Vol. 15(12), pp. 519-528, December 2021
DOI: 10.5897/AJEST2021.3064
Article Number: 0CCAC4768313
ISSN: 1996-0786

http://www.academicjournals.org/AJEST

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African Journal of Environmental Science and Technology

Full Length Research Paper

An analytical assessment of climate change trends and their impacts on hydropower in Sondu Miriu River Basin, Kenya

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Received 3 September, 2021; Accepted 19 October, 2021

Hydropower is cost effective environment friendly and worldwide proven sustainable energy source. Driven by streamflow stream flows, it is vulnerable to climate change and land use change. The hydropower production from the two-existing run-of-river hydropower projects on the Sondu Miriu River are vulnerable to rainfall variability and requires proper understanding of the climate change trends and policies to support sustainable hydropower development and put in place strategies for building resilience for the local communities. The objective of this paper is to examine climate change trends and their impacts on hydropower in the Sondu Miriu River basin. The methodology involved analysis of downscaled climate data from CORDEX for the period from 1950 to 2100, gridded data from Kenya Meteorological department for a period of 2007 to 2018, river flows data from Water Resources Authority for a period of 2007 to 2018 and hydropower output data from KenGen for a period of 2007 to 2018 to examine the climate change trends within the Sondu Miriu River basin and impacts on hydrology and hydropower. The results indicate that maximum and minimum annual temperature increased by 0.7 and 0.9°C, respectively between 1950 and 2005. Both the maximum and minimum annual temperatures are projected to increase by 1.9°C based on the RCP4.5 and RCP8.5 scenarios between 2006 and 2100 within the Sondu Miriu basin. Annual rainfall increased by 74.8 mm between 1950 and 2005. This is projected to increase by 24.7 and 117.8 mm based on RCP4.5 and RCP8.5 scenarios, respectively. For the period between 2007 and 2018, the observed maximum increased by 5°C while the minimum temperatures decreased by 1°C. The rainfall decreased by 193.14 mm while the mean daily river flows decreased by 0.3 m^3/s annually during the same period. This resulted in the decrease of hydropower production by 8.3 GWh in Sondu Miriu HPP between 2007 and 2018 while the production reduced by 14.18 GWh for Sang'oro HPP between 2012 and 2018. Understanding climate change trends within Sondu Miriu River basin should guide the planning for hydropower development projects.

Key words: Climate change, hydropower, Sondu Miriu River basin, downscaling, impacts.

INTRODUCTION

In the twenty first century, substantial temperature rise is expected because of the projected concentration levels increase of greenhouse gases (GHGs) (Hamududu and Killingtveit, 2012; Kumar et al., 2011; Milly et al., 2005).

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The mean temperature globally is projected through scientific consensus to increase by approximately 3°C by the close of twenty first century because of the current economic and population growth rates. The precipitation levels globally is also expected to accompany this temperature rise by approximately 15% increase (Kumar et al., 2011; Milly, Dunne and Vecchia, 2005). The future global precipitation will affect run-off characteristics and therefore influencing water resources availability (Hamududu and Killingtveit, 2012; Milly et al., 2005). Climate change particularly associated with reduction of rainfall, shortening of rainfall seasons, delayed rainfall onset, increased drought events and rising temperatures are locally perceived to be the main drivers of some changes such as continuous increase in rivers and streams seasonality and progressive reduction in water flows (Kangalawe, 2017).

There is already consensus that water resources availability is expected to be affected globally, regionally, and locally by climate change (Milly et al., 2005). The changes in characteristics of the river flow particularly in timing and quantity usually accompanied by increased reservoirs water losses through evaporation have higher chances to negatively impact on the hydropower generation.

The Eastern African countries except Ethiopia are anticipated to have increase in hydropower generation by 2050 (Hamududu and Killingtveit, 2012). There is expectation of a lot of impacts of climate change on hydropower system operations as well as on the local communities neighbouring the hydropower projects (Harrison et al., 1998). Run-of-river hydropower projects are vulnerable and sensitive to the impacts of climate change such as floods and droughts.

Hydropower constitutes about 38% of the installed electricity generation capacity in Kenya with Sondu-Miriu and Sang’oro hydropower schemes being the most recent to be developed (Kenya Power, 2018). The schemes within the Sondu-Miriu River basin, therefore, offers an opportunity as a case study to learn lessons on integrating climate change adaptation into hydropower developments that results in socioeconomic, environmental, and technical sustainability. As there is still existing potential within Sondu Miriu River basin, this can give guidelines on how to develop future hydropower projects with climate change adaptation fully integrated. Opportunity exists in responding to climate change and awareness enhancement that maintains ecosystem functioning for supporting livelihood and development fundamentally (Shackleton and Shackleton, 2012), and able to motivate new development trajectories (Niang et al., 2014).

The main objective of this paper was to examine climate change trends in Sondu Miriu River basin from 1950 to 2100 and evaluate their impacts on the generation of hydropower in the two-existing run-of-river hydropower projects.

LITERATURE REVIEW

The design life for hydropower infrastructure is usually more than 100 years and economic design life of 60 years (Kumar et al., 2011). The global energy system is moving towards achieving a less carbon-intensive and sustainable future being a response to the Sustainable Development Goals (SDGs), where a major role is expected to be played by development of hydropower (Zhang et al., 2018).

Electricity supply is projected to affect directly by changing climate through influencing water availability for hydropower generation. Improving the understanding on how water resources availability and temperature are most likely to be impacted on by the changing climate is therefore important (Van Vliet et al., 2016). The general perception that small run-of-river hydropower plants are renewable energy sources associated with little or no environmental impacts has resulted into a global spread of this hydropower technology. Interdisciplinary research progress involving different stakeholders is crucial to harmonize conflicting interests and enable the sustainable development of small run-of-river hydropower plants (Kurigi et al., 2021).

Climate change and hydrology

During the 21st century, the use of multi-model ensembles in the climate projections has shown that rainfall is projected to increase globally (Milly et al., 2005). Almost all the models project rainfall increases in parts of the tropics (Kumar et al., 2011). The maximum and minimum annual temperatures are also projected to rise by between 0.5 and 3.5°C under the RCP 8.5 with the increase in minimum temperatures being projected to be higher during the cold season of JJAS compared to the MAM and OND rainfall seasons (Olaka et al., 2019). Few studies have examined the possible climate change impacts on hydropower resource potential. Kenya is particularly vulnerable because 38% of installed electricity capacity is based on hydroelectric power.

Hydropower development in the face of climate change

Climate change impacts on water resources and extreme hydrological events is one of the major challenges for hydropower development (Biao, 2017). Based on the various greenhouse gas emission scenarios, there is evidence that climate change has affected various aspects of water resources and this situation is expected to continue throughout the twenty first century (Shahram et al., 2012). Hydrologic impacts assessment usually relies on spatial downscaling for the translation of large scale GCM projections to the scales that represent more physical climate change implications (Kopytkovskiy et al., 2015). Hydropower generation and water resources availability are highly influenced by global warming because of increasing global temperatures that alters the rainfall patterns (Shu et al., 2018). Rainfall generally leads to runoff that affects the water availability for use in hydropower generation. The energy system globally is moving towards achievement of sustainable and less carbon-intensive future under the Sustainable Development Goals (SDGs), where development of hydropower will be expected to play a critical role (Zhang et al., 2018).

Impacts of climate change on hydropower generation

Changes in water resource availability resulting from variations in rainfall, temperature increase, and evaporation rate rise facilitates the escalation of the extreme hydrological events frequency (Qin et al., 2020). It is projected that the fluctuations in streamflow distribution will cause reduction in the net hydropower generation and operation globally under the RCP8.5 scenario near the end of the nineteenth century (Wang et al., 2019; van Vliet et al., 2016). Both the run-of-river and the storage hydropower plants types are affected by spatial and temporal variations in rainfall and temperature, but the storage type of hydropower is stable due to its flexibility provided by its storage capacity while the run-of-river type of hydropower being the most affected due to its sensitivity to any climate change (Hamududu and Killingtveit, 2012; Koch et al., 2011).

Many research projects have been conducted on the climate change impacts on generation of hydropower (Markoff and Cullen, 2008; Madani and Lund, 2010; Hamududu and Killingtveit, 2012; Gaudard et al., 2013; Viola et al., 2015; Arango-Aramburo et al., 2019). On the other hand, only a few research papers on the impacts of hydropower reservoirs on climate change have been published (Wu et al., 2012; Song et al., 2017; Balagizi et al., 2018) because the surface area covered by hydropower reservoirs is low globally (Hunt et al., 2020). The hydropower generation is projected to grow by 75% globally from 2008 to 2050 in the business as usual case while with aggressive actions aimed at reducing the greenhouse gas (GHG) emissions, it could grow by approximately 85% during the same period (Hamududu and Killingtveit, 2017).

Overall, climate change has a possibility of decreasing dry season hydropower potential, while combined effects of deforestation also have the potential of increasing interannual variability. Therefore, incorporation of future climate change and coordination of hydropower reservoir operations should the principle in energy planning for the development of energy portfolios that are more resilient (Arias et al., 2020). For accurate regional quantitative predictions of impacts, analysis of changes in both the temporal distribution of river flows and average river flows is necessary using hydrological models for conversion of climate scenarios time series to runoff scenarios time series (Kumar et al., 2011).

MATERIALS AND METHODS

Study area description

Sondu Miriu River basin has got two ROR hydropower projects running. The basin supports various socioeconomic activities within the basin and in the neighbouring basins. It is, therefore, of interest to study the interaction between hydropower development and socioeconomic and environmental activities in this area.

Study area location and description

Located in the western Kenya, Sondu Miriu River basin is as one of the basins within the Lake Victoria drainage system (Figure 1). There are two run-of-river hydropower projects within the Sondu Miriu basin that draw water from Sondu Miriu River, namely Sang'oro and Sondu Miriu, for generation of hydroelectric power into the Kenya national electricity grid.

The location of Sondu Miriu River basin is geographically confined within latitude 0°17' S and 0°53'S and longitude 34°45'E and 35°45'E. Among the Kenya's river basins draining into Lake Victoria, Sondu Miriu River basin is the fourth largest covering an approximate area of 3,500 km^2 (Masese et al., 2012). The main tributaries of the Sondu Miriu River are Yunith and Kapsonoi rivers. Sondu Miriu River originates from the Mau Complex which is an expansive water catchment within Kenya. Diverse development activities and land use types characterize the Sondu Miriu River basin. The development activities and land use include industries, energy, settlements, agriculture, and forestry, among others. The various current existing human activities that have been occurring at different intensities and scales over the years within Sondu Miriu basin have capability to cause a wide range of reaching consequences to several matters in the basin. A number of these issues included general river ecological status, the river system aquatic biodiversity and the various water uses quality. The sedimentation rates that have been observed to be on the increase within Sondu Miriu River have compromised, over the years, the river water quality in the basin (Masese *et al*., 2012).

Development of climate modelling

Simulation of the present climate to predict the future climate change has resulted into the GCMs development. Despite demonstration of significant skill at hemispheric and continental spatial scales with the incorporation of large proportion of global system complexities, GCMs are not able to represent the local dynamics and features inherently (Xu, 1999). Therefore, for the GCMs to be applied at the local or basin level such as Sondu Miriu River Basin, downscaling techniques for downscaling GCMs outputs are necessary (Xu et al., 2005).

A hierarchy of climate models are applied for the projections of changes in the climate system. These models range from simple to intermediate complexity, comprehensive, and Earth System Models. The simulated changes by these models are done on the basis of a set of anthropogenic (human caused) forcing scenarios. The Representative Concentration Pathways (RCPs) which is a new set of scenarios has been applied for the recent simulations by climate modelling which were carried out under the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) by

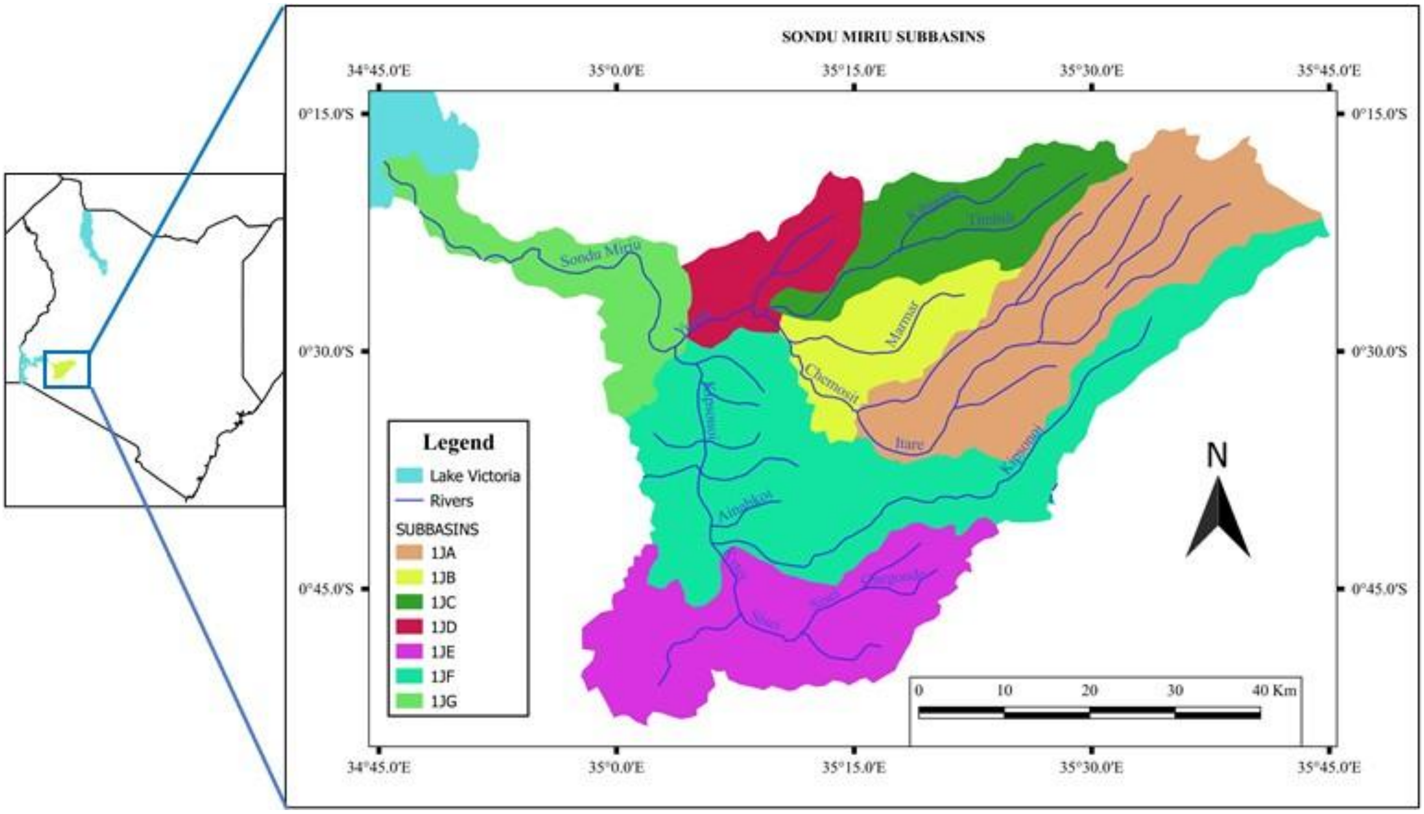

Figure 1. Map of Sondu Miriu River basin.
Source: World Resource Institute, 2017

the World Climate Research programme. Many Earth System and comprehensive climate models have taken part in the Coupled Model Intercomparison Project Phase 5, with the results forming the foundation of the climate system projections (IPCC, 2013).

Land use may substantially affect the precipitation and climate regionally (Hunt et al., 2020). These impacts can vary to a larger scale. For instance, precipitation patterns can be affected by converting forest land into agricultural farms (Li et al., 2009; Adnana and Atkinson, 2011; Price, 2011; Hunt et al., 2020), the regional average temperatures can be affected by deforestation (Bonan, 1997; Hunt et al., 2020) alongside other impacts (DeAngelis et al., 2010; Mueller et al., 2016; Chen and Dirmeyer, 2017). Besides land use changes, the regional climate can also be affected by water consumption patterns through evapotranspiration (Hunt and Leal Filho, 2018; Liu et al., 2018; Zou et al., 2018; Hunt et al., 2020). Therefore, water and land management practices have a major influence on climate patterns regionally (Betts, 2001; Tomer and Schilling, 2009). The relationship between climate patterns and land and water management are being proposed as one of the effective regional adaptation measures to manage global warming (Hirsch et al., 2017; Hunt et al., 2020) and to be incorporated into climate models (Li et al., 2018).

Representative concentration pathways (RCPs)

The RCPs are scenarios comprising the concentrations and emissions time series of full set of aerosols and greenhouse gases together with gases which are chemically active, including land cover and land use (Moss et al., 2008). Term “representative” implies that every single RCP is only one presentation of the several potential scenarios that can lead to the characteristics of specific radiative forcing. The term “Pathway” puts more emphasis on the trajectory taken during the period to reach the anticipated outcome in addition to the long-term concentration levels (Moss et al., 2010).

The RCPs are references to the concentration pathway section extending to the year 2100, for which the corresponding emission scenarios by the Integrated Assessment Models were produced. The four RCPs that were utilized as the basis for the climate projections and predictions in the latest IPCC Assessment to produce the 5th IPCC Assessment Report were produced from Integrated Assessment Models which were selected from the published literature. The four RCPs included a mitigation scenario leading to forcing levels that are extremely (RCP2.6), stabilization scenarios (RCP4.5 and RCP6), and a scenario considering extremely high greenhouse gas emissions (RCP8.5). Their identification is based on the approximate total radiative forcing such as 2.6 Wm^{-2} for RCP2.6, 4.5 Wm^{-2} for RCP4.5, 6.0 Wm^{-2} for RCP6.0, and 8.5 Wm^{-2} for RCP8.5 (IPCC, 2014).

Downscaling climate information to regional level

The necessity for climate change information is a fundamental matter within the climate change discussions. This is especially happening at both the regional and local scale. This information is extremely critical for evaluating the impacts of climate change on the natural systems and human livelihood including coming up with suitable adaptation strategies at both the local and national level

(Giorgi et al., 2009).

Regional climate downscaling (RCD) through the application of both dynamical and statistical tools have been increasingly used in addressing most of the issues relating to climate change. Presently RCD has become a significant methodology for climate change research (Huntingford and Gash, 2005). There has been underutilization of the RCD based products. It is believed that the main reason for this underutilization can be attributed to absence of coordinated framework for evaluating the techniques based on RCD to produce ensemble projections which are of adequate quality that allows for characterization of the underlying uncertainties on climate change projections regionally. These coordinated frameworks exist for global models including the Coupled Model Intercomparison Projects 1-3 (CMIP1-3) or Atmospheric Model Intercomparison Project (AMIP). This has given a lot of benefits to the global climate modelling community immensely from such coordinated activities. The benefits have been in terms of understanding the process, evaluation of the model and generation of the climate change projections. There has been isolation of the studies on RCD which have been continually tied to specific targeted research interests. This has been done to allow for a comprehensive analysis of climate change projections at regional level based on RCD experiments that are not currently available (Giorgi et al., 2009)

Coordinated regional climate downscaling experiment (CORDEX) programme was initiated with an aim of providing a framework for benchmarking for evaluation and possibly improvement of models, on one hand while on the other hand having a set of experiments to provide for exploration to the highest-level possible influence of the various sources of uncertainty. CORDEX, therefore, essentially aims at providing a framework for evaluating and benchmarking model performance (model evaluation framework) as well as designing experiments for producing climate projections suitable for utilization in the studies for impact and adaptation within the framework of climate projection (Giorgi et al., 2009).

Framework for climate projections is currently based on new global model simulations within the CORDEX which were planned to support the IPCC Fifth Assessment Report referred to as CMIP5. These simulations are inclusive of various experiments that range from the 21st century simulations of new GHG scenarios, dekadal prediction experiments and other experiments such as the carbon cycle and the ones aiming at investigations of individual feedback mechanisms (Taylor, 2009).

The methodology applied and the results of the 5-member ensemble simulation of the African climate for the period 1950-2100 using climate modelling system PRECIS carried out over the CORDEX Africa domain suggest that Regional Climate Model (RCM) simulations improve the fit to precipitation and temperature observations in most of the African sub-regions. It should be noted that that the range of RCM projections usually differs from the ones from the GCMs in these regions (Buontempo et al., 2014).

Climate scenarios

The course spatial scale of GCM outputs for water resources studies is among the primary factors limiting the direct application of climate projections to hydrologic modelling. The development of future projections is usually based on the GCMs at resolutions of hundreds of kilometres which makes them difficult to relate to models at watershed scale (Kopytkovskiy et al., 2015). The climate change projections based on the watershed scale can give indications on the performance of future hydropower generation.

The purpose of climate projection scenarios is to guide researchers in exploring the consequences, which are long term in nature, of the present decisions being made while taking into considerations the inaction within both the socioeconomic and physical systems. The climate projection scenarios provide important reference for emerging research with economic and technological models (Moss et al., 2008). Currently, the research community on climate are applying the four new key scenarios of the Representative Concentration Pathways (RCPs) that give descriptions of a wide range of potential future projections scenarios for the main climate change drivers such as greenhouse gases, land use and air pollutant emissions. The RCP scenarios range from high to low emissions projections (Jubb et al., 2013).

Data collection

Downscaled climate data from 1950 to 2100, consisting of daily rainfall, minimum temperatures, and maximum temperatures from CORDEX were downloaded from https://cordex.org/data-access/ for the purpose of extracting historical and future climate scenarios for the Sondu Miriu River basin. The gridded daily minimum temperatures, maximum temperatures, and rainfall data for the Sondu Miriu River basin from 2007 to 2018 were obtained from Kenya Meteorological Department (KMD). The daily river flow from and monthly energy generation data from 2007 to 2018 was collected from Water Resources Authority (WRA) and Kenya Electricity Generating Company (KenGen), respectively. The hydropower projects within the Sondu Miriu River basin have been in operation from October 2007.

CORDEX historical and projected climate scenarios were used to compare with the present trends from 1981 to 2018 to facilitate the determination climate change status of over Sondu Miriu River basin. The scenarios were based on the downscaled global circulation models. Scenarios from five models were considered namely Canadian Climate Change Modelling and Analysis (CCCMA), National Centre for Meteorological Research (CNRM), Max Planck Institute for Meteorology (MPI), Model for Interdisciplinary Research on Climate (MIROC), and National Oceanic Atmospheric Observations (NOAA). Ensembles for the five models were used for the analysis of the historical and projected scenarios. The historical scenarios were for the period from 1951 to 2005 while projected scenarios were from 2006 to 2100. The CORDEX projections were used due to their improved fit to observations of precipitation and temperature in most of the African sub regions. CORDEX downscaled projections were based on the Representative Concentration Pathway (RCP) methodology as was adopted by the IPCC for the preparation of the fifth assessment report (IPCC, 2014). For this study, RCP8.5 and RCP4.5 have been adopted as the most likely scenarios. The RCP4.5 represents stabilization scenario while RCP8.5 represents high emission scenario.

Data analysis

The annual and seasonal trends of climate scenarios (RCP4.5 and RCP 8.5), grided rainfall and temperature data, river flows and electricity output data were determined through trend analysis using Microsoft excel. The data was grouped into annual and seasonal data sets. The data was subjected to curve fitting to capture the trends in climate change and their magnitudes within the Sondu Miriu River basin. Linear curve fitting was adopted to determine the rate of change with time. The curve fitting was performed for all the data sets both annually and seasonally.

The data used for the assessment of climate change impacts on the production of hydropower was from 2008 to 2019 and 2013 to 2019 for Sondu Miriu and Sang'oro, respectively to perform correlation analysis between the climate scenarios and hydropower output. This also considered annual and seasonal changes. Correlation analysis between the observed river flow and observed rainfall was performed to determine the level of influence rainfall over the catchment influences river flow for Sondu Miriu River.

During the same period (2008 – 2018), the observed and projected rainfall and temperature was also compared through correlation analyses and statistical t-test for confidence level to determine the reliability of the climate projection scenarios. T-test was selected as suitable for comparing two groups (flow and rainfall, observed and projected climatic conditions).

RESULTS AND DISCUSSION

Historical temperature change over Sondu Miriu River Basin

From 1951 to 2005, there was an annual increase of 0.89 and 0.73°C for minimum and maximum temperatures, respectively. During the same period, the seasonal minimum temperatures increased by 0.81°C for January and February season, 0.83°C for March to May season, 0.85°C June to September season, and 0.96°C for October to December season. The seasonal maximum temperatures also increased by 0.43°C for January and February season, 0.90°C for March to May season, 0.95°C for June to September season and 0.74°C for October to December season. The results have shown that the minimum temperatures have recorded higher rise compared to the maximum temperatures within Sondu Miriu River basin. This is consistent with the findings that the eastern Africa equatorial regions have faced a substantial temperature rise since early 1980s (Anyah and Qiu, 2012) and the Famine Early Warning Systems Network (FEWS NET) reports indicating that over the last 50 years Kenya among other countries has experienced an increase in seasonal mean temperature (Funk et al., 2012).

Temperature projections over Sondu Miriu River Basin

Within the 21st century, minimum and maximum temperature increases are projected within Sondu Miriu basin. Minimum temperature is expected to rise by about 1.89°C annually the RCP4.5 projection scenario and 4.6°C in the RCP8.5 projection scenario while the maximum temperature in the RCP4.5 projected scenario is projected to increase by 1.85°C annually and in the RCP8.5 projection scenario projected scenario is projected to increase by 4.47°C. In the RCP4.5 projection scenario, seasonal minimum temperatures are projected to increase by 1.86, 1.85, 2.24 and 1.62°C for January to February, March to May, June to September and October to December seasons, respectively while under the RCP8.5 projection scenario the seasonal temperatures are projected to increase by 4.58, 4.23, 5.39 and 4.10°C for January to February, March to May, June to September and October to December seasons, respectively. On the other hand, the seasonal maximum temperatures under the RCP4.5 are projected to increase by 1.76, 1.64, 2.34 and 1.49°C for January to February, March to May, June to September and October to December seasons, respectively while under the RCP8.5 projection scenario the seasonal maximum temperatures are projected to increase by 5.04°C for January and February season, 4.93°C for March to May season, 3.46°C for June to September and 3.71°C for October to December season.

The drier seasons of January to February and June to September are projected to have higher minimum and maximum temperature increase than the long rainfall and short rainfall season under the RCP4.5 projection scenario. This trend applies also to minimum temperatures in the RCP8.5 projection scenario. The first two seasons of the year (January to February and March to May) have higher maximum temperature increase in the RCP8.5 projection scenario than the last two seasons (June to September and October to December) of the year. March to May rainfall season is projected to have higher increase than the October to December rainfall season. Even though the results agree with the earlier findings that minimum temperature increase is projected to be higher for the June to September season than for the long rainfall and short seasons (Olaka et al., 2019), the hot dry (January to February) was omitted in the earlier analysis. Looking at all the four seasons of the year, the cold and dry seasons of the year are projected to experience the highest minimum and maximum increase compared to the rainfall seasons.

Both the minimum and maximum temperatures are projected to increase within the Sondu Miriu River basin within the century. This is expected to enhance the rate of evaporation from open water sources including the main Sondu Miriu River. As a result, the water losses will increase within the basin due to increased water demands from other water users.

Historical rainfall over Sondu Miriu River Basin

Annual rainfall over Sondu Miriu River basin has increased by about 18.27 mm. The seasonal rainfall has also increased in all the seasons except for the June to September season that has declined. The seasonal rainfall has increased by 1.10 mm for January and February season, 55.55 mm for March to May season, and 36.30 mm for October to December seasons while June to September has decreased by 18.15 mm. Several studies over the eastern Africa region have indicated a decline in rainfall during the March to May and June to September season in the last three to five decades of the 20th century (Funk et al., 2008; Williams and Funk, 2011; Lyon and DeWitt, 2012; Williams et al., 2012; Rowell et al., 2015). The difference in the historical trends is only in the March to May season which may be attributed to spatial variability controlled by a range of physical processes (Rosell and Holmer, 2007; Hession and

Moore, 2011). A study by Rwigi et al. (2016) on the "Assessment of Potential Changes in Hydrologically Relevant Rainfall Statistics over the Sondu River Basin in Kenya Under a Changing Climate" also found out that the observed seasonal rainfall variation in overall indicate a possibility of shifting rainfall patterns where the comparatively dry season of January and February season and short rainfall season of October to December are getting relatively wetter while the long rainfall season of March to May and cold season of June to September are getting relatively drier.

Projected rainfall over Sondu Miriu River Basin

The rainfall amount is expected to increase annually within Sondu Miriu River basin in the 21st century by 24.70 mm based on the RCP4.5 projection scenario and by 117.80 mm based on the RCP8.5 projection scenario. This also concurs with the finding of Rwigi et al. (2016) that found out a general tendency of possible increasing rainfall amounts within the Sondu Miriu River basin together with neighbouring basins moving towards future climate periods. Towards 2030 and 2050, more rainfall is projected to be received within Sondu Miriu basin which will be in terms of rainfall days per month having higher probabilities of more wet days per month (Rwigi et al., 2016). The seasonal rainfall is projected to decrease in the June to September by 19.95 mm under the RCP4.5 projection scenario and 40.85 mm under the RCP8.5 projection scenario. The seasonal rainfall is projected to increase by 13.30 mm in the January and February season and by 138.70 mm in the October to December season in the RCP4.5 projection scenario, while for the RCP8.5 projection scenario the projected seasonal increase is by 34.20 mm in the January and February season and 74.10 mm in the October to December season. The March to May seasonal rainfall is projected to decrease by 11.40 mm in the RCP4.5 projection scenario and to increase by 50.35 mm in the RCP8.5 within the 21st century. The findings agree with other recent studies conducted within the region that project rainfall increase within the 21st century including the long rains of March to May season and short rains of October to December season (Moise and Hudson, 2008; Shongwe et al., 2011; Rowell et al., 2015; Olaka et al., 2019). The study also concurs with other studies in the region that the seasonal rainfall for June to September is projected to decline in the 21st century (Patricola and Cook, 2011). A study by Olaka et al. (2019) on "the projected climatic and hydrologic changes to Lake Victoria basin rivers under three RCP emission scenarios for 2015 to 2100 and impacts on the water sector" indicated that the June to September seasonal rainfall is projected to decrease in the RCP8.5 projection scenario but increase in the RCP4.5 projection scenario (Olaka et al., 2019).

Climate change impacts on hydrology and hydropower generation

During the period between 2008 and 2019, when the existing two hydropower projects have been in operation within the Sondu Miriu River basin, the annual rainfall has declined. The same trend has been replicated in the seasonal rainfall patterns except the June to September season. The river flow has followed the same pattern with declining annual and seasonal flows except for June to September season. The hydropower output in the two hydropower projects have also followed the same trend whereby the output has been declining annually and in all the seasons except for June to September season. This is an indication that the hydrology and hydropower production will respond to rainfall pattern in the region. This concurs with Olaka et al. (2019) that high variability in projected discharge will have impacts on hydropower production in Sondu Miriu River and this could have the potential to reduce the average electricity production during the drought years (Olaka et al., 2019).

With the rainfall projected to increase within the basin, hydropower generation is expected to remain stable, and this presents an opportunity for more hydropower development within the basin. Generally, the climate change impacts on hydropower output could vary a lot and differ locally, depending on the flow regime change. The impacts of the changing climate are expected to be felt more on the run-of-river hydropower systems compared to other systems with storage (Storage hydropower systems). Since rainfall is projected to increase, storage hydropower systems should be considered to manage the climate variability. A special report on "renewable energy sources and climate change mitigation" by IPCC made a conclusion that the expected overall climate change impacts on existing hydropower generation may be small, or even marginally positive. However, the possibility of substantial variation within countries and even across regions is indicated in results (Berga, 2016).

The correlation between the observed river flows and observed rainfall within the Sondu basin is a strong with an R^2 of 0.78, an indication that rainfall data in the basin can be utilised to estimate the streamflow and how it can influence the hydropower production. The strong correlation between the observed rainfall and projected rainfall with R^2 of 0.63 for the RCP4.5 projection scenario, and 0.60 for the RCP8.5 projection scenario indicate the reliability of climate change projection scenarios. Therefore, the climate change projections can be used to develop trends that can guide on the future water resource availability for development within the Sondu Miriu River basin.

Statistical significance

The statistical test of significance using the t-test has indicated no significant difference between the streamflow characteristics in Sondu Miriu basin. Based on the period the two run-of-river hydropower projects have been in existence, the t-test for significance indicates no significant difference between the observed and the projected rainfall characteristics within the basin.

Conclusion

Hydropower development could significantly be undermined by climate change especially for instances where critical resources such as water are threatened, and the incidence and severity of climate extremes such as droughts and floods are increased. The existing hydropower projects in the Sondu Miriu River basin, which are run-of-river type, are vulnerable due to the projected climate variability and climate change in the 21st century. Implementing hydropower projects with storage in the basin can help in adapting to the climate change and climate variability. As the climate change projections indicate that the rainfall is projected to increase as well as temperature, water resources management may be a challenge due to increased evapotranspiration and rainfall variability that may affect the existing run-of-river generation projects in the Sondu Miriu River basin. Putting in place structural and nonstructural measures are required to minimize the impacts. The projected climate change trends can be made use of in determining future availability of water resource within Sondu Miriu River basin for hydropower development by influencing the non-structural and structural measures to be established.

RECOMMENDATIONS

Both technological and innovative management interventions which are proven through research are required for the management of anticipated changes to minimize the negative impacts climate change may have on the existing hydropower plants in terms of hydropower energy production and future planned hydropower projects in the basin. There should be a close collaboration between the research institutions and the hydropower development institutions interested in the Sondu Miriu River basin to enhance regular updates on climate change trends. This will assist hydropower development institutions in planning appropriately based on the projected climate change trends to minimize any negative impacts that may occur on hydropower generation within the basin. The collaborations should be based on the proposed strategies and backed up by the relevant policy options. The current existing County Development Integrated Plans for the relevant counties should be implemented, monitored, and evaluated based on their effectiveness and improvements suggested to make the better. The research institutions and hydropower development institutions should also actively be involved in the processes for developing policies that are aimed at integrating adaptation into the development of hydropower in particular and energy sector in general at national level and in the relevant counties interacting with Sondu Miriu River basin. Further research is required for understanding the detailed interaction between catchment conservation and management practices and basin climate change characteristics. This will assist in proposing relevant and appropriate strategies and policies to promote climate change adaptation within the Sondu Miriu River basin.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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