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Impacts of hydro climatic conditions on lesser flamingo, *Phoeniconaias minor,* Geoffroy populations in three Kenyan alkaline lakes

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ABSTRACT

Hydro climatic conditions are critical factor determinants of lesser flamingo ecology in the alkaline Lakes of Nakuru, Elementaita and Bogoria in Kenya. Based on lake levels, rainfall and river inflows, eight hydro climatic periods were designated and lesser flamingo numbers analyzed relative to them and other limnological conditions. Dry hydro climatic periods with reduced surface water inflows and evaporative concentration cycles were strongly correlated with challenging limnological conditions such as conductivity and pH, altered lake basin configurations and low lesser flamingo numbers. Similarly, extra wet hydro climatic conditions led to desertions as the ecosystems characteristics were altered through dilutions and limnological conditions changes resulting from excessive fresh water inflows. The shallow Lakes Nakuru and Elementaita were the most vulnerable to hydro climatic impacts and were deserted by lesser flamingos in the dry periods as the shorelines receded and largely dried out on two occasions in 1995 and 1996. Lesser flamingos shifted in large numbers to the deeper and more hydrologically stable Lake Bogoria. A similar pattern prevailed in the early relatively wet periods in 1998 and to a lesser extent in the very wet phase between the years; 2013-2015. At water depths of 70cm to 120cm in normal hydro climatic periods, lesser flamingo occupancy was highest in the Lake Nakuru and Elementaita compared to a 4m depth in lake Bogoria. As lake levels rose beyond previously unprecedented levels after 2012, lesser flamingos have increasingly moved away from the region. The study concludes that lesser flamingo populations in the alkaline lakes are intricately linked to climatic conditions and their coupled ensuing hydrological dynamics. The findings suggest that increased climatic variability associated with climate change is adversely impacting the ecology of the three alkaline lakes' ecosystems and consequently imperiling the lesser flamingo population and its conservation in Kenya.

1. Introduction

Lesser flamingos *Phoeniconaias minor*, Geoffroy are the most numerous bird species in the Kenyan alkaline lakes constituting 20% of the total avian biomass. These lakes constitute part of the range of the lesser flamingos that includes the alkaline eastern rift valley lakes in Ethiopia, Kenya and Tanzania. Populations of lesser flamingo also occur in Makgadgadi and Etosha pans of Southern Africa [5] while outlier populations occur in West Africa and the coastal areas of Western India. The lesser flamingos aggregate in large numbers and at times a single lake can hold upwards of 500,000. The ecology of the lesser flamingos in these lakes is to a large extent driven by limnological conditions that are in turn affected by climatic conditions in the catchments. Despite local abundances of food resources, the lesser flamingos exhibit inter-lake nomadic movements and a lake may be deserted for a few days or continuously occupied for months [26]. The primary producer ecology of the alkaline lakes and the subsequent ecology of the consumers in the alkaline lakes are dependent on the water chemistry and other limnological conditions that are intricately linked to the water balance in the lakes [27;28] The water chemistry determines which algal species are able to establish and thrive [30] and hence determine the food availability to lesser flamingos. This study was part of an investigation into the ecological factors and processes that are associated with or trigger these movements and occupancy of the alkaline lakes in the central rift valley region of Kenya.

The main study was undertaken between 1994 and 1998 on the relationship between climatic conditions, limnological dynamics and lesser flamingo numbers in Lakes Nakuru, Bogoria and Elementaita that account for the largest proportion of the flamingo population in Kenya. Other smaller lakes such as Lake Simbi, the Oloidien and Sonachi crater satellite lakes around Lake Naivasha, and Lake Magadi hold smaller congregations of lesser flamingos. The research period was climatically highly variable and spanned two extremely dry period of the years 1995-1996 and a relatively wetter one of 1997-1998 in the Central Rift Valley region of Kenya where the three lakes are located. A subsequent period with extremely elevated lake levels has persisted from 2012 to this year 2022. Data on lesser flamingo populations in the three lakes for the high lake levels period was obtained for 2014 and 2015 as the midpoints.

Study lakes

The alkaline lakes of the Eastern Rift valley have features that are rarely found anywhere else in the world [15]. The lakes occur in a geographical range from Ethiopia to Central Northern Tanzania which comprise the range of lesser flamingos in this region and are associated with inland drainage basins in the rift system. In Kenya, three lakes, namely Elementaita, Nakuru and Bogoria have for a long time been identified as important lesser flamingo habitats and were the focal points for the study. The lakes are in close proximity of each other with Lake Nakuru located 150 km northwest of Nairobi, and Lake Elementaita 20 km southeast of Lake Nakuru, while Lake Bogoria is 100 km north from Nakuru (Figure 1). The three lakes share limnological characteristics associated with alkaline lakes but differ in basin morphometry, inflow characteristics and hydrological regimes.

Lakes Nakuru and Elementaita share several similarities in that both are shallow pans and have ephemeral tendencies in their water levels and inflow characteristics [25]. Lake Nakuru is fed by three main rivers comprising of Njoro, Nderit and Makalia Rivers and the Baharini Springs in the northern part of the lake. The rivers are increasingly becoming seasonal with time and land use changes [9]. Lake Elementaita receives its main water supply from River Mbaruk that is supplemented by the Meroroni Springs in the north east and some warm springs in the south [16]. Lake Bogoria is deeper and has a fissure morphometry and elongated shape. It has a copious water supply from hot and cold springs located within it and shoreline periphery in addition surface inflow from River Sandai-Ewasseges in the north. The inflows from the array of fumaroles, hot and cold springs counterbalances evaporative water loss [23] resulting in a lower amplitude of lake level variations compared to the two other lakes.

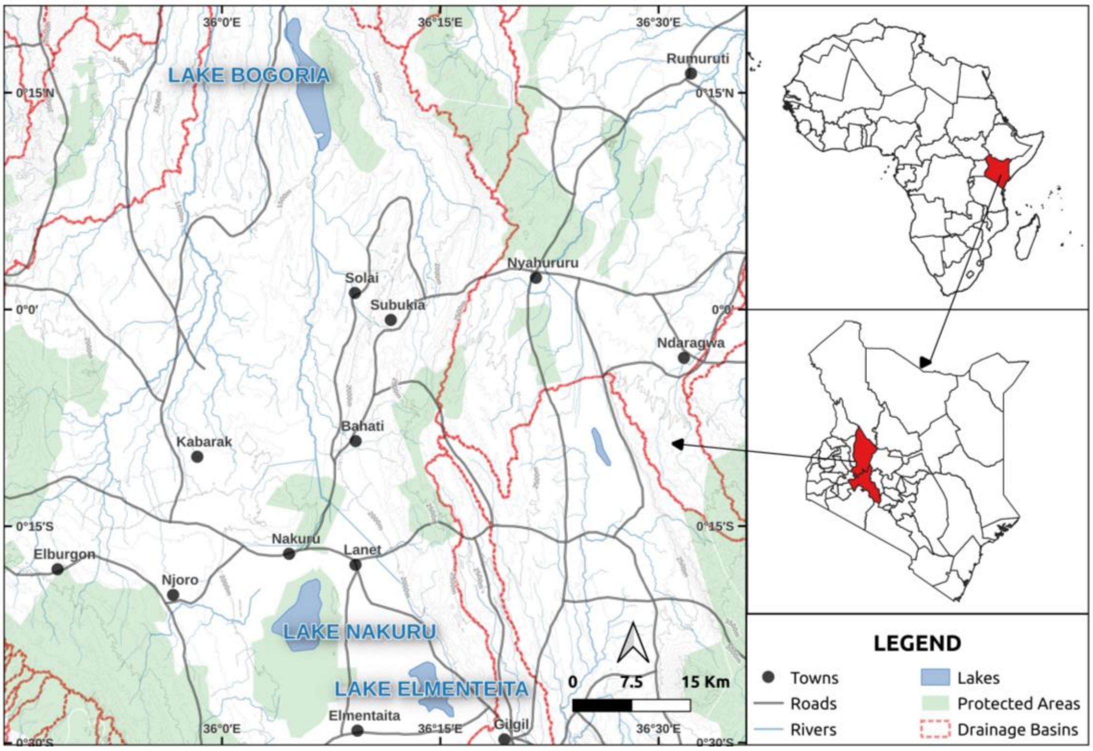

Figure 1: Location of Lakes of Nakuru, Elementaita and Bogoria in Kenya

The lakes inflow characteristics, shoreline configurations and basin morphometry present a diversity of microhabitats within and between the lakes that has made them ideal to study the ecological factors that influence the inter-lake and intra-lake utilization patterns and movements of lesser flamingos. At times in the past, the three lakes held almost the entire population of the East African lesser flamingo [3;5;11;25;26]. This is indicative of the crucial role of the three lakes in lesser flamingos' existential ecology.

Climate and hydrology

The climatic regime that prevails in the geographical zone of the study lakes range from arid to semi-arid, where Lakes Nakuru and Elementaita fall into ecological Zone IV and Lake Bogoria in Zone V as classified by [18]. The rainfall in the lakes basins exhibit altitudinal and seasonal variations, a bi-modal distribution of two wet and dry seasons characterized by inter and intra-annual differences. Annual precipitation is higher and more evenly distributed around higher elevation Lake Nakuru at 1875m asl and Elementaita at 1774m asl than in the lower-lying environs at 950m asl, of Lake Bogoria basin. The temperature ranges are high ranging from 6^oC to 39^oC in the cold and hot periods, respectively, with a large precipitation-evaporation deficit. The endorheic hydrology of the three lakes is characterized by dendritic internal drainage associated with rivers from the eastern and western rift valley escarpments such as a Mbaruk, Njoro and Sandai-Ewasseges.

Environmental conditions in many shallow Inland African lakes are affected by a myriad of factors both internal and external that interact. These comprise of physical and chemical, abiotic and biotic processes that are constrained by basin morphometry and climatic determinants that include rainfall and hence inflow terms in the hydrological cycle [22]. This interplay of factors leads to variability in time and space that ultimately determines the ecology of producer and consumer organisms in these lakes. The study alkaline lakes are located in basins with different microclimates and exhibit different physiographic configurations and limnological characteristics leading to substantive primary production variations between them [9]. Changes in the physical and limnological attributes had been suggested as possible factors that may induce lesser flamingo movements and result in differentiated occupancy patterns in the alkaline lakes [2;26]. Differences in basin climatic conditions, hydrological regimes, lake morphometry, water chemistry and biotic processes may result in ecological variations in the alkaline lakes that may affect occupancy and trigger nomadic movements. It has been observed that the Eastern Africa region has undergone considerable and substantial climatic variability in the past and recent times that is superimposed on the recurrent annual seasonal variability [7;20]. The hydro climatic variability of the East African region has resulted in dramatic changes in lake levels, river flow regimes and morphometric reconfigurations of the lakes as documented by [12]. These changes affect the limnological characteristics of the lakes, affect their ecological processes and have implications on the biotic assemblages in the lakes [9;10]. The hydro climatic period differentials have been enhanced by the increasing frequency of extreme weather events associated with climate variability and change in the Kenyan Rift Valley region [14]. Lesser flamingo occupancy trends of the three alkaline lakes were analyzed for the highly variable hydro climatic periods of 1995-April 1996, 1998 and the 2012 and 2022 periods.

2. Materials and methods

Climatic and hydrological parameters

Climatic data in Lake Nakuru vicinity was obtained from a station near the main gate to the Lake Nakuru National Park and for the catchment from the Kenya Agricultural Research Institute Plant Breeding Station at Njoro to the west of the lake. A series of automated Gauging Stations recorded flow regimes for Rivers Njoro, Makalia and Nderit. Two sets of staff gauges in the northern and southern parts of Lake Nakuru were used to document lake levels. Lake Nakuru had a very comprehensive data set hydrological and meteorological variables that were used to designate the hydro climatic periods used in this analysis.

Rainfall data for Lake Elementaita was recorded at the Soysambu Ranch Offices, 2.5 km west of the lake while lake water levels were read from staff gauges in the northwest part of the lake near the Lord Delamare Tented Camp. Rainfall records for Lake Bogoria were obtained from reserve offices 3 km north of the lake.

The staff gauges in Lake Bogoria were nonfunctional as the plates and scales were too corroded for any reliable readings to be made from them. As such Water levels were indicated as low or high from known points along the shoreline in Lake Bogoria.

The general climatic conditions and trends were similar in the central rift valley during the period with variations that were site specific due to altitudinal, topographic and agro climatic conditions. The extended droughts and major precipitation episodes were widespread with locally defined variations. As such the data for lake levels for Lake Nakuru and flows in its influent rivers were used as proxies for hydrological conditions in the general larger region.

Limnological parameters

The physical-chemical parameters considered important in the ecological functioning and characterization of the alkaline lakes were conductivity, pH, oxidation-reduction potential (ORP), dissolved oxygen concentration, light penetration, temperature and lake depth. These parameters are strongly influenced by water levels, hydrological inflows characteristics and climatic conditions in the alkaline lakes. These were measured *in situ* using portable electronic meters and appropriate equipment at selected sampling points.

Electrical conductivity and temperature were measured with a digital meter Kasagau Model UC-35 while pH and ORP was determined using a Kasagau Meter Model UC-23 with a combined pH-ORP (Oxidation-Reduction Potential) probe port. Dissolved oxygen concentration was measured in milligrams per liter using a Kasagau Model UC-2 meter. A quartered 15-cm diameter Secchi disc was used to determine water column light penetration. A weighted nylon rope was lowered vertically into the water to measure depth at offshore sampling points and a graduated rod (in cm) pushed into the substrate to measure the organic ooze depth. All parameters were sequentially determined from the water surface to the bottom for Lake Nakuru and Elementaita.

Water samples were collected for analysis of phytoplankton species composition in the laboratory. The phytoplankton were identified to species level where possible and genus level in some cases. Samples of 1ml were pipetted into a Sedgewick rafter counting chamber and placed on an inverted microscope stage and at x100 magnification the number of cells/l was determined.

Lesser flamingo census

A variation of the shoreline census methods [1;2;4] was adopted in counting lesser flamingo numbers in the lakes. The numbers were estimated from elevated viewpoints around the lakes using a 15-60X telescope. The combination of the telescope and elevated positions enabled distinction of individual birds in contrast to the level shoreline census method where the birds blend and mask each other. The elevated positions selected and markers placed along the shorelines conferred a composite view of the lakes and positions were visited within short time periods. Counts were conducted in the morning between 7.30 and 10.30 A.M. and in the afternoon from 4.00 and 6.00 P.M. To avoid repeated same individual counting, calm weather days when intra-sites movements was minimal were preferred. Numbers present in each field of view were counted using a tally counter. Where individuals were evenly distributed, blocks with known numbers were counted and extrapolated to adjacent areas with the similar densities. Counts were made at least every two weeks in Nakuru or more frequently depending on prevailing conditions or noticeable fluctuations in numbers. Counts were more sporadic in Lakes Elementaita and Bogoria depending on logistics. Annual flamingo counts for the lakes have been obtained for 2014 and 2015 from Kenya Wildlife Service and the National Museums of Kenya that were conducted using the traditional shoreline based method. Visits were also made to nearby smaller alkaline lakes and numbers monitored from partners in other regional alkaline lakes.

3. Results

Hydro climatic periods

Data on river flow regimes; rainfall and lake water levels and temperature were used in the statistical designation of the hydro climatic periods. Lake Nakuru had a comprehensive data set for the target parameters and was used in the analysis and complemented with data from Lake Bogoria and Lake Elementaita. Eight (8) periods with distinct climatic and hydrological conditions were retrospectively designated.

Table 1: Variations in limnological parameters in Lake Nakuru, Elementaita and Bogoria for climatic periods designated between April 1994 and July 1998(N/s = Not sampled).

	Period								
Parameter	**Lake**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**
Duration		June 94-Jan 95	Feb 95-June 95	July 95-Nov 95	Dec 95-April 96	May 96-Nov 96	Dec 96-April 97	May 97-Dec 97	Jan 98-July 98
Rainfall (mm)	Nakuru	100.0±28.6	73.1±7.46	80.1±21.7	48.2±14.6	105.4±19.4	46.8±34.2	103.917.3	107.8±26.6
	Elementaita	48.9±9.2	61.6±21.9	73.8±17.4	77.6±35.7	52.6±33.	55.6±33	95.9±18.7	64.0±14.1
	Bogoria	37.7±11.1	44.3±8.7	41.0±15.8	83.6±15.3	32.7±18.4	46.6±13.8	37.5±16	50.6±27.3
Lake level (cm)	Nakuru	22.2±8.6	25.0±10.3	0	0	63.7±11.9	0	75.13±11.6	354.8±16.0
Electrical conductivity (µS/cm)	Nakuru	45,870	72,340	82,610	59,360	46,450	93,500	55,315	17,890
	Elementaita	17,640	40,850	45,970	88,620	29,880	N/s	37,060	46,770
	Bogoria	53,460	84,930	74,740	87,970	68,260	81,750	59,750	10,760
PH	Nakuru	10.14	10.18	10	10.02	10.06	10.38	10.37	9.78
	Elementaita	10.25	10.24	10.35	10.1	9.82	N/s	10.06	9.58
	Bogoria	10.26	10.26	10.09	10.24	9.83	10.28	9.87	9.94
Temperature (°C)	Nakuru	26.8	28.1	27.1	27.7	27	29.5	26.95	24
	Elementaita	26.75	23.1	20.8	30	25	Dry	19.12	22.5
	Bogoria	27.3	27.5	27	28.8	30	32	31.3	30.3
Dissolved Oxygen (mg/l)	Nakuru	10.13	8.5	8.9	8.5	14.1	9.6	8.2	9.2
	Elementaita	10.4	4.8	2.6	12	15	Dry	10.4	7.7
	Bogoria	14.2	11.3	13.5	7.6	17.7	9	14.9	13.5
Secchi (cm)	Nakuru	6.5	6.26	8.7	-	7.8	7.6	6.7	17.8
	Elementaita	6.3	-	-	-	7.3	Dry	4.8	15
	Bogoria	16.4	16	20.5	11	23.5	21.7	17.2	18.7
ORP (mV)	Nakuru	-	-179	-186	-111.3	-69.2	-121	-22.6	16
	Elementaita		-	-146	-123.6	-31.6	Dry	-134.2	-117.5
	Bogoria		-156	-183	-213.4	-84.9	-61	-161.6	-73.8

In period I, Lake Nakuru had a mean water level of 55 cm, the catchment had good rainfall and the rivers were influent into the lake (Figure 2). A similar situation prevailed in Lake Elementaita with a mean depth of 45 cm, wet climatic conditions and good inflows in River Mbaruk. In Lake Bogoria, River Sandai-Ewasseges was influent and there was no evidence of water recession along the shorelines. This period lasted from June 1994 to January 1995 when a dry phase designated as period II set in. It spanned the dry season from February to June 1995 and was characterised by extensive shoreline recessions in Lake Nakuru and Elementaita. Rainfall was low, erratic and river flow completely ceased in all the three lakes. In period III, rainfall received in the region was lower than the mean expectation 80.1 mm and river inflows were inadequate to restore water in Lake Nakuru and Elementaita. Large swathes of the lakebed in Lake Nakuru and Elementaita were exposed mudflats in some places covered by a few centimetres of water underlain by thick superficial organic ooze deposits. In Lake Bogoria, water levels dropped by 0.5 m to 3.5m in the northern bay area an extensive portion near the Sandai-Ewasseges river mouth exposed. Strong south-westerly winds caused frequent water column mixing and deposition of bottom sediments along the western shoreline. Foul odours of decomposing organic matter and hydrogen sulphide emanated from the lake in Period III.

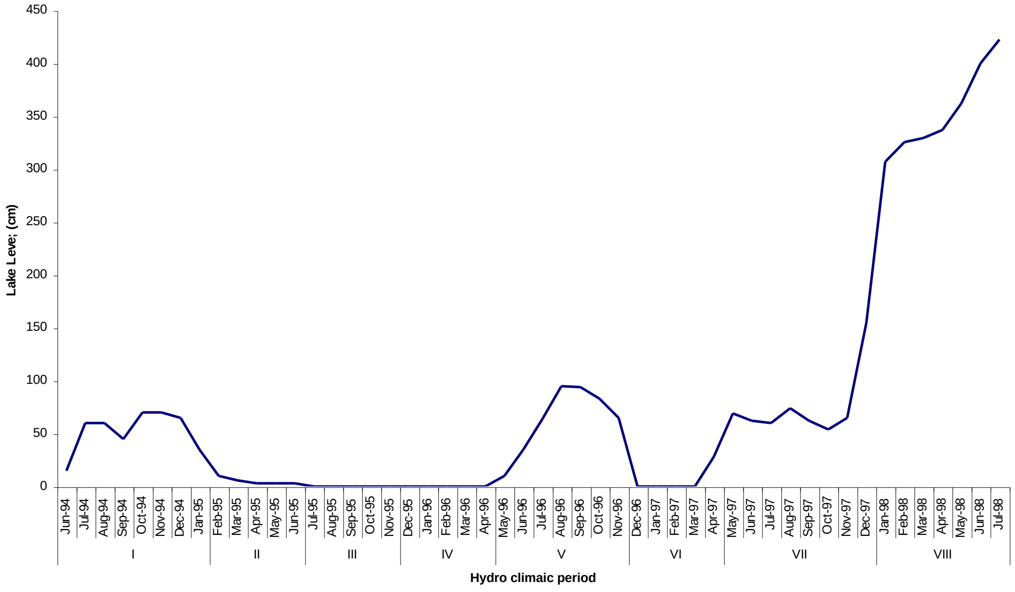

Figure 2: Water levels in Lake Nakuru used in conjunction with inflows to designate the hydro climatic periods

The onset of the dry season in period IV compounded the drought situation that prevailed in period III and Lake Nakuru and Lake Elementaita remained dry with few standing pools where springs emerged on the dry lake beds. The cumulative pan evaporation recorded meteorological station at Lake Nakuru National Park was 190.2 mm for this period, resulting in a precipitation-evaporation deficit of 142 mm. Intense soda ash laced dust storms were experienced in Lake Nakuru and Elementaita. Normal rains fell in period V, and resulted in sufficient water flow in the rivers that elevated water levels in the lakes with 4.3 m in Lake Bogoria. Levels in Lake Nakuru and Elementaita rose to 65 cm and 55 cm respectively in Period V, but an organic ooze layer about 20 cm thick persisted above the firm lake bed. In period VI, drought conditions recurred again in the region and water levels in the lakes declined. A pan evaporation of 257.8 mm was documented at Lake Nakuru with a resultant precipitation-evaporation deficit of 211 mm in Nakuru. Lakes Nakuru and

Elementaita dried out and strong winds stirred soda ash/dust storms, while water levels in Lake Bogoria fell to 3.7 m.

In period VII rain fell in the region, the rivers became influent and lake water levels rose and stabilized near those that prevailed in period I and V. The rains did not abate in December 1997 as expected for normal seasons but continued. Unusual precipitation occurred in January marking the onset of the *El nino* phenomena in the region. Water levels increased substantially and shoreline areas in all three lakes were submerged. The peak water level was measured at 4.5m in Lake Nakuru when the observations ended in July 1998.

Limnological parameters

Limnological parameters that could potentially influence flamingo ecology and are linked to hydrological and climatic conditions were documented in the study (Table 1). The elevated electrical conductivity and high pH induce challenging physiological challenges for most organisms that determines the biotic assemblages that can become established and thrive in these alkaline lakes extreme environments. The high electrical conductivity values embody the ionic compounds concentration in the water column and associated osmotic stress, and the high pH the alkaline nature of the medium. The electrical conductivity values were elevated during the dry periods such as II, III, IV and VI for the three lakes as shown in Table 1. In Lake Nakuru, mean values of 82, 620 and 93,500 µS/cm were recorded in period III and VI respectively. Figure 3 shows the trends of conductivity in Lake Nakuru in the different hydro climatic periods. The conductivity increased with reduced water levels reflecting an evaporative concentration phase and declined as inflows resumed into the lake setting off a dilution cycle. Similar variation in electrical conductivity by hydro climatic period were observed for the other two lakes as indicated in Table 1. The highest mean value in Elementaita was documented in period IV at 88,620 µS/cm while that of Bogoria is at 87,970 µS/cm.

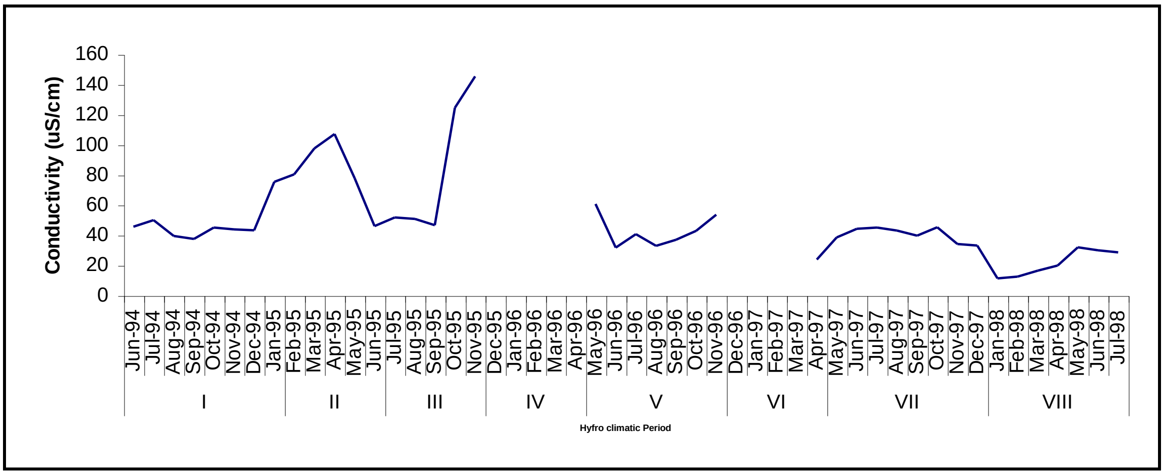

Figure 3: Electrical conductivity (µS/cm) in Lake Nakuru in the hydro climatic periods

The three lakes went through a dilution cycle in period VIII when the salt concentration decreased due to enhanced freshwater inflows. The flooding of the lakes since 2013 to 2022 has been linked to increased precipitation in the wider catchments of the study lakes among other possible factors. In 2014 the conductivity in Lake Nakuru decreased to 9,800 µS/cm.

The pH was above 10 for all the lakes in Periods I, I, II, IV and was consistent for Lake Nakuru until period VII. In period VIII, the pH fell below 10 for the three lakes indicating a widespread dilution cycle in tandem with the reduction in electrical conductivity. The dilutions led to the loss of the buffering capacity of the water column attributable to the sodium bicarbonate/carbonic acid equilibrium that maintained a high pH and its subsequent; lowering.

Temperatures were consistently elevated for Lake Bogoria but varied with seasons for Lake Nakuru and Elementaita where drier periods resulted in higher temperatures compared to the wet periods. This correlated with reduced lake levels in dry periods that enhanced solar radiation absorption by the dark substratum and hence the elevated water column temperatures.

The dissolved oxygen levels and Secchi depths were recorded as proxy parameters indicative of phytoplankton productivity and density. Dissolved oxygen levels were higher when water levels were high in Lakes Nakuru and Elementaita (Table 1). The dissolved oxygen levels in Lake Bogoria ranged between 11.3 mg/l and 17.7 mg/l for all the periods except for IV and VI when overturn events resulted in the mixing of the water column. Strong winds were able churn the water and welled up anoxic bottom water layers that lowered dissolved oxygen levels. Anoxic conditions in lake Nakuru were encountered 5-10 cm below the surface in the water column in the periods I, IV, and VII while in period VIII, this occurred at 2.8m. A similar pattern was observed in Lake Elementaita.

The Secchi depths as measures of light penetration and phytoplankton densities were persistently low for Lakes Nakuru and Elementaita. Their shallow Secchi depths were associated with a proliferation floating phytoplankton mat in all periods except period VIII. The shallow depth at <5cm, of the water column and dry outs in Lakes Elementaita and Nakuru prevented the determination of the Secchi depth at times. In Lake Bogoria the Secchi depths were consistently high ranging between 16cm and 23.5cm.

The oxidation reduction potentials measure the oxidation or reduction state in the water column due to organic matter decomposition by bacteria. Negative values recorded in Lakes Nakuru and Elementaita in the dry periods arose from dead algal biomass decomposition that formed an organic ooze layer above the firm lake bed. Sediments disturbance resulted in strong odours of hydrogen sulphide gas and anoxia in the water column with 0 mg/l dissolved oxygen levels.

In the study lakes, phytoplankton densities varied with hydro climatic conditions as shown in Figure 4. The densities in Lake Bogoria were persistently high while those of Lake Nakuru and Elementaita varied with hydro climatic conditions. In period I, Lake Nakuru had high phytoplankton densities dominated by *Spirulina.* These were later replaced by codominant mixtures of *Microcystis flos-aquae* and *Anabaenopsis sp* until VII when *Spirulina platensis* re-emerged as the dominant algal species. In Lake Bogoria, the low Secchi depth value of 11 cm in period IV coincided with a mixing period and explosive growth of *Anabaenopsis sp* and *Microcystis flos-aquae* that formed mucilaginous floating algal mats. They replaced the previously dominant *Spirulina platensis Arthrospira fusiformis* in the water column that had high densities at 14 cm depth. Lesser flamingo deaths occurred in this period and were probably attributable to ingestion of algal toxins as the dominant species are known producers of phytotoxins. In period V, the phytoplankton communities in Lakes Nakuru and Elementaita were dominated by *Anabaenopsis sp* and *Microcystis flos-aquae.* They are mucilaginous and gelled into floating mats that were deposited by winds as scums along the shorelines. A marked decline in algal densities occurred in Lake Nakuru and Elementaita during period VIII. Phytoplankton densities were depressed and consisted of a mixture of species that included *Euglenophyta spp*. In period VIII Lake Bogoria had still a high density of phytoplankton relative to the other two lakes that was a mix of *Spirulina platensis, Anabaenopsis* sp and *Microcystis flos-aquae*.

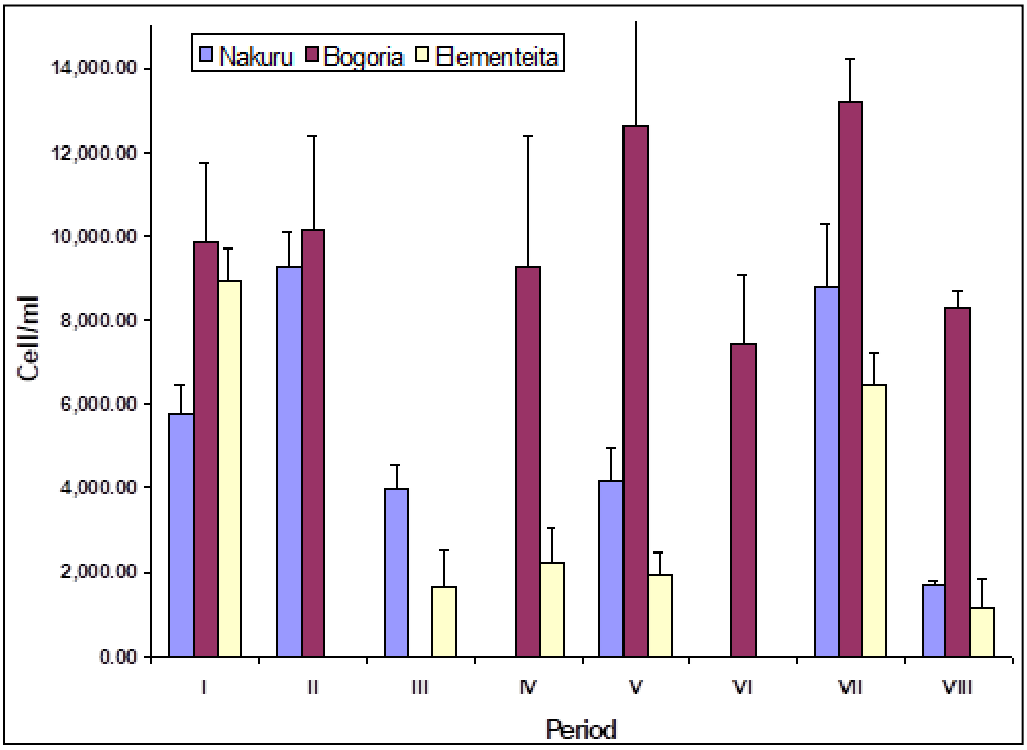

Figure 4: Phytoplankton counts in the three study lakes for hydro climatic periods

Trends of lesser flamingo numbers in the study lakes

The variations in distribution and partitioning of lesser flamingo numbers in the three lakes during the designated hydro climatic periods are shown in Figure 5. Flamingo numbers for 2014 and 2015 shown in Table 2 were obtained from KWS/National Museums of Kenya annual water fowl counts for the lakes. A census was not conducted for July 2015. The flamingo population in the lakes fluctuated widely within and between the three study lakes and the entire region for the periods under consideration. In period I of June to December 1994, the numbers in the three lakes ranged between 1,000,000 and 150,000 birds. Peak populations exceeding one million birds were recorded in September and December 1994. A sustained desertion of the lakes occurred from March 1995 to July 1996 spanning periods II, III and IV, and the total combined numbers for the central rift valley period were below 300,000.

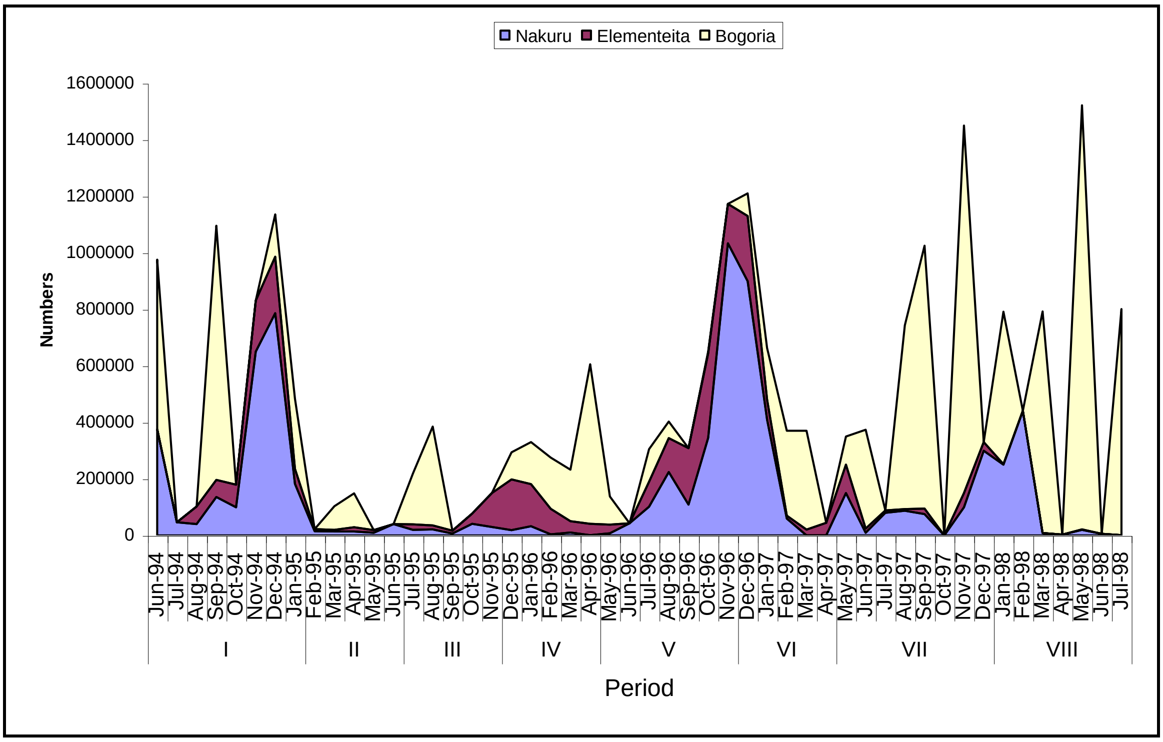

Figure 5: Overall lesser flamingo numbers trends in the study lakes for 1994-1998 period

Table 2: Lesser flamingo counts for Lakes Nakuru, Elementaita and Bogoria for 2014 and 2015. Courtesy of KWS/National Museums of Kenya

	2014		**2015**
Lake	January	July	January
Nakuru	3,271	1,859	430
Elementaita	5,381	243	4,332
Bogoria	1,028	3,064	5,613

During these dry hydro climatic periods, counts of less than 5,000 individuals were recorded in Lake Nakuru. There was a small influx of lesser flamingos into Lake Bogoria and Elementaita in April 1996 in period IV with an overall decline to less than 200,000 in the May-July 1996 transition to period V. In these regional desertion periods II-IV, high numbers of lesser flamingos were reported to be present in Lakes Manyara and Eyasi in Northern Tanzanian [31]. There were also relatively high numbers of lesser flamingos present in other smaller alkaline lakes in Kenya such as Lake Simbi with 10,000 individuals, Crater Lake in Naivasha and in Nakuru Town sewerage ponds [9]. Sporadic lesser flamingo mortalities occurred in Lake Nakuru and Bogoria in these periods.

Lesser flamingo numbers peaked at 1,200,000 individuals in Lake Nakuru and Bogoria from October 1996 to January 1997 spanning the later part of period V and earlier parts of period VI. The largest proportion of this population was domiciled in Lake Nakuru (Figure 5). The population subsequently stabilised at less than 400,000 individuals until June 1997 in Period VII. A population that fluctuated between 800,000 and 1,500,000 individuals subsequently resided in the lakes between July 1997 and July 1998 spanning period VII and VIII. They numbers were, however, almost wholly confined to Lake Bogoria and the other two lakes were largely deserted. This was during the *El nino* phenomenon from March 1998 to July 1998 and lesser flamingo mortality recurred in Lake Bogoria.

An analysis of the mean population of lesser flamingos in the study lakes in the different hydro-climatic periods was performed as shown in Figure 6. There was a pattern of alternate occupancy in the lakes with some distinct trends. The largest proportion was resident in Lake Bogoria from January 1995 to June 1996, which spanned the prolonged drought period experienced in the region. In these high evaporative periods of II, III and IV, the largest proportion of lesser flamingos was in Lake Bogoria.

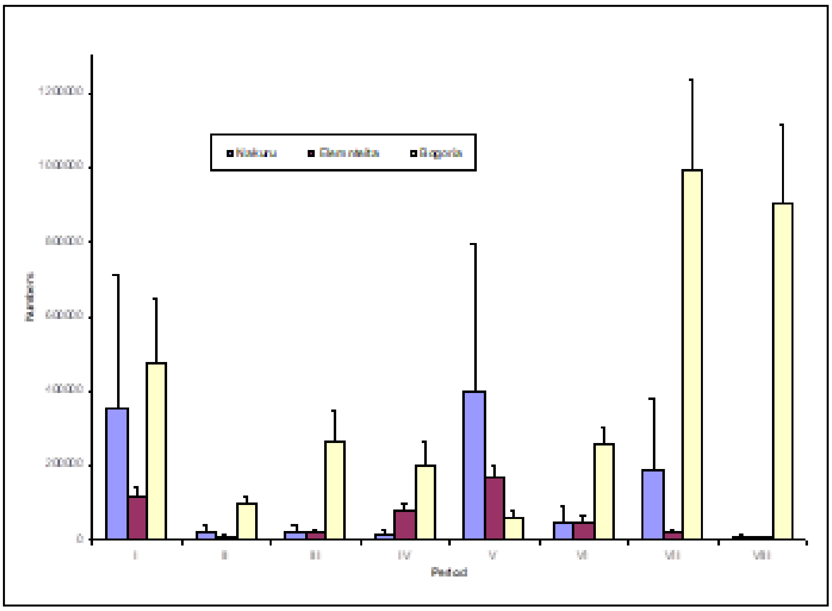

Figure 6: Lesser flamingo numbers in individual lake by designated hydro-climatic periods between June 1994 and June 1998.

In the region, low flamingo numbers were counted in the lakes in hydro climatic periods characterized by drought conditions and reduced river inflows into the lakes. When the climatic and hydrological conditions were near their long-term means, hydro climatic periods such as I, V and VI had higher counts of lesser flamingos. In Periods VIII between 1997-1998 and 2014-2015 with significantly high rainfall and enhanced river flows, Lake Nakuru and Elementaita were virtually deserted with counts of mostly juveniles in their hundreds (Figure 6 and Table 2).

The three lakes underwent catastrophic increases in size with Nakuru expanding by 40% to 65 km^2 in 2014 [17]. Table 2 shows the corresponding counts of lesser flamingos in the three lakes in January and July counts for 2014 and 2015. The low members in hundreds and few thousands coupled by lakes sizes increases are proxies for undocumented ecosystem characteristics transformations with pH falling below 8 and conductivity to 5,400 µS/cm in Lake Nakuru [14].

Statistical analysis was conducted to establish the relationships between flamingo members in the three lakes. Significant differences were found between overall lesser flamingo numbers in the three lakes ($p < 0.05$). Lake Bogoria held the highest number of lesser flamingos during the study period and Lake Elementaita the lowest. There was a positive significant correlation between numbers in L. Nakuru and Elementaita with $r^2 = 0.556$, $p<0.05$ and a negative relationship between numbers in Lake Bogoria and Elementaita at $r^2= -0.45$, $p<0.05$. No significant relationship was found between numbers in Lake Nakuru and Lake Bogoria. Correlation analysis based on extreme weather periods was performed to test whether there was inverse alternate occupation of the three lakes. A negative relationship was found between numbers in Lake Bogoria and Elementaita during the dry seasons had $r^2 = -0.52$, $p<0.05$ but a positive correlation occurred between Lake Nakuru and Elementaita with $r^2= 0.574$, $p < 0.05$. The relationship between numbers in Lake Nakuru and Bogoria was not significant.

4. Discussion

The division of the study period into distinct hydro climatic periods demonstrates the linkage between hydrology and climate that affects flamingo ecology in the lakes as shown in Table 1 and Figure 2. The major variations in limnological conditions were linked to prevailing hydro climatic conditions. Electrical conductivity, pH and temperature were elevated during dry periods with reduced hydrological surface inflows and declines in lake levels. The high temperatures resulted in evaporative concentration cycles that corresponded with low oxygen concentrations, receding water depths and negative oxidation-reduction potentials as decomposing organic matter accumulated. Rivers stopped flowing into the lakes and water recharge was restricted to springs in the three lakes. Lake Nakuru dried out in period III, IV and VI and the exposed lake beds consisted of swathes of soda ash encrusted mud as shown in Figure 2. Lake Elementaita dried out during the same period while Lake Bogoria underwent a decline in water levels that was not as drastic as for the other two shallow pan lakes.

The heavy rainfall precipitation that was associated with an *El nino* phenomenon occurred late in 1997 during Period VII, and continued into mid 1998 Period VIII, when the water levels rose in the lakes to unprecedented peaks. Water levels in Lake Nakuru rose in two months to 3.5m and to 2.75m in Lake Elementaita. In Lake Bogoria, water levels in the northern bay rose by 2 m from a depth of 4.5 m in period VI to 6.5m in period VIII, submerging hot springs along the shoreline. The elevated lake levels led to shoreline flooding and destruction of littoral vegetation in all the three lakes. In Lake Nakuru, the *Sporoblous spicatus* grassland patches along the shoreline were submerged and *Acacia xanthophloea* trees that fringe the Lakes Nakuru died at several points. The extensive dilution by inflows radically altered the physical-chemical characteristics of the lakes as indicated in Table 1. The shoreline habitats and their configurations were also drastically altered affecting lesser flamingo roosting sites. The extensive flooding phase that has lasted from 2012 to 2022 has completely transformed the Physico-chemical conditions of the lakes and their sizes with Lake Nakuru expanding by 45% to over 65km^2 from its historical mean of 45km^2 [12;14]. This was essentially an extreme dilution cycle with uncharacteristic pH values of 7-8 from 10-11 being recorded in Lake Nakuru recently. The levels increment and extent of shoreline flooding exceeds that of the 1997-1998 by several magnitudes.

The impacts of extreme drought induced ecological conditions and loss of habitat through desiccation resulted in lesser flamingo numbers declines in Lake Nakuru and Lake Elementaita in periods II, IV and VI. Periods I, V and early VII were within the normal ranges for water parameters reported in past studies for depth, pH and conductivity [25;26]. The extreme variations in physical and limnological attributes indicate that the three Kenya alkaline lakes ecosystems are stochastic environments which are highly impacted by prevailing hydrological and climatic conditions. The hydro climatic conditions in concert with other lake specific features and factors determine the lakes' individual ecological processes and characteristics. Climatic and hydrological conditions govern water level fluctuations, and influence the ionic composition of the water column, and ultimately the ecological status of the alkaline lakes [24;29] noted that water balance in a lake is an important determinant of its chemistry, and therefore its biota. The fluctuations in water levels, induced by evaporative concentration or dilution cycles, affected ionic concentrations and composition, which was manifested through electrical conductivity variations (Figure 3).

Phytoplankton densities in the lakes fluctuated in tandem with the hydro climatic periods in Figure 4. Lake Bogoria maintained high algal densities but with slight fluctuations. The shallower lakes of Nakuru and Elementaita exhibited drastic fluctuations with high densities in moderately wet periods and very low densities in the dry hydro climatic periods as well as under extreme inundation. The ionic variations altered the osmotic environments and in addition to catchment derived nutrients resulted in modified phytoplankton species composition and establishment of *Anabaenopsis sp* and *Microcystis flos-aquae* in the lakes as the dominant species. The two species replaced *Spilrulina platensis* (= *Arthrospira fusiformis*), the main food for lesser flamingos in the lakes' water column during periods V and VII. The biotic content and chemical composition of water columns are interlinked and this resulted in the observed occupancy patterns for the lesser flamingo in the lakes. This tessellates with conclusion that in the alkaline lakes, hydrological interactions, climatic conditions and water chemistry determine the phytoplankton productivity and ultimately the ecology of consumer organisms [26]. The water level changes associated with hydrology and climatic conditions is thus a key driver of the ecology of the alkaline lakes. Water level change has previously been described as a critical factor in alkaline ecosystems which, together with other factors such as mixing regimes and nutrient cycling, determines algal species composition and primary productivity [13].

Analysis of data on lesser flamingo numbers in the study lakes shows a differential occupancy of the three lakes with numbers partitioned according to prevailing climatic and limnological conditions in each lake. From 1994-1998 Lake Bogoria emerged as the most important lake during periods associated with severe hydro climatic impacts such as periods II-IV and VIII in terms of overall occupancy. Lake Elementaita was the least utilised having the lowest numbers except in period IV as shown in Figure 5. Lake Nakuru during favourable hydro climatic periods such as I and V had occupancy levels of over 90% of the population that was localized in the three lakes.

The lesser flamingo population in the study lakes fluctuated markedly with time showing influxes and net desertion of the region (Figure 5 and 6). Figure 5 shows the flamingo trends in the three lakes in time which indicates that build up in numbers or reductions can happen abruptly. Lake Nakuru had large numbers in December 1994 and again in October 1996 to January 1997 in periods I, V and VI respectively. Lake Bogoria held the largest proportion of lesser flamingo numbers when dry hydro climatic conditions prevailed in periods II, III and IV. During the *El nino* phenomena lasting from October 1997 to June 1998 (Periods VII and VIII), the lesser flamingo numbers were persistently low. This indicates that both short term and long-term factors are simultaneously involved in triggering the movements between the lakes and in the larger dispersal areas in different hydro climatic periods.

A large flamingo population was resident in the lakes from June to December 1994 (Period I). Across the region, the low occupancy in periods II to IV and the subsequent one in period VI show that long term drought conditions and low lake levels are push out factors that affect the lesser flamingo populations. The higher numbers in the more hydrologically stable Lake Bogoria reinforces this observation. There was a slight decline in numbers from January to March 1998, after which a population in excess of one million became resident in the three lakes studied. The low population periods coincided with dry climatic conditions and reduced river discharge in the study lakes region. The normal seasons where the rainfall was within mean historical ranges as well as lake level were characterised by large numbers of lesser flamingos into the three lakes. Extremely wet periods also resulted in the lakes being deserted as happened during period VIII in 1997-1998 and the 2014-2015 flooding cycle. Lesser flamingos do not exhibit site fidelity and have an uneven and unpredictable distribution in space and time with periods of congregations and exodus that are linked to prevailing ecological conditions and their needs.

Lake Nakuru and Lake Elementaita shrunk in surface area with associated drastic reduction in water levels and eventually reduced to standing pools where springs existed. Basin configuration changes in Lake Bogoria were less pronounced due to its fissure morphometry and its diverse inflows that tempered level variations induced by low catchment water discharge and evaporative loss. The lesser flamingo distribution patterns during the study period were similar to the findings of [25;26] and during counts by Brown in 1968 [5]. The highest numbers were at times encountered in Lake Nakuru and at other times in Lake Bogoria. There were also periods when the overall population in the three lakes was very low [25]. The numbers occupying the three lakes varied depending on climatic conditions and its associated habitat characteristics change.

Lake Nakuru and Elementaita have shared similarities in lake basin morphometry and ecology with a common geological history [25]. The positive significant correlation between flamingo populations in these two lakes further reinforces aspects of shared ecological similarities between them. Lake Elementaita underwent drastic hydrological changes and can be considered to have been continuously waxing and waning without distinct stable periods. The negative significant correlation between flamingo numbers in this lake and Lake Bogoria demonstrates the diametric ecological nature of the two ecosystems. Lake Bogoria and Elementaita have catchment basins in the western Aberdare Ranges under the same general climatic regime. The ecological differences between them can only be partly accounted for by lake specific variances in basin morphometry and hydrological characteristics. Lake Bogoria is deeper and has a constant water recharge from numerous hot and cold springs and geysers supplemented by inflows from rivers Sandai–Wasseges and Emsos. Lake Elementaita is mostly dependent on catchment surface in the north by River Mbaruk and warm springs in the southern part inflows. In addition, L. Elementaita is a shallow basin with a near uniform bottom profile that makes it prone to rapid evaporative water loss compared the low surface area relative to volume ratio for Lake Bogoria.

The unique morphometry and hydrology of Lake Bogoria tempered extreme changes in size and ranges in limnological conditions compared to the other two lakes. The lesser flamingos congregated in the lake during the extreme drought periods. Lesser flamingos congregated in Lake Bogoria again during the *El nino* phenomena that led to shore line submersion in the other two lakes. The extreme dilution and loss of lesser flamingo habitats through reconfiguration of attendant shorelines affected residence in the Lake Nakuru and Lake Elementaita. Lake Bogoria had lower amplitude in the alteration of limnological conditions and less habitat modification, and therefore provided a relatively better refuge for lesser flamingos during this period. The *El nino* phenomena was widespread in East Africa, and as one of the deeper alkaline lakes in the region, Lake Bogoria supported a large proportion of the East African lesser flamingo population. There were estimates of about 900,000 individuals relative to the total lesser flamingo estimated population of 1,500,000 birds in East and Southern Africa [19].

There was widespread dispersal of lesser flamingos to other lakes and water bodies in period IV when a population of 10,000 lesser flamingos was found in Lake Simbi in western Kenya. The periods designated as II, III and IV which were dominated by evaporative cycles are comparable to those that prevailed in 1974-1976 where less than 200,000 birds were resident in Lakes Bogoria and Nakuru [25]. The period was similarly characterised by extensive water level declines and below average rainfall [8;27]. Dispersal to water bodies that are infrequently visited is a possible survival mechanism by lesser flamingos to escape severe condition induced by drought in their major feeding lakes. From censuses conducted in Northern Tanzanian lakes in 1995 there were 700,000 and 377,369 lesser flamingos in Lakes Eyasi and Manyara respectively [31]. Evidence from Southern Africa during the same period indicated the presence of high numbers in the Makgadigadi pans in Botswana and that a breeding event took place [21].

The correlation of flamingo numbers to water levels and other physical parameters indicates that climatic processes are important determinants of flamingo ecology in the alkaline lakes. Water levels affect lesser flamingo habitat characteristics, shoreline configuration and susceptibility to predation. The climatic processes in conjunction with water level strongly influence the limnological conditions within a lake and therefore its phytoplankton dynamics. The attainment of critical thresholds with respect to limnological characteristics, site characteristics and foraging returns ultimately determines the utilisation of a lake and trigger inter-lake movements once the thresholds are exceeded [9]. This validates the postulate by [3] that despite the spectacular and local abundance of lesser flamingos, they may be markedly affected by limnological conditions. These as demonstrated here are dependent on hydro climatic conditions coupled to lake specific conditions. Climate change and climatic variability are expected to result in more frequent and extreme hydro climatic variations potentially affecting lesser flamingos that will occupy an increasingly stochastic environment. The transformation of Lake Nakuru to a near freshwater lake, the dilution and expansion of Lakes Elementaita and Bogoria into wooded patches that are dangerous to lesser flamingo represent a loss of key lake habitats in the eastern rift valley range of lesser flamingos. A reversal to more arid climatic conditions in the future is also possible, representing an uncertain future for lesser flamingos and their habitats in view of the potentiating negative environmental consequences of climate change, human land use systems and environmental degradation.

It is concluded that hydro climatic variability plays a key role in lesser flamingo nomadic movements, occupancy and utilization of the alkaline lakes. As habitats for a threatened species, the climatically and hydrologically sensitive alkaline lakes need closer monitoring and action to protect their catchments from climate change and degradation.

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