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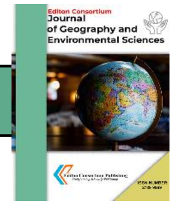

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Determination of the effects of climate change on hydropower generation in Kamburu Dam, Kenya

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Abstract
This study aimed to determine the effects of climate change on hydropower generation at Kamburu Dam, Kenya. Kamburu power plant has been experiencing low volumes of water with the shortage of rainfall from its catchment area. This study primarily utilised rainfall and temperature data, as well as field survey data collected through questionnaires. Primary data was collected using questionnaires, photography, checklists, and observation guides. Secondary data sources included Kengen and the meteorological department's annual reports. The study used simple stratified sampling. The four villages of the Kivaa sub-location were sampled into 20 households, making a total of 80 households; Kengen and meteorological stations sampled every 10 respondents to make a total of 100 respondents. Collected data from the questionnaires were coded and analysed using SPSS 29. The results of this research showed that the area experiences increasing temperatures of 0.044°C every year and decreasing rainfall of 0.5897mm every year. The research forecasted a decadal increase in temperature of 0.44°C and a decadal decrease in rainfall of 5.897mm. The research also showed a decrease in hydropower of 18,790MWH every year, translating to a decadal decrease of 187,790MWH. The research concluded that climate change has greatly affected hydropower production at the Kamburu Dam power plant. The research recommends afforestation and re-afforestation activities, putting rules and regulations of watershed management, upgrading the Kamburu dam infrastructure to fit climate-resilient, expanding the capacity of the dam, and energy storage, among others.

Key words: Climate change, hydropower, Kamburu catchment, rainfall, reservoir.

INTRODUCTION

Hydropower generation from the Kamburu dam is under threat of climate change, especially due to challenges relating to fluctuating river flows, high temperatures, decreasing and sporadic nature of rainfall and extreme evaporation rates. There is a strong correlation between precipitation and dam levels in seven forks dams (Mango et al., 2014). Stream flow and the dam's volume regime are highly dependent on different climatic factors, among which the most important is rainfall, in terms of frequency, intensity and seasonal distribution of rainfall events (Mango et al., 2014). According to Mango et al. (2014), the cause-effect relationship between precipitation and discharge becomes more noticeable in non-perennial rivers, where stream flow mainly relies on surface runoff. Thus, the study of the hydrological regime under transient climate conditions results particularly relevant in ephemeral river basins, where the variations in stream flow characteristics strongly depend on the underlying precipitation patterns.

Climate change is one of the great challenges of the 21st century. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which to natural climate variability observed over comparable periods' (Hickmann et al., 2019).

Little rainfall in an area may lead to drought, which is one of the critical natural disasters that has a greater effect on river basins and reservoirs, water resource systems, and ecosystems at large. Irrespective of the absolute change in gross technical potential, more frequent and intense extremes of rainfall variabilities are projected (Giacomo et al., 2019). In the last decades (in particular during the wet season in unimodal rainfall climates, where rain falls only during one period per year), prolonged droughts have resulted in severe power crises in several hydropower-dependent countries (including, for instance, in Kenya, Tanzania, Ghana, Zimbabwe and Zambia during the 2015-16 El Niño period, characterised by oceanic and atmospheric shifts in the Pacific Ocean which affect weather and climate across the tropics, and in Malawi in 2017), with frequent outages and power rationing (Giacomo et al., 2019).

Temporal reliability and treads of rainfall and stream flow in the Tana River basin found that there has been instability of river fluctuations caused by the unreliable rains around the area, causing fluctuations of stream flow and further worsening of hydropower generation (Kiringu, 2015). Kamburu dam has been experiencing both temporal reliability of rainfall and Tana river flow, which has greatly affected its hydropower output. Kenya, as a country, highly depends on hydroelectric power, and more of the electricity generated in the country is obtained from five major generating hydropower dams, which are situated along the upper Tana River basin. Nyokabi et al. (2021) conducted an assessment of rainfall, streamflow and reservoir level trends for the Malewa River catchment in Naivasha, Kenya. The rainfall values showed an increasing trend starting in 2011, but this trend was not statistically significant.

On the other hand, only a few studies on the impacts of climate change on hydropower reservoirs have been published (Wu et al., 2012; Song et al., 2021; Balagizi et al., 2018) because the surface area covered by hydropower reservoirs is low globally (Hunt et al., 2020). No single research has been done on how Kamburu Dam has been affected by climate change for the past few years or since its establishment. This research, therefore, sought to determine the effects of climate change on hydropower generation at Kamburu Dam, Kenya.

LITERATURE REVIEW

An understanding of the spatial and temporal dynamics of rainfall variability is essential for developing a sustainable water resource management plan (Issa et al., 2017). Global warming and climate variability that affect atmospheric circulation play an important role in influencing drought occurrences in Kenya. According to Suleiman and Ifabiyi (2014), reservoir operation and management are usually patterned after a background of long-standing experience in water resources management. Reservoir management for optimum power production at any hydropower station requires constant assessment of the quantity of available water. The hydrographic responses of flow monitoring and statistical analysis of instrumental hydro-met records, especially rainfall and stream flow, provide the necessary springboard for sound operational decisions (Suleiman & Ifabiyi, 2014).

Using regional climate projections documented in IPCC Fourth Assessment Report: Climate Change (2017) for climate scenario analysis, the research found that minimum changes in temperature and precipitation for each season of the year resulted in a 25.34 per cent reduction in stream flow. Climate change has the potential to substantially alter river flow regimes by shifting the timing of river flow regimes (Arnell et al., 2013). Pumo et al. (2016) commended that the hydrology of an area is determined by the rainfall received in that area. Pumo further stated that. Little rainfall in an area may lead to drought, which is one of the critical natural disasters that has a greater effect on river basins and reservoirs, water resource systems, and ecosystems at large. It is defined as a hydro-meteorological event on land characterised by temporary and recurring water scarcity. Drought has been identified as the most complex natural hazard since it is difficult to detect; it develops slowly and impacts numerous aspects within a region, including water features. The success of rainfall variability preparedness and mitigation depends upon timely information on its seasons and propagation in terms of temporal and spatial extent. Heavy rainfalls also destroy dam structures and lead to high dam inflows, together with a high sedimentation rate, hence reducing the dam floor (Pumo et al., 2016).

Njoroge et al. (2024) looked at the contribution of climate variability and land use change to streamflow variations in the Thika Dam watershed. With a breakpoint in 2003, it was discovered that the average annual streamflow in the Thika River had dropped dramatically during the previous 50 years. This streamflow shift was shown to be 46 per cent the result of climate variability and 54 per cent the result of changes in land use. Drought studies further confirmed decreased streamflow and rainfall by showing an increase in both types of droughts after 2003. HDs, on the other hand, outnumbered MDs, demonstrating the compounding effect of climate variability and land use change on streamflow reduction. This thorough method that combines drought analysis with the Budyko methodology provides insightful information about the intra-annual dynamics and transitions of climate variability as well as the effects of land use change on streamflow. As hydrological constraints change, the study emphasises the significance of making educated decisions in watershed planning and management by integrating interventions aimed at appropriate land use and climate-resilient water management.

In the Tana River Basin, rainfall and streamflow variability and trends help plan studies, hydrological modelling, and assessing the effects of climate change. The effects of climate fluctuation and change are becoming more and more difficult when it comes to solving global issues with food and water security (Langat et al., 2017). The public is very concerned about extreme or unpredictable weather occurrences and climate-related phenomena, and they are quite interested in how these events will dynamically behave in the upcoming decades. Comprehending past climate shifts is crucial for optimising water resources and food production. In climatological and hydrological applications, such as hydrological modelling, climate variability, and water resources planning and management for a variety of uses, including agricultural production, environmental flows, and engineering designs, historical datasets are crucial sources of information on the temporal patterns of rainfall and streamflow time series (Langat et al., 2017).

The area catchment's average annual precipitation based on the Nyeri weather station indicates that the amount of precipitation is gradually but steadily declining (Suleiman & Ifabiyi, 2014). Masinga and Kamburu catchment rainfall has been decreasing by 3.93 mm annually; therefore, for a period of 30 years, the average annual precipitation will drop by 118 mm on average. Decreasing catchment precipitation adversely affects both the reservoir volume trend and river base-flows, especially during dry spells. Reservoir operation and management is usually patterned after the background of long-standing water resources management experience. Reservoir management for optimum power production at any hydropower station requires constant assessment of the quantity of available water (Suleiman & Ifabiyi, 2014).

Hydropower generation from Kamburu dam is under threat of climate change, especially due to challenges relating to fluctuating river flows, high temperatures, decreasing and sporadic nature of precipitations and extreme evaporation rates. There is a strong correlation between precipitation and dam levels in seven forks dams (Mango et al., 2014). Stream flow and the dam's volume regime are highly dependent on different climatic factors, among which the most important is surely the precipitation in terms of frequency, intensity and seasonal distribution of rainfall events (Mango et al., 2014). According to Mango et al. (2014), the cause-effect relationship between precipitation and discharge becomes more noticeable in non-perennial rivers, where stream flow mainly relies on surface runoff. Thus, the study of the hydrological regime under transient climate conditions results particularly relevant in ephemeral river basins, where the variations in stream flow characteristics strongly depend on the underlying precipitation patterns.

METHODOLOGY

The research design refers to the overall strategy that one chooses to integrate the different components of the study coherently and logically, thus making sure that you will effectively address the research problem; it overally constitutes a blueprint for the whole research thesis (Sovacool et al., 2018). This study used a descriptive research design to get in-depth social data from the respondents and to get information for other studies. This design employed the following approaches: pre-field work, fieldwork, review of relevant materials and documents, Data collection, Data analysis and interpretation.

Data for this study included the changes in rainfall amount around the Kamburu dam area and Kamburu reservoir volume over the years; both primary and secondary data were collected. Primary sources of data included data on the perception of people around the dam on climate change, data collected from Meteorological officers through interviews, and resource persons from Kengen staff. Secondary data sources for this study included data from Kengen and meteorological stations, publications, annual and quarterly reports on climate and hydropower, books, journals, periodicals and existing spatial information like maps of the study area.

The study population consisted of KENGEN, meteorological staff and household people living near the Kamburu dam. This provided the information needed to meet the study objectives. The Kamburu dam area has an estimated population of 13,539 (KNBS, 2019). The sample size was determined using the recommended formula by (Nassiuma et al., 2021) as follows;

$$n = \frac{NCv^2}{(Cv^2 + (N-1)e^2)}$$

Where n=sample size
N=population (13,341)
Cv=Coefficient of variation (take 0.5)
e=Tolerance of the desired level of confidence, take 0.05 per cent at 95 per cent confidence level.

Based on the above formula, the sample size was 99.3, rounded off to 100 persons. The study, therefore, gathered field data from 80 households and 20 from relevant institutions (KENGEN and meteorological stations).

This research study employed both purposive and stratified random sampling to collect the desirable and valid data for the study. Purposive sampling represents a group of different non-probability sampling techniques (Mugenda & Mugenda, 2013). This sampling is also called judgmental, selective or subjective sampling. Purposive sampling relies on the researcher's judgment when it comes to selecting the units (e.g. people, cases/organisations, events, pieces of data) to be studied (Mwendwa, 2014). This sampling method enabled the researcher to focus on particular characteristics of the population that are of interest. The researcher selected respondents based on age, experience with the climate of the area, hydropower, and the number of years the respondents have lived in the Kamburu catchment area. This purposive sampling was done based on the researcher’s judgments on the interest of data to be collected.

RESULTS AND DISCUSSIONS

Climate data of the study area was obtained from the Kenya Meteorological Department (KMD) situated at Embu. The data acquired include rainfall and temperature records for the years between 2000-2023 periods making a total of 24-year study period. Kamburu reservoir levels and power output for the years were acquired from Kenya electricity and generating company (KenGen). Data on soils, land use and topography was downloaded from the World Resource Institute (WRI) and the County government of Machakos (2023).

Rainfall Variability in Kamburu

Based on the trend analysis, the dam inflow rates show a steady decline. The highest inflow and the lowest inflow to the reservoir have occurred in the last two decades, in the years 2011/12 and 2020, respectively; this indicates an increase in extreme weather events like droughts and floods. Many years in the study period of 24 years have received little rainfall, causing very low dam levels. During the 24 years, the years that the dam has ever had overflows are very few. The lowest ever recorded reservoir volume levels are the years 2009/10 and 2019 (Figure 1). This is the year that the Kamburu plant operation was halted, and the reservoir water levels declined to worrying levels. The major causes of variations in inflow are the alternating scarce and abundant rainfall patterns, high evapotranspiration rates, and increasing catchment temperatures. Reduction in reservoir inflows unswervingly threatens the operation of the Seven Forks Project in general, and because Kamburu reservoir is the second subsequent dam after Masinga dam and which plays regulatory functions for subsequent dams and sediment trapping as a more recent function, this Kamburu power plant is also highly affected.

Kamburu dam catchment annual average rainfall based on Embu weather station shows that the amount of rainfall received between 2000 and 2023 is gradually and steadily decreasing, as shown by the graph trend line (Figure 1). Decreasing Kamburu catchment precipitation affects both the Tana river flows and the Kamburu reservoir levels and its volum,e especially during the dry season,s which occur between June and September and January to March. The months of July and August are the driest, while the wettest months are May and December. The graph's trend line has a negative gradient of –0.5897, as shown by the graph trend line equation of Y=-0.5897x +116.35 (Figure 1); this implies a decadal decrease of precipitation of about 5.8 mm. This gives a decrease of 14.15mm of rainfall in the past 24 years. If this trend of decrease in precipitation is maintained, this can arrive at a decrease of 58.97mm of rainfall in about 100 years. This poses a big risk to the Kamburu catchment area in terms of water resources and the generation of hydropower in the future. Even though the decline in catchment rainfall is gradual, a highly invariable rainfall pattern endangers the ability of catchment river flows to sustain economic and steady hydropower generation. The precipitation in the Kamburu catchment is sporadic in nature.

Some of the years in the study period, like 2005/06, 2011/12 and 2020, had a high annual mean precipitation, depicting extreme seasons of wetness, which at times are caused by Elnino phenomena (Figure 1). This, to a great extent, suggests that the catchment will always be subjected to more frequent torrential floods, which, even though they fill the reservoirs more quickly, don't provide sustainable water supply and negatively lead to reservoir sedimentation, raising the dam floor and lessening the dams, holding water capacity. Many of the years throughout the study period receive little rainfall, most especially during extreme dryness and droughts, with the driest years being 2000, 2010, 2017, and 2018. This low precipitation in the catchment area is the reason for low reservoir levels and, subsequently, shaky hydropower generation. These findings agree with Mwanzia (2020), who found out that many of the areas in Machakos County have been experiencing a decline in rainfall due to climate change. Further, studies done by Kisaka (2015) found that the Kamburu area is attributed to high temperatures, prolonged dry spells and erratic rainfall.

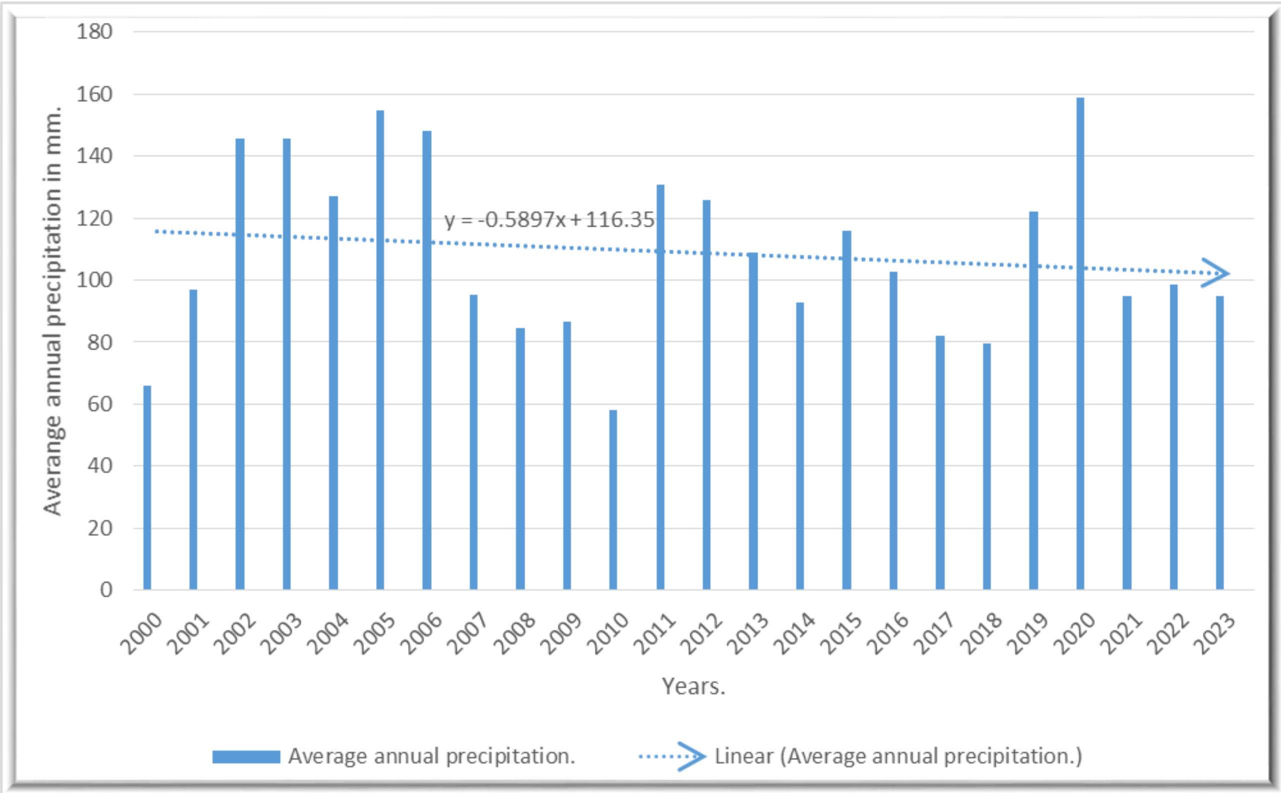

Figure 1: Average Annual Rainfall for the Kamburu Catchment Area

Source: Field survey 2024

The findings of this study, after collecting the respondents' perception of the rainfall received in the area, show that the rainfall received has been low (Table 1).

Table 1: Respondents' View on Rainfall Amount in the Catchment Area

Rainfall received	**% Response**
High rainfall	05
Moderate rainfall	12
Low rainfall	83

Source: Field survey 2024

There was a general agreement among the respondents of the Kamburu area that rainfall has been decreasing every year. The respondents confirmed that the amount of rainfall received in the area recently is decreasing at an alarming rate with a few exceptional seasons, which are extremes of high rainfall. About 83 per cent of the respondents held the view that the rains experienced in the area are low, while 12 per cent of the respondents said that the rainfall received in the area is moderate. Further, 5 per cent of the respondents said that the area has been receiving high rainfall (Table 1). Similarly, Langat et al. (2017) observed that annual rainfall trend analysis showed a negative monotonic trend in seven rainfall stations and positive trends in three stations, indicating an increasing rainfall in high-elevation areas and more drying conditions for low areas within the Tana River basin. According to Langat et al. (2020), the Kamburu catchment is a low-lying area within the Tana River basin, and therefore, it experiences low rainfall, which correlates with these study findings.

Kamburu Dam Levels for the Years between 2000-2023

Daily dam reservoir levels were collected from the Kenya Power Generating Company (KENGEN) for the period between 2000 and 2023. From the obtained data, the mean annual reservoir volume is about 15920000M^3. At this level, the dam operates at its optimum capacity. According to KenGen hydropower engineer, the minimum water level required for power generation is 10350000M^3.

According to Figure 2 below, there is a negative trend line equation of Y=-0.0922x+17. 069. This depicts a downward trend of the decline of Kamburu reservoir volume for the years between 2000 and 2023. This records a decrease in water volume by 92,200M^3 every year. This also translates to a decadal decrease of the dam's volume by 922,000M^3. This decrease is at an alarming rate if this trend is maintained. According to weather experts, little rainfall leads to low dam volume, and if nothing is done about climate change, the reservoir volume will have devastating effects. Reduced dam volume will, without a doubt, lead to reduced hydropower generation and operations at the Kamburu dam plant.

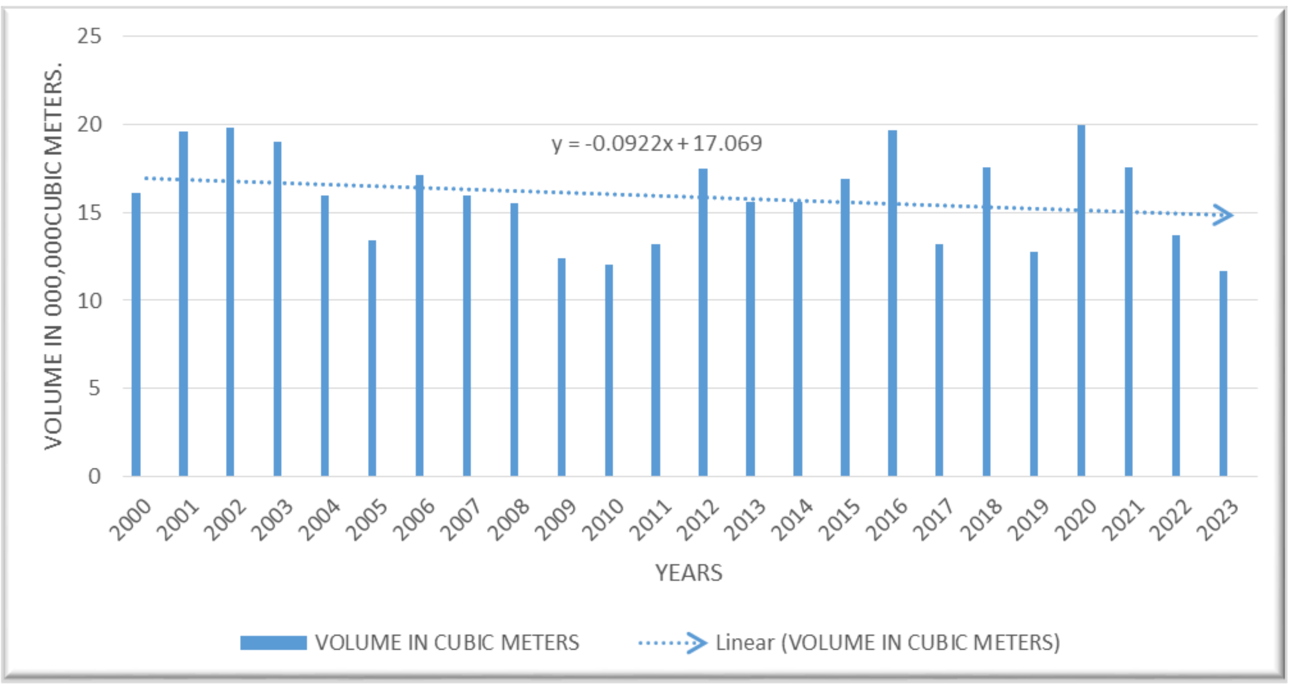

Figure 2: Kamburu Reservoir Volume in Cubic Meters

Source: Field survey, KenGen 2024.

High dam levels result in higher dam head efficient, and therefore,e less water is required to generate a single unit of energy. The higher the dam levels, the greater the reservoir's surface area and, thus, the higher the water storage capacity. Subsequently, any drop in the dam levels adversely affects power generation, especially during dry seasons where inflows are minimal. A decline in stream flow in the Kamburu catchment area has resulted in reduced dam volume over the 24-year study period which further again has led to disturbance in hydropower output.

During the field surveys, different opinions were collected from people concerning their views on how to manage and solve the problem of decreasing volume at the Kamburu reservoir. The responses were coded, tabled in percentage tables and further presented in pie charts to bring about the eye appeal for easy analysis. Figure 3 below gives the respondents' perception of what should be done to ensure a high water volume in the Kamburu reservoir.

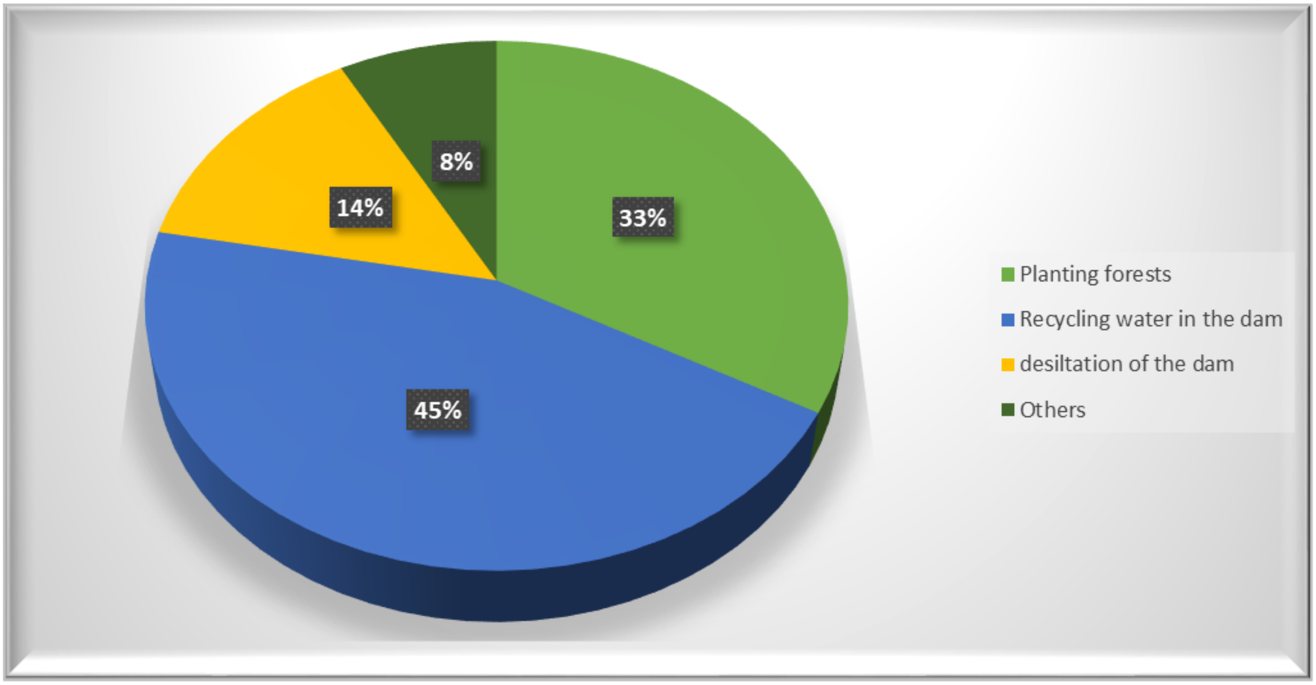

Figure 3: Ways of Ensuring a High Water Volume in Kamburu Dam

Source: Field survey, 2024

The area respondents provided ways to maintain the dam's volume despite challenging climate changes. About 33 per cent gave a solution of planting more trees and forests, while 45 per cent indicated recycling of water in a dam. Further,14 per cent of respondents commented on de-siltation, and 8 per cent of others were the responses given to increase the volume of the dam. These measures are the main ones obtained from the field survey to ensure that there is high rainfall in the area and also make sure that the dam will store a lot of water collected, coupled with recycling water to run turbines. Figure 3 makes clear that the best solution to maintain the dam's volume, as per the people's opinion, is to recycle water in the Kamburu reservoir. A good mechanism should be formulated to make sure that the water collected and stored in the Kamburu reservoir after heavy rains is recycled to run the turbines and generate power. Planting trees was also seen as a better option and environmentally friendly way to avert climate change and its effects. Many tree belts and forests planted in the region of the catchment area will modify the climate and, therefore, lead to high rains in the future. Further, de-siltation was another way given to deal with this problem. The Kamburu reservoir has been silted heavily by flash floods, which have caused the elevation of the reservoir floor and, hence, less water storage. This factor leads to less water in the dam and subsequently affects the whole hydropower production. These findings concur with Okibe et al. (2015), who established that Pico hydropower in Nigeria could be improved through the recycling of water in the dam tail to curb the shortage of water volume amidst climate change effects. Similarly, these findings partly concur with Adamo et al. (2021), who found out that a dam's capacity can be increased through de-siltation of sedimentation to raise its water levels.

The Figure 4 below shows the relationship between rainfall variability in the Kamburu catchment area and the Kamburu reservoir volume for the last 24 years.

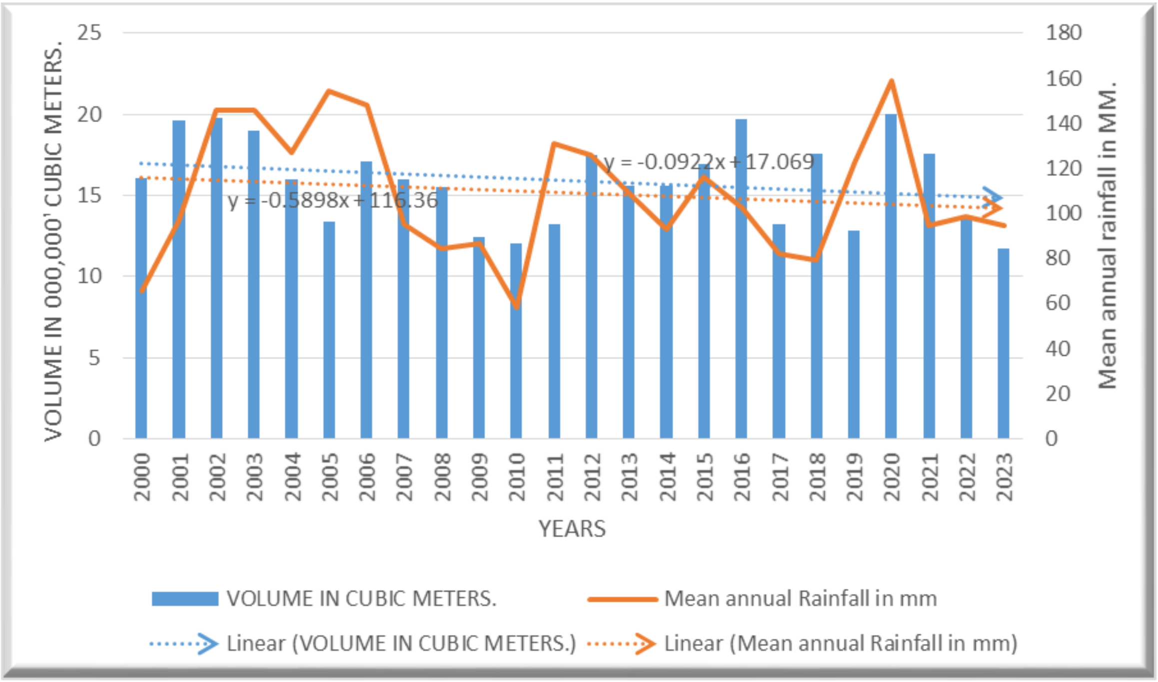

Figure 4: Relationship between Annual Rainfall in mm and Reservoir Volume in M³
Source: Field survey, 2024

It is clear that the rainfall received in the catchment area nearly determines the Kamburu reservoir volume (Figure 4). The graph shows both rainfall and dam volume with a negative trend line depicting that the catchment area has had declining rainfall and subsequently declining reservoir levels during the study period.

This shows that the occurrence of extreme climatic events, especially droughts, negatively impacts hydropower generation. The high correlation of these two variables suggests clearly that high rainfall translates to high reservoir volume, which in turn leads to high power output and vice versa. The graph trend line in Figure 4 above clearly shows both rainfall received in the area and Kamburu dams' volume with a nose-diving trend.

CONCLUSION AND RECOMMENDATIONS

Conclusion: The Kamburu dam hydropower plant, which is situated at the section of Tana River and which is also fed by other streams, both permanent and seasonal, from the catchment area, is very vulnerable. The risk factor of this dam is very high as a result of projected rainfall variability and climate change in this current 21st century. The climate change projections indicate that there is a high rate of rainfall variability, which is a factor in decreasing trends.

Rainfall data collected from the Kamburu catchment area showed a declining trend from the year 2000 to 2023. The area records a negative annual rainfall of -0.5897mm each year. This further translates to a future decadal decrease of rainfall of about 5.9mm and, if this trend is further sustained, a further decrease of 58.97mm of rain in a century to come. This decrease in rainfalls is so high that it can lead to a high loss of water resources, hence greatly affecting hydropower production at the Kamburu dam.

Kamburu reservoir volume has had a decreasing curve, suggesting that the volume levels have been going down for the past 24 years except for some years of variability. The volume has recorded a negative equation, giving a drop of -0.0922M³ every year. This translates to 92200M³ of water lost in the reservoir every year. The projection in 10 years gives a drop of 922000M³ of water in the reservoir.

This study concluded that the Kamburu catchment has had decreasing rainfall over the last 24 years caused by climate change. The decreasing rainfall led to decreasing Kamburu reservoir volume and further led to declining power output.

Recommendations: This study, therefore, recommends afforestation and re-afforestation activities in the Kamburu catchment areas. Planting a community of trees to increase vegetation cover around the Kamburu reservoir will check soil erosion and lessen sedimentation in the dam. This will also lead to a micro-climate around the catchment area, reducing the rate of evaporation of reservoir water. The government of Kenya, in collaboration with Kengen management, should upgrade the Kamburu dam infrastructure to make it climate-resilient in order to make the dam withstand the temporal climatic variabilities. The Kengen company should devise a mechanism for adapting water management techniques that conform to rainfall variabilities, thereby having measures that spell out how the water in the dam should be best controlled and used. Kengen should also carry out a thorough assessment of the possibility of hydropower water recycling technology in order to devise a technology measure for reusing water to generate power. This makes sure that the water used to run turbines doesn't go to waste even during periods of rainfall shortage. The government of Kenya should prioritise the allocation of enough funds in the energy production and climate change mitigation sectors to assist in research on climate change mitigation as well as increasing hydropower generation in the energy sector. Finally, the government of Kenya should contract professionals who remove silt and sentiments from the Kamburu reservoir, for this has the potential to increase water yield in the Kamburu reservoir.

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