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Research Article

Assessment of Rising Water Levels of Rift Valley Lakes in Kenya: The Role of Meteorological Factors

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Abstract

The impacts of increased water levels in Kenyan lakes are a major problem that is affecting communities and their livelihoods. Upsurge in water levels of the Rift Valley Lakes is one of the recent climate extremes witnessed over Eastern Africa where the rises appear to be consistent with the occurrence of enhanced seasonal rains between 2016 and 2020. Considering that many explanations have been provided as possible causes, there is still little empirical evidences. This study aimed at assessing the link between meteorological factors and the rises in lake levels in order to see if these can explain the causes. Further using surface observations potential to predict the water levels was examined. Datasets on rainfall, temperature and water levels from four Lakes in Kenya were used to establish the changes in these variables using statistical methods. Generalized Linear Models were used to predict the water levels in the study lakes. Results indicate that rainfall and temperature as well as other climate drivers has been changing over the last recent years with increased precipitation being consistent with the observed high stands in the Rift Valley lakes. Specifically, the results of the forecasted levels indicate substantial and slight increase for lake levels in Naivasha while the Lake Baringo levels are predicted to rise sharply within the study data periods.

Introduction

Climate change impacts across natural and man-made systems continue to be a subject of interest globally. Rising global temperatures associated with greenhouse gas forcing are causing frequent extreme weather patterns resulting in climate disasters across regions and especially the sub-Saharan Africa where prolonged droughts and floods are common [1,2]. Alongside climate change, increasing human population, demand for more food, water and other needs continue to add pressure on most eco-system resources [3]. Water scarcity on its part is a critical issue in the sub-Saharan region which highly depend on rain-fed agriculture [4]. This might explain why despite climate extremes impacts being experienced across many sectors, most studies in the region focus on those on agriculture and food security [5,6]. Nonetheless, other localised but less common climate extremes which bear significant impacts on communities in the region receive less attention. Upsurge in water levels of the Rift Valley Lakes is one of the recent climate extremes witnessed over Eastern Africa [7]. The rises appear to have been consistent with the occurrence of enhanced seasonal rains between 2019 and 2020 in the region [8]. Media reports show that the highest water levels of Lake Tanganyika occurred during the October (2019)-May (2020) long rain season and resulted in significant damages to surrounding homes and other areas due to the heavy rainfall. The water levels rose by more than 10 m and fluctuated between 773m and 776m where for some years they had shown no declining patterns (https://regionweek.com/water-level-variations-in-lake-tanganyika-raise-concerns/). Similar changes were reported over Lake Kyoga in Uganda where an estimated 550 pit latrines were submerged in 2019 (https://www.independent.co.ug/rising-l-kyoga-water-submerges-549-latrines-in-nakasongola/). Yet, similar patterns were reported over other lakes in Africa where water levels of Lake Chilwa in Malawi increased by 60% in 2019 due to heavy rains after experiencing drying trends and lowest levels in the previous two years (https://www.maravipost.com/malawis-lake-chilwa-rises-again-from-death-bed/; https://www.mwnation.com/lake-chilwa-water-levels-appreciate/). Between January and March 2021, the water levels of Lake Kariba, the world's largest man-made lake located on the border of Zambia and Zimbabwe rose by 5 meters to reach a high of 480.76m (https://www.herald.co.zw/rising-inflows-bode-well-for-kariba-power-generation/). Elsewhere, Lake Michigan in the USA has in the last 5 years experienced increased water levels due to increased rainfalls in history since 2013 (https://www.woodtv.com/weather/rising-waters/widespread-impact-the-rising-waters-of-lake-michigan/). Shugar et al., indicate that glacial lakes have expanded in volume by about 48% since the 1990s in response to climate change. In Kenya, a gradual lake levels rise, reaching unprecedented heights and claiming vast portions of land and damage to property has been a matter of public concern in the recent past [9]. Due to the high water levels, many families had to abandon their homes whereas businesses and tourist sites including the hot water springs and geysers of Lake Bogoria were submerged. Fear of attacks from several aquatic animals such as crocodiles, hippos and snakes has been a major concern. According to [10] and media reports Lakes Baringo and Lake Bogoria are expected to merge if the rising trends continue. Interestingly, rises in water levels of lakes in Kenya are not new. Increased lake levels were observed in the 1730s (Stager et. al., 2002) and 1929-1930 11]. Research reports also reveal there were high stands on Lake Turkana during the period 1740-1770. Exceptional cases of lakes overflow have been indicated in two distinct periods: 1700-1900 and 1900-2020. The first period lacked sufficient insitu observations compared to 1900-2020 period which has more reliable observational data. In the first period, Nicholson's (1997) carried out reconstructions of the lake levels over the East African region and those from the floods records of the River Nile River dating back to the 7th century. One of the documented overflows of Lake Victoria resulted from the flooding of the River Nile around this period.

Possible causes and hypotheses

To put into perspective the possible causes of the lake water level rises, it is crucial to first understand the climate of Kenya which is located in East Africa. It has a total area approximately 582,650 km2 and generally exhibits a bimodal rainfall distribution pattern occurring from March-May (Long rains season) and from October-December (Short rains season) apart from the western parts extending to the Lake Victoria Basin which experience rainfall in most of the year [12]. Some parts of the central regions experience some rainfall peaks in August. The mean annual rainfall ranges from 150mm (arid and semi-arid regions) to an excess of 2000mm (highlands to the west and east of the Rift Valley and central region), which largely contribute to the runoff that recharges streams that feed the lakes. Daily temperature vary from a minimum of <100C in central regions and more than 36^{0}C in the northern and north eastern regions. According to a report by the government of Kenya and the United Nations Development Programme, the latest high stands in the lake levels was caused by combination of hydrological, meteorological, land use changes and geological factors (GOK and UNDP, 2021) [13] cites increased siltation and reduced salinity of the lake waters as the main cause of the rises which in effect caused the disappearance of algae and withdrawal of flamingos from some of the Rift Valley lakes. But still, there exists different explanations on the causes or drivers of the lake level rises. Most of the published works have offered little or no evidence of rainfall associated events such as El Nino– Southern Oscillation (ENSO) and Indian Ocean Dipole analyses to explain high stands of the lakes in Kenya [14-16]. However these events tend to warm western Indian Ocean sea surface temperatures and contribute to positive rainfall anomalies in East Africa [17-19, 13] suggests that increases in rainfall in the Kenyan Highlands are highly correlated to the rises in the Eastern African Rift Valley lake levels and that there is a 50-year cycle based on the flooding incidences of 1901 and 1963. However, considering the frequency of extreme weather events and other climate change signals, this may not entirely hold. For instance the water levels of Lake Victoria have exhibited striking variations comparing the 1900 - 1961 and the 1961-2002 periods. A study by Kenya Water Towers Agency (2015) addressed five hypotheses that were commonly thought to be possible causes of lake high stands especially regarding the Rift Valley lakes during the 2010-2013 periods. They concluded that the rise in lake water levels was mainly due to enhanced rainfall, coupled with increased seismic activity observed during the period. The report argues that the seismic activities may have caused increased siltation that could have contributed to the rise in the lake levels. The seismic activities, the report adds, could have triggered flow of water into the lakes from aquifer systems through new fractures created in the process. However, without data and analytical support it remains unclear how the water from the aquifer systems only infiltrated into lakes and no other aquatic systems such as rivers and dams. The other hypotheses advanced on causes of rising lake levels was increased lake sedimentation and reforestation of the Mau Catchment. The Mau catchment is one of the largest catchments in Kenya. These two reasons given were dismissed on account of inadequate evidence or supportive data. The study observes that there was heightened incidence of seismic activities during the 2010-2014 period, though this could not exclusively be used to explain the lake level rise. To support a better understanding of the problem and respond to widespread public concern, a team from the Kenya Meteorological Department (KMD) visited Lakes Bogoria and Baringo in mid-September 2020 to confirm and assess the extent of the rising lake levels Though without any measuring devices, the visit was critical in assessing the physical extent of the shift in the water levels of the two lakes through looking and engaging the communities living in the riparian areas. We relied on witness information on the changing environment, some of the community members having been victims of the changes in the lake water levels. We noted that Lake Bogoria is an alkaline water body and well known for hot springs and geysers, features that are now not possible to access due to the changes in the water levels. We also noticed that Lake Baringo which is not located far from Lake Bogoria was a fresh water lake that was recharged by several rivers [20]. Whereas the four lakes we selected have been studied severally with varied explanations on the water level rises, the novelty of this case study is to assess and validate if meteorological factors play the leading role in the lake levels rising patterns, a phenomenon that is being observed across all the Rift Valley lakes in Kenya, including Lake Victoria. This can inform the use of climate indices to predict future trends in the lake water levels which may be useful in early warning and response.

Study objectives

The main objective of this case study was to investigate the extent to which meteorological factors are linked to the rises in the lake levels in Kenya. Specifically, the study sought to:

a) Examine the historical changes in the lake levels in Kenya and the meteorological factors in the lake catchment areas
b) Establish the relationship between meteorological factors and lake levels in Kenya
c) Determine the causes of the rising lake levels
d) Predict the lake levels

Materials and Methods

Study areas

The lakes considered in this study were; Baringo, Bogoria, Nakuru and Naivasha, all located in the Rift Valley of Kenya (Figure 1). Lakes Bogoria and Nakuru are alkaline and existing between eastern and western escarpments. In contrast, Lakes Naivasha and Baringo are both freshwater lakes and are more open lake systems [13]. All the four lakes have no surface outlets and are generally small and shallow and highly sensitive to hydro-meteorological fluctuations as well as human interferences.

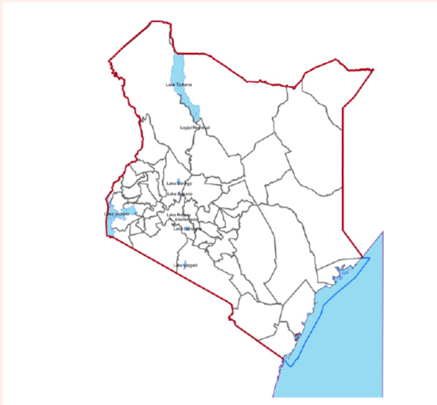

Figure 1: Location of study lakes from the northernmost to the southernmost, Lake Baringo, Bogoria, Nakuru and Naivasha.

Climate of the study areas

The area the lakes occupy has varying climatic patterns. Strong seasonal variations are observed in the mean monthly rainfall patterns. These variations occur in association with the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ), which is the main rainfall generating mechanism in the region. Time series plots of monthly rainfall reveal the existence of three rainfall seasons. As indicated earlier, the peak rainfall seasons occur in March-May (MAM), followed by a second peak in June-August (JJA) and October-December (OND)-the short rains season. Most of the rainfall is received in the peak months of April, August and November for the three rainy periods annually. In the Lake Baringo catchment, day time temperatures vary from 16.7°C during the cold months of June and July to 33.8°C during the warmer months of January to March and September-October. Lake Nakuru catchment located in the central Rift Valley has daily temperatures that range between 9.4°C during the cold months and 26.8°C during the warmer months (Figure 2) shows the meteorological station network around the Mau complex which contributes to the precipitation that feeds the study lakes and surrounding areas.

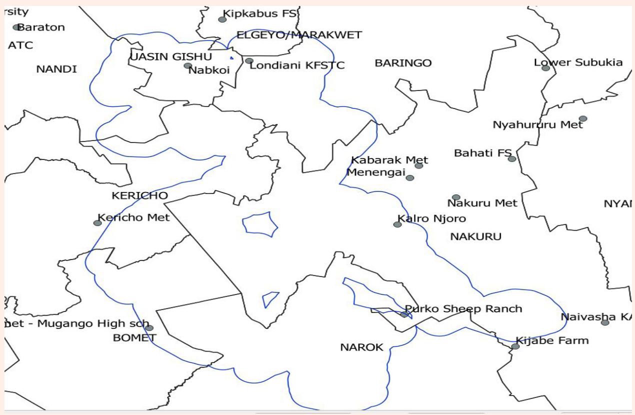

Figure 2: Meteorological station network around the Mau complex which contributes to the precipitation in the study lakes.

Data sets and Analysis methods

Systematic desk review of published and grey literature has been used to assess the historical changes in the lake levels with respect to meteorological factors in Kenya [9]. Meteorological data from the Kenya Meteorological Department (KMD) is used to describe the trends in rainfall and temperature for some stations within the study area for the period 1961-2018. Data on the water levels in the study lakes from the Water Resources Authority (WRA) was utilized from 2000-2018 to provide the temporal patterns and changes in the water levels in the four study lakes. To check normality of both datasets, we used QQ plots to visualize and the Shapiro-Wilk Normality test to ascertain the statistical significance. Also, to establish the relationship between meteorological factors and lake levels, lake water levels data from Water Resources Authority and meteorological datasets from KMD was analysed for possible link between the two variables. We used graphical methods to be able to visualize the two datasets through different plots. For each location, we plotted both variables on one graph using the R-statistical program. To establish the relationship between the two variables, correlation methods were used [21]. The simple Pearson correlation method is used in this study for its use on continuous or interval measurements and also it evaluation of the linear correlation between two. The measurement metric is the correlation coefficient (r) that is given by:

$$r = \frac{N\sum xy - \sum x \sum y}{\sqrt{N\sum x^2 - (\sum x)^2}\sqrt{N\sum y^2 - (\sum y)^2}} \quad (1)$$

r is the correlation coefficient, N is the size of the population (observations), and $\sum$ x and $\sum$ y are the sums of x and y scores respectively, $\sum$ xy defines the sum of x and y scores. When the value of r is 1, there is a perfect linear correlation between the variables while when r = -1, relationship is perfect negative linear correlation. With r = 0 there is no relationship that exists between the variables. To establish the causes of the increases in lake levels, the linkages between meteorological factors and lake water levels are compared with rainfall performance reports from 2016 -2021. These reports obtained from KMD provide summaries on rainfall and other weather event that occurred the previous season. Further analyses were carried out to establish the predictability of the lake levels in Kenya by running out the meteorological and water levels variables on generalized linear models. We applied the Holt-Winters' regression method with both additive and multiplicative seasonality to forecast seasonal levels of the study lakes. There are two differences to this regression method with regard to nature of the seasonal element. The additive method is used when the seasonal fluctuations are roughly constant across the observations, whereas the multiplicative method is chosen if the seasonal fluctuations are varying proportional to the level of the data series.

Results

Historical changes and trends in lake water levels and meteorological factors

Temporal variations in the lake levels are visible across all study lakes. For example, water levels in Naivasha successive increasing and declining trends between 2000 and around 2011 but a sharp increasing trend thereafter (Figure 3 and 4).

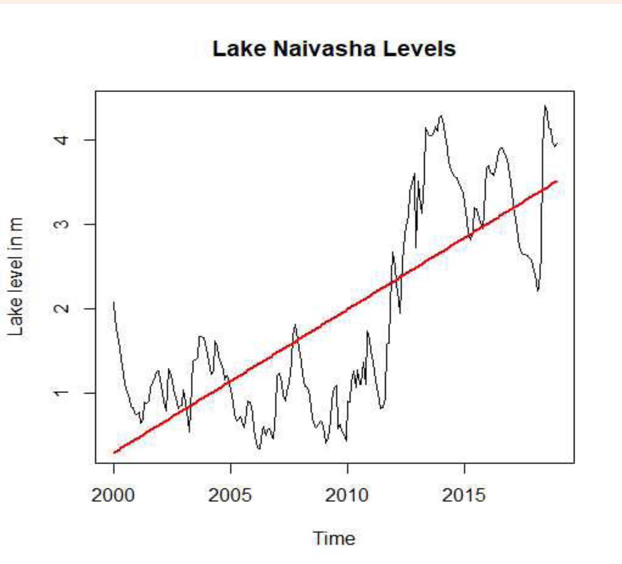

Figure 3: Monthly water levels in Lake Naivasha with a linear regression trend line (2000-2013).

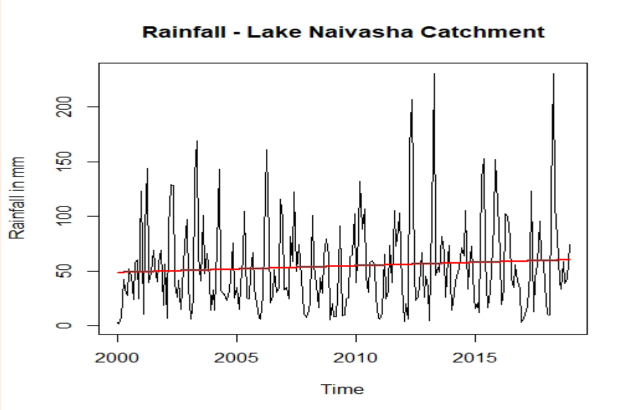

Figure 4: Monthly rainfall over Lake Naivasha with a linear regression trend line (2000-2013).

Normality checks of the rainfall data from the different stations in the catchments showed normal rainfall distribution in Subukia (W=0.933, p value=0.054), Naivasha (W = 0.989, p-value = 0.809), Crescent-Naivasha (W = 0.958, p-value = 0.176) and Egerton (W = 0.969, p-value = 0.154), Nakuru (W = 0.950, p-value = <<0.05) and non-normal for Njonjo Girls (W = 0.900, p-value = 0.042), Snake Farm (W = 0.891, p-value = 0.0003), Gilgil (W = 0.918, p-value = 0.006). (Figure 5) clearly shows that all patterns of the water levels in the three lakes were not normally distributed (Naivasha (W = 0.810, p-value <<0.05), Baringo (W = 0.775, p-value << 0.05) and Nakuru (W = 0.873, p-value <<0.05)).

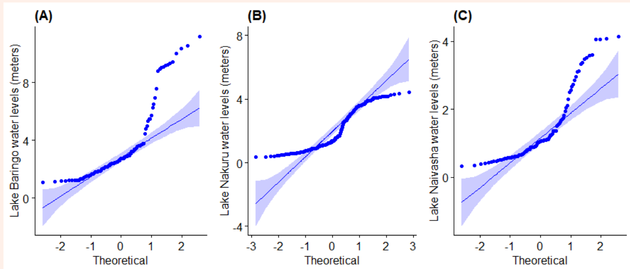

Figure 5: QQ-plots for water levels over Lake Baringo, Nakuru and Naivasha.

Normal distribution patterns were indicated in the maximum temperature for Baringo and Bogoria (p-value = 0.837 and p value = 0.553). Whereas the minimum temperature for Baring showed non-normality (p value=0.0001), Lake Bogoria showed normal patterns (p value = 0.1). In contrast the maximum temperature for Nakuru and Naivasha indicated non-normal distribution (p value=0.0003 and p=0.02) while the minimum temperature indicated the opposite patterns (p value=0.308 and p value=0.166). The water levels at Lake Baringo rose by 0.76m per year, at Lake Naivasha by 0.29m per year (p value=0.0000) since 2005 and at Lake Nakuru it rose by 2m per year (p value<<0.05). Checking on other meteorological variables, those that showed significant increasing trends include precipitation for Baringo (p value=0.08), maximum temperature for Bogoria (p value=0.06), Nakuru (p value=0.03) and Naivasha (p value=0.01) and minimum temperature for Baringo (p value=0.02) and Bogoria (p value=0.07). Rainfall in Naivasha for instance appears to have had seasonal fluctuations in most of the years since 1935 with little trend indicated. The lowest annual rainfall was recorded around 2002. Declining annuals rains are indicated in the Egerton area from 1960 up to late 1970s and an increase and upward trend in the following years. Naivasha and Egerton are in the vicinities of Lake Naivasha and Lake Nakuru respectively. Whereas the water levels at Lake Naivasha rose as the rain increased (supplementary material), the rainfall trend was not significant despite contributing to the rising levels of the lake. The East Indian Ocean Dipole Mode Index (DMI, pvalue=0.006) and West Indian Ocean Dipole Mode Index (DMI, pvalue=0.0000) (Supplementary material: Figure 24).

Relationship between meteorological factors and lake levels

Rainfall and temperature are key meteorological factors associated with the lake water levels. Correlation analysis reveal that despite the increasing trend in precipitation in Nakuru area, it did not influence the water levels in Lake Naivasha (p value>0.05). Interestingly, analysis revealed that the lag correlations between 6-month Standardized Precipitation Index and lake level anomalies were positive and statistically significant. The correlation is strongest at lag 3 for Lake Naivasha (r=0.421) and lag 2 for Lake Baringo (r=0.223, Figure 6). Both the western and Eastern Indian Ocean Dipole Modes indicate a warming trend of the sea surface temperatures over Lake Naivasha. With a correlation of r=0.24, there is some indication that the warming was influencing the rises in lake water levels. As the levels on Lake Baringo rose, the DMI over the western Indian Ocean took the opposite direction, rising from 2010 (supplementary material). On the contrary, a different pattern is depicted by the upward trend of the DMI over the eastern parts of the Indian Ocean, which indicates warming of the seas surface temperatures with the rising water levels of Lake Baringo.

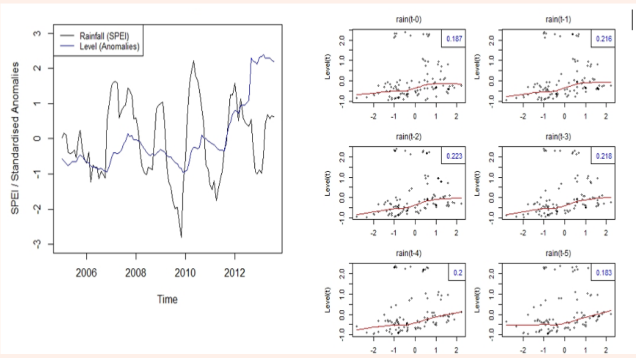

Figure 6: Lake Baringo monthly SPEI and lake level anomalies (left) and lagged correlations between SPEI and lake level anomalies (right). The highest correlations were found in lag 2.

Maximum and minimum surface temperatures correlated against water levels for Lake Naivasha and Lake Baringo indicted weak relationship. The associations are either on a downward trend or very low. For Lake Baringo, as an example, maximum temperature tends to decrease as the lake levels rise, though the decline is not statistically significant (Figure 7), depicts weak correlations between lake water levels and precipitation and other factors for Lake Naivasha and Lake Nakuru. The strongest associations are those between minimum temperature and precipitation over Lake Naivasha (r=65.6%) while the weakest correlations occurred between Nakuru precipitation and the lake levels. This suggests that the influence could be coming from other sources e.g. highlands in western or central regions. Moreover the probability distributions of precipitation in Nakuru compared to lake water levels depicts non-normal distributions patterns. Slightly enhanced associations occur more between lake levels and the ocean indices (DMI).

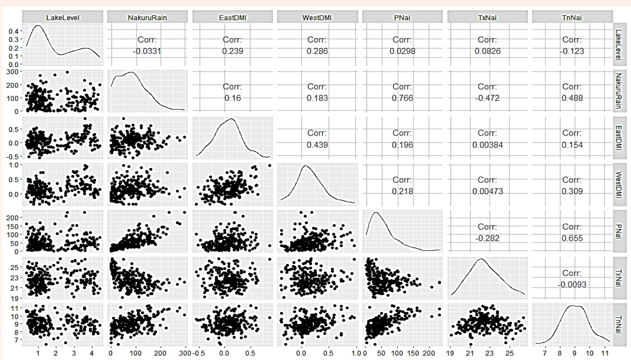

Figure 7: Probability distributions of Lake Nakuru water levels, Nakuru precipitation, eastern and western Indian Ocean Dipole Mode Indices and associated correlations between the lake water levels (Lake level), Naivasha rainfall (PNai) and temperature (TxNai, TnNai) and DMI (EastDMI and West DMI).

The analyses of probability distributions of Lake Baringo and Lake Naivasha water levels, rainfall records for Nakuru, Baringo and Bogoria areas, eastern and western Indian Ocean Dipole Mode Indices and associations showed that most of the variables were not normally distributed. The strongest correlations are indicated between the water levels of Lakes Baringo and Naivasha (r=0.97) and the rainfall totals of Nakuru, Baringo and Bogoria (r>0.70) and minimum temperatures of the three locations (r>0.80).

Causes of the rising lake levels

From the previous results, it appears that increasing water levels are triggered by increase in precipitation and influenced by climatic drivers such as the DMI. In addition, the following summaries obtained from Kenya Meteorological Department (www.meteo.go.ke) show the rainfall performance for all seasons between 2016 and 2021:

a. In MAM 2016 most parts of the country experienced near-normal rainfall which was well distributed. Some stations in western Kenya, Nairobi and the Coastal strip recorded enhanced rainfall which constituted more than 125 percent of the long term mean rainfall for the MAM season.

b. In the OND 2016 depressed rainfall was recorded over most parts of the country and was poorly distributed. Despite this, several parts of Western, Central Rift Valley and Central Highlands including Nairobi recorded substantial amounts of rainfall in late December 2016 and January 2017.

c. MAM 2017 rainfall was depressed and poorly distributed apart from the south eastern and coastal regions.

d. June-August 2017 season recorded close to average rainfall in several parts of western Kenya and this was followed by enhanced rainfall across many parts in OND 2017 season.

e. MAM 2018 recorded enhanced (heavy) rainfall in many parts of the country while OND 2018 recorded depressed (low) rainfall over most parts of the country

f. MAM 2019 experienced poor rainfall in most parts of the country apart from few areas in western and coastal regions while OND 2019 reported enhanced rainfall across the whole country.

g. MAM 2020 recorded enhanced rainfall in most parts of Western Kenya, Lake Victoria Basin, parts of Northwestern Kenya, central Rift Valley and central Kenya. In OND 2020 many parts of the country reported depressed rainfall apart from some parts of western and central highlands.

h. MAM 2021 rainfall was generally depressed in most parts of the country apart from western Kenya where substantial rainfall occurred.

Apart from OND 2016, MAM 2017 and OND 2018 seasons which had depressed rainfalls, it appears that the rainfall was enhanced in most of the other times in the catchment areas that feed the Lakes system. See for example (Figure 8) which shows forecasted rains that were near average to above average rainfalls in catchment areas. This tend to be consistent with the trend analysis of historical rainfall patterns which show that increased rainfall was the key cause of rising water levels in the Rift valley lakes. In most of the time since 2016, the catchment areas received 100% or more of their long term seasonal rainfall amounts.

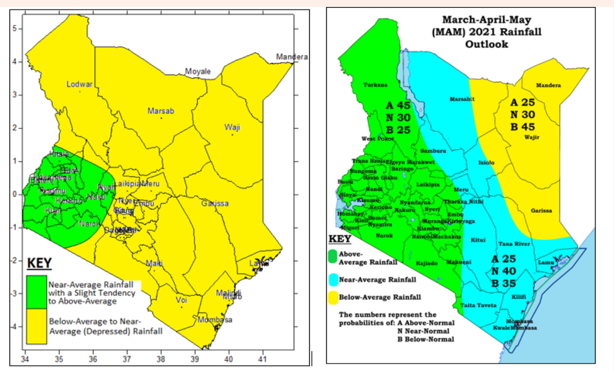

Figure 8: OND 2016 (left) and the MAM 2021 (right) rainfall Outlook

Predicting lake level rises

The model forecast of lake water levels on Lake Naivasha and Baringo is shown in (Figure 9). The levels for Lake Naivasha are predicted to be constant up to 2020 and expected to be between 2m and 3m using the additive method, whereas the multiplicative method shows a decline into 2020. The levels of Lake Baringo are predicted to rise for both additive and multiplicative methods and (were) expected to reach up to 16m by 2015. Lack of recent levels on Lake Baringo impedes forecasting ahead. Applying the

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same methods for predicting the changes 24months ahead indicates rising levels over the Lake Naivasha and Lake Baringo. The forecasts show the expected levels for 2014, 2015, and 2016.

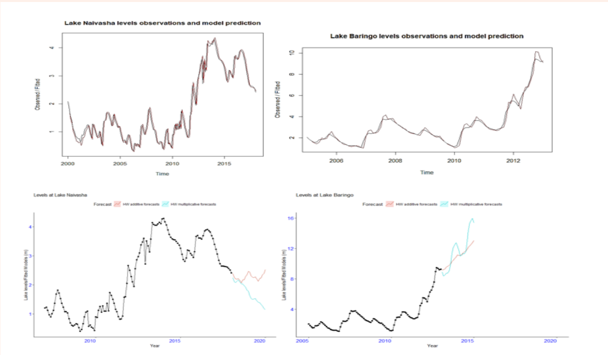

Figure 9: Forecasting water levels at Lake Naivasha (top left panel) and Baringo (top right panel) using observed data. The bottom panel shows prediction of the water levels over Lake Naivasha and Baringo using additive and multiplicative models.

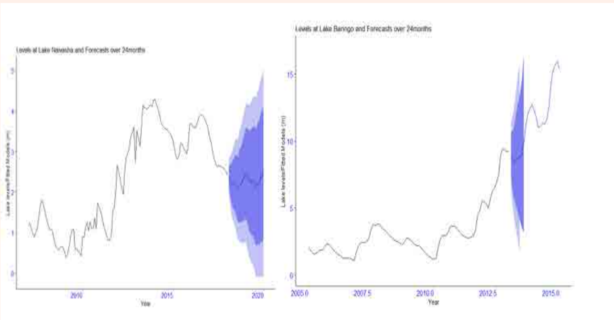

Figure 10: Forecast of levels at Lake (left) and using additive method with upper and lower 95% prediction intervals (canvas in blue). The upper 95% prediction intervals are similar to those around 2014 and 2016/2017. In Lake Baringo (right) the upper 95% prediction intervals are similar to those around in the forecasting window (2014-2015) while the upper limits of the lower 95% prediction are similar to lake levels of 2007 and 2011 and 2012.

Discussion of results and Conclusions

The study addresses the problem of rising water levels on four Kenyan lakes, due to the significant impact it has had on the communities and the environment (Figure 10). Whereas different causes have been advanced, both meteorological and lake levels observations indicate that over the last several years, the levels of the lakes have been rising consistent with increasing rainfall which corroborates other similar studies in the region [9]. Water levels of most lakes are determined by meteorological and hydrological factors such as precipitation and stream flow. For example, historical lake levels for the Great Lakes indicate positive associations between periods of high precipitation and increasing lake water levels. Precipitation is key function of the ground and surface water including other climate drivers [22] showed that extreme weather impacts such flooding was correlated more directly to periods of enhanced precipitation than low water levels. Water rise in the lakes may be related water recharge processes. Based on the water balance, [23] indicate that to establish the nature of groundwater flow systems, the analysis of natural isotopes may provide potential to estimating groundwater flows from Lake Naivasha, Lake Nakuru and Lake Bogoria among others. This stand point is consistent with our findings the locations and lower elevations of the lakes. For example Lake Naivasha is at 1885m above mean sea level (asl) and Lake Nakuru at 1755m, which are sinks for runoff water and other factors [23]. The temporal and spatial variability analysis of rainfall in the catchment stations showed that with lake water levels, historical data show that periods of enhanced rainfall is consistent with high stands on the study lakes and vice versa. Low stand periods coincide with droughts periods which results in retraction of the water levels. In the (Figure 11) below, stations such as Eldoret and Kitale in the western highlands areas of the catchment indicated consistent increasing trends in both annual and seasonal rainfall.

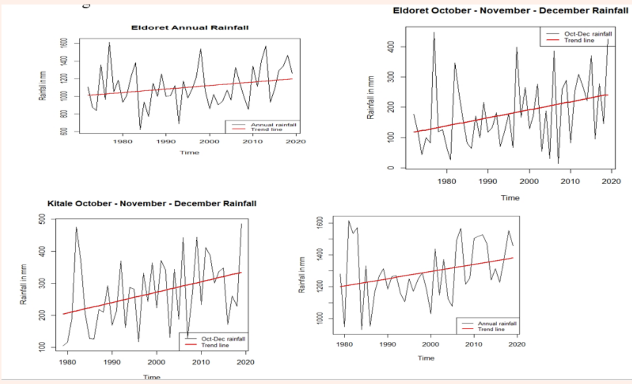

Figure 11: Rainfall from 1961-2020 for Eldoret at annual and seasonal timescale (left and right panels respectively) and for Kitale (bottom panel).Using the Standardized Precipitation Index (SPI) and the standardized precipitation evaporation index (SPEI) may be useful in identifying periods of high stands and low stands. Findings from the analysis with these indices shows that better parts of 2018 and 2019 expected wet conditions hence enhanced lake levels in Baringo.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2009	1.002	1.026	0.460	-0.791	-1.210	-1.382	-1.755	-1.979	-1.956	-2.336	-2.794	-1.282
2010	-0.551	0.592	1.583	1.888	2.211	1.812	1.647	1.356	0.851	0.464	-0.739	-0.870
2011	-1.313	-1.438	-1.194	-1.759	-1.474	-1.142	-0.933	-0.264	-0.159	0.590	1.247	1.254
2012	1.569	1.101	0.517	1.137	0.609	0.468	0.389	0.365	0.558	-0.225	-0.949	-1.004
2013	-0.882	-0.980	-0.481	0.409	0.689	0.577	0.651	0.622	0.862	0.372	0.517	0.587
2014	0.511	0.518	-0.036	-0.732	-1.409	-1.676	-1.721	-1.628	-1.746	-0.889	-0.156	0.223
2015	0.399	0.286	-0.132	-0.411	-0.185	-0.349	-0.389	-0.605	-0.595	-1.010	-0.614	-0.104
2016	0.202	0.441	0.078	0.222	0.170	-0.192	-0.258	-0.246	0.173	-0.306	-1.157	-1.748
2017	-1.785	-1.619	-1.762	-1.797	-0.848	-1.062	-0.665	-0.701	-0.219	1.212	0.980	1.166
2018	1.140	1.087	1.540	1.165	1.482	1.915	1.875	1.859	1.273	0.783	-0.488	-1.418
2019	-1.341	-0.798	-0.137	0.137	0.969	1.579	1.525	1.599	1.830	2.434	2.506	2.485

KEY

extremely dry
severely dry
moderately dry
Normal
moderately wet
very wet
extremely wet

Figure 12: Lake Baringo catchment 6-month Standardized Precipitation Evapotranspiration Index.

The lag correlations between 6-month Standardized Precipitation Index and lake level anomalies for Lake Naivasha and Lake Baringo are positive and statistically significant (Figure 12). The relationship is strongest at lag 3 for Lake Naivasha (r=0.421) and at lag 2 for Lake Baringo (r=0.223). This observation is consistent with the results of a study by [24] on the temporal variability of rainfall and stream flow into Lake Nakuru, in which the SPEI and SPI results depict 2010 to 2018 as representing a period of wetter than normal rainfall as well as being the longest continuous wet period in the history of the data analyzed [24], describe Lake Nakuru as an enclosed lake where water loss only takes place through high evaporation, rendering the lake a hydrologically-impacted ecosystem. Small changes in inputs can produce large fluctuations in water levels owing to the shallow nature of these lakes. Given that the Rift Valley lakes are influenced by tectonics, there are possibilities that there could be an influx of geothermal water also contributing to an increase in the lake levels [24-30]. The hydrological study by the Water Towers Agency found that all the rivers that drain into Lake Nakuru and Lake Elementaita are mostly seasonal, except River Njoro, dry up during the dry season. It was observed, however, that these rivers were flowing throughout the 2010-2013 period. It is during this period that the lake levels rose. The analyses carried out in this case study indicates that the available observed data can be used to estimate lake levels with certain lead times [31-35]. The models used here however require refinement to ascertain high degrees of accuracy. Further studies are required so as to establish the meteorological variables that could be the key drivers of lake level fluctuations [36-44]. Correlations with ocean indices, particularly the Indian Ocean Dipole (IOD) has proved to be sensitive to lake level variations. In conclusion, the results of the forecasted levels indicate substantial and slight increase for lake levels in Naivasha while the Lake Baringo levels are predicted to rise sharply within the study data periods. It is also recommended that research into flooding cycles be carried out to complement the on-going efforts aimed at developing and establishing a suitable prediction model for lake level variability. Such interrogation would help ascertain the authenticity of arguments such as the wet phases of 30-year and 84-year cycles that seem to provide a perfect match for the extreme levels of the lakes, and which also suggest that the lake elevations of the 2019-2022 are likely to behave like the conditions of the 1930-1933 period (Supplementary Figure 1-14).

Supplementary Materials

Figure S1: Houses and business stalls around Lake Naivasha submerged.

Figure S2: Submerged house at the shores of Lake Bogoria (left) while one of the submerged Lake Baringo access roads (right) now serves as a car wash facility.

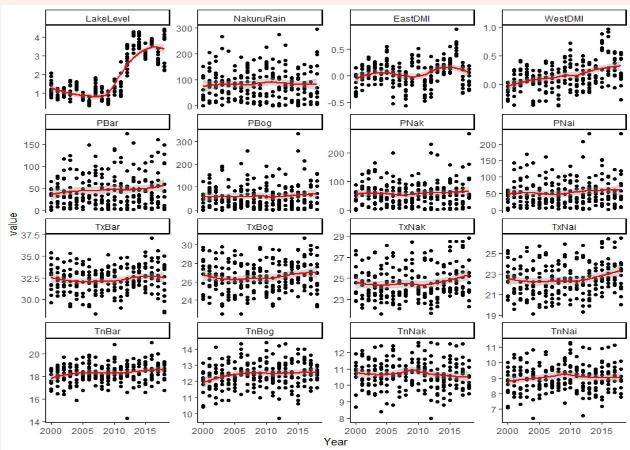

Figure S3: Time series of Lake Naivasha levels and other meteorological variables (EastDMI-East Indian Ocean Dipole Index, WestDMI-West Indian Ocean Dipole Index, PBar, PBog, PNak, PNai are averaged precipitation for Baringo, Bogoria, Nakuru and Naivasha respectively, TxBar, TxBog, TxNak, TxNai are averaged maximum temperatures for Baringo, Bogoria, Nakuru and Naivasha respectively, and TnBar, TnBog, TnNak, TnNai are averaged minimum temperatures for Baringo, Bogoria, Nakuru and Naivasha respectively for the period 2000 - 2015.

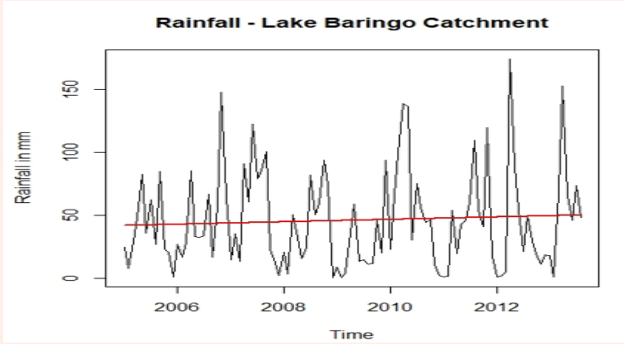

Figure S4: Monthly Lake Baringo catch ment rainfall and trend line (2000-2013).

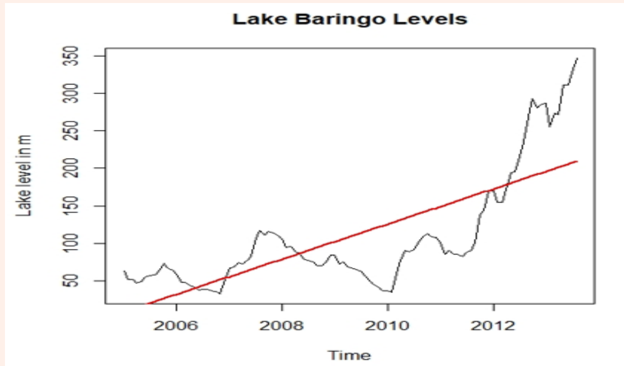

Figure S5: Monthly Lake Baringo levels and trend line (2005-2013).

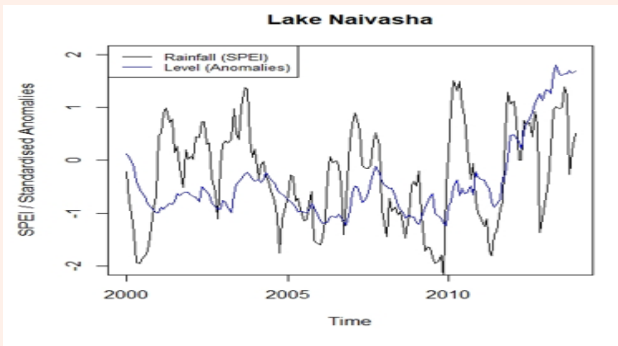

Figure S6: Lake Naivasha monthly SPEI and lake level anomalies.

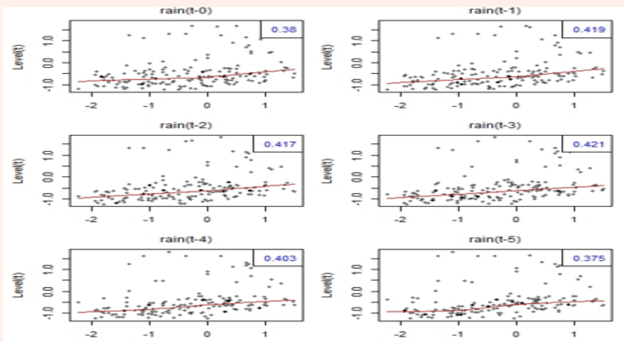

Figure S7: Lake Naivasha lagged correlations between SPEI and lake level anomalies.

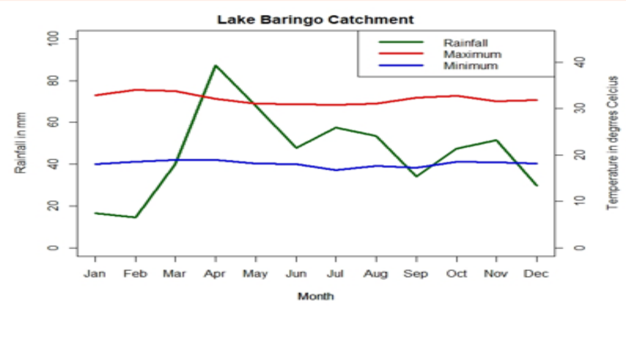

Figure S8: Lake Baringo catchment annual rainfall and temperature regime.

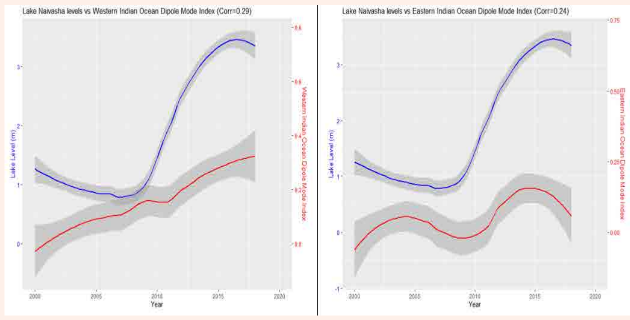

Figure S12: Comparing Lake Naivasha water level with the Western Indian Ocean Dipole Mode Index (*left*) and the Eastern DMI (*right*).

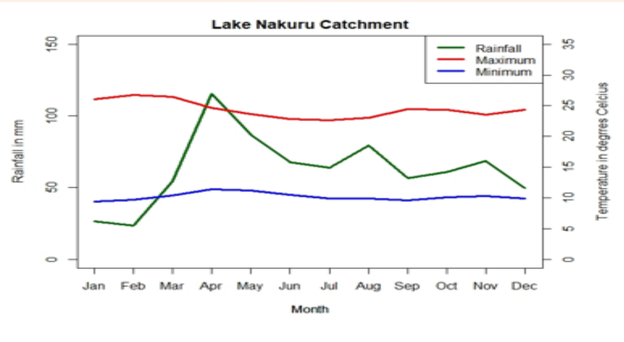

Figure S9: Lake Nakuru catchment annual rainfall and temperature regime.

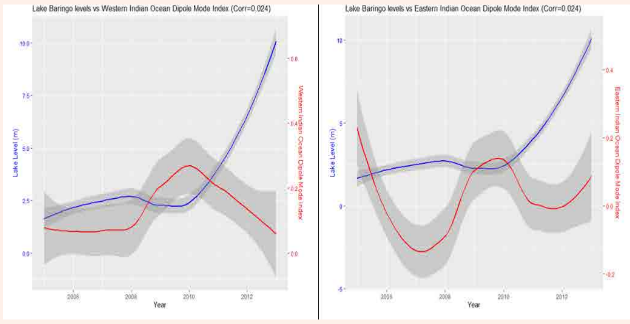

Figure S13: Comparing Lake Baringo water level with the Western Indian Ocean Dipole Mode Index (*left*) and the Eastern DMI (*right*).

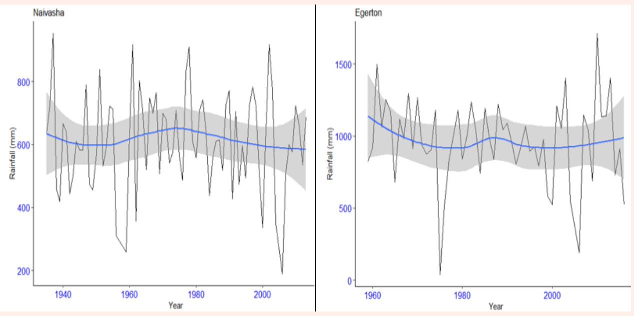

Figure S10: Annual rainfall time series for Naivasha (1935-2013) and for Egerton from 1959-2016.

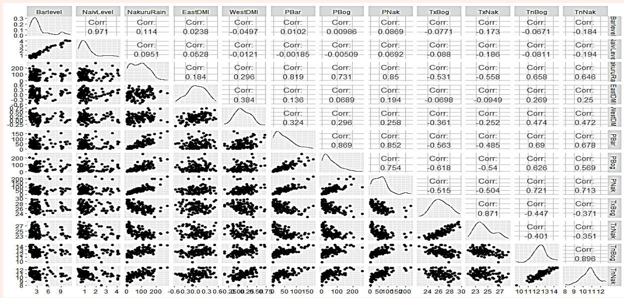

Figure S14: Probability distributions of Lake Baringo, Lake Naivasha water levels and correlations with rainfall records for Nakuru, Baringo and Bogoria areas, and DMI.

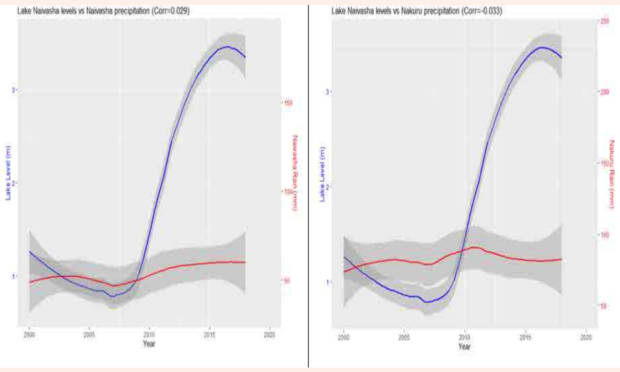

Figure S11 (*left*): Lake Naivasha water levels compared to rainfall in Naivasha area and (*right*): Lake Naivasha water levels compared to rainfall in Nakuru area.

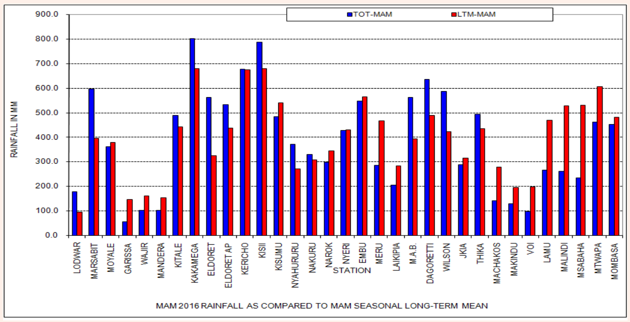

Figure S15: MAM 2016 rainfall compared to the long term mean rainfall across stations in Kenya.

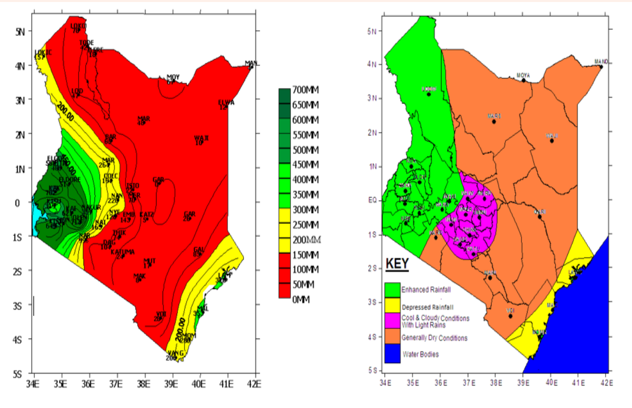

Figure S16: 2016 Normal JJA Rainfall Distribution (left) and JJA Rainfall Outlook (right).

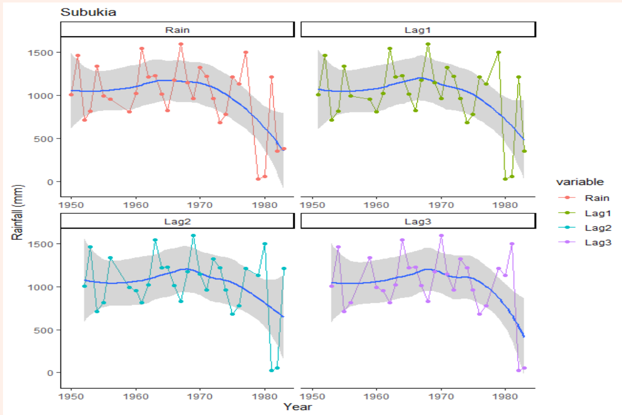

Figure S19: Plot of annual rainfall at Subukia from 1950-1983 and at lag1, 2, and 3 and fitted with a loess regression. Rainfall was found to have a negative trend even up to lag 3.

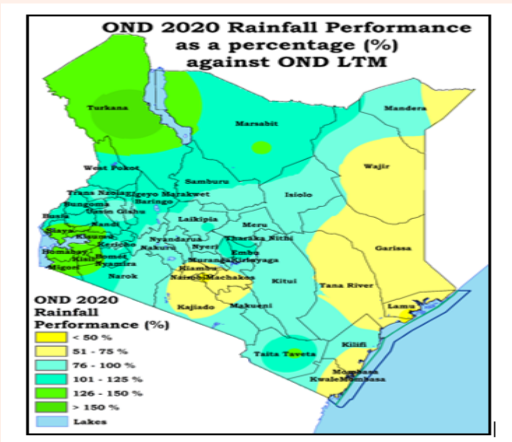

Figure S17: OND 2020 Rainfall Performance relative to the LTM.

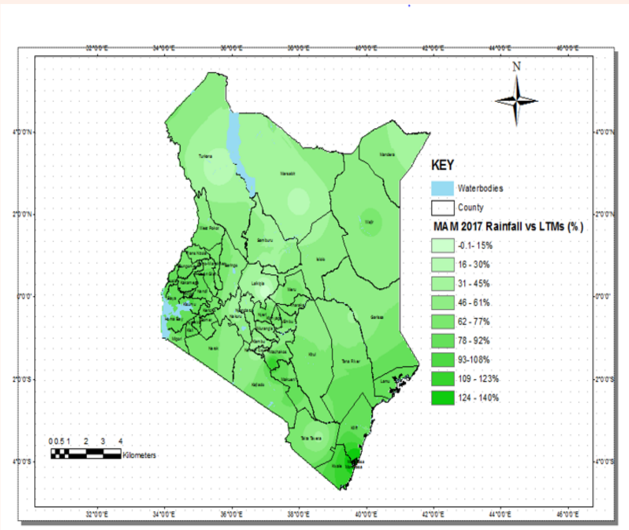

Figure S18: Performance of MAM 2017 Rainfall versus Long Term Mean.

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