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Influence of Spatiotemporal Variability of Rainfall on East African Shared Surface Water Resources (Case of Lake Victoria)

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Abstract: Studying rainfall distribution is important for sustainable water resource control and economic activities. This research explored seasonal and annual spatiotemporal rainfall variability and trends in East Africa and their impacts on Lake Victoria water levels to update information to support planning, management, and improvement of water-dependent socio-economic activities. Surface water observations for both the satellite (DAHITI altimetry) and ground station for 30 years were used in the study. The datasets were normalized, and analysis of rainfall variability and trends was carried out to determine its influence on lake victoria water levels the shared lake of East Africa. Study results showed an rise in water levels in Lake Victoria for the previous 30 years. The precipitation trends indicated a non-significant increase, as verified by Mann Kendall and the linear fit (Sen's) test. Moreover, there was an obvious variation in seasonal rainfall, where rainfall seasons was varying much compered to dry seasons. Significant correlations were observed between rainfall from Bunjumbura and Gisozi ground-based rainfall stations and Lake Victoria water levels, although a weak relationship exists with other ground-based stations around the Lake Victoria basin. The study concludes that rainfall affects the variations in the lake water levels to a lesser extent; hence, it is recommended considering the analysis of other different water resources in the Lake Victoria catchment, especially inlet rivers and ground water. The evidence acquired from this research will be important for decision-makers to take proper adaptive measures in water resource management.

Keywords: *Rainfall Variability, Water Levels, Lake Victoria, East Africa.*

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I. INTRODUCTION

Water resources are already demonstrated to have been affected by natural and anthropogenic factors, resulting in an increased frequency and severity of extreme weather events globally. If international environmental complications are to be addressed efficiently, a harmonized international approach is required (Schmidt et al., 2016), (Dibbern & Pavan Serafim, 2022).

East Africa experiences varying rainfall, where some areas receive heavy rains that have result in property damage and death of both livestock and human beings, while other areas are affected by drought and subsequently severe famine (Gebremeskel et al., 2019). This pattern of alteration prompted research aimed at identifying whether rainfall patterns have been varying and their impacts on lake water levels (Wilcox E. J., 2022.). Studying the temporal and spatial features of rainfall is very crucial to water resource planning and management (Awange et al., 2008); (Herrnegger et al., 2021).

Other studies indicated that hydrological procedures are characterized by high inconsistency of rainfall both in space and time, recognizing them as sensitive to small-scale temporal and spatial precipitation variability (Cristiano et al., 2017). Over the last decade, water bodies in East African region have witnessed an increase in water levels, area coverage, and volume, thus negatively impacting the rich neighboring biodiversity, infrastructure, and living of the local communities (Herrnegger et al., 2021).

Rainfall is a vital parameter for the lake's ecological system, as it accounts for a large percentage of its recharge (Awange et al., 2008; Herrnegger et al., 2021). Elsewhere, it has been indicated that water cycle processes are categorized by high variability of rainfall both in space and time, qualifying them as sensitive to small-scale temporal and

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spatial rainfall inconsistency (Cristiano et al., 2017). Rainfall is proved as one of the main sources of water that pours into the lake; therefore, its variation in water levels should be of paramount importance. Perhaps, rainfall variability and the associated rainfall events have over several decades caused abrupt changes in water levels, transport difficulties, socio-economic losses (due to the loss of fish), and famine. Recently, the water level of Lake Victoria has extended to extraordinary heights as a result of increased rainfall in the East African region, which started in August 2019 (Mafaranga, 2020).

According to Awange et al. (2008), Lake Victoria's water height has been reducing at an alarming rate and threatening all socio-economic activities associated with it over the last decade; however, several lakes over the East African regions have witnessed an increase in the water levels, volume, and area, thus impacting the neighboring biodiversity, organization, and lives of the local societies (Herrnegger et al., 2021).

In recent years, extreme events, such as drastic water level changes, have caused the public to outcry for attention. The diverse threat of high water levels from Lake Victoria caused the shutdown of several socio-economic activities such as the fishing industry, small-scale market centers, recreation centers, agriculture, disease outbreaks, displacement of downstream communities, etc. The surrounding areas of the Lake Victoria basin and the Kampala metropolitan area in Uganda were submerged by floodwater, affecting the transport and movement of people and goods. This affected the lives of many people living around the Victoria basin, as it was reported that over 200,000 people were displaced because of the floods (Mafaranga, 2020).

Variations in the rainfall amounts within the Lake Victoria basin have raised several concerns, and several scientists have recommended the need for continuously carrying out temporal analysis of rainfall using updated datasets to analyze the present trends in rainfall over the basin (Kizza M. W., 2010.). Thus, this study aims to investigate seasonal and annual spatial-temporal inconsistence trends of precipitation in East Africa and its impacts on Lake Victoria water levels to update information to support planning, management, and improvement of water-dependent socio-economic activities.

II. MATERIALS AND METHODS

A. Area of Study

The study concentrated on the Lake Victoria basin, which comprises five nations located in the Eastern region of the African continent. The area is enclosed within the geographical latitudes 5.11° N to 11.75° S and longitudes 29.0° E to 41.89° E. Lake Victoria is a low-water lake made as a result of a topographical system identified as warping. It is well-thought-out one of the most significant shared natural resources of the East African Community countries Thomas C. Johnson, Kerry Kelts, and Eric Odada 2015)., Henry Wichura et al 2018). The lake is shared by Kenya with 6%, Uganda with 43%, and Tanzania with 51% of the total area of 69,000 km^2. Rainfall is a very critical factor in the lake's ecological system, as precipitation accounts for 80 percent of the recharge of Lake Victoria (Awange et al., 2008; Herrnegger et al., 2021). There are also rivers such as Kagera, which originates from Burundi and Rwanda, and other streams that recharge Lake Victoria, which all account for about 20% (Awange et al., 2008).

Generally, East Africa has two main rainy seasons; that is March, April, and May (MAM), usually known as the ‘long rains’, and October, November, and December (OND) declared as the ‘short rains’ (Gamoyo et al. 2015; (Majambo Gamoyo, 2014), Ongoma and Chen 2017). Ogwang et al. 2016; The rain is also affected by atmospheric phenomena such as the El-Nino Southern Oscillation (ENSO) (Gan and Ntale 2004) also the Indian Ocean Dipole (IOD) (Caroline C., 2009) (Behera et al. 2005). The El Niño Southern Oscillation (ENSO) occurrences are strongly related to the inter-annual variability of precipitation in this area (Indeje et al. 2000).

In the current study, to explore the spatiotemporal variability of rainfall, 13 rainfall stations in the East Africa region, namely Entebbe, Kampala, Jinja, Kampala, Bukoba, Musoma, Mwanza, Kisumu, Gitega, Bujumbura, and Gisozi were considered. The position of designated stations is shown in Fig. 1. Regular datasets for rainfall and water levels were attained from the Uganda l Meteorological Department and the Directorate of Water Resources Management covering the Lake Victoria catchment. The data period varied across several regional climatological stations; therefore, only 30 years (1990–2020) of records have been designated as a common period between all stations and finally transformed into monthly data. To examine the monthly descriptive statistics of precipitation, statistical features like mean and median were used. The coefficient of variation was used to determine the distribution.

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Fig 1: Map of Lake Victoria Basin in East Africa Displaying the Location of Meteorological Stations

B. Climate of the Area

The location of Lake Victoria extents to latitudes 0.33° N–3° S and longitudes 31.67° E–34.88° E and is the third biggest lake in the world after Lake Superior the second and Caspian Sea the biggest of the Great Lakes. It receives annual rainfall of about 1200.0 mm throughout the year, usually distributed into two different rainfall seasons (Nicholson, 2017). The Lake Victoria basin has a bimodal rainfall structure, with one long rain season which approximately stretches from March to May (MAM) that coincides with the ITCZ (Intertropical Convergence Zone), which follows the overhead sun around March 21st (Kizza et al., 2009; Nicholson, 2017). This is followed by a long dry season stretching from June to August (JJA). A shorter rain season is experienced from September to November (SON), followed by a short dry season in the following months of December to February (DJF) (Ogwang et al., 2016).

Like most areas of East Africa, the lake basin climate is affected by synoptic systems such as intertropical convergence zone, subtropical anticyclones, tropical cyclones, monsoons, global sea surface temperatures, El-Nino and southern oscillation (Cai et al., 2020).

C. Data Collection and Sources

To determine the long-term spatial average (1981–2020) annual and seasonal rainfall changeability over the Lake Victoria basin, meteorological Hazards Group Infrared Rainfall with Station datasets version 2 (CHIRPS2.0) basing on thermal infrared (IR) from geostationary satellites were used. It is composed of a spatial resolution of 5km (0.05 degrees) and a daily temporal resolution. CHIRPS2.0 began in 1981 and is prolonged to the present time (2023, in this study). It is based on cold-cloud duration from two geosynchronous thermal IR archives produced by NOAA. The thermal IR data are combined with African gauge data, using 'smart' interpolation methods that consider the spatial correlation arrangement. The CHIRPS2.0 data have low bias and better gauge coverage over Africa compared to other related products (Bathsheba et al., 2020; Ngoma et al 2021).

For in-situ data Meteorological stations around Lake Victoria basin (the study area), which include Entebbe meteorological station under the Uganda National Meteorological Authority, Kisumu weather station in Kenya, and Musoma, Bukoba, and Mwanza meteorological stations in Tanzania, Gitega, Bujumbura in Burundi, and Gisozi in Rwanda were considered. Lake Victoria water level data were obtained from the DAHITI satellite altimetry database: https://dahiti.dgfi.tum.de/en/products/water-level-altimetry/. The in-situ (ground observation station) precipitation and DAHITI lake level statistics were used to investigate the trends and relationship between the two variables.

III. METHODS OF DATA ANALYSIS

A. Data Analysis and Tools

Python: Python which is a computer software design language, to automate tasks, and conduct data analysis was used for statistical computing and graphical analysis. Time series plots, trend, and correlation analysis were performed using the normalized rainfall and water level records. Graphical methods were applied to examine the seasonal and annual time series and trends of the two variables for 30 years. The seasons considered were March, April, and May (MAM), June, July, and August (JJA), September October November (SON), and December and January February (DJF).

The correlation between the variables was investigated using the Pearson correlation coefficient (r). Pearson correlation coefficient (r) is the utmost common and powerful way of calculating a linear correlation considering the normal distribution of the variables. It is a number between –1 and 1 that determines the strength and direction of the connection between two variables (Chen et al., 2023). The Pearson correlation coefficient also describes whether the slope of the

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line of best fit is negative or positive. Once the slope is negative, r is negative. When the gradient is positive, r is positive. When r is 1 or -1, all the points fall exactly on the line of best fit: When r is greater than 0.5 (strong positive correlation) or less than -0.5 (strong negative correlation), the points are close to the line of best fit: When r is between 0 and 0.3 or between 0 and -0.3, the points are far from the line of best fit: (weak positive correlation) or less than -0.5 (weak negative correlation) respectively. When r is 0, a line of best fit does not help describe the correlation between the variables: (no correlation). calculating the Pearson correlation coefficient (*r*) is as shown in equation 1:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2 \, n\sum y^2 - (\sum y)^2}} \quad \text{.............................(1)}$$

Where x is the independent variable (rainfall), y is the dependent variable (lake level), n is the sample size, and Σ represents a summation of all values.

B. Grid Analysis and Display System (GrADS)

Spatial analysis that was critical in investigating spatial variability of rainfall was performed using Grid Analysis and Display System (GrADS).

The Grid Analysis and Display System (GrADS) is an collaborating desktop tool that is used for easy access, manipulation, and visualization of earth science data, (H. Johan et al 2018). The format of the statistics may be either binary, GRIB, NetCDF, or HDF-SDS (Scientific Data Sets). GrADS uses a 4-dimensional data environment: longitude, latitude, vertical level, and time. Data sets are placed within the 4-D space by use of a data descriptor file. GrADS understands station data, as well as gridded data, and the grids, may be regular, non-linearly spaced, Gaussian, or of variable resolution. Joe Wielgosz, 2003. In this study, the NetCDF data format was used.

OriginPro was used for temporal (Annual and seasonal) analysis of rainfall inconsistency in the Lake Victoria water basin and was objectively assessed for graphics generation.

IV. OUTPUTS AND DISCUSSION

A. Spatial Variability of Rainfall

The spatial distribution of mean (30-year average) annual and seasonal precipitation (rainfall) across the area study was examined during the observation period (1991-2020), as depicted in Figures 2 and 3. The spatial distribution of mean Annual, MAM, and JJA rainfall (Climatological) over the Lake Victoria basin in East Africa. During the SON season, the rainfall distribution shows that climatological mean rainfall decreases to the south, while during the DJF season, the rains are concentrated in the south in agreement with the position of ITCZ. In this study, a large portion of the area (about 70%) of Lake Victoria basin experiences a mean annual rainfall of 900 to 1500 mm, followed by a category of 1500 to 2300 mm (about 20% areal coverage), and about 1 % of the area receives the highest level of the mean annual precipitation, ranging from 2300 to 2500 mm. The remaining portion of the basin experiences less than 900mm of rainfall annually on average.

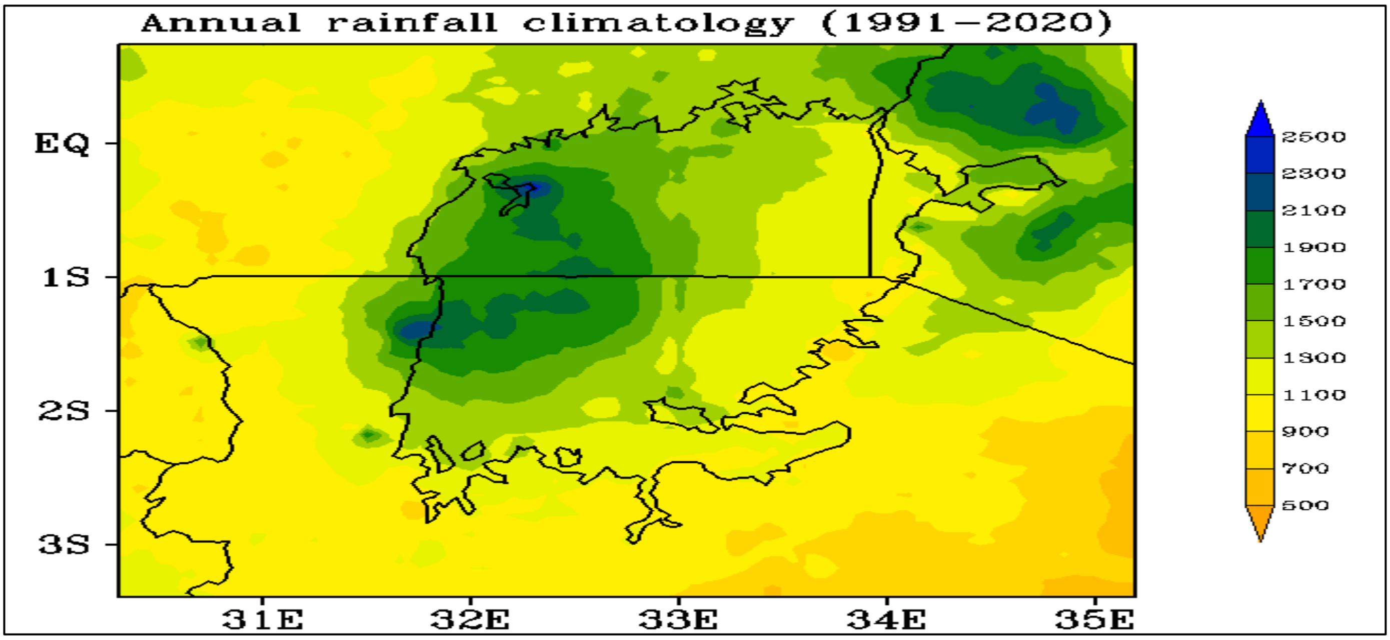

Fig 2: Mean Annual Rainfall Over Lake Victoria Basin in East Africa

Different colors in Figures 2 and 3 indicate different values of rainfall, from minimum (orange) to maximum wetness (deep blue), both annual and seasonal. Climatological average rainfall during the MAM season ranges between 300 mm and 800 mm; JJA mean precipitation ranges between 20 mm and 350 mm; and OND average rainfall ranges between 300 mm and 550 mm. The rainfall characteristics investigated in this section partially describe the seasonal performance and scale factor values determining variations in water levels in Lake Victoria.

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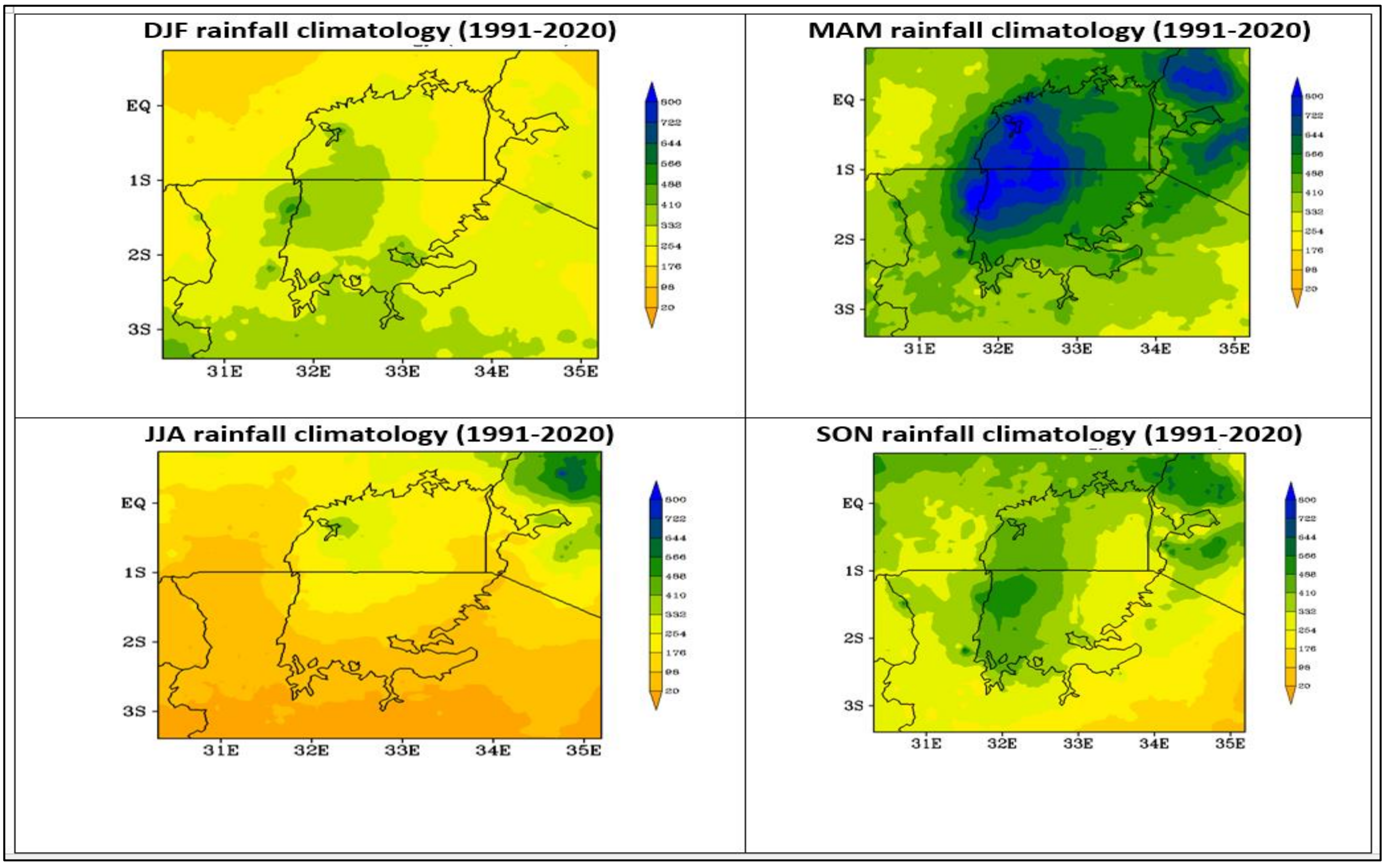

Fig 3: Seasonal Spatial Distribution of Rainfall during 1991-2020.

- *Time Series and Trend of Rainfall.*

The time series of annual rainfall from Kamenyamigo, Kawanda, Jinja, Kituza, and Entebbe ground-based stations.

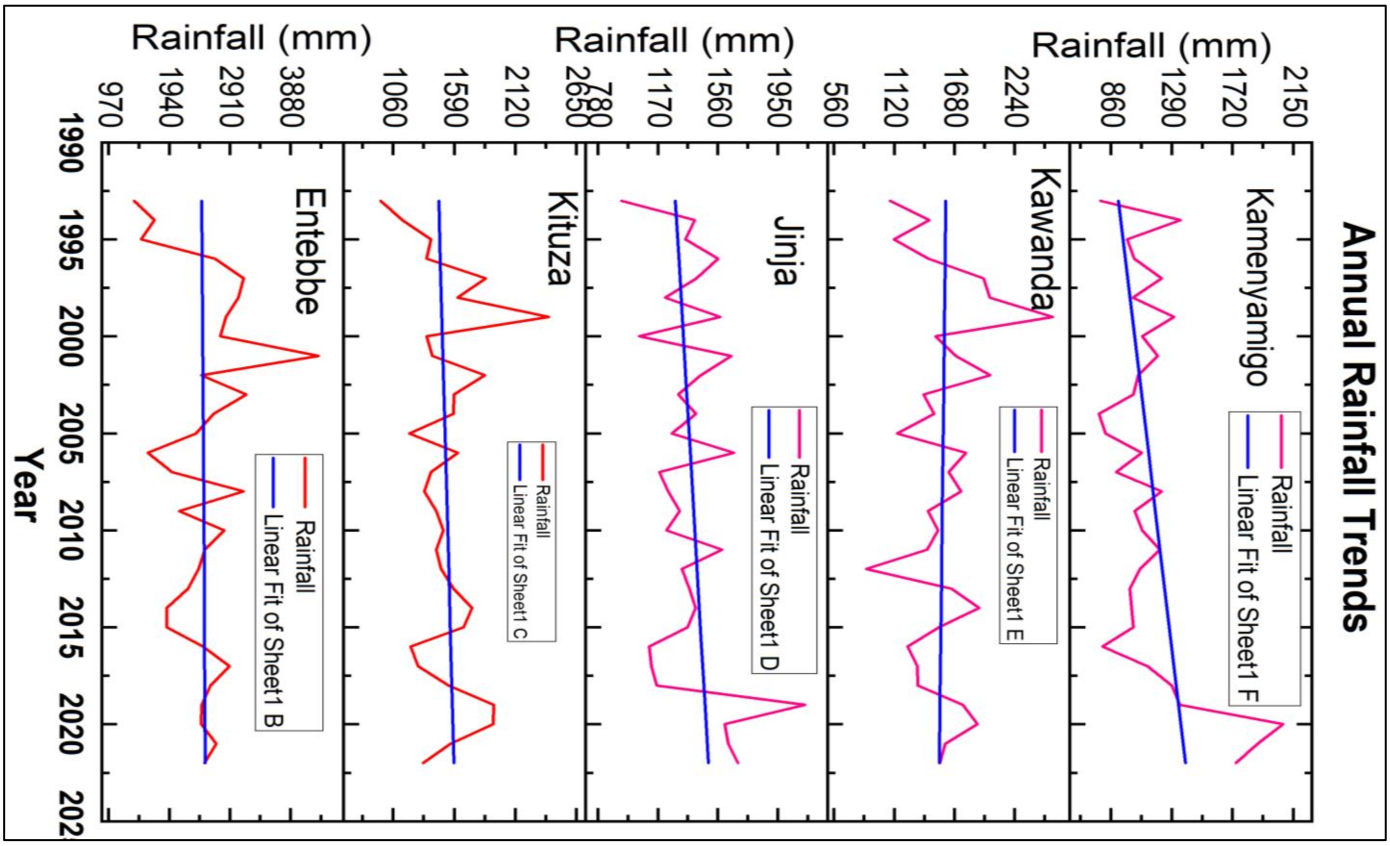

Fig 4: Variation of Annual Rainfall for Ground-Based Stations within the Lake Victoria Basin

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The results show that the highest amount of rainfall of 4365 mm was recorded around 2001 at Entebbe station, and the least amount of about 900.0 mm was registered in 1993 at Jinja. However, almost all stations showed greater temporal variability in rainfall between 1993 and 2010, and an increasing annual rainfall trend between 1991 and 2020, although statistically insignificant when applied through the Mann-Kendal trend test (Tumusiime et al., 2022).

B. Analysis of Water Level Fluctuations

Figures 6, 7, and 8 show the temporal variation of the average seasonal Lake Victoria water level taken from Entebbe station in Uganda. Results revealed that Lake Victoria's water level fluctuated between 10.2m and 13.4m with a constant increase during the JJA and OND seasons from 2005 to 2022.

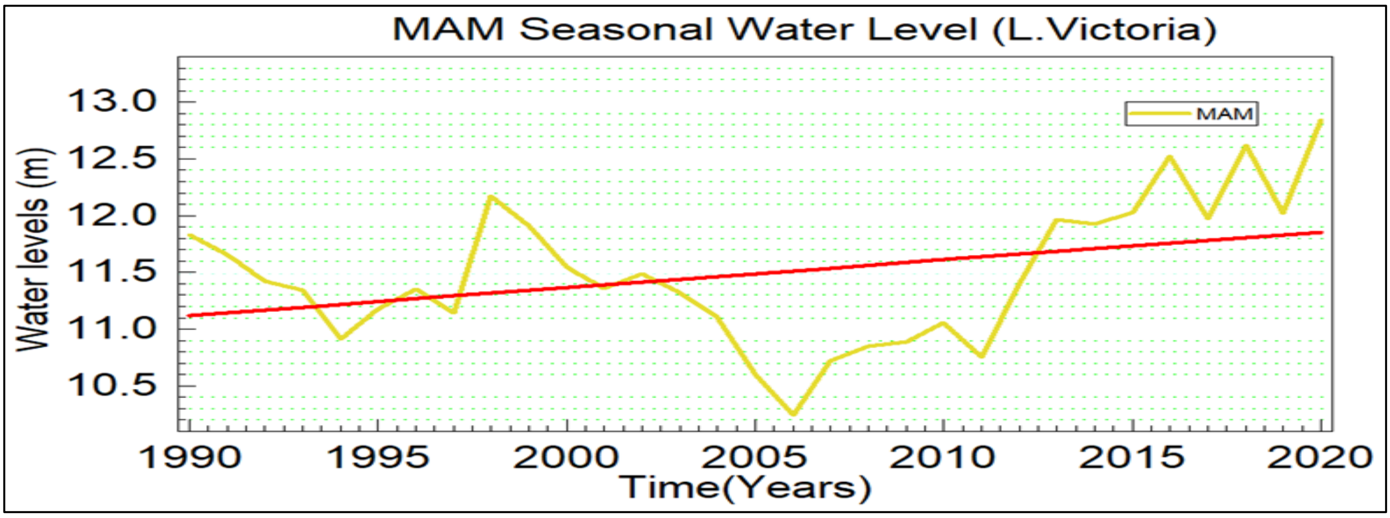

Fig 5: Seasonal Fluctuation of Lake Victoria Water Levels during MAM

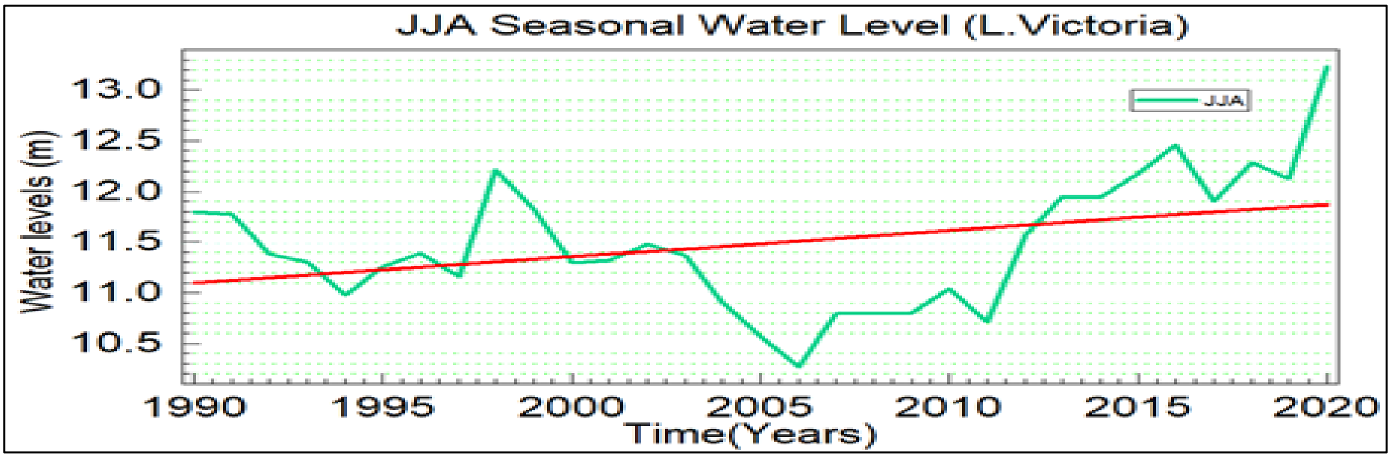

Fig 6: Seasonal Fluctuation of Lake Victoria Water Levels During JJA.

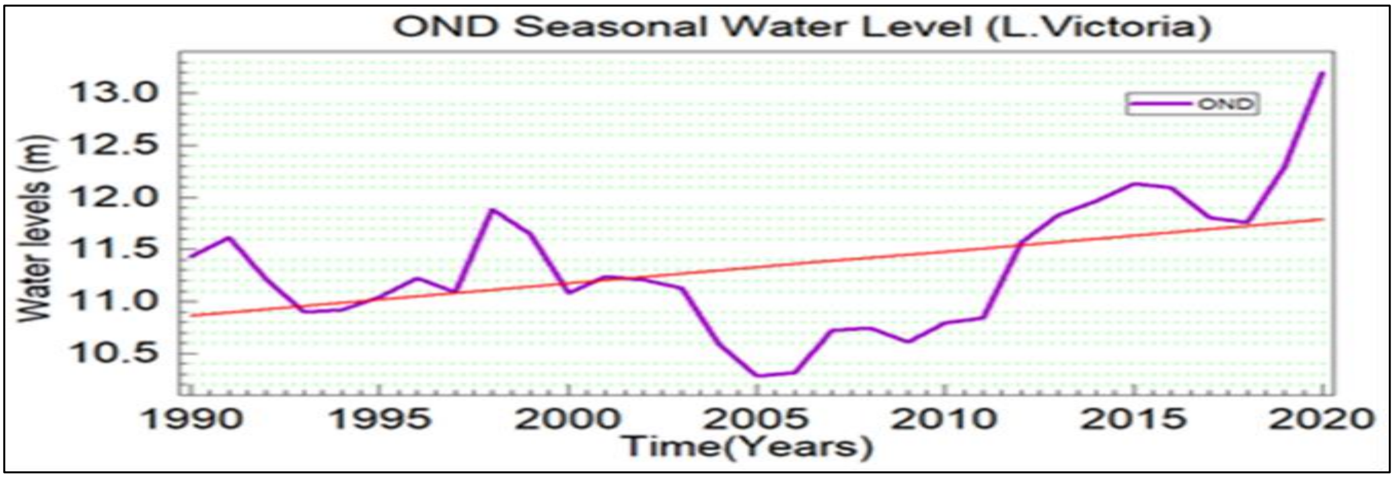

Fig 7: Seasonal Fluctuation of Lake Victoria Water Levels during OND.

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The trends of Lake Victoria water levels are significantly positive, as indicated by the Mann-Kendall test (Table 1). This implies that water levels have been gradually increasing with time for the last 30 years, as indicated in Figures 5, 6, and 7, the increment of water levels generates more negative impact than positive on the social-economic activities of communities living within the lake basin which includes displacement, death of population and lose of biodiversity. In this study it was necessary to compare data sets from different sources, in situ station rainfall indicated significant positive trends for individual stations in Figure 9. There is a significant trend of increasing water levels, which agrees with the known principle that an increase or decrease in rainfall should have a positive or negative significant impact on surface water levels (Stager, 2017), which implies some other factors such as discharges at Owen Falls and Nalubale Dams and inflows from rivers such as Kagera within the lake victoria catchment areas could also influence the fluctuations in lake levels (Hagai, 2019). For that reason, the satellite altimetry dataset from DAHIT data sets was also used for the analysis of Lake Victoria water levels and was compared with the observed datasets. The results indicate that both the observed and satellite-based lake-level datasets showed a similar pattern, as shown in Figures 8 and 9.

➢ *Normalized Water Level Variation (1991-2022)*

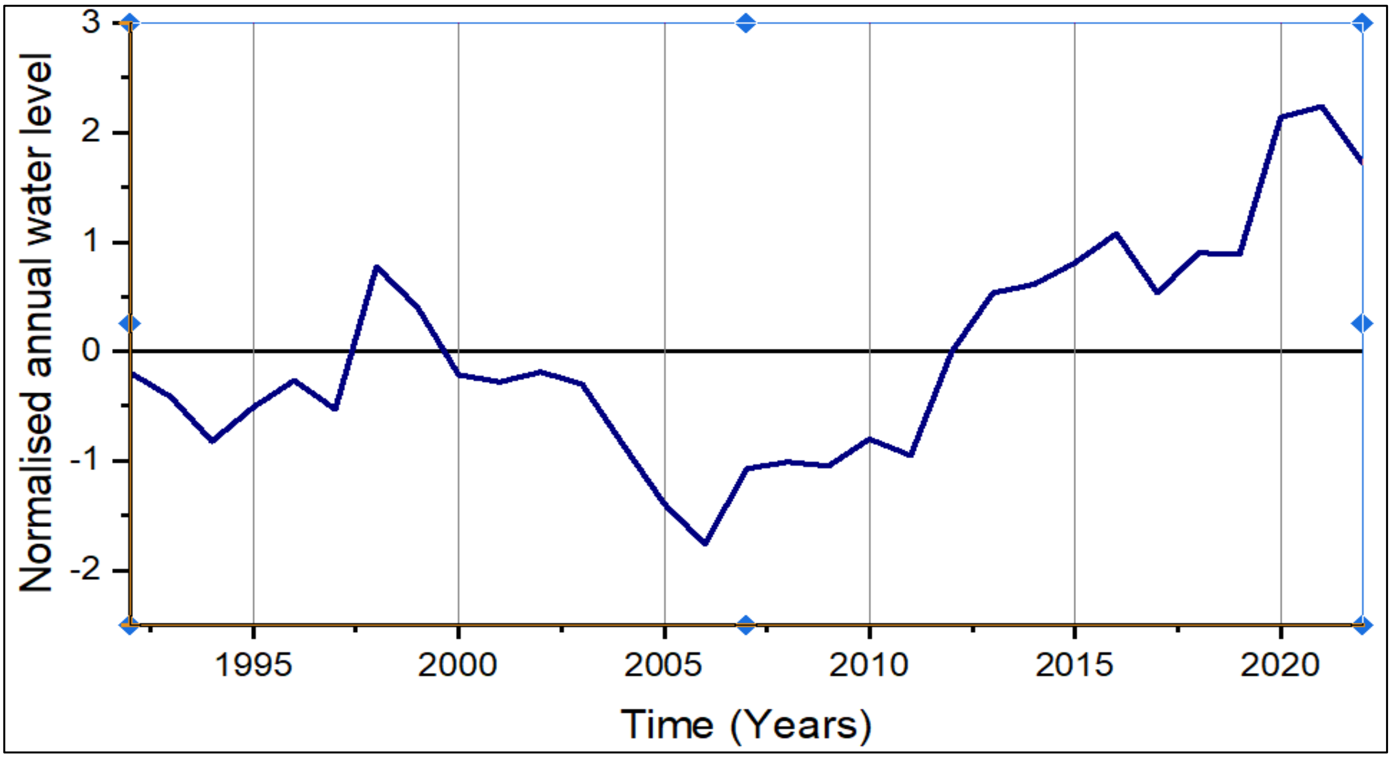

Fig 8: Anomaly of Annual Fluctuation of Lake Victoria Water Levels

The normalized annual water level time series analysis in Figure 8 shows below-average Lake water levels for 9 years from 1991 to 1997 followed by a peak of above average in 1998. Water levels declined for 13 years as fluctuations were in the negative range from 2000 to 2012. It was observed that the water level increased to above average for 10 years from 2012 to 2022. Outputs from the Altimetry dataset analysis from 1991-2023 Figure 9, results indicate that Lake Victoria experienced great fluctuations for the period 1991-2023. The maximum height of 1120.18 meters above mean sea level (MSL) was observed in 2020, followed by 1998, and the minimum height of 1117.62 meters occurred on October 28, 2006. These results show that Lake Victoria's water level dropped by about 2.5 meters during this period. The average height during this period was 1118.74 meters above mean sea level. The fluctuations of the lake height can be divided into six periods, as follows:

- The relatively stable period from 1991 to 1997;
- The significant increase period from 1998 to 1999;
- The sharp drop period from 2000 to 2006;
- The gradual increase period from 2007 to 2016
- The gradual increase period from 2016 to 2018 and
- The gradual increase period from 2018 to 2020

During the significant rise period from 1998 to 1999, the lake height rose by about 1.7 meters; however, the lake levels dropped about 2.5 meters during the sharp drop period from 2000 to 2006. These results are constant according to GRLM, which uses a combination of T/P, Jason-1, and Jason-2 radar altimetry data.

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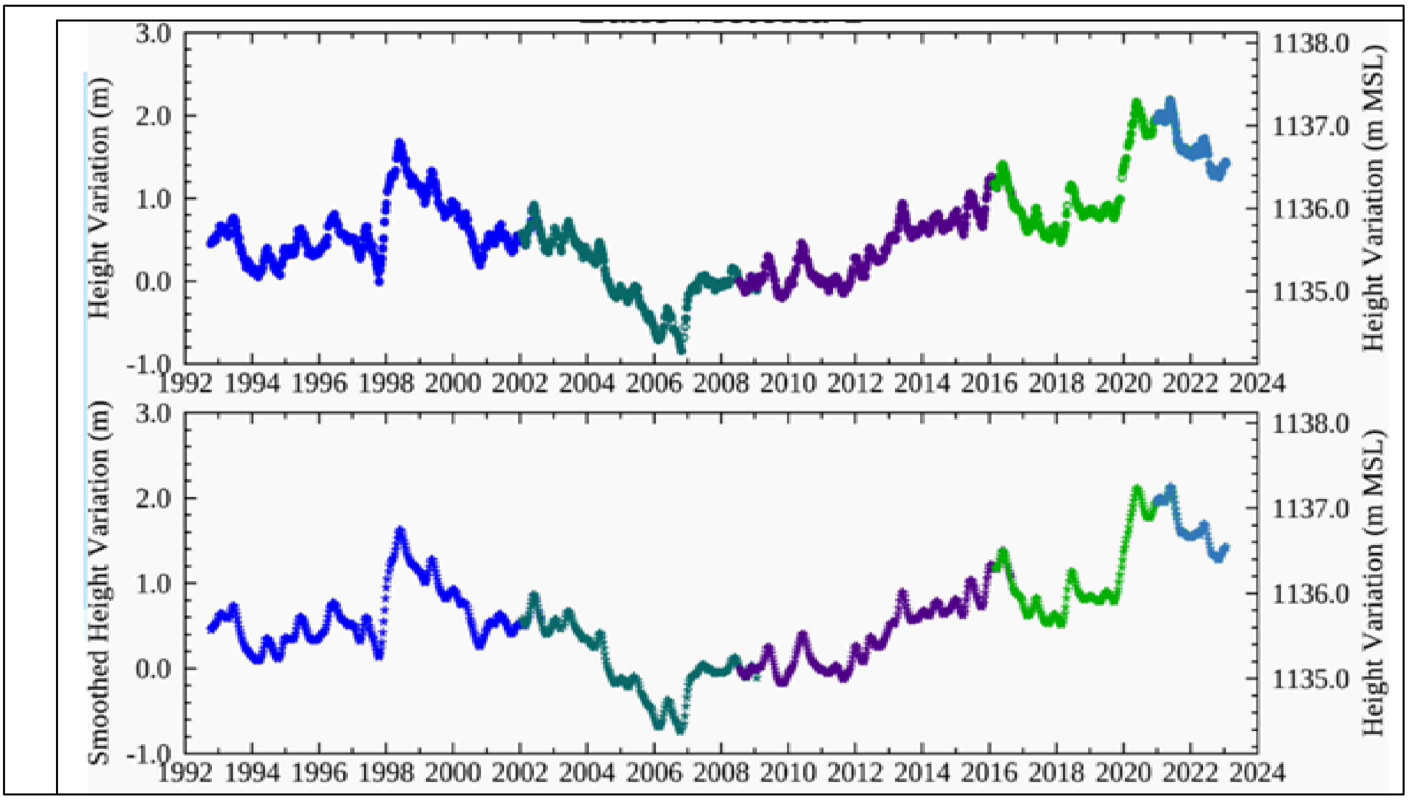

Fig 9: Fluctuations of Lake Victoria Water Levels Derived from DAHITI Altimetry Satellite Station

HYDROWEB, G-REALM altimetry databases, and in-situ water level gauge stations for Lake Victoria from 1992 to 2023. This study considered DAHITI as a source of satellite altimetry datasets for lake level due to its continuity and consistency with in-situ data compared to other external altimeter databases such as G-REALM and HYDROWEB as addressed in the study of Schwatke et al. (2019).

Table 1: Mann Kendall Test Results

Kendall's tau	**0.251**
S	109.000
Var (S)	3141.667
p-value (Two-tailed)	0.054
Alpha	0.050
Sen's slope	0.032

H_0 – there is no trend in the series
H_a – there is a trend in the series

Therefore, since the computed p-value is greater than the 0.05 level of significance, the null hypothesis cannot be rejected. Thus, there is no significant trend in the series of water levels. However, the positive Sen's slope value (0.032) implies water levels present a positive trend besides being non-significant.

Table 2: Summary of Water Level Analysis Results

Minimum	**Maximum**	**Range**	**Mean**	**Standard deviation**
10.24	13.02	2.78	11.40	0.61

The table above shows that over the past 30 years, the maximum recorded water level is approximately 13.02 m, while the minimum is 10.24 m, a range of 2.78 m observed for the period under study. The average water level is calculated to be approximately 11.4 m with a standard deviation of 0.62 m, meaning that the average water level can be less or greater by 0.62 m.

Table 3: Correlation Analysis Results

January	**February**	**March**	**April**	**May**	**June**
-0.0729	0.279434	0.125554	0.091908	0.202014	0.029121
July	August	September	October	November	December
0.06	-0.37	0.08	-0.28	0.08	0.16

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➢ *Interpretation criteria of correlation coefficient (R);*

- +/- R > 0.6 strong relationship
- +/- 0.3>R<0.6 Moderate relationship
- +/- R< 0.3 Weak relationships
- R=0 No relationship

From the analysis in the table above, no correlation coefficient equals zero, which means the two variables, water level, and rainfall are correlated. It further shows that most of the correlation coefficient values are less than 0.3 apart from August which has got 0.37 implying that the relationship ranges from weak to moderate.

January, August, and October have negative correlation coefficients, while the rest of the months have positive correlation coefficients. A negative correlation defines the degree to which two variables move in differing directions, while a positive correlation occurs when two variables move in the same direction. Therefore, for January, August, and October, the variables were in inverse correlation, and vice versa for the rest of the months. The highest absolute correlation between water level and rainfall occurred in August, and it's a negative correlation whereas the lowest absolute correlation of 0.029121 occurred in June.

Applying the seasonal analysis, MAM presents the highest correlation value (positive) although is less than 0.3, implying that it is a weak relationship. DJF also shows a weak positive relationship. The JJA and SON seasons present the least correlation coefficients and negative, meaning the relationship between variables is much weaker and inverse. The annual correlation coefficient is 0.07, which generally shows a weak relationship between the two variables.

Table 4: Seasonal Analysis for MAM Presenting Correlation Between Rainfall and Lake Levels

MAM	JJA	SON	DJF
0.19	-0.11	-0.08	0.13

It is noticed that the correlation coefficients (r) along the diagonal of the table are all equal to 1 because each variable is perfectly correlated with itself. These cells aren't useful for interpretation. The purpose of this study was to calculate and find out the relationship between rainfall and water level. The outcomes indicate that there is a weak positive correlation amongst Lake Victoria water levels and rainfall analyzed from 12 stations within the lake catchment since r is between -0.1 and 0.4. But 2 stations (Bujumbura and Gisozi) indicate a correlation of 0.6 implying that there is a strong positive correlation because r is greater than 0.5.

The outcomes of the research and analysis of spatial-temporal changes in rainfall and Lake Victoria water levels using the Pearson method demonstrate that there was a direct and minor relationship between the two parameters. Pearson linear correlation coefficient revealed a level of 95% confidence, and there is no significant relationship between Water levels and precipitation in Lake Victoria.

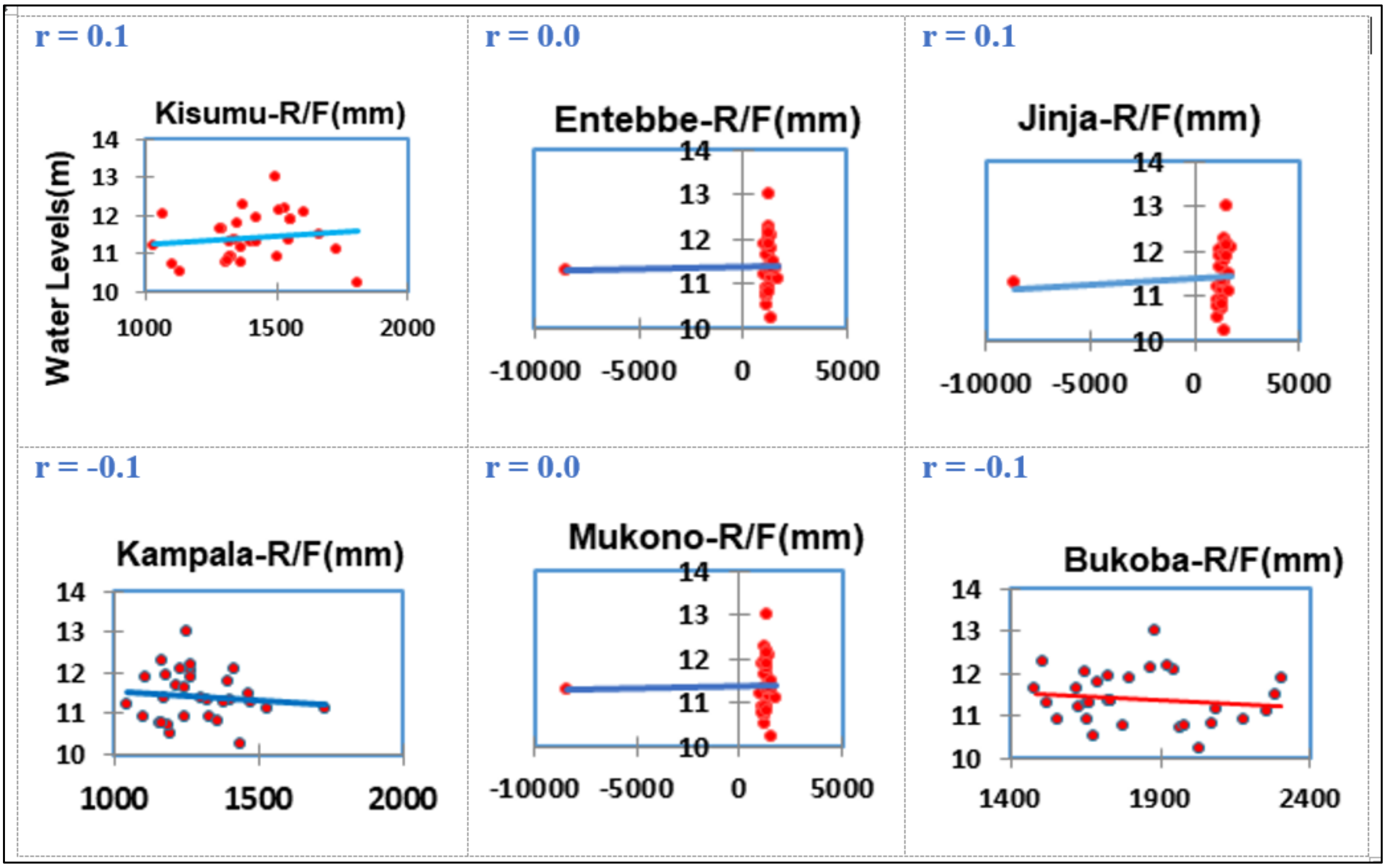

Fig 10(a): The Correlation Between Rainfall and Water Levels

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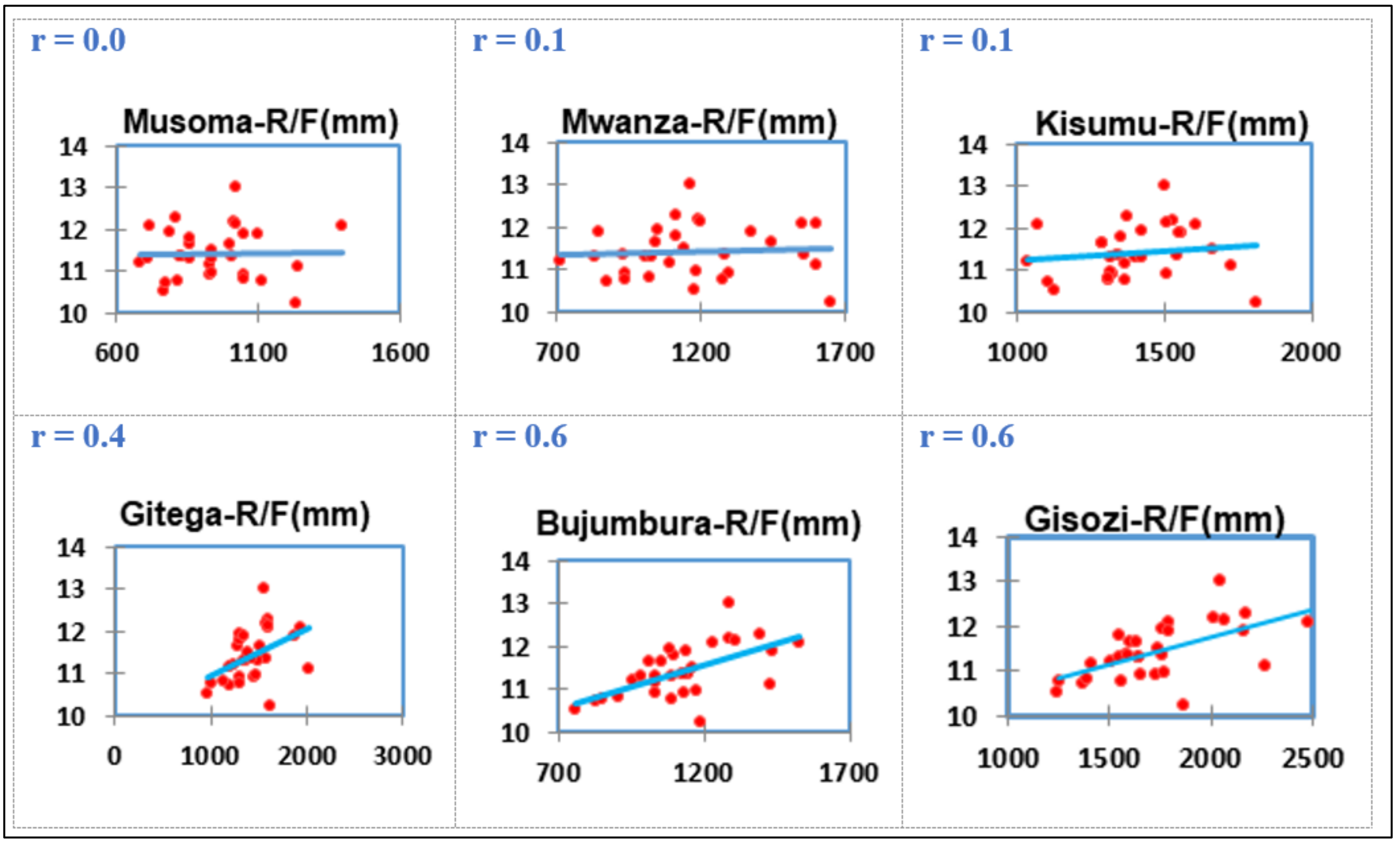

Fig 10(b): The Correlation between Rainfall and Water Levels

Two rainfall stations (Bujumbura and Gisozi) were observed with high correlation where r = 0.6 which is greater than 0.5 implying a "strong positive correlation" as indicated in table 9. The results above are generated with the application of a correlation matrix (Pearson) running from 'Origin Pro.

V. CONCLUSION AND RECOMMENDATIONS

Rainfall and water levels are important climatic parameters affecting socio-economic activities and livelihoods. Geospatial analysis plays an important role in mapping, and examining spatial and temporal changes, as well as aiding water resource planning. In this study, spatial analysis was done using the GrADS software package to assess rainfall inconsistency in the area of study in the Lake Victoria basin. Statistical analysis reveals a weak to moderately strong relationship between lake levels and rainfall causing water levels to increase to the highest peak of 13.4m. Water rise at this height means loss of property and life which requires much attention considering more research on the projections and forecasting of water levels for future life protection and water management for economic development along Lake Victoria and East African countries.

It is necessary to conduct further studies on the water levels of Lake Victoria and major inlet rivers to identify trends and the cyclicality of their variability and assess their relationship with other factors such as changes in land use/land cover, soil infiltration, evapotranspiration, rivers flow, and discharge. Exceptional attention should be paid to further calibrating and validating satellite data from G-REALM and HYDROWEB satellite altimetry because they vary significantly from each other and in-situ datasets at the local water level gauge stations. The relationship between altimetry and in-situ data could support in the re-calculation of water level information specific for Lake Victoria, River Kagera, and other basin inlet major rivers. All these efforts will make it possible to improve forecasting services for management and the safe operation of the lake for sustainable development.

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DECLARATION

All writers have revealed no conflicts of interest. The project was funded by the first Author. We at this moment state that the article authored by us is an original work. It has neither been submitted for publication nor published elsewhere in any print/electronic form. It does not infringe on the rights of others and does not contain any libelous or unlawful statements.

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