as expressed in equation (5).

$$f(t) = Qt + B \quad \text{……………………….(5)}$$

where Q is the slope and B is a constant. The slope Q in the equation (5) was obtained by first calculating the slopes of all data pairs *Qi* as shown in equation (6) where *Xj* and *Xk* are data values at time *j* and *k*.

$$Qi = \frac{Xj - Xk}{j-k} \quad \text{………...……………….. (6)}$$

The Sen’s estimator of the slope is the median of all N values of Q_i calculated was calculated using equation (7) when N is odd and equation (8) when N is even.

$$Q = T_{\frac{N+1}{2}} \quad \text{……………………………….. (7)}$$

$$Q = \frac{1}{2}\left\{T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right\} \quad \text{…………………….. (8)}$$

Positive value of Q indicates an increasing trend and a negative value of Qi indicates a decreasing trend in the time series.

Pearson Product Moment Correlation

The Pearson product moment correlation was used to uncover the relationship between weather parameters and the electricity generated, in order to observe their correlations. The correlation analysis used the formula presented in equation (9):

$$r = \frac{n(\sum(xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x)^2 - (\sum x)^2][n(\sum y^2) - (\sum y)^2]}} \quad \text{…………………………………………(9)}$$

Where: x is the independent variable, y is the dependent variable and n is the number of data pairs, r values range from -1 to 1 and show the weight of the relationship between variables.

Regime Shift Detection

The Sequential Analysis of Regime Shifts (SARS) was used, which automatically detects a statistically significant shift in the mean and the magnitude of the fluctuations in the time series. The test was performed at a significance level of 5%, Huber weight parameter at 6 and a cut-off length of 10 years, as average years for analysing climate change. Since 1980-2014 rainfall in the region experienced two shifts in the years 2000 and 2012. The results show that rainfall in the region has been decreasing with the percentage of change being more than 10%. Average temperature in Tanga experienced four shifts, the first one in 1984 was a negative shift where the temperature decreased, but the remaining three shifts show a positive shift in the average temperature as shown in Figure 2.

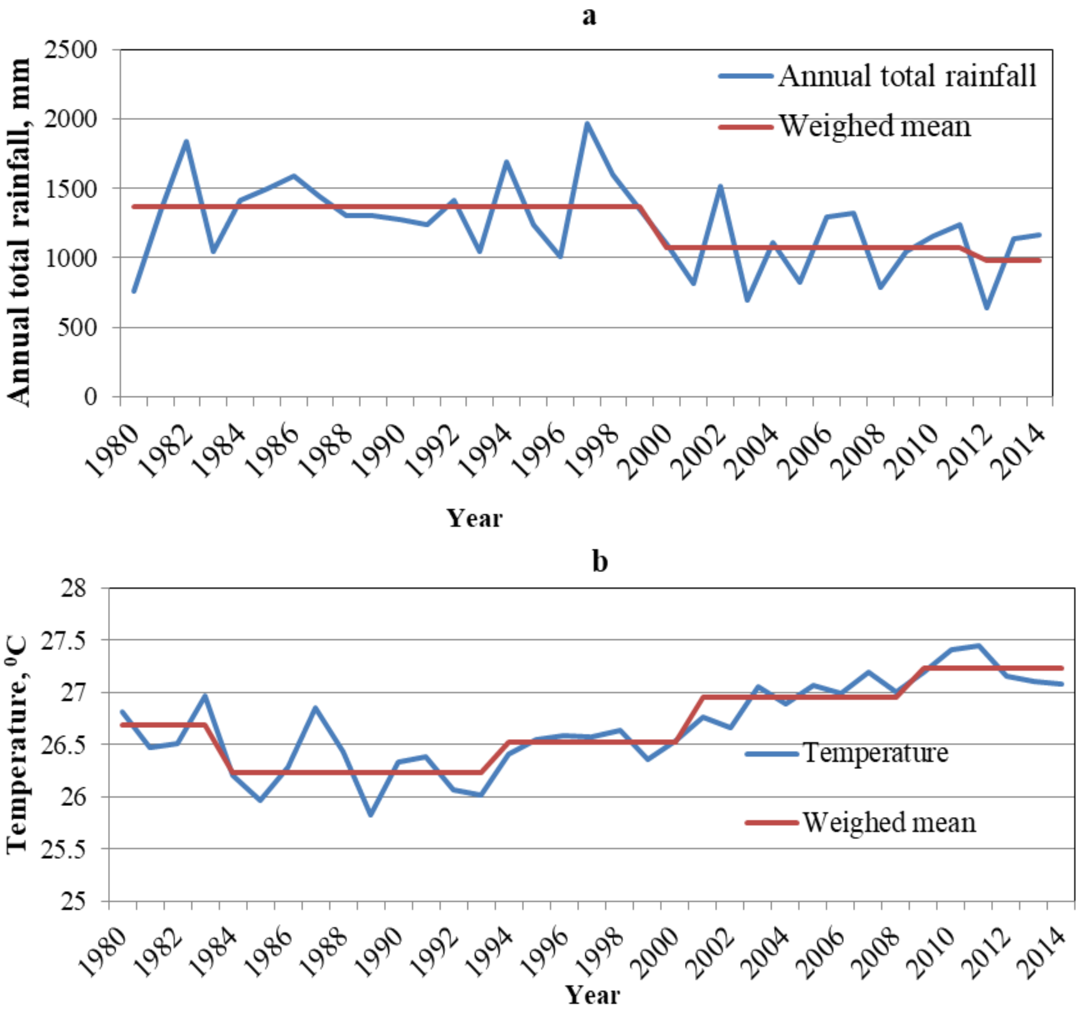

Figure 2: Regime shift in (a) Annual total rainfall (b) Temperature

Rainfall, Temperature and power generation

The study area receives bimodal type of rainfall with the main peak in March-April-May which is identified as the main rainfall season. The periods of OND and JF normally receive less rainfall and are identified as early rainy season and mid-rainy seasons, respectively (Figure 3). These seasons provide sufficient water for electricity generation. The dry season in the period of JJAS receive an average precipitating of less than 80 mm with July being the driest month in Tanga. The main rainy season (MAM) contributes about 47.1% of the annual rainfall and early rainy season of OND contributes an average of 26.9%.

Both minimum and maximum temperature regimes in the region are unimodal with peaks developing from the month of October ending in May. The average warmest month in Tanga is March with an average temperature of 33.1°C and the coldest being August with 20.4°C

Any changes in seasonal availability of rainfall especially in MAM rainfall season will have a significant impact on water level in the dam and electricity generation. Correlation coefficients between weather parameters and generation parameters are presented in Table 2. Strong positive linear relationship of 0.98 was observed between River inflow to the dam and electricity generation. This means that variability in the amount of water from Pangani River entering the dam will definitely affect the amount of electricity generated.

Temperature on the other hand is not likely to affect electricity generation and rainfall since it exhibits a weak positive and negative relationship (0.085 and -0.082) with rainfall and electricity generation, respectively. The high power generation was observed between April and June as shown in Figure 4.

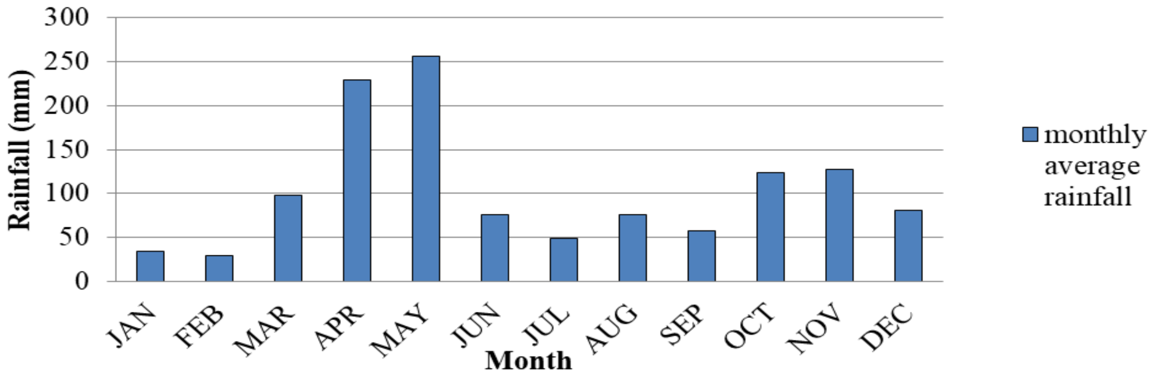

Figure 3: Monthly average rainfalls

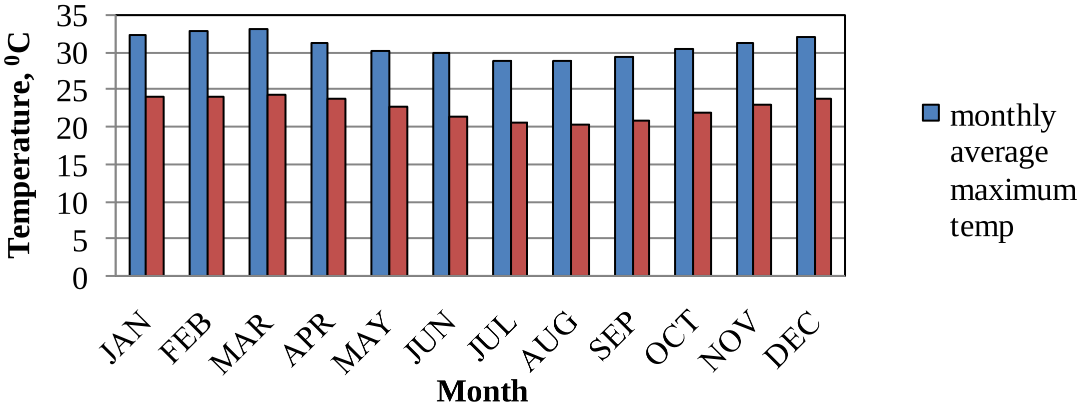

Figure 4: Monthly average Temperature variations

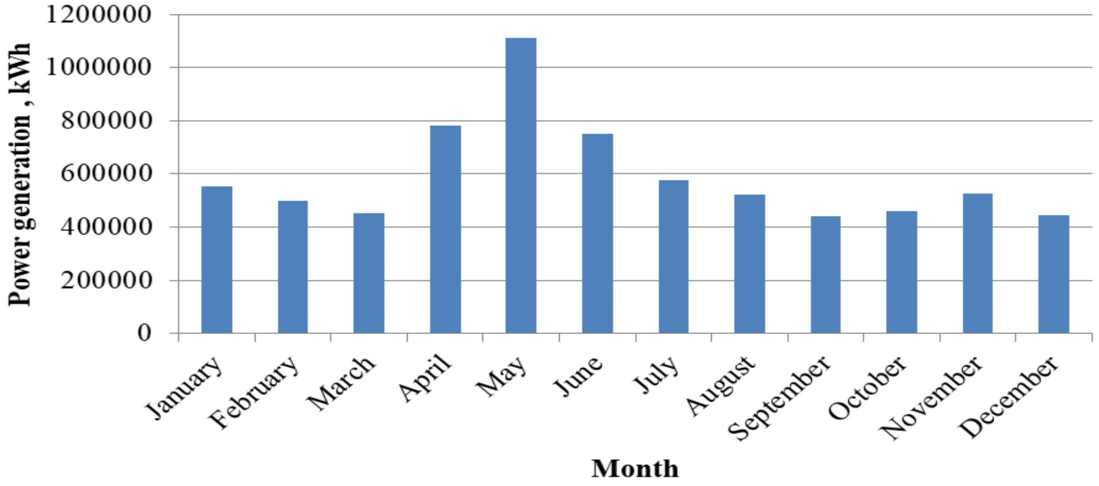

Figure 5: Monthly average power generation

Table 2: Correlation coefficients between variables

	Rainfall	Temperature	Inflow	Dam Level	Generation
Temperature	0.085				
Inflow	0.537	0.124			
Dam Level	0.671	0.252	0.938		
Power Generation	0.568	0.112	0.981	0.953	
Discharge	0.736	-0.082	0.907	0.929	0.920

Annual Trend

The annual rainfall time series shows a decreasing trend with Z= -2.41 at $\alpha = 0.05$ and the slope Q = -9.64E-01 (Figure 1a). This depicts a significant decrease in rainfall with time which has impacts to river discharge and hydropower generation. In the average annual maximum and minimum temperature series, Mann-Kendall test indicates an increasing trend at $\alpha = 0.1$ with Z = 1.73 and $\alpha = 0.001$ with Z= 4.04 respectively as shown in Figure 6 (a), (b) and (c). The Sen's slope gives positive slope for both maximum and minimum temperature. Thus, a monotonic increase is probable with both Sen's method and Mann-Kendall. This trend in both temperature and rainfall signifies a change in climate that has impacts in hydroelectricity. Further results for trend analysis are presented in Table 3.

Table 3: Seasonal trend analysis

Parameter		Z score	Significance	Slope (Q)
Rainfall	**MAM**	-2.78	**	-3.031
	JJAS	-1.62	_	-0.511
	OND	-0.34	_	-0.340
	JF	-0.28	_	-0.085
Maximum temperature	**MAM**	0.27	_	0.003
	JJAS	2.94	**	0.018
	OND	1.76	+	0.021
	JF	-1.62	_	-0.015
Minimum temperature	**MAM**	4.21	***	0.041
	JJAS	4.96	***	0.041
	OND	4.65	***	0.041
	JF	4.41	***	0.041

(*** for $\alpha = 0.001$, ** for $\alpha = 0.01$, * for $\alpha = 0.05$, + for $\alpha = 0.1$ and _for $\alpha > 0.1$)

Regime Shift Detection

Since the region expressed changes trend with Mann Kendall test, regime shift detection analysis was performed to determine the incidence and the direction of the shifts. The total annual rainfall contributing to New Pangani Falls dam has shown a decrease with time. Since 1980-2014 rainfall in the region experienced two shifts (Figure 7) in the years 2000 and 2012. The results show that rainfall in the region has been decreasing with the percentage of change being more than 10%. This unravels the possibility of climate variability in the region, which may potentially reduce the reservoir capacity hence affecting electricity generation.

Average temperature in Tanga experienced four regime shifts, the first one in 1984 was a negative shift where the temperature decreased but the remaining three shifts show a positive shift in the average temperature (Figure 8). This increase in temperature signifies the increase in evaporation and evapotranspiration in the dam reducing the dam's storage. A phenomenon related to climate variability in the area.

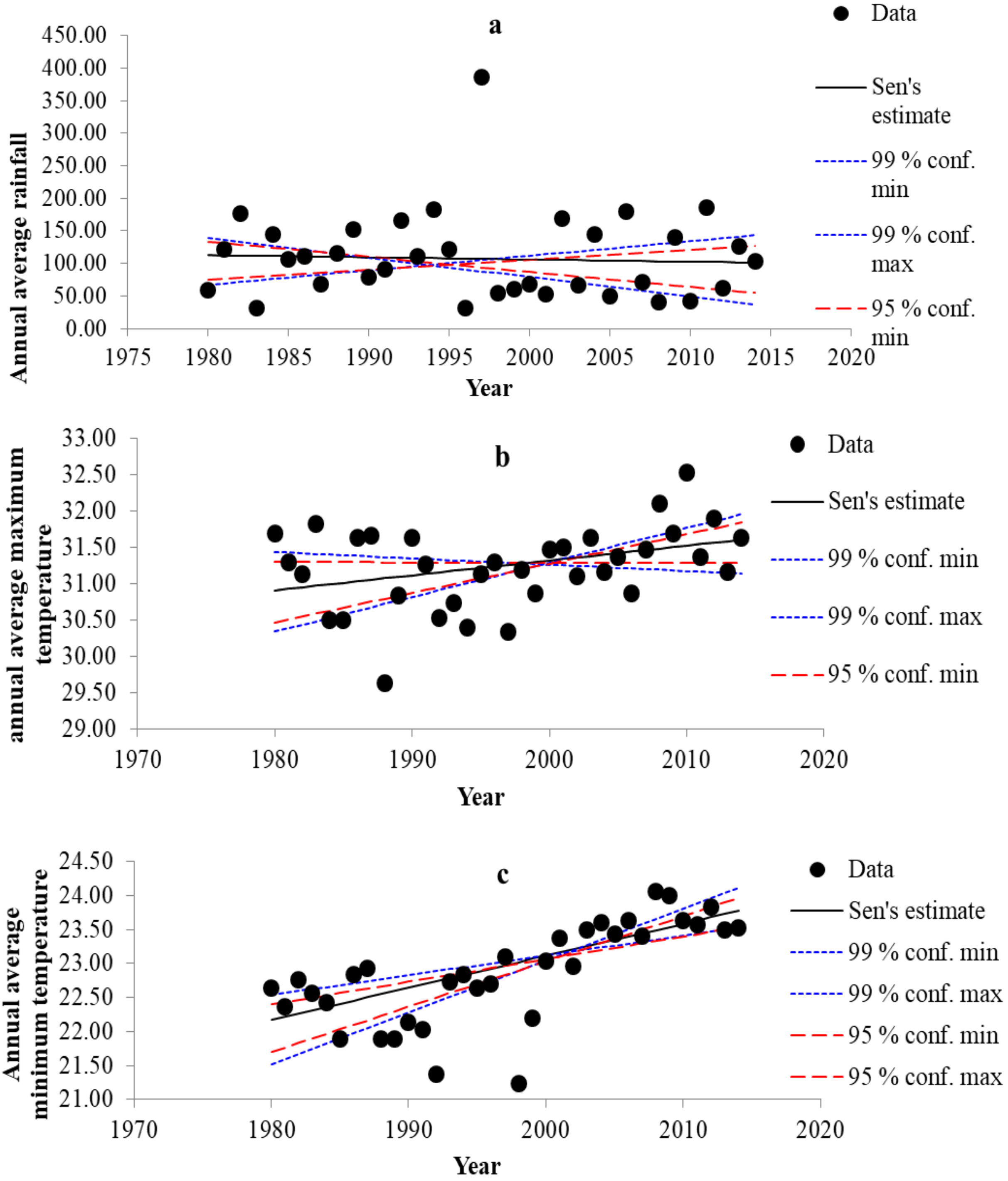

Figure 6. Average annual time series and trend statistics (a) rainfall (b) maximum temperature (c) minimum temperature in Tanga

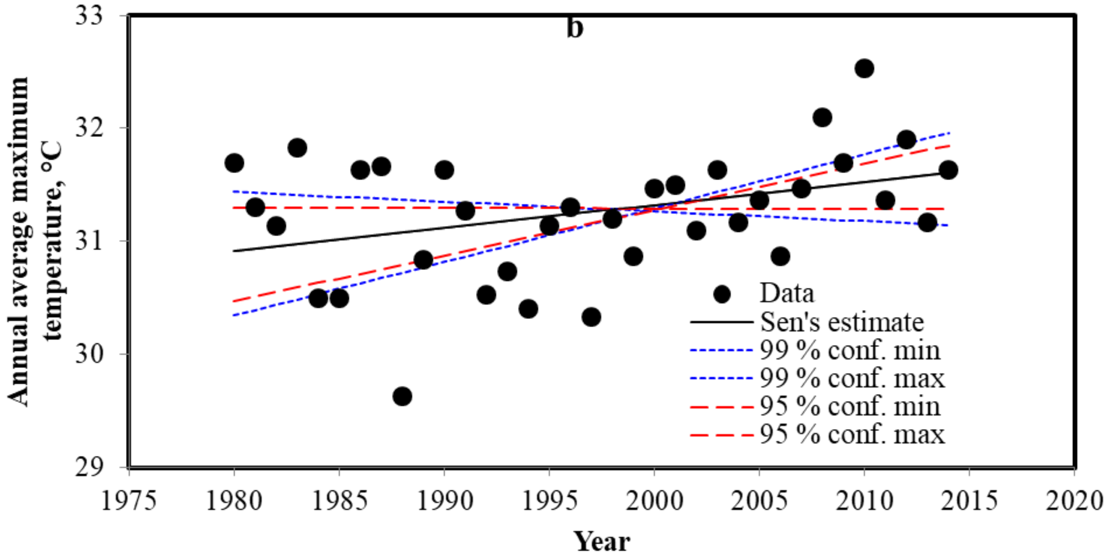

Figure 7: Annual total rainfall regime

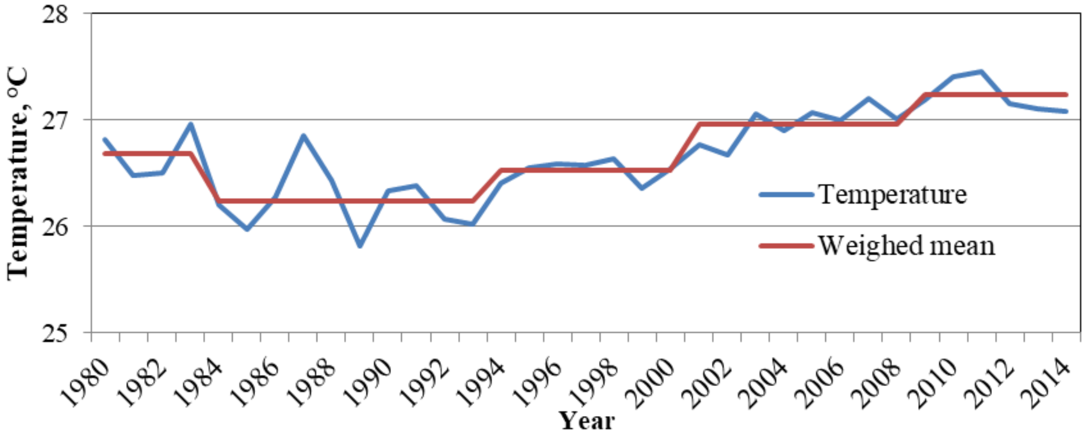

Figure 8: Average temperature regime

CONCLUSION

The study area is characterized by significant spatial and temporal variations in rainfall and temperature. Thus, it can be concluded that there is enough evidence of climate variability in the region. The MK test results for annual precipitation showed a significant negative trend at $\alpha = 0.01$ while temperature expressed a positive trend. This change has brought unfavourable climatic conditions around New Pangani Falls as revealed by decrease in rainfall during the wet seasons and increase in temperature during the warm season. These changes can lead to decreased inflow into the dam compared to the power house discharge, which may affect the dam operation due to decrease in dam storage. Decrease in rainfall and increasing in temperature, both being a sign of climate variability have negative impacts on water availability for hydropower generation.

It was observed from the 1980-2014 regime shift analysis that the region has been experiencing significant shifts (5% significance level) for both rainfall and temperature. The negative shifts were observed in rainfall, with both shifts occurring in the last fifteen of the analysed years this could serve as a warning that the region's general precipitation has been decreasing. Correlation analysis between variables showed strong positive relationship (r = 0.98) between dam inflow and electricity generation thus decrease in the river flow will due to the observed rainfall variability will reduce the plant's electricity generation.

Therefore, it is recommended for the Pangani Basin office to ensure sustainable water use in the catchment and a controlled issue and management of water obstruction permits in relation to the current climatic trend. It is essential for climatic factors to be given priority in water resource planning.

Hydropower in Tanzania is a fast growing source of electricity for both industrial and domestic supply. With construction of larger plant on the way, climate may not be the only environmental factor affecting generation. Thus adequate, detailed climatic study should be done before construction of any hydropower plant. This will provide a baseline for future studies on the impact of climate variability on power generation.

ACKNOWLEDGEMENT

We are grateful to the Center for Climate Change Studies at the University of Dar es Salaam for the financial support. Special gratitude to the staff at the University of Dar es Salaam and Pangani Hydro-system for their insight and support that greatly assisted in completion of this research and for dedicating their time and resources whenever requested.

REFERENCES

Andersson R., Wanseth F., Cuellar M. and Von Mitzlaff U. (2006). Pangani Falls Re-development Project in Tanzania. Sida Evaluation. Swedish International Development Cooperation Agency (SIDA), Stockholm (unpubl.).

FAO (1969). Survey and Plan for Irrigation Development in the Pangani and Wami River Basin. Rome.

Harrison G., Whittington H. and Gundry S. (1998). Climate change impacts on hydroelectric power. Proc Univ Power Eng Conf.

Helsel B.D.R. and Hirsch R.M. (2002). Statistical Methods in Water Resources. Retrieved from http://water.usgs.gov/pubs/twri/twri4a3/

Hoegh-Guldberg O. (2010). The Impact of Climate Change on the. Ecological Research, 1523(August), 6–10. https://doi.org/10.1126/science.1189930

IRENA (2012). Renewable Energy Technologies: Cost Analysis Series (Vol. 1). Bonn, Germany.

IUCN (2011). Pangani River system, Future of the Basin Report. Available online at http://commons.wikimedia.org/wiki/File: Panganirivermap.png Retrieved on 15th May 2021.

IUCN Eastern and Sounthern africa Programme (2009). Pangani Basin : A Situation Analysis (2nd ed.). Nairobi, Kenya: IUCN-ESARO Publications Services Unit.

Kaunda C.S., Kimambo C.Z. and Nielsen T.K. (2012). Hydropower in the Context of Sustainable Energy Supply : A Review of Hydropower in the Context of Sustainable Energy Supply: International Scholarly Research Network Renewable Energy, December, 15. https://doi.org/10.5402/2012/730631

Kichonge B. (2018). The Status and Future Prospects of Hydropower for Sustainable Water and Energy Development in Tanzania. Journal of Renewable Energy, 1–12. https://doi.org/10.1155/2018/6570358

King J., Brown C., Turpie J., Clark B., Lugomela G., Sadiki H. and Benno B.L. (2010). Pangani River Basin Flow Assessment. Basin Delineation Report.

Ministry of Energy and Minerals (2013). Power System Master Plan 2012 Update. Dar es Salaam, Tanzania.

Obahoundje S., Ofosu E., Akpoti K. and Kabo-bah A. (2017). Land Use and Land Cover Changes under Climate Uncertainty: Modelling the Impacts on

Hydropower Production in Western Africa. Hydrology. https://doi.org/10.3390/hydrology4010002

PBWB/IUCN. (2009). IUCN Water and Nature Initiative Pangani Basin Water Board Pangani River Basin Flow Assessment. Task 5 Report : An Assessment of Understanding and Knowledge Gaps, December, 54.

Rajabu K.R.M. (2007). Water Availability And Use Dynamics And The Sustainability Of Water Resources Management In The Great Ruaha River Catchment In Tanzania. Sokoine University of Agriculture.

U.S. Energy Information Administration. (2017). International Energy Outlook 2017. International Energy Outlook Vol. IEO2017. https://doi.org/www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf

World Bank (2007). Water Resources Assistance Strategy: Improving Water Security for Sustaining Livelihoods and Growth, II, January, https://doi.org/10.1787/9789264177949-147-en

Huvisa T. (2012). National Climate Change Strategy, United Republic Of Tanzania Vice President Office.

http://www.tanesco.co.tz/index.php/pangani-hydro-system, Retrieved on 26th February 2021.