Water Level Fluctuations and Fish Yield Variations in Lake Naivasha, Kenya: The Trends and Relationship

George Morara[1, 2*], Reuben Omondi[2], Beatrice Obegi[1, 2], Albert Getabu[2],
James Njiru[2, 3] and Nehemiah Rindoria[4]

ABSTRACT

Water level fluctuations (WLF) influence the distribution and abundance of aquatic species. This study analyzed Lake Naivasha's WLF and fish yield datasets from 1980 to 2019 to determine their trends and interrelationships for sustainable fishery management. Trends detection applied the Mann-Kendall formula, while the effect of WLF on fish yield was tested using simple linear regression. Results show an average annual water level elevation of 1887.4 m above sea level and average annual fish yield of 446.1 tonnes·year^{-1}. Both WLF and fish yield depicted significant monotonic increasing trends ($p<0.0001$ and $p<0.0001$, respectively). Fish yield and WLF showed a positive relationship. Simple linear regression confirmed that fish yield could be predicted by trends in WLF. Significant regression equations were found in both direct ($p = 0.0227$; $r^2 = 0.1396$) and indirect ($p = 0.005$; $r^2 = 0.2096$) datasets. Periodic WLF affect available fish habitat area and stock abundance, with consequent implications for total annual fish yield. Given the fluctuating water level conditions, effective control of fishing effort in Lake Naivasha is likely to have positive influence on its annual fish yield. Sustainable management of the lake's fishery resource should include measures aimed at mitigating both human and climate-induced impacts on the lake level.

Keywords: Climate variability, Ecosystem dynamic, Fish catch, Lake level, Management

INTRODUCTION

Tropical and temperate lakes constitute a significant component of the surface water bodies considered essential to a wide range of ecosystem services (Baker *et al*., 2007; Kiani *et al*., 2017). Rift valley lakes represent some of the world's critical freshwater ecoregions of high biodiversity (Odada *et al*., 2003; Sayer *et al*., 2019). These lacustrine ecosystems host vital natural resources for socio-economic development (Cohen *et al*., 1996). As global surface temperatures increase by 0.6 ºC (Houghton *et al*., 2001), associated impacts on freshwater ecosystems are likely to vary broadly in different regions according to the geological characteristics of various water bodies (Mooij *et al*., 2005; Haghighi and Klove, 2015). In lakes, water level fluctuations (WLF) manifest effects of climate change, hydrological regimes, and other factors such as land use (Haghighi and Klove, 2015; Kiani *et al*., 2017). Historical WLF and seasonal extremities of aquatic habitat conditions associated with global warming impacts (Wantzen *et al*., 2008; Finlayson *et al*., 2013; Sayer *et al*., 2019) influence quantity and quality of aquatic biodiversity. For instance, WLF are critical to ecosystem processes that

---

[1] Kenya Marine and Fisheries Research Institute, Naivasha, Kenya
[2] Department of Aquatic and Fishery Sciences, Kisii University, Kisii, Kenya
[3] Kenya Marine and Fisheries Research Institute, Mombasa, Kenya
[4] Department of Biological Sciences, Kisii University, Kisii, Kenya
* Corresponding author. E-mail address: g_morara@yahoo.com
Received 5 March 2021 / Accepted 6 October 2021

influence the distribution and abundance of aquatic species in lakes (Gownaris *et al*., 2018). According to Amarasinghe and De Silva (2015), water level changes from stable to fluctuating systems and varying mean depth conditions are useful fish yield predictors in lakes and reservoirs. Reservoirs situated in semi-arid areas experience WLF that change their sediment biogeochemical processes (Keitel *et al*., 2016).

Lake Naivasha is a case study of lacustrine ecosystem services that are affected by water level fluctuation. The lake surface area varies between 100 and 180 km^2 during dry and wet spells, respectively, with a maximum depth between 4 and 10 m (Litterick *et al*., 1979; Harper, 1991; Muchiri and Hickley, 1991; Oyugi *et al*., 2011). It lacks known surface outlets but maintains its freshwater conditions through a unique balance between surface inflows and underground seepage (Becht *et al*., 2005). Historically, the basin was adjoined with Lakes Elementaita and Nakuru (Richardson and Richardson, 1972), but the frequent recess occasioned by drier conditions caused the larger single basin to separate into the present three (Harper *et al*., 1990). The Lake Naivasha ecosystem consists of four physico-chemically distinct parts (Gaudet and Melack, 1981): Crescent Island, main lake, Oloidien and Sonachi. Ecological status of the lake basin is atypical of many other natural lakes, and instead more akin to human-made reservoirs (Harper and Mavuti, 1996).

Lake Naivasha supports a unique fishery based on exotic species (Muchiri and Hickley, 1991; Njiru *et al*., 2017). The fishery resource comprises largemouth black bass *Micropterus salmoides* (Lacepède, 1802), blue-spotted tilapia *Oreochromis leucostictus* (Trewavas, 1933), red-belly tilapia *Coptodon zilli* (Gervais, 1848), common carp *Cyprinus carpio* (Linnaeus, 1758), Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758), and African catfish *Clarias gariepinus* (Burchell, 1822). Only one endemic species, the black lampeye *Aplocheilichthys antinorii* (Vinciguerra, 1883), existed in Lake Naivasha until 1962 (Elder *et al*., 1971), and it is suspected to now be extinct (Muchiri and Hickley, 1991; Njiru *et al*., 2017). This species' disappearance is attributed to historical drying of the lake and introduction of exotic fish species (Muchiri and Hickley, 1991; Harper and Mavuti, 1996). Commercial gillnet fishing began in 1959 (Muchiri and Hickley, 1991), and high fluctuations in the annual fish yield have been attributed to various factors, including fishing effort (Hickley *et al*., 2002), climate variability leading to periodic lake level fluctuations (Muchiri and Hickley, 1991), and habitat degradation driven by human socio-economic activities (Harper and Mavuti, 2004; Hickley *et al*., 2004). Analysis of time series data of WLF and fish yield provides insights into trends and their inter-relationship. Therefore, this study aimed to assess the WLF and annual fish yield trends to understand their relationship and support management decisions for a sustainable fishery in the lake.

MATERIALS AND METHODS

Study site description

Lake Naivasha (Figure 1) is a shallow freshwater body situated in Kenya's Eastern Rift Valley. It is the country's third largest inland lake after the gulf portion of Lake Victoria and Lake Turkana in western and northern Kenya, respectively.

The lake lies about 190 km south of the equator (0°46'S, and 36°20'E) at about 1890 m above sea level. The surface area fluctuates between 110 and 160 km^2 as influenced by dry and wet spells. An extensive catchment area, which hosts several rural and urban settlements, maintains the lake's water volume and other ecosystem services. River Malewa, with a catchment area of about 1,730 km^2, contributes about 90 % of the lake's water recharge. The rest of the recharge flows from River Gilgil, with a catchment area of about 420 km^2, and from small ephemeral streams. The lake's fresh water is ideal for domestic and agricultural uses, and currently supports a flourishing horticultural industry. The water quality is also conducive for a wide range of introduced fish species that support an active fishery. Apart from its socio-economic significance, Lake Naivasha is among Kenya's Ramsar-protected wetlands and is internationally recognized for its unique biodiversity and mode of management.

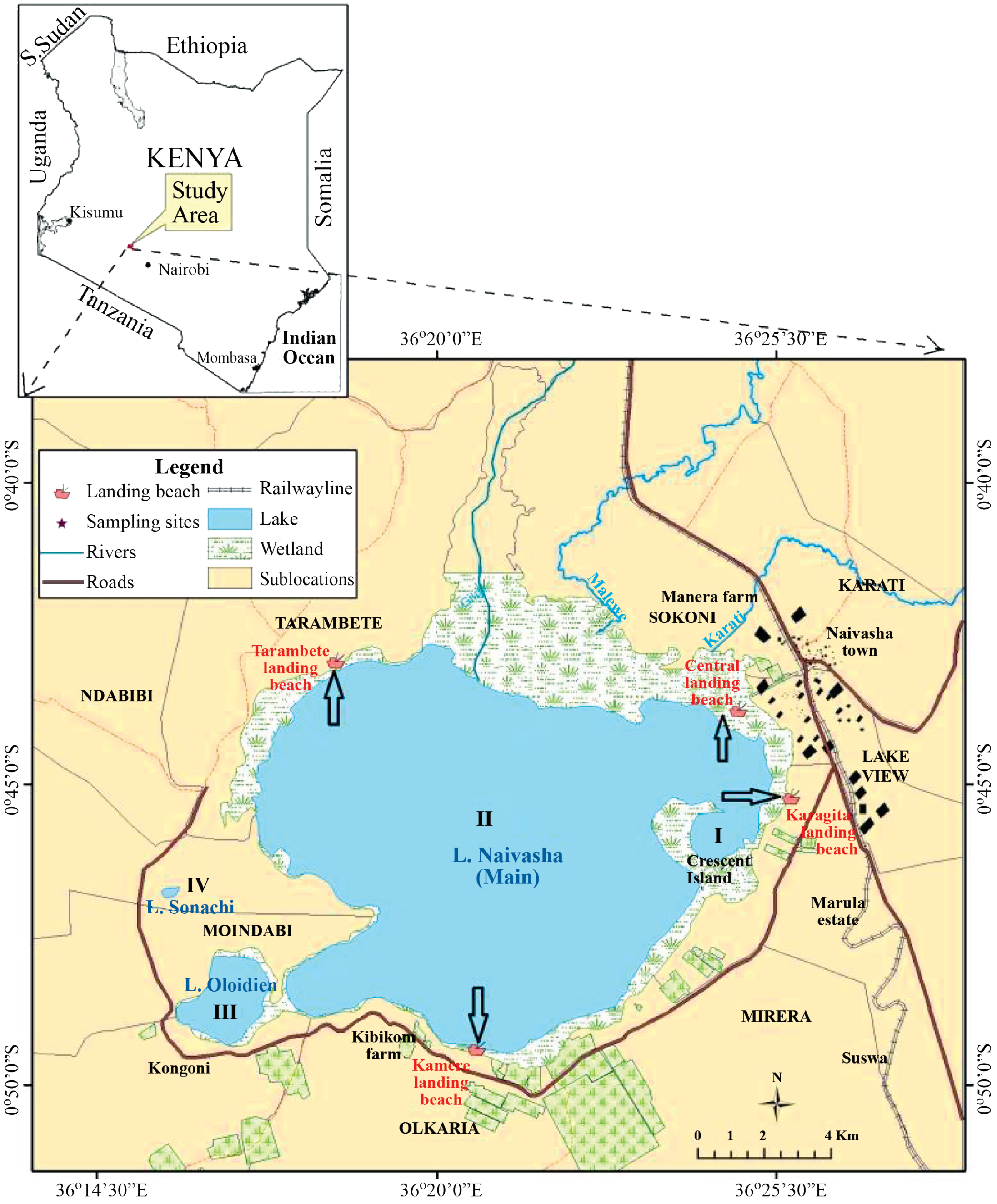

Figure 1. Location of Lake Naivasha (Kenya) and the four official fish landing sites (indicated by arrows). The four distinct basins (I-IV) are shown (map adopted from Morara *et al*., 2021).

Datasets and analyses

Water levels of Lake Naivasha are routinely monitored by the Water Resource Authority (WRA), a state agency vested with oversight mandates for all the water resource bodies in Kenya. The agency keeps monthly and annual average lake level data, recorded using two water level gauges permanently stationed in the eastern part (Crescent Island) and the southern part (Oserian bay). Therefore, water level readings were taken in terms of water surface elevation (altitude) relative to the historically highest point of 1892.81 m above sea level (m asl), and the lake's boundary is based on the riparian mark recorded in 1900. The trend analysis focused on the time series of WLF from 1980 to 2019. The dataset of WLF from 1980 to 2010 was truncated and examined separately to assess, explicitly, whether a significant decreasing trend in water levels was detectable.

The lake's fish yield data were recorded at the four official fish landing beaches (Figure 1). The daily fisheries data included the total weight of fish landed by licensed fishers. The data were compiled into annual total fish landings and maintained by the Fisheries Department (FD) in Naivasha. Therefore, the datasets from 1980 to 2019 were analyzed for trends and compared against the WLF. Trend visualization was accomplished by moving averages (MA), a method that eliminated the fluctuations in datasets by taking averages of three-year data intervals and creating serially arranged average values.

Subsequently, the Mann-Kendall (MK) trend test was used to detect the presence or absence of trends. The MK is a rank-based nonparametric test and considered powerful for detecting trends in non-normally distributed time-series datasets (Yue and Pilon, 2004). For this reason, various studies have applied MK to test the significance of monotonic (linear or non-linear) trends (Hisdal *et al*., 2001; Wu *et al*., 2008; Shadmani *et al*., 2012; Ahmad *et al*., 2015). The test operated on the null hypothesis (H_0) that no significant increasing or decreasing trends exited in the observed time-series historical data. The elaborate mathematical expressions provided in various publications (Wu *et al*., 2008; Shadmani *et al*., 2012; Ahmad *et al*., 2015) explain the derivation of MK trend statistic (S), square root of the variance for S (se), and the standardized test statistic (Z). According to this method, if there is no monotonic trend (the null hypothesis being true), then for time series dataset with more than 10 elements, $Z \sim N(0, 1)$, implying z has a normal distribution. A positive value of Z shows a monotonically increasing trend and a negative Z shows a decreasing trend. A zero value of Z denotes absence of a clear trend direction. The statistical significance, $Z_{1-\alpha/2}$, was assessed at a p-value of 0.05 in the normal curve (Z) table. When the calculated Z statistic was greater than $Z_{1-\alpha/2}$ at a p-value of 0.05, the null hypothesis was rejected.

Simple linear regression analysis was carried out to examine the relationship between lake level fluctuations and annual fish yield in Lake Naivasha, and to test whether WLF significantly predicted fish yield. Fish yield trend was treated as dependent on the WLF trends. In the first analysis, annual fish yield was regressed directly against the annual lake level. In the second analysis, fish yield was regressed against the previous year's lake level, creating a one-year lag between WLF and fish yield. In both cases, a scatter diagram and a line of best fit regression model was drawn to show the direction of association. The scale of WLF influence on fish yield was inferred by a regression equation and the significance was tested at 95 % confidence limit.

RESULTS

Water level fluctuations

The annual water levels in Lake Naivasha depict frequent changes between 1980 and 2019 (Figure 2). The difference between minimum and maximum water levels is 4.2 m. Highest lake level (1,889.8 m asl) was recorded in 1982, whilst the lowest (1,885.6 m asl) was in 2009. Except for a phenomenal water level rise (1,888.5 m asl) in 1998, between 1980 and 2010 lake level fluctuations were characterized by a significant downward trend (Table 1). Conversely, the period from 2010 to 2019 shows a steady rebound with considerable rise in water levels.

The dataset further reveals that the lake maintained higher water level conditions (above 1,888.0 m asl) from 2012 to 2019, with slight inter-annual variations. The broad lake basin's mean annual water level was 1,887.4 m asl. The recent water level rise contributed to a statistically significant upward trend during the entire assessed period (Table 2).

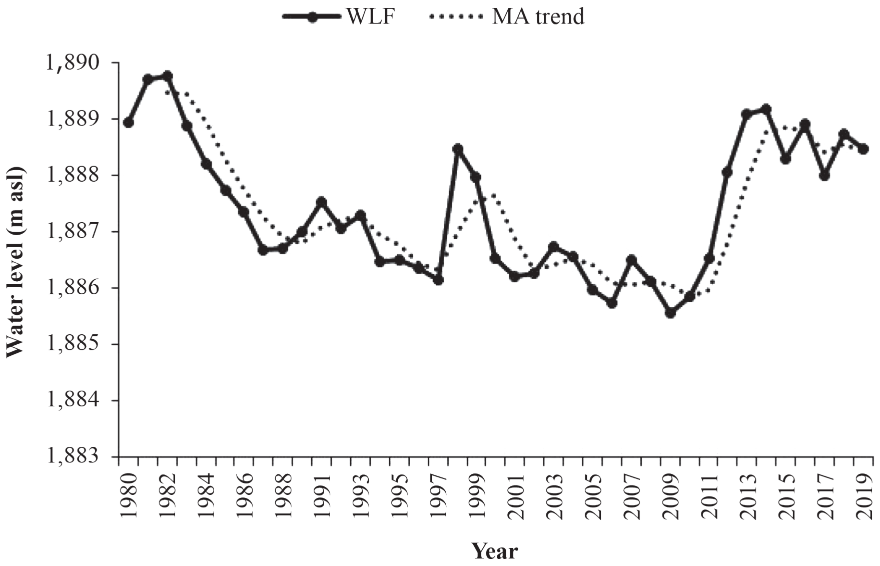

Figure 2. Lake Naivasha annual average water level fluctuations (WLF) and the corresponding three-year moving average (MA) trend from 1980 to 2019.

Table 1. Summary of descriptive statistics and Mann-Kendall trend analysis of annual water level fluctuations (WLF) and fish yield in Lake Naivasha from 1980 to 2010; SE = standard error.

Descriptive trend test	**Variables**	
	Lake WLF (m asl)	**Fish production (tonnes)**
Period (years)	30	29
Minimum value (m asl)	1,885.6	37
Maximum value (m asl)	1,889.7	609.1
Annual mean (m asl) ±SE	1,887.4±0.2	223.8±164.4
MK test statistic (S)	-279	-54
Square root of var. of S (se)	50.05	53.31
Normalized test statistic (Z)	-4.96	-0.99
Probability (p-value)	<0.0001	0.3201
Trend significance (95 %)	Yes (falling)	None

Fish yield trend

Fish yield data for Lake Naivasha (Figure 3) show high fluctuations in catches, ranging from 37 to 3,146 tonnes (in 1980 and 2019, respectively). Annual catches depict two phases of fish yield trends: declining from 1980 to 2000, and increasing from 2001 to 2019. Highest fluctuations were observed from 1980 to 2010 with a downward trend, which was not statistically significant (Table 1). The fishery had declined and almost completely collapsed in 2000, prompting a year-long fishing ban in 2001 to allow the recovery of fish stocks. Since 2001, fisheries management interventions in Lake Naivasha have led to a phase of fishery rejuvenation, with steady growth trends observed from 2013 (Figure 3). While the average yearly fish yield during the declining period was 237.3 tonnes·year^{-1}, average annual landings of 678.2 tonnes·year^{-1} were recorded during the increasing period. Overall average annual fish yield was 446.1 tonnes·year^{-1}, and fish yield over the entire period (1980-2019) reveals a significant increasing trend, as shown in Table 2.

Table 2. Summary of descriptive statistics and Mann-Kendall trend analysis of annual water level fluctuations (WLF) and fish yield in Lake Naivasha from 1980 to 2019; SE = standard error.

Descriptive trend test	Variables	
	Lake WLF (m asl)	Fish production (tonnes)
Period (years)	39	38
Minimum value (m asl)	1,885.6	37
Maximum value (m asl)	1,889.7	3146
Annual mean (m asl) ±SE	1,887.4±0.2	446.1±104.2
MK test statistic (S)	666	630
Square root of var. of S (se)	82.7	79.5
Normalized test statistic (Z)	8.0	7.9
Probability (p-value)	<0.0001	<0.0001
Trend significance (95 %)	Yes (rising)	Yes (rising)

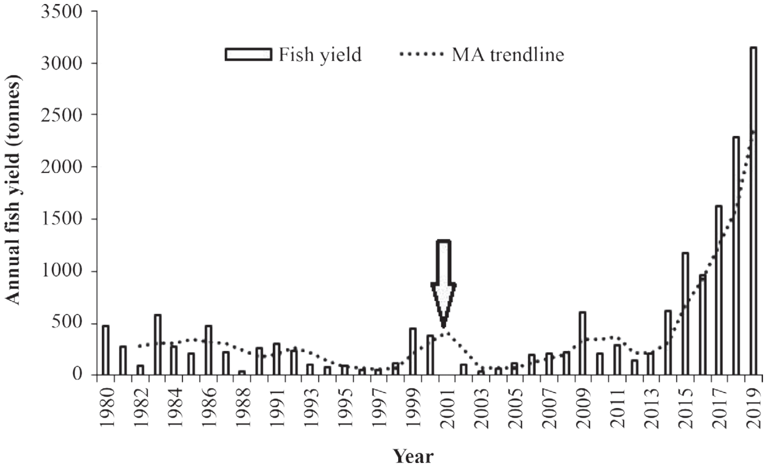

Figure 3. Lake Naivasha annual fish yield (bars) and the corresponding three-year moving average (MA) trend from 1980 to 2019; arrow indicates a one-year fishing ban in 2001.

Fish yield and WLF relationship

The regression test showed a positive linear relationship between fish yield and WLF in Lake Naivasha (Figure 4). The simple linear regression confirmed fish yield could be predicted by WLF. Significant regression equations were found in both the direct dataset ($F_{[1,35]} = 5.6772$, $p = 0.0227$; $r^2 = 0.1396$) and indirect dataset ($F_{[1,34]} = 9.0166$, $p = 0.0049$; $r^2 = 0.2096$) as shown in Figure 4a and 4b, respectively. However, the latter dataset had a stronger fit of the regression line and confirmed the delayed influence of WLF on fish yield.

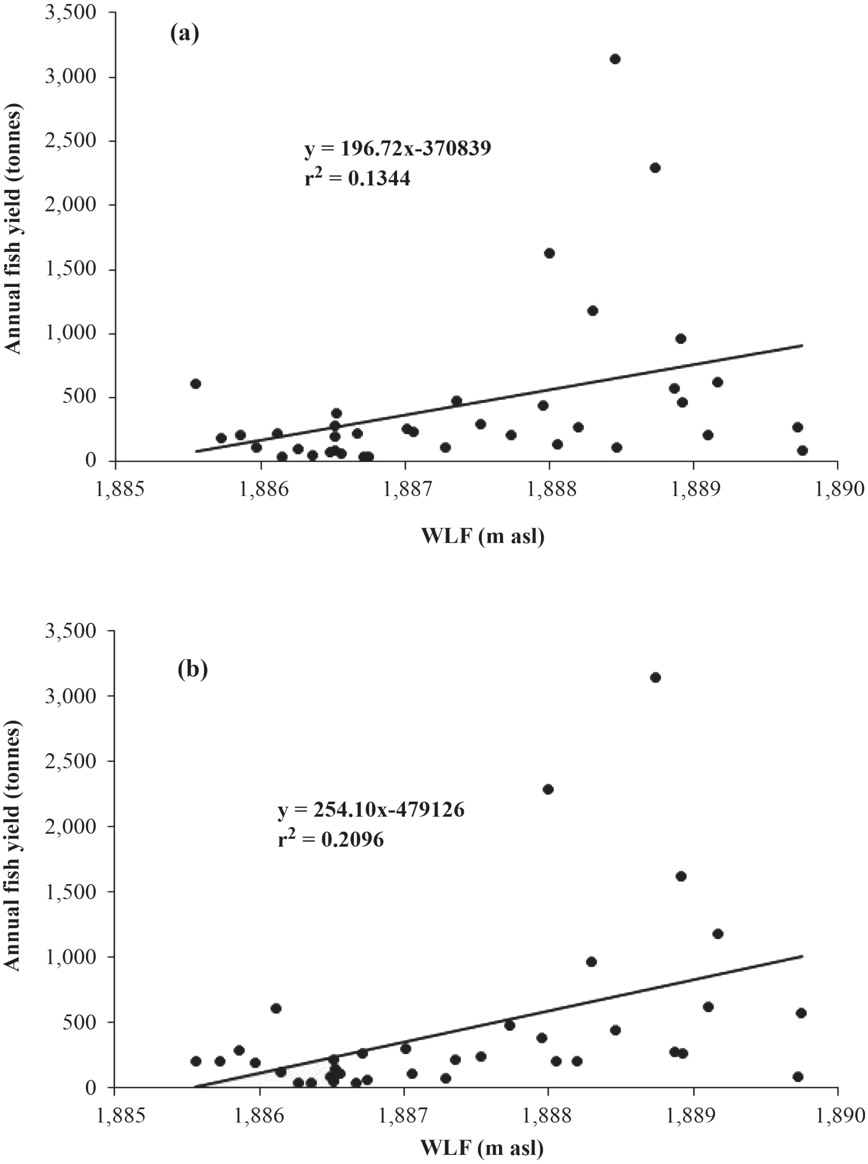

Figure 4. Regression lines on scatter diagrams showing WLF and annual fish yield relationship in Lake Naivasha: (a) direct regression of fish yield data against corresponding water level data; (b) indirect regression of fish yield against water level fluctuations after one-year time lag.

The regression results for datasets before and after imposition of the fishing ban in Lake Naivasha are shown in Figure 5. Prior to the one-year fishing ban (Figure 5a) fish yield and WLF trends had a non-significant but positive relationship ($F_{[1,18]} = 3.0982$, $p = 0.0954$; $r^2 = 0.1468$). On the other hand, fish yield and WLF trends had a significant positive relationship ($F_{[1,16]} = 6.5848$, $p = 0.0207$; $r^2 = 0.2916$) in the period after the fishing ban (Figure 5b).

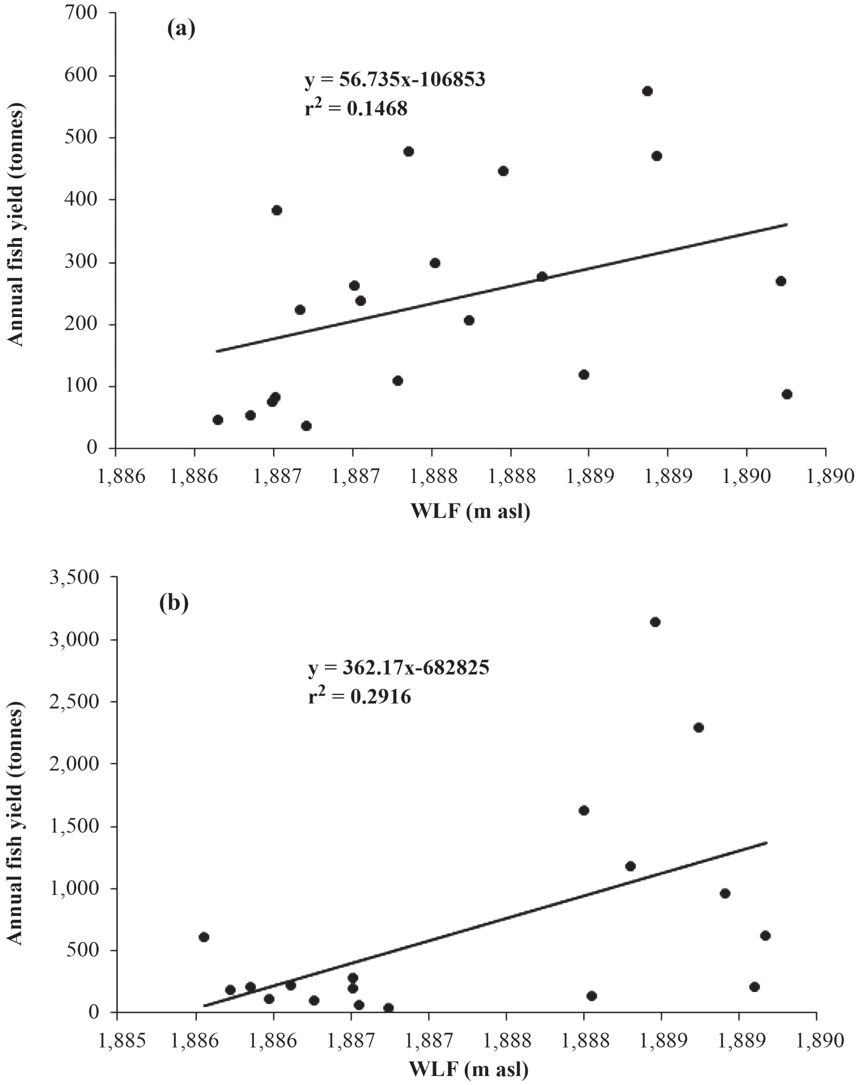

Figure 5. Regression lines on scatter diagrams showing WLF and annual fish yield relationship in Lake Naivasha in the periods (a) before imposition of a one-year fishing ban and (b) after the fishing ban.

DISCUSSION

Lake Naivasha WLF are crucial factors that characterize the fishery environment and determine its productivity. This study found remarkable variation in the lake levels, with an amplitude of about 4.2 m observed between 1980 and 2019. Despite these fluctuations, the time series dataset confirmed an increasing trend in mean water level over the study period. Possible explanations for the recessions and rebound in lake level include periods of extended dry and wet seasons and excessive water abstraction from the lake and its catchment basin for crop irrigation and other human uses (Becht *et al*., 2005). Climatic factors, mainly the precipitation and evaporation rates within the lake basin, strongly influence the water level. Past studies (Vincent *et al*., 1979; Verschuren *et al*., 2000; Becht *et al*., 2005) observed the lake's dynamic behaviour and reported water levels varying by an amplitude of about 12 m over the last 100 years. These fluctuations were in resonance with the prolonged cycles of dryer and wetter seasons. The lake and its catchment area lie within the region of the Inter-Tropical Convergence Zone (ITCZ). Therefore, the monsoon winds' influence casts a considerable amount of rain shadow over the basin with a bi-modal rainfall distribution pattern (Harper and Mavuti, 1996; Becht *et al*., 2005).

On the other hand, the anthropogenic impacts on WLF in Lake Naivasha are related to excessive water abstraction from the surface and underground aquifers for the extensively irrigated agricultural farms spread throughout the lake basin. The land area under horticultural irrigation around Lake Naivasha is about 4,000 ha, with more than 50,000 people directly or indirectly employed by the industry (Becht *et al*., 2005). The pressure to maintain both the farming businesses and the dependent livelihoods poses significant challenges in sustainably managing the water resources. Nevertheless, other studies (e.g., Nicholson, 1998) firmly attributed the climatic factors to WLF rather than anthropogenic influence. The datasets for Lake Victoria and three other lakes (Lakes Stefanie, Turkana, and Naivasha) in East Africa's northern Rift Valley showed similar shallow levels during the first half of the 19th century, followed by very high stands towards the fall of that period.

This study found a continuous and significant rising trend in lake level between 2010 and 2019. The trend could be largely attributed to changes in the precipitation pattern, both within the Lake Basin and its catchment area. A study by Nyokabi *et al*. (2021) reported an increasing trend of rainfall values in the catchment area from 2011, although in erratic patterns. Their study confirmed an upward trend of water levels in Lake Naivasha and asserted that the East African Rift Valley lakes of Kenya have experienced phenomenal water level rise from 2011 onwards.

Results of the present study further demonstrate high fluctuations in fish yield with statistically significant upward trend. From 1980 to 2000, the fishery mostly experienced declining catches in concert with highly fluctuating water levels. The fishery suffered from uncontrolled and excessive fishing with adverse impacts leading to its collapse in 2000 (Becht *et al*., 2005; Kundu *et al*., 2010). This situation may help explain the observed weak and insignificant relationship between fish yield and WLF during the period. But since 2002, fixed numbers of fishing vessels and fishermen have been licensed, and fishery managers are expected to maintain the maximum limit of ten gillnets and three crew per boat. These control measures abetted recovery of the fish stocks in Lake Naivasha. Notably, despite the lowest water level being witnessed in 2009, high fish yield for that year may be attributed to fish being aggregated in a small areas after the lake’s surface area had shrunk. Therefore, fish were highly vulnerable to capture, with eventual negative consequences for the recruitment process. Following this overexploitation, the trend of fish catches continued to decline until 2014, when the boom period began in tandem with increasing water levels. This observation suggests the need to consider reduction of fishing effort and pressure on fish resources during low water levels periods.

A significant relationship found between WLF and fish yield trends in Lake Naivasha corroborates the observation made by Muchiri and Hickley (1991) that both fishing pressure and lake level fluctuations caused by climatic variability are likely to influence the fishery status of Lake Naivasha. The present study assumed no change in fishing technology, which would be attributed to large variations in catches. Habitually, fishing in Lake Naivasha is predominantly an artisanal type with regulated fishing gears. Illegal fishers do not submit their catches for recording at the landing beaches. A study by De Silva (1985) observed that yield of Mossambique tilapia in a Sri Lankan reservoir was positively influenced by WLF, but after a two-year time lag. Another study comparing the habitat and fishery characteristics of Lakes Naivasha and Baringo reported the implications of habitat degradation for the fishery collapse in both lakes (Hickley *et al*., 2004). The same survey noted that fishing effort in the two lakes is only an additional pressure on fish resources after the environmental stressors that directly influence the annual fish yield. An indirect attribution of WLF to the annual fish catch variations (increase or decrease) was somewhat stronger than the direct one, implying that the effect of water level on yield was not immediate after the lake level rise. Logically, the increase or drop in water levels influences the requisite abiotic and biotic conditions for natural fish repopulation, the consequences of which would be observed later, in the successive year after successful spawning and recruitment events.

Results of the present study also concur with the observations by Gasith and Gafny (1990) that long term water level fluctuations in lakes and reservoirs may lead to periodic changes of the littoral slope and substrate composition of the lacustrine systems. Water level fluctuation in lakes can be considered an essential environmental disturbance factor, which maintains fish habitats' temporal and spatial heterogeneity, especially in the littoral zones. During low water levels, the semi-aquatic floral community that inhabits the exposed littoral zone provides vegetative habitats after inundation during high water levels. These macrophytes have also been attributed to the retention and release of phosphorus in sediments during dry and wet seasons (Keitel *et al*., 2016). In essence, the increased vegetation cover of the *Cyprus papyrus* swamp in Lake Naivasha is associated with wet seasons causing a rapid rise in the lake level (Harper and Mavuti, 1996).

Wantzen *et al*. (2008) reported a significant correlation between water level changes and water quality parameters in many lakes and reservoirs. Kolding and van Zwieten (2006) suggested that productivity limits for natural and man-made aquatic systems exist, and that these are based on both physical and biological factors, leading to limits set by either the carrying capacity or the scale of influence by climatic variability. Studies have shown that tropical water bodies exhibit hydrodynamic regimes that play vital roles in the injection and re-suspension of nutrients, a phenomenon that has strong influence on the aquatic communities and their productivity (Kolding and van Zwieten, 2012). Furthermore, it has also been proven that hydrologic regimes have influence on water quality and trophic status of reservoirs (Nadarajah *et al*., 2019). Seasonal water level fluctuations positively correlate with aquatic organisms' primary production and biomass (Gownaris *et al*., 2018), although negative attributes such as eutrophication and algal bloom phenomena have been reported (Plisnier *et al*., 1999; Li *et al*., 2018). For instance, a fish kill in Lake Naivasha in early 2010 was attributed to the deterioration of water quality in 2009, as lake level recessions were experienced (Njiru *et al*., 2015).

According to Patrick (2016), fish stocks usually recover from low abundance after periods of high water levels, because of reduced fishing efficiency and fish dispersion to the newly inundated areas. In Sri-Lanka, Bandara and Amarasinghe (2017) found that the nesting behavior of *Oreochromis niloticus* varied according to the slope of the littoral area, water turbidity and the amplitude of water level fluctuations in the reservoirs. Fishing pressure, in concert with WLF, significantly influences the reproductive biological traits of reservoir populations of *O. niloticus* (Bandara and Amarasinghe, 2018). It is worth noting that Lake Naivasha's fish species, particularly the cichlids, utilize the littoral zone for their feeding and reproduction activities. This consideration justified the delineation and protection of four sites (Crescent Island, Malewa river mouth, Korongo bay and Oserian bay) for fish breeding in Lake Naivasha (Yongo *et al*., 2013). Shallow areas around the lake are equally important for their rich detritus and ideal nursery grounds for juvenile fish. Therefore, the periodic WLF directly influence the area of habitats available for the various fish species; hence, the stock abundance in Lake Naivasha. This observation validates earlier reports that water level amplitudes in reservoirs have a strong predictive power of fish yield (Nadarajah *et al*., 2018) and that relative lake level fluctuations can be used to predict fish yield in tropical lakes and reservoirs (Kolding and van Zwieten, 2006; 2012).

Results of this study implied the association of rising and relatively stable lake levels from 2010 to 2019 with favorable habitat conditions for both enhancement and natural repopulation of the fish stocks in Lake Naivasha. The re-introduction and subsequent restocking of *O. niloticus* fingerings in Lake Naivasha commenced in 2011 (Waithaka *et al*., 2020). Earlier attempts in the 1970s had failed, probably because of either high predation on fry and fingerlings by bass (Njiru *et al*., 2017) or the harsh habitat conditions during extreme water recessions. *Oreochromis niloticus* is tolerant to a wide range of habitat conditions, with high capability to switch its feeding and reproductive behavior (Getabu, 1992; Njiru *et al*., 2004; 2008). Hence, water level rise in Lake Naivasha avails larger surface area with additional refugia for this species and other commercially exploited species utilizing the littoral zones for reproductive and feeding activities. Subsequent to a water level increase, fishing intensity on fish stocks declines because of the expansive new fishing grounds created.

In contrast, water level recessions are likely to shrink the available area of fish habitats and make the stocks more vulnerable to capture as fishing effort is concentrated in a more limited area. This implies that higher catches may be recorded during periods of low water levels, with associated low recruitment due to ecosystem overfishing. However, such catches are usually short-lived and precede a catastrophic decline in the subsequent years if appropriate management interventions are delayed. This argument explains the observed phenomenally high fish catches (690 tonnes) in Lake Naivasha during 2009, when the lake level was at its lowest, and subsequent years had dismal catches until 2014. Other factors which may have caused increases in yield include the successful stock enhancement with the reintroduction of *Oreochromis niloticus* in 2011. Success of the stocking program for this species may have been enhanced by lake level rise, with extensive habitat area for reproduction and feeding. The positive results of the restocking program may have influenced the high catches recorded from 2014 to 2019. This factor likely affected the power of determination in the relationship regression equations reported.

CONCLUSION

There was a significant trend in WLF-fish yield historical data. The strong correlation between water level and fish yield variations illustrates that water level variations are a critical factor influencing Lake Naivasha’s annual fish yield. Therefore, management strategies should aim towards ecosystem-based approaches to mitigate both the anthropogenic and climate-induced impacts on the lake's water levels. Such management strategies include the rehabilitation of catchment areas and capacity building for the best water resource use practices. Furthermore, management ought to align fishing effort control and stock enhancement with the changing lake level conditions. A reduction of fishing effort during low water level is likely to ease pressure on the resource and allow for stock-replenishment. In occasions of rising water levels, large scale restocking of fish species like *Oreochromis niloticus* may be a better option to boost stock recruitment for subsequent improved fish yield and support to many livelihoods.

ACKNOWLEDGEMENTS

The Kenya Marine and Fisheries Research Institute (KMFRI) and Kisii University through the African Development Bank (AfDB) Scholarship supported this study. The authors are indebted to the staff of KMFRI, Water Resource Authority (WRA), and the Nakuru County Directorate of Fisheries Department (FD), through Naivasha Station, who provided access to the datasets used in this study.

LITERATURE CITED

Ahmad, I., D. Tang, T.F. Wang, M. Wang and B. Wagan. 2015. Precipitation trends over time using Mann-Kendall and Spearman's rho tests in Swat River Basin, Pakistan. **Advances in Meteorology** 2015: 431860. DOI: 10.1155/2015/431860.

Amarasinghe, U.S. and S.S. De Silva. 2015. **Fishes and fisheries of Asian inland lacustrine waters.** In: Freshwater Fisheries Ecology (ed. J.F. Craig), pp. 384-403. Wiley-Blackwell, Chichester, UK.

Baker, C., R.L. Lawrence, C. Montagne and D. Patten. 2007. Change detection of wetland ecosystems using landsat imagery and change vector analysis. **Wetlands** 27: 610-619.

Bandara, K.V.S.N. and U.S. Amarasinghe. 2017. Factors related to nesting sites of *Oreochromis niloticus* (Cichlidae) in irrigation reservoirs, Sri Lanka. **Asian Fisheries Science** 30(4): 319-335.

Bandara, K.V.S.N. and U.S. Amarasinghe. 2018. Influence of fishing pressure and water level fluctuations on the reproductive biology traits of *Oreochromis niloticus* (Linnaeus 1758) in irrigation reservoirs of Sri Lanka. **Asian Fisheries Science** 31: 127-145.

Becht, R., E.O. Odada and S. Higgins. 2005. **Lake Naivasha: Experience and lessons learned brief.** http://ezproxy.utwente.nl:2048/login?url=https://webapps.itc.utwente.nl/library/2005/tech_rep/becht_lak.pdf. Cited 3 Mar 2021.

Cohen, A.S., L. Kaufman and R. Ogutu-Ohwayo. 1996. **Anthropogenic threats, impacts and conservation strategies in the African Great, Lakes: A review.** In: The Limnology, Climatology and Paleoclimatology of the East African Lakes (eds. T.C. Johnson and E. Odada), pp. 575-624. Gordon and Breach, Toronto, Canada.

De Silva, S.S. 1985. Observations on the abundance of the exotic cichlid *Sarotherodon mossambicus* (Peters) in relation to fluctuations in the water-level in a man-made lake in Sri Lanka. **Aquaculture and Fisheries Management** 16: 265-272.

Elder, H.Y., D.T. Garrod and P.J.P. Whitehead. 1971. Natural hybrids of the African cichlid fishes *Tilapia spirulus nigra* and *T. leucosticta*, a case of hybrid introgression. **Biological Journal of the Linnean Society** 3(2): 103-146.

Finlayson, C.M., J.A. Davis, P.A. Gell, R.T. Kingsford and K.A. Parton. 2013. The status of wetlands and the predicted effects of global climate change: the situation in Australia. **Aquatic Sciences** 75: 73-93.

Gasith, A. and S. Gafny. 1990. **Effects of water level fluctuation on the structure and function of the littoral zone.** In: Large Lakes (eds. M.M. Tilzer and C. Serruya), pp. 156-171. Brock/Springer Series in Contemporary Bioscience, Springer, Berlin, Heidelberg, Germany.

Gaudet, J.J. and J.M. Melack. 1981. Major ion chemistry in a tropical African lake basin. **Freshwater Biology** 11: 309-333.

Getabu, A. 1992. Growth parameters and total mortality in *Oreochromis niloticus* (L) from Nyanza Gulf, Lake Victoria. **Hydrobiologia** 232: 91-97.

Gownaris, N.J., K.J. Rountos, L. Kaufman, J. Kolding, K.M.M. Lwiza and E.K. Pikitch. 2018. Water level fluctuations and the ecosystem functioning of lakes. **Journal of Great Lakes Research** 44(6): 1154-1163.

Haghighi, A.T. and B. Klove. 2015. A sensitivity analysis of lake water level response to changes in climate and river regimes. **Limnologica-Ecology and Management of Inland Waters** 51: 118-130.

Harper, D.M. 1991. Primary production in Lake Naivasha, Kenya. **Verhandlungen Internationale Vereinigung Limnologie** 24: 1112-1116.

Harper, D.M. and K.M. Mavuti. 1996. **Freshwater wetlands and marshes.** In: East African Ecosystems and Their Conservation (eds. T.R. McClanahan and T.P. Young), pp. 217-240. Oxford University Press, New York, USA.

Harper, D.M. and K.M. Mavuti. 2004. Lake Naivasha, Kenya: Ecohydrology to guide the management of a tropical protected area. **Ecohydrology and Hydrobiology** 4(3): 287-305.

Harper, D.M., K.M. Mavuti and S.M. Muchiri. 1990. Ecology and management of Lake Naivasha, Kenya, in relation to climatic change, alien species' introductions, and agricultural development. **Environmental Conservation** 17(4): 328-336.

Hickley, P., M. Muchiri, R. Boar, R. Britton, C. Adams, N. Gichuru and D. Harper. 2004. Habitat degradation and subsequent fishery collapse in Lakes Naivasha and Baringo, Kenya. **Ecohydrology and Hydrobiology** 4(4): 503-517.

Hickley, P., R. Bailey, D.M. Harper, R. Kundu, M. Muchiri, R. North and A. Taylor. 2002. The status and future of the Lake Naivasha fishery, Kenya. **Hydrobiologia** 488(1): 181-190.

Hisdal, H., K. Stahl, L.M. Tallaksen and S. Demuth. 2001. Have streamflow droughts in Europe become more severe or frequent. **International Journal of Climatology** 21: 317-333.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. Van der Linden and D. Xiaosu. 2001. **Climate Change 2001: The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).** Cambridge University Press, Cambridge, UK. 881 pp.

Keitel, J., D. Zak and M. Hupfer. 2016. Water level fluctuations in a tropical reservoir: the impact of sediment drying, aquatic macrophyte dieback, and oxygen availability on phosphorus mobilization. **Environmental Science and Pollution Research** 23(7): 6883-6894.

Kiani, T., M.H. Ramesht, A. Maleki and F. Safakish. 2017. Analyzing the impacts of climate change on water level fluctuations of Tashk and Bakhtegan lakes and its role in environmental sustainability. **Open Journal of Ecology** 7: 158-178.

Kolding, J. and P.A.M. Van Zwieten. 2006. **Improving productivity in tropical lakes and reservoirs.** CGIAR Challenge Program on Water and Food-Aquatic Ecosystems and Fisheries Review, Series 1. World Fish Centre, Cairo, Egypt. 139 pp.

Kolding, J. and P.A.M. Van Zwieten 2012. Relative lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. **Fisheries Research** 115-116: 99-109.

Kundu, R., C.M. Aura, M. Muchiri, J.M. Njiru and J.E. Ojuok. 2010. Difficulties of fishing at Lake Naivasha, Kenya: is community participation in management the solution? **Lakes and Reservoirs: Research and Management** 15: 15-23.

Li, Q., J. Xiao, T. Ou, M. Han, J. Wang, J. Chen, Y. Li and N. Salmaso. 2018. Impact of water level fluctuations on the development of phytoplankton in a large subtropical reservoir: implications for the management of cyanobacteria. **Environmental Science and Pollution Research International** 25: 1306-1318.

Litterick, M.R., J.K. Gaudet and J.M. Melack. 1979. **The limnology of an African lake, Lake Naivasha, Kenya.** Workshop on an African Limnology, United Nations Environment Programme, Nairobi, Kenya. 61 pp.

Mooij, W.M., S. Hülsmann, L.N. De Senerpont Domis, B.A. Nolet, P.L.E. Bodelier, P.C.M. Boers, M.L. Dionisio Pires, H.J. Gons, B.W. Ibelings, R. Noordhuis, R. Portielje, K. Wolfstein and E.H.R.R. Lammens. 2005. The impact of climate change on lakes in the Netherlands: A review. **Aquatic Ecology** 39: 381-400.

Morara, G.N., J.M. Njiru, A.M. Getabu, R. Omondi, R. Lewo, B. Obegi and R. Mwangata. 2021. Illegal unregulated and unreported fishing: Methods and increasing trends in Lake Naivasha, Kenya. **Lakes and Reservoirs: Research and Management** 26(1): 13-22.

Muchiri, S.M. and P. Hickley. 1991. **The fishery of Lake Naivasha, Kenya.** In: Catch Effort Sampling Strategies: Their Application in Fresh Water Fisheries Management (ed. I.G. Cowx), pp. 382-392. Fishing News Books, Blackwell Scientific Publications, Oxford, UK.

Nadarajah, S., W.M.H.K. Wijenayake and U.S. Amarasinghe. 2018. Empirical production predictive models for the fisheries of irrigation reservoirs in Sri Lanka. **Sri Lanka Journal of Aquatic Sciences** 23(2): 201-208.

Nadarajah, S., W.M.H.K. Wijenayake and U.S. Amarasinghe. 2019. Influence of hydrology on water quality and trophic state in irrigation reservoirs of Sri Lanka. **Lakes and Reservoirs: Science, Policy and Management for Sustainable Use** 24: 287-298.

Nicholson, S.E. 1998. **Historical fluctuations of Lake Victoria and other lakes in the northern rift valley of East Africa.** In: Environmental Change and Response in East African Lakes (ed. J.T. Lehman), pp. 207-231. Springer, Dordrecht, Netherlands.

Njiru, J., E. Waithaka and P.A. Aloo. 2017. An Overview of the current status of Lake Naivasha fishery: Challenges and management strategies. **The Open Fish Science Journal** 10: 1-11.

Njiru, J., G. Morara, E. Waithaka and J. Mugo. 2015. Fish kills in Lake Naivasha, Kenya: What was the probable cause? **International Journal of Fisheries and Aquatic Studies** 3(1): 179-184.

Njiru, M., A. Getabu, T. Jembe, C. Ngugi, M. Owili and M. Van Der Knaap. 2008. Management of the Nile tilapia *Oreochromis niloticus* (L.) fishery in the Kenyan portion of Lake Victoria, in light of changes in its life history and ecology. **Lakes and Reservoirs: Research and Management** 13(2): 117-124.

Njiru, M., J.B. Okeyo-Owour, M. Muchiri and I.G. Cowx. 2004. Shift in feeding ecology of Nile tilapia in Lake Victoria, Kenya. **African Journal of Ecology** 42: 163-170.

Nyokabi, W.E., R.M. Wambua and R.O. Okwany. 2021. Assessment of rainfall, streamflow and reservoir level trends for Malewa River Catchment, Naivasha, Kenya. **Journal of Civil, Construction and Environmental Engineering** 6(1): 1-8.

Odada, O.E., O.D. Olago, F. Bugenyi, K. Kulindwa, J. Karimumuryango, K. West, M. Ntiba, S. Wandiga, P. Aloo-Obudho and P. Achola. 2003. Environmental assessment of the East African rift valley lakes. **Aquatic Science** 65: 254-271.

Oyugi, D.O., J. Cucherousset, M.J. Ntiba, M.S. Kisia, D.M. Harper and R.J. Britton. 2011. Life history traits of an equatorial common carp *Cyprinus carpio* population in relation to thermal influences on invasive populations. **Fisheries Research** 110: 92-97.

Patrick, A.E.S. 2016. Influence of rainfall and water level on inland fisheries production: A review. **Archive of Applied Science Research** 8(6): 44-51.

Plisnier, P.D., D. Chitamwebwa, L. Mwape, K. Tshibangu, V. Langenberg and E. Coenen. 1999. Limnological annual cycle inferred from physical-chemical fluctuations at three stations of Lake Tanganyika. **Hydrobiologia** 407: 45-58.

Richardson, J.L. and A.E. Richardson. 1972. History of an African rift lake and its climactic history. **Ecological Monographs** 42(4): 499-534.

Sayer, C.A., A.F. Palmer-Newton and W.R.T. Darwall. 2019. **Conservation priorities for freshwater biodiversity in the Lake Malawi/Nyasa/Niassa catchment.** International Union for Conservation of Nature, Cambridge, UK and Gland, Switzerland. 214 pp.

Shadmani, M., S. Marofi and M. Roknian. 2012. Trend analysis in reference evapotranspiration using Mann-Kendall and Spearman's Rho tests in arid regions of Iran. **Water Resource Management** 26: 211-224.

Verschuren, D., K.R. Laird and B.F. Cumming. 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. **Nature** 403: 410-414.

Vincent, C.E., T.D. Davies and U.C. Beresford. 1979. Recent change in the levels of Lake Naivasha, Kenya, as an indicator of equatorial westerlies over East Africa. **Climatic Change** 2: 175-191.

Waithaka, E., E. Yongo, N. Outa and E. Mutethya. 2020. Population biology of Nile tilapia (*Oreochromis niloticus*) in Lake Naivasha, Kenya. **Lakes and Reservoirs** 25(2): 244-249.

Wantzen, K.M., K.O. Rothhaupt, M. Mörtl, M. Cantonati, L.G. Tóth and P. Fischer. 2008. Ecological effects of water level fluctuations in lakes: an urgent issue. **Hydrobiologia** 613: 1-4.

Wu, H., L.K. Soh, A. Samal and X.H. Chen. 2008. Trend analysis of streamflow drought events in Nebraska. **Water Resource Management** 22: 145-164.

Yongo, E.O., G. Morara, J. Ojuok, C. Nyamweya, O.W. Ojwang and M. Masai. 2013. Socio-economic aspects of fisheries management in Lake Naivasha. **African Journal of Tropical Hydrobiology and Fisheries** 13: 27-32.

Yue, S. and P. Pilon. 2004. A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection. **Hydrological Sciences** 49(1): 21-37.