ATTRIBUTION ANALYSIS OF CLIMATE CHANGE AND HUMAN ACTIVITIES TO WATER VOLUME VARIATION IN LARGE LAKES

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ABSTRACT:

Lakes are important components of the Earth's surface water bodies, and their fluctuating water levels and changing water volumes can have an important impact on ecological processes and landscape patterns within a watershed. Climate change and human activities are the main drivers of water volume changes in lakes. We applied a long time series analysis approach using classical statistics and geographic information system (GIS) technics to quantitatively attribute water volume variations in Lake Victoria from 2000 to 2019. We examined several drivers of lake water volume variations: meteorological factors including regional climate change (precipitation, evaporation) and global climate change (El Niño/Southern Oscillation events), and anthropogenic factors including socio-economic development and land use/cover change. The results show that regional climate change has a greater impact on lake water volume variations than global climate change; among them, the correlation coefficient between precipitation and lake water volume variations is the largest (0.410), with an impact lag of 1 month. For anthropogenic factors, variations in lake water volume are more pronounced in areas with rapid economic development and high population growth, with correlation coefficients greater than 0.440. Different types of land use/cover have varying impacts on Lake Victoria's water volume variations. Overall, the influence of anthropogenic factors is greater than that of meteorological factors. This study results not only provides a scientific basis for exploring the hydrological changes and their drivers in the world's large transboundary lakes, but also be great scientific significance to rational use of water resources and sustainable regional development.

1. INTRODUCTION

Lakes regulate regional climate, record environmental changes and maintain ecological balance; they are one of the most significant components of the Earth’s surface water (Vasistha and Ganguly, 2020; Cao et al., 2021). Among the many elements of water systems, lake water volumes are highly sensitive to climate change and profoundly affect water and energy exchange between the surface and the atmosphere (Lu et al., 2013; Tong et al., 2016). As global temperatures rise, the Earth will face more extreme weather events, which will have a major impact on the world's and regions' existing lakes (Jeppesen et al., 2014; Woolway et al., 2019). Rapid urbanization accompanied by economic prosperity and population growth also has the potential to alter the hydrological characteristics of the subsurface of lake basins, which could have a substantial impact on lake water elements (Yang and Ke, 2015). Therefore, further attribution analysis of lake water volume variations is necessary to provide a scientific basis for sustainable solutions for climate change adaptation and water conservation.

In recent decades, the impacts of climate change on lake water elements have been increasing attention in the international geographical and ecological field (Shadkam et al., 2016; Yunana et al., 2017). Climate change directly leads to variations in precipitation and temperature, with temperature variations closely related to changes in evaporation and water vapor content (Trenberth, 2005; Warnatzsch and Reay, 2019). Water balance models show that meteorological factors such as precipitation and evaporation will directly affect lake water dynamics (Kumambala and Ervine, 2010), while potential climate change will also alter vegetation patterns and soil properties within the watershed, which will further have complex impacts on lake water volumes. For watersheds with rapidly evolving climate, more attention should be paid to the persistence of precipitation, evaporation, and temperature changes to avoid drought/flood disasters (Zhang et al., 2023). In the literature, intense urbanization and the rapid evolution of land use/cover patterns are equally significant in affecting the water component of lakes (Yang et al., 2020; Bucak et al., 2018; Mugo et al., 2020). Accelerated urbanization implies population growth and economic development, which increases water consumption and pollution (Zhao et al., 2013). The land use/cover dynamics induced by human activities are mainly reflected in the encroachment of ecological land by urban expansion, visually manifested in the shrinking area of lakes and wetlands (Gao et al., 2020; Xie et al., 2017; Mo et al., 2023).

To address the attribution of water volume variations, lake water volume variations should be analysed for a long time series of observations, as long-term hydrological reconstructions allow recent trends and extreme climate events to be studied in a broader context. Meanwhile, the causes of water volume variations should be understood by a multi-factorial analysis of climate change and human activities. There are several transboundary water bodies in the world, such as Lake Victoria

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in Africa, which is rich in resources but the surrounding countries are mostly underdeveloped economies. In recent years, overfishing and deforestation have led to erosion in Lake Victoria, triggering lake pollution and climate changes (Nassali et al., 2020), which have combined to affect hydrological changes in Lake Victoria, particularly rapid variations in lake water volume. The hydrological and political implications of transboundary waters are enormous and require the joint attention of scientists and policy makers (Shams and Muhammad, 2022). Such a large lake is therefore deficient in terms of water use and environmental protection, and the evolution of their parameters/indicators (especially water volume) needs joint attention of international research in meteorology, hydrology and geography. There is an urgent need to monitor spatio-temporal trends in lake water volume change over long time series and to analyse the effects of climate change and human activities on water volume dynamics. There are two types of questions need to be investigated: 1) What are the laws governing the spatio-temporal evolution of lake water volume and its drivers, and 2) How do meteorological and anthropogenic factors influence variations in lake water volume?

In this paper, supported by multi-source satellite data and based on the "water level-water area-water volume" model (Lin et al., 2020), we estimated the water volume variation of Lake Victoria from 2000 to 2019, and analysed its spatio-temporal evolution characteristics and quantitatively attributed the causes. Based on remote sensing and Geographic Information System (GIS) technologies, we conducted a study using statistical methods and spatial analyses. First, we investigated the spatio-temporal variation characteristics of meteorological factors (including precipitation and evaporation, which represent regional climate change, and El Niño/Southern Oscillation (ENSO) events, which represent global climate change) affecting the water volumes of Lake Victoria, and analysed their correlation with the water volume variations. We then explored the impacts of anthropogenic factors such as economic development, population growth and land use/cover changes on the lake's water volume variations. This study reveals the relationships among socio-economic conditions, land use/cover changes, basin climatic factors and water volume in Lake Victoria, which can provide a scientific basis for potential water resources protection and regional environment improvement.

2. STUDY AREA

Lake Victoria is located on the East African Plateau, covering an area of approximately 69400 km², making it the largest lake in Africa and the second largest freshwater lake in the world (Figure 1). It is a tectonic lake formed by the subsidence of the entire earth's crust, and its genesis is completely different from that of other large lakes in the East African Plateau (Khaki and Awange, 2021). It lies on the equator at an altitude of 1134 meters above sea level and has a savannah climate (Awange et al., 2019). The average annual temperature is about 26°C, with visible seasonal variations. The lake evaporates at a high rate due to abundant sunlight. Precipitation is strongly influenced by the seasons, with most of it falling during the rainy season (March-May and October-November each year). The precipitation mainly originates from the monsoonal circulation near the equator, with the equatorial side being well-watered and gradually decreasing from east to west (Akurut et al., 2014). Overall, it is a wetland lake with high precipitation and evaporation (Kizza et al., 2012),with the water level fluctuations are mainly caused by precipitation and dam runoff. The lake is surrounded by a tropical rainforest climate zone with a rich and diverse vegetation, dominated by palm trees, banana trees and plantain. The soil is silty and rich in nutrients, making it suitable for agricultural production.

Lake Victoria is the boundary among Tanzania (TZA), Uganda (UGA) and Kenya (KEN), these three countries control 51%, 43% and 6% of Lake Victoria respectively in terms of area (Egessa et al., 2020). The lake basin is rich in aquatic products and has a well-developed plantation industry that supports nearly 30 million people around the lake, making it one of the most densely populated areas in Africa. Therefore, studying the water volume variations in Lake Victoria and analysing their causes is important for the rational use of local water resources, and can also provide a reference for studying the water volume variations in other lakes.

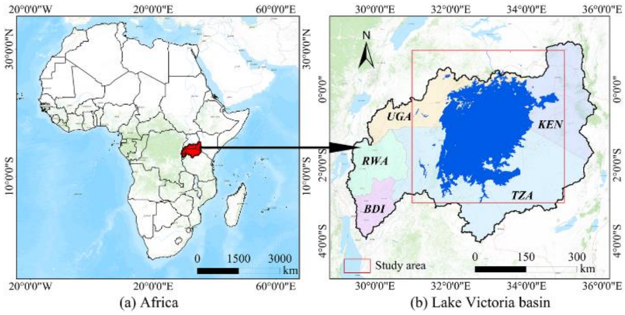

Figure 1. Lake Victoria study area: (a) location; and (b) administrative map of the basin.

3. METHODOLOGY

3.1 Technic route

We have designed an integrated technic route, combining long time series of remote sensing images, statistical data and vector maps with classical statistical and GIS analysis to quantitatively attribute the spatio-temporal evolution of Lake Victoria's water volume over the last 20 years (Figure 2).

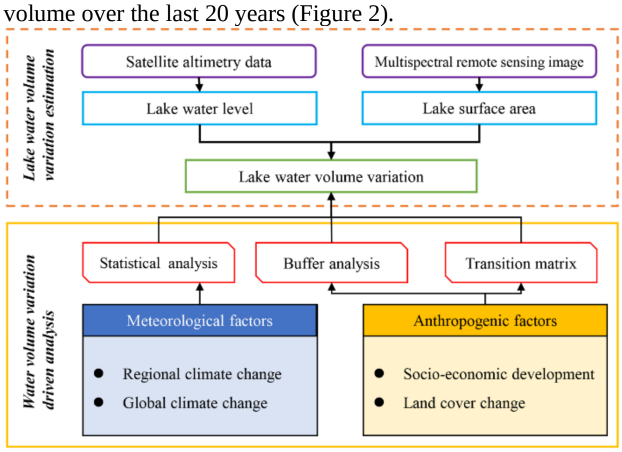

Figure 2. Workflow of this study.

1) Lake water volume variations estimation

Based on the extracted high-precision lake water level and lake surface area, Lin et al. (2020) developed a water level, water area and water volume variations relationship model to estimate the relative water volume of Lake Victoria for the past 15 years. In this study, TOPEX/Poseidon, Jason series altimetry data, Envisat and SARAL (https://www.aviso.altimetry.fr/en/home.html) were used to acquire Lake Victoria water levels; Moderate Resolution Imaging Spectroradiometer (MODIS) images (https://ladsweb.modaps.eosdis.nasa.gov/) were used to extract Lake Victoria surface area sequences. The relative water volume of Lake Victoria from 2000-2019 was estimated by modelling the effective relationship between water level, water area and water volume variations. Earlier studies have shown that the estimated lake relative water volumes can be validated against terrestrial water storage acquired based on satellite gravity data (Lin et al., 2020).

2) Water volume variation factors selection and analysis

In this paper, two types of drivers that potentially have a substantial impact on lake water volume variations were selected: meteorological factors and anthropogenic factors. Meteorological factors include precipitation and evaporation provided by the Tropical Rainfall Measuring Mission (TRMM) 3B43 (from Goddard Earth Science Data and Information Service, https://daac.gsfc.nasa.gov/) and the operational Simplified Surface Energy Balance (SSEBop) ET (from AρρEEARS, https://appeears.earthdatacloud.nasa.gov/). The impact of global climate change is reflected by the ENSO event metrics (from the National Oceanic and Atmospheric Administration, https://www.noaa.gov/). Anthropogenic factors include the Gross Domestic Product (GDP) and population (POP) factors, which reflect socio-economic development, and the long time series of land use/cover factors. We acquired population density data from the Gridded Population of the World Version 4 (GPWv4), GDP and population numbers statistics from the World Bank (https://www.worldbank.org/), and land use/cover maps from the Climate Change Initiative (CCI, https://climate.esa.int/en/). Drivers were collected for the same period as Lake Victoria water volume variations, and then the relationship between water volume variations and drivers was analysed quantitatively using a combination of classical statistics (Mann-Kendall test, correlation analysis and principal component analysis) and GIS spatial analysis method.

3.2 Driver Analysis

3.2.1 Meteorological factors: precipitation, evaporation and ENSO events

The water balance model reflects that precipitation and evaporation are among the meteorological factors that directly affect lake volume (Yin and Nicholson, 1998). Therefore, we chose these two factors to analyse the correlation between lake variations and regional climate changes. Based on TRMM 3B43 images from 2000 to 2019, the monthly average precipitation rate of Lake Victoria was acquired by averaging the digital number (DN) values of pixels located within Lake Victoria (longitude 31°45′−34°E and latitude 0°15′N–2°30′S).

Since the TRMM 3B43 product is a monthly average precipitation rate with a variable number of days per month, the monthly precipitation amount must be calculated based on the number of days per month as follows:

$$P = \bar{p} \times 10^{-6} \times 24 \times Days \times A_m \quad (1)$$

where P (km^3/month) = the monthly precipitation

$\bar{p}$ (mm/hr) = the average DN of the pixels in the TRMM image, which is the precipitation rate

Days=the number of days in each month (Days=30,31,28,29)

A_m= the average area of Lake Victoria over a 20-year period (A_m=66228.74 km^2).

In addition, we acquired the actual average evaporation of Lake Victoria based on the monthly product of SSEBop ET (version 4.0), which was used to analyse the impact of evaporation changes on the water volume. According to the actual average evaporation $\overline{et}$ (mm), the monthly evaporation of the lake can be given as:

$$ET = \overline{et} \times 10^{-6} \times A_m \quad (2)$$

where ET (in km^3/month) = the monthly evaporation.

The above precipitation and evaporation data represent the impact of Lake Victoria's regional climate on lake water volume variations. Against the background of global warming, ENSO has caused global atmospheric circulation, temperature and precipitation anomalies, which can be used to represent the impact of global climate change. The monthly NINO3.4 index, one of the ENSO event metrics based on sea surface temperature, refers to the average sea surface temperature anomalies in the region of 5°N–5°S, 170°W–120°E (Barnston and Tippett, 2013), and can be used to analyse the relationship between lake water volume and ENSO events. The Trans-Niño Index (TNI) is used to measure the gradient of the equatorial east-central Pacific Sea Surface Temperature anomaly, which further differentiates between the Nino 1+2 region and the Nino 4 region. The TNI is often used in conjunction with the NINO 3.4 index to determine the uniqueness of each El Niño or La Niña event (Trenberth and Stepaniak, 2001).

3.2.2 Anthropogenic factors: economy, population and land use/cover

In this study, economic development, population growth and land use/cover change in Lake Victoria and its buffer zone (within a 1° radius of the lake's shoreline) were selected as anthropogenic drivers to analyse the impact of human activities on lake water volume variations.

Figure 3a-c shows the annual GDP and population numbers for three countries around Lake Victoria: Uganda, Tanzania and Kenya. This indicates the economic boom and population explosion in the three countries over the last 20 years. Figure 3d shows the population densities within the three countries and the buffer zone in 2000, 2005, 2010, 2015 and 2020, with annual population density growth rates of 13–18% in the four regions. In particular, the average population density in the Lake Victoria buffer zone is significantly higher than in the three countries, already reaching approximately 279 people/km^2 in 2020. Economic development and population growth led directly to changes in water use, putting Lake Victoria under tremendous water pressure.

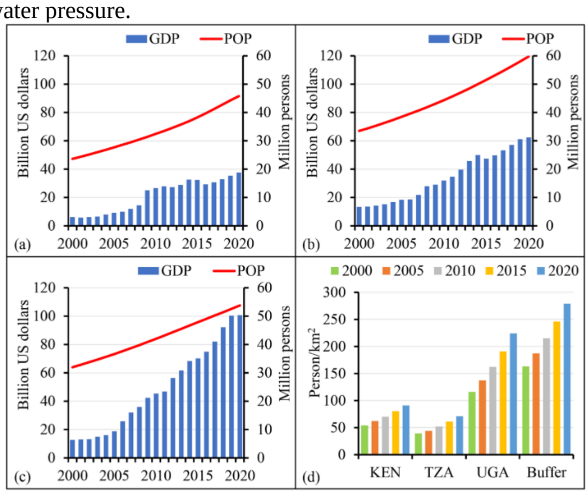

Figure 3. Socio-economic factors of lake water volume variations: (a) UGA, (b) TZA, (c) KEN, and (d) population densities of three countries and buffer zones around Lake Victoria.

The CCI-LC Land Cover Project has produced annual global classification time series based on AVHRR HRPT (1992~1999), SPOT-Vegetation (1999~2012) and PROBA-V (2013~2015). We used the CCI-LC data from 2000 to 2019, with the initial CCI data having a resolution of 300 m for 22 land use/cover categories. In addition to lakes (water body), ecological lands such as wetland, grassland, and forest are important for maintaining the ecological functions of the watershed, while urban and cultivated land have a notable impact on the use of lake water resources. Due to the similarity in characteristics of the land use/cover categories, we reclassified the land use/cover categories around Lake Victoria into 7 categories, which are cultivated land, forest, grassland, wetland, urban, water body and others.

4. RESULTS

4.1 Spatio-temporal variations of lake water volume

Based on the water level-water area-water volume model, we acquired the relative water volume variations of Lake Victoria from 2000 to 2019. Figure 4 shows the lake's relative water volume over the past 20 years, with minimum water volume (0.0 km^3) occurring on October 26, 2006, and the maximum water volume occurring on May 14, 2016, with a maximum variation of 147 km^3. The two periods with the most pronounced variations in water volume are: a) 2000 to 2006, a period of declining water volume, and b) the end of 2006, a period of rapid water volume growth. Earlier studies suggested that this scenario was due to excessive lake discharge and drought. The maximum relative water volume during the year usually occurs in May-June and December, while the minimum relative water volume mostly occurs in October-November and March. Both the maximum and minimum annual water volume occur in December-February and August. This anomaly may be caused by the different arrival and duration of the rainy and dry seasons each year, and the seasonal distribution of precipitation is influenced by various factors such as monsoon, topography, and climate change. In addition, human activities may have directly affected the lake's water volume.

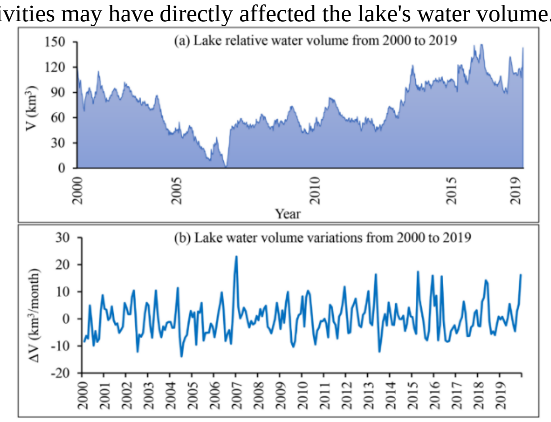

Figure 4. The water volume in Lake Victoria and its variations from 2000 to 2019.

4.2 Meteorological factors impact on lake water volume

4.2.1 Change patterns of meteorological factors

Figure 5a shows the average monthly precipitation rate for Lake Victoria during 2000-2019. Overall, precipitation rates have been relatively variable, with an average rate of 0.19 mm/hr over the 20-year period. In conjunction with Figure 4, there were three water volume changes in Lake Victoria over the 20-year period that were closely associated with extreme precipitation during the same period, occurring in October 2006, April 2018, and October 2019.Figures 5b and 5c show in detail the annual 12-month precipitation rates for Lake Victoria over the last 20 years. The annual peak of precipitation in Lake Victoria occurs mainly from March to May and October to December, showing a double-peak pattern.

From 2003 to 2019, the total annual evaporation rate from Lake Victoria has varied steadily between 1300 and 1310 mm (Figure 6a). Over the past 17 years, evaporation from Lake Victoria has been approximately the same for each month of the year, averaging approximately 108.626 mm, with smaller evaporation from April to June and larger evaporation in October and March (Figure 6b). For Lake Victoria, there are differences in topography, solar radiation, and air humidity exist at different locations, resulting in greater evaporation on the eastern shore of the lake than on the western shore. Relatively high evaporation occurs in the northeastern part of the lake in January each year, showing a southward trend over time, with high evaporation gradually returning to the northern part of the lake in September.

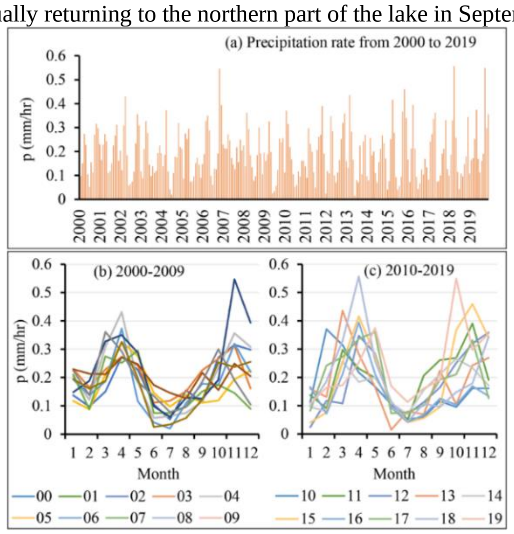

Figure 5. Precipitation rate in Lake Victoria from 2000 to 2019.

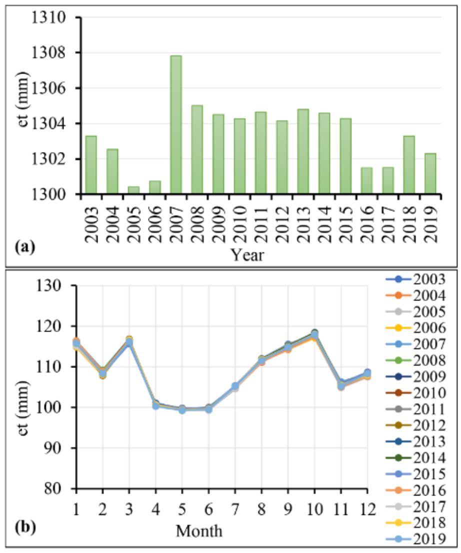

Figure 6. Evaporation rate in Lake Victoria from 2003 to 2019.

Figure 7 shows the monthly NINO3.4 and TNI indexes from 2000 to 2019, which are used to represent the impact of ENSO events over the last 20 years. An ENSO event is identified when the mean value of the NINO3.4 index exceeds +0.4°C for five consecutive months, while a La Niña event is identified when the mean value of the NINO3.4 index exceeds -0.4°C for at least six consecutive months . The frequency of the NINO3.4 index below than -0.4 is 69, while the frequency above than 0.4 is 80. The trend of the TNI is similar to that of the NINO3.4. Temporally, the frequency of La Niña events was higher from 2006 to 2012, while the duration of El Niño events was longer from 2014 to 2016.

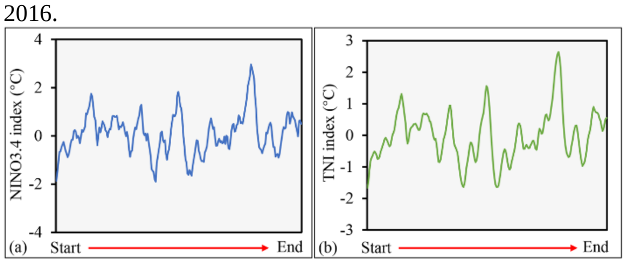

Figure 7. Nino SST indexes (NINO3.4 index and TNI index) from 2000 to 2019.

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4.2.2 Relationships between lake water volume and its meteorological drivers

MK test results show that, for the lake water volume, the test results show a z-value of 7.97 and a p-value of less than 0.01 (Table 1), indicating an increasing and stronger trend in the water volume series. Precipitation and evaporation both have z-values less than 0 and p-values greater than 0.9, indicating a weaker decreasing trend. Both ENSO event metrics show an increasing trend, but the TNI has a stronger increasing trend, while NINO 3.4 has a weaker increasing trend.

Category	z	p-value	N (Sample number)
Water volume	7.9674	1.621e-15	240
Precipitation	-0.044	0.965	240
Evaporation	-0.058	0.953	204
NINO 3.4	1.8936	0.058	240
TNI	2.357	0.018	240

Table 1. Results of the MK trend test for lake water volume and its meteorological drivers.

We then analysed the trends of Lake Victoria water volume and the three meteorological factors in the same time dimension. Overall, the trend of lake water volume variations in Lake Victoria from 2000-2019 are generally consistent with the trend of precipitation variations. When precipitation increases, the lake water volume showed an increasing trend, but the water volume variation had a temporal lag compared with the precipitation variation (Figure 8a). Evaporation from Lake Victoria has generally varied little over the 20-year period, with higher evaporation leading to a decrease in lake water volume. Evaporation is stronger during periods of low precipitation, when the variation in lake water volume is negative (Figure 8b). Figure 8c shows that trends in ENSO event metrics reflecting global-scale climate oscillations do not fully coincide with trends in water volume, sometimes differing significantly from water volume variations (e.g. 2004-2008) and sometimes coinciding with trends in water volume variations (e.g. post-2015), an inconsistency that suggests a relatively weaker relationship between ENSO events and lake volume variations compared to precipitation and evaporation.

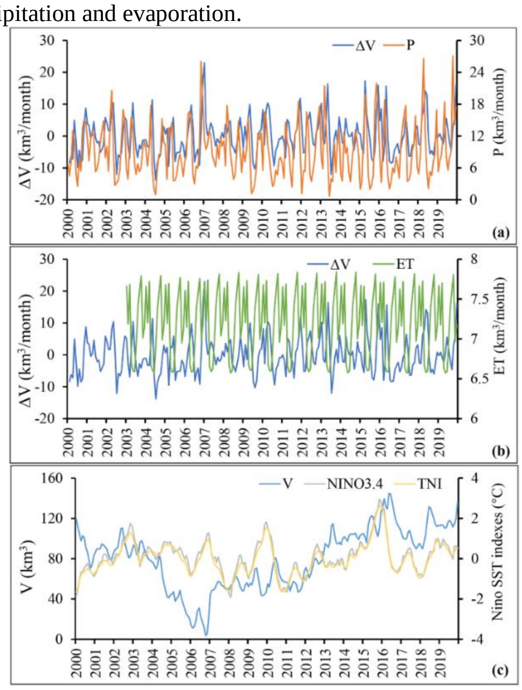

Figure 8. Relationship between lake water volume variation and meteorological factors: (a) precipitation, (b) evaporation and (c) ENSO events.

To further analyse the relationship between meteorological factors and lake water variations, we performed a Pearson correlation coefficient analysis on meteorological factors. Table 2 shows that precipitation, evaporation, and ENSO events passed the significance test with a confidence level of 0.01. Of the three meteorological factors, precipitation and ENSO events are positively correlated with lake water volume, while evaporation is negatively correlated with lake water volume. The Pearson correlation coefficients are 0.410 and -0.373 for precipitation and evaporation, respectively, while the maximum Pearson correlation coefficient for ENSO events is only 0.252. These results show that all three meteorological factors in this study are the main drivers of water volume variation in Lake Victoria, with precipitation being the driver that has the greatest impact on lake water volume. In addition, the correlation coefficient between the difference in precipitation and evaporation (P-E) and the water volume variation is 0.431, indicating that water volume variation is affected by multiple factors.

Category	Pearson correlation	Significance	N
Precipitation	0.410**	0.000	239
Evaporation	-0.373**	0.000	204
P-E	0.431**	0.000	204
NINO 3.4	0.211**	0.001	240
TNI	0.252**	0.000	240

Note: ** indicates significant correlation at the 0.01 level (two-sided).

Table 2. Correlation of lake water volume variation with meteorological factors.

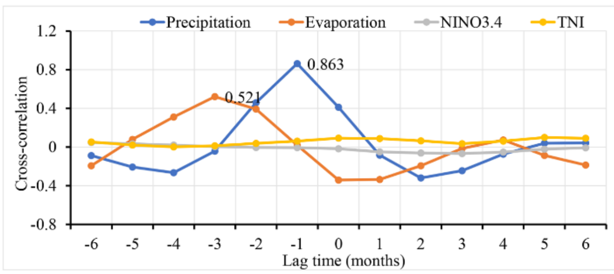

Figure 9. Cross-correlation between lake water volume variations and meteorological factors.

4.3 Anthropogenic factors impact on lake water volume

4.3.1 Change patterns of anthropogenic factors

Economically, Kenya has experienced the most rapid economic development, followed by Tanzania, while Uganda has experienced the least fluctuating economic development, and has not experienced any visible growth since 2010 (Figure 3). It would appear that the unbalanced economic development around Lake Victoria has led to different levels of environmental pollution and ecological damage to the lake in different geographical locations, which in turn affects the variations in lake water volume. In terms of population numbers, the three countries surrounding Lake Victoria have seen a linear increase in total population numbers, with Uganda and Tanzania in particular almost doubling their total population numbers over the last 20 years. Overall, the population density within the Lake Victoria buffer zone increased by 116 persons/km² between 2000 and 2020. The increase in demand for living land due to economic development and population growth may have an unavoidable impact on the lake's water volume.

To elucidate the gradient change in population numbers, we constructed 16 buffers cantered on the Lake Victoria centroid, where the inner buffer is a circle with a radius of 0.2 decimal degrees, and the other buffers are concentric rings with a width of 0.2 decimal degrees (Figure 10). The enlarged areas 1 and 2 show that Kenya, located in the northeastern part of the buffer zone, had the most visible change in population numbers over the 20-year period. In addition, Kampala, Entebbe and Jinja in Uganda, Mwanza, Musoma and Bukoba in Tanzania, and Kisumu in Kenya also show a visible increase in population numbers. Figure 10b shows that the population numbers are highest at 1.6 decimal degrees from the centre of the lake, with a downward trend as the distance increases. The increase in population numbers directly leads to incremental demand for residential land and domestic water, resulting in frequent changes in lake shorelines, which in turn affects the lake area and water volume.

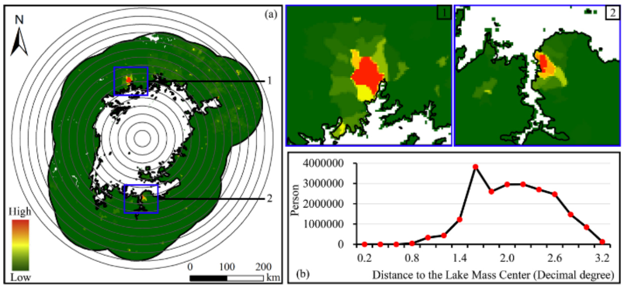

Figure 10. Comparison of population numbers of Lake Victoria and its buffer zone (2000 vs. 2020).

Figure 11a-c shows that cultivated land around Lake Victoria is widely distributed throughout the buffer zone. The forest land in the southwestern part of the lake shows a clustered distribution, and large areas of forest are also distributed in the northern and northeastern parts. Urban land around Lake Victoria is concentrated in the northern part of the lake, with a visible increase in the size of urban patches from 2000 to 2019. During the same period, the area of forest land in the eastern part of the lake decreases, while the area of cultivated land shows an expansion trend. This suggests that urban domestic and agricultural irrigation water demand will increase, which will inevitably lead to changes in the water volume of Lake Victoria. In addition, visual inspection revealed minor changes in the spatial pattern of other ecological lands (such as grasslands and wetlands) on the lake's western and eastern shores, but there is still a continuous trend for their area to shrink continuously. This could lead to environmental problems such as soil erosion and thus have an impact on the variations of the lake's water volume. Figure 11d shows characteristics of the quantitative changes in each land use/cover type over the last 20 years. Land use/cover around Lake Victoria in 2000 shows that cultivated land accounts for 69.2% of the total buffer zone, increasing in 2010 and showing a decreasing trend in 2019. Forest land cover was highest in 2000 at 15%, decreasing in 2010 (14.4%), with a slight rebound trend in forest land cover in 2019 (14.7%). For urban land within the buffer zone, the urban area accounted for only 0.1% of the total buffer zone in 2000 and only 0.4% in 2019, but this land use/cover type showed the most visible change in area over the 20-year period, with a growth rate of about 200%, i.e. urban area in 2019 was approximately three times larger than in 2000. The rate of change in area for land use/cover types other than urban ranged from -7% to 2%, with visible declines in forests, grasslands and other lands, and insignificant changes in water bodies and wetlands. Overall, each land use/cover type change has a different impact on lake water volume variations.

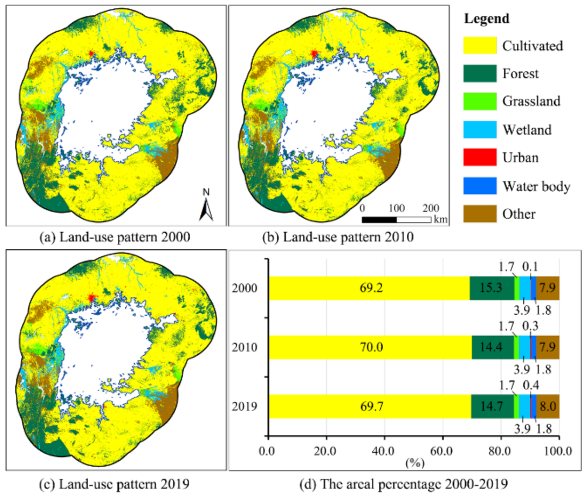

Figure 11. Comparison of land use/cover changes in the Lake Victoria buffer zone from 2000 to 2019.

4.3.2 Relationships between lake water volume and its anthropogenic factors

The Pearson correlation coefficients were likewise applied to quantify the impacts of socio-economic factors and land use/cover on lake water volume variations (Table 3). We analysed the correlation between total annual water volume variations and the total GDP, total population numbers and pixels for each land use/cover category of the three countries respectively. Socio-economic factors were positively correlated with lake water volume variations, with correlation coefficients above 0.440 in all cases. Among them, economic development has a slightly stronger correlation with the lake water volume variations, with a correlation coefficient of 0.449; the correlation coefficient for POP is slightly smaller at 0.441. Therefore, for Lake Victoria, the rapid socio-economic development of the surrounding area had a more prominent impact on the lake's water volume from 2000 to 2019.

Category	Pearson correlation	Significance	N
GDP	0.449*	0.047	20
POP	0.441	0.052	20
Cultivated	0.420	0.065	20
Forest	-0.518*	0.019	20
Grassland	-0.487*	0.029	20
Wetland	0.472*	0.036	20
Urban	0.491*	0.028	20
Water	0.344	0.137	20
Other	-0.225	0.340	20

Table 3. Correlation of lake water volume variation with anthropogenic factors.

For land use/cover change, urban land is positively correlated with lake water volume and has a high Pearson correlation coefficient (0.491). The urban land change follows roughly the same trends as GDP and POP, and therefore its correlation with lake water is the same as for socio-economic factors. Cultivated land is negatively correlated with lake water volume, which may be due to an increase in irrigated agricultural water use leading to a decrease in lake water. The correlation between different ecological lands and lake water volume varies: wetlands are positively correlated with lake water volume variations with a correlation coefficient of 0.472, while forest land and grassland are negatively correlated with lake water volume variations, both with larger correlation coefficients of -0.518 and -0.487, respectively. Other lands are negatively correlated with lake water volume variations with the smallest correlation coefficient of -0.225.

4.4 Principal component analysis of meteorological and anthropogenic factors

Further principal component analysis of the meteorological and anthropogenic drivers shows that the cumulative contribution of the first, second and third principal components are ⩾ 85% and have eigenvalues > 1 (Table 4). Among them, the contribution of the first principal component is 48.504%, mainly urban land, GDP and POP factors have higher loadings. The loadings of the anthropogenic factors in the first principal component are greater than those of the meteorological factors, indicating that the first principal component is dominated by anthropogenic economic and social development impacts. The contribution rate of the second principal component is 22.665%, mainly water land, wetland and forest land factors have high loading values, indicating that the second principal component is dominated by human-induced land use/cover changes. The third principal component contributed 14.800%, with higher loading values for the NINO3.4 and TNI indexes, indicating that the third principal component is dominated by global climate change.

Drivers	1st principal component	2nd principal component	3rd principal component
Precipitation	0.052	0.164	-0.155
Evaporation	0.051	-0.076	-0.066
NINO3.4	-0.043	0.046	0.468
TNI	-0.034	0.050	0.464
GDP	0.194	0.059	-0.009
POP	0.193	0.070	0.005
Cultivated	-0.066	0.182	-0.030
Forest	-0.035	-0.288	0.002
Grassland	-0.161	0.051	0.044
Wetland	0.143	0.309	0.051
Urban	0.200	0.117	0.008
Water	-0.066	0.220	0.146
Other	-0.150	0.060	0.018
Eigenvalue	6.306	2.947	1.924
Contribution rate (CR)	48.504	22.665	14.800
Cumulative CR	48.504	71.169	85.969

Table 4. Principal component matrix for drivers of water volume variations in Lake Victoria.

5. CONCLUSIONS

Trends in lake water volume are closely related to climate, hydrology, and land use/cover changes under the influence of urbanization development and human activities in recent years. We quantitatively analysed the relationship between meteorological and anthropogenic factors and the water volume of Lake Victoria. The results show that 1) among the meteorological factors, the impact of regional climate change is greater than the impact of global climate change. Precipitation and ENSO events are positively correlated with variations in lake water volume, precipitation has a strong influence but with a 1-month lag, while evaporation is negatively correlated with the process of water volume variations; 2) among the anthropogenic factors, economic development, population growth, increase in urban land and cultivated land and loss of ecological land in the countries surrounding Lake Victoria have an impact on the variations of lake's water volume; 3) The correlation between anthropogenic factors and Lake Victoria water volume was greater than meteorological factors during 2000-2019. Our study reveals the relationship between lake water volumes, and climate change as well as human activities, and provides a basis for decision making and data support for lake water management.

This study also shows that the visible water variation is closely related to the heavy precipitation during the same period. Against the background of increasingly intense and frequent extreme weather, the relationship between extreme precipitation and lake water volume variations has not received sufficient attention. This is due to the small sample and short time series of extreme events in the limited measured data. In addition, our research has focused on exploring the impact of drivers on water volume that can be acquired and inverted based on remote sensing means (precipitation and evaporation), and failed to analyse the impact of other primary natural conditions in the lake on water volume. However, our paper provides a research basis for addressing the above issues. Future work is 1) to explore the laws and causes of lake water volume variations under extreme weather and 2) to improve the accuracy of the drivers acquired by remote sensing-based methods.

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