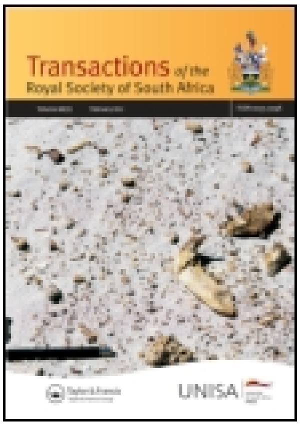

Transactions of the Royal Society of South Africa
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ttrs20

The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe

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To cite this article: Mzime Regina Ndebele-Murisa, Emmanuel Mashonjowa & Trevor Hill (2011): The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe, Transactions of the Royal Society of South Africa, 66:2, 105-119

To link to this article: http://dx.doi.org/10.1080/0035919X.2011.600352

Transactions of the Royal Society of South Africa
Vol. 66(2), June 2011, 105–119

The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe

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The influence of climatic variables (rainfall, temperature and evaporation rates) and lake water levels on the stocks of the sardine fish species *Limnothrissa miodon* (Boulenger), commonly known as Kapenta in Lake Kariba, was investigated. Secondary data of the climatic variables, water levels and fish catches recorded from 1963 to 2008 were analysed to determine their trends over time as well as the relationships among them. The analyses showed that rainfall is decreasing at a rate of 0.63 mm per year around Lake Kariba, while evaporation rates have increased by 31% at an average rate of 2.77 mm per year since 1963. The temperatures around the Kariba area have been rising since 1964; with the maximum range increasing at a faster rate than the minimum temperatures. Kapenta fish production has decreased significantly ($R^2 = 0.85$, $P \leq 0.05$) since 1974 at an average rate of 24.19 metric tons per year. This pattern of decrease was also observed in the artisanal fish catches that have declined at an average rate of 37.26 metric tons per year between 1974 and 2003. All the climatic factors as well as the water levels could explain variations in the Kapenta fish catches with the water levels exerting the greatest influence ($R^2 = 0.84$, $P \leq 0.05$); followed by maximum temperature ($R^2 = 0.72$, $P \leq 0.05$), evaporation and rainfall. In turn, water levels are largely influenced by climate with temperature and rainfall explaining a significant portion of the variation in the water levels ($R^2 = 0.99$, and $R^2 = 0.93$, $P \leq 0.05$) in that order. This suggests that both climate (maximum temperature in particular) and nutrients, which are influenced by water levels, are the primary determinants of Lake Kariba's Kapenta production. Concerning are the possibilities that a changing climate in and around the lake may continue to adversely affect water levels, the stratification cycle, nutrient fluxes and the Kapenta fish production in the lake.

Keywords: temperature, rainfall, evaporation rates, lake water, Kapenta, fishery, climate change.

INTRODUCTION

Climate change is likely to be exerting much influence on biotic interactions in aquatic ecosystems (DeSanker & Magadza, 2001; Phoon *et al.*, 2004; Komatsua *et al.*, 2007; IPCC, 2007). Despite this, the link between climate, hydrological factors, plankton and fisheries has not been documented widely in Lake Kariba and in most African aquatic systems in contrast to the extensive research in the temperate regions and oceans where research shows that climate change has reduced phytoplankton productivity and fish production (Alheit & Niquen, 2004; Atkinson *et al.*, 2004; Barnard *et al.*, 2004; Beardell & Raven, 2004; Hays *et al.*, 2005; Thompson *et al.*, 2007; Taylor, 2008). However, a number of works (Hernes *et al.*, 1995; Hulme 1996; Ringius *et al.*, 1996; Joubert & Hewitson, 1996; Joubert *et al.*, 1997, 1999; Hewitson & Crane, 1998; Hewitson & Joubert, 1998; Hulme & Carter, 1999; Hulme *et al.*, 2001) have shown the precarious extent to which climate changes may occur and therefore adversely influence ecosystems in the African continent.

The Intergovernmental Panel on Climate Change (IPCC) has projected temperature rises ranging from 1.4 to 5.8°C (IPCC, 2001) over the African continent while regional assessments for southern Africa give a warming of 1.7–2.5°C by 2050 and 2 to 3°C by 2100 (Hulme *et al.*, 2001; IPCC, 2001) and more recent projections give estimates of 1–3.5°C by 2100 (IPCC, 2007). Hulme *et al.* (2001) showed that areas over the Sahara and semi-arid parts of southern Africa such as the Zambezi Valley, where Lake Kariba is located, will warm up by as much as 2.5°C by 2050 while IPCC (2001) has shown how surface runoff will decrease in the Zambezi Basin; this supported by evidence from Cambula (1999), Vörösmarty and Moore (1991), Arnell (1999) as well as DeSanker and Magadza (2001). In addition to these forecasts, present climate trends suggest a gradual reduction in river flow and velocity as well as in the regularity and intensity of annual inundations of the Zambezi floodplain in the heart of the region (Magadza, 1994), due to the level precariousness already described, this potentially having rapid and catastrophic impacts and implications for productivity in Lake Kariba.

Increased water temperature influences the thermal stratification and internal hydrodynamics of lakes. In warmer years, surface water temperatures are higher, evaporative water loss increases, summer stratification occurs earlier in the season, and thermoclines become shallower (IPCC, 2007), thereby adversely affecting nutrient levels and availability and consequently the production chain in the lakes. Also due to warming, many tropical lakes exhibit prolonged stratification with decreases in surface layer nutrient concentration and prolonged depletion of oxygen in deeper layers. High evaporation coupled with decreased rainfall due to global warming means there will be reduced water flow and water levels in the lakes and as a result, the nutrient concentrations in the water bodies are also reduced, which, in turn, reduces phytoplankton biomass and production. The reduction in primary production

ISSN 0035-919X Print / 2154-0098 Online

DOI: 10.1080/0035919X.2011.600352
http://www.informaworld.com/ttrs

consequently has adverse, cascading impacts on the higher trophic levels' production such as in zooplankton and fish. Evidence of the impacts of climate changes expected in freshwater ecosystems and particularly those in the tropics include changes in species composition, organism abundance, productivity and phenological shifts including earlier fish migration as a consequence of warming and subsequently high evaporation rates, reduced rainfall and water levels (IPCC, 2007). However, despite on-going and past research efforts, direct linkages of the impacts of climate change on African aquatic ecosystem functions have, up to now, not been documented widely (Ndebele-Murisa *et al.*, 2010). The link between climate, hydrological factors and fisheries has been noted and it is clear that long-term changes in plankton will have significant knock-on effects on fish stocks. The evidence for these impacts on the phytoplankton community and consequently fish production has been documented for Lakes Kivu, Malawi, Tanganyika and Victoria (O'Reilly *et al.*, 2003; Bergamino *et al.*, 2007; Hecky *et al.*, 2007; Stenuite *et al.*, 2007; Awange *et al.*, 2008).

Kapenta fish catches have been declining in Lake Kariba since the early 1990s (LKFRI, 2010), and it is possible that this is a consequence of climate changes. However, the question is how sensitive Lake Kariba is to climate variability and more importantly to what extent climate changes will impact the fishery. Studies have already shown that there is a relationship between climate, hydrological factors and sardine catches (Marshall, 1982, 1988; Mtada, 1987; Karenge & Harding, 1995; Magadza, 1996; Chifamba; 2000). Using secondary data, Chifamba (2000) found a strong correlation of air temperature with total water inflow, lake levels and the Kapenta sardine (*Limnothrissa miodon*) fish catches in Lake Kariba. In her study, she showed that there were positive relationships between temperature, hydrological factors and catch per unit effort (CPUE) in the pelagic Kapenta fishery although precipitation and rainfall were negatively related to CPUE. Marshall (1982) and Magadza (1996) showed declines in the Kapenta as well as the pelagic fishery of the lake in relation to drought episodes. In addition, it has been noted that the temperature of the Gwembe Valley, where Lake Kariba is situated, has warmed up by an average of 2.6°C since 1964 (C.H.D. Magadza, 2010). All these changes in temperature and hydrology and the resultant impacts on the thermal structure of the lake pose potential adverse impacts on the lake fishery stocks.

This study investigated the trends in the climate, water levels and Kapenta fish production since the successful introduction of the sardine into the lake in 1968 (Bell-Cross & Bell-Cross, 1971). An attempt was made to determine the influence of climate and water levels on the fish production as well as investigate the cause(s) to the declining fish stocks.

MATERIALS AND METHODS

Description of site

The study was conducted at Kariba, in Zimbabwe (16.5°S, 28.8°E; 518 m above sea level). Kariba is predominantly semi-arid with mean annual temperatures of 26°C and mean annual rainfall and evaporation of 766 mm and 1700 mm, respectively (Sayce, 1987). Kariba lies wholly in Natural Region V (5) of Zimbabwe, which is characterised by low and erratic rainfall. The rainfall coefficient of variability for Kariba is about 30%, reflecting the unreliable nature of rainfall in the area.

Collection of secondary data

Historical data were collected from various organisations and research groups that have been investigating the climate, water levels and fisheries of Lake Kariba. In an attempt to cover the period from when the lake was created to date, as much data from the earliest records which could be obtained, were collected. These data included fisheries production levels of the artisanal fishery obtained from experimental gillnetting and *Limnothrissa miodon* (Kapenta) catches obtained from declared landings by fishermen and the Catch per unit effort (CPUE), daily climatic data (rainfall, evaporation rates and temperature) and lake water levels. All the climate data were collected at the Kariba Weather Station.

The pelagic Kapenta fishery is license-controlled, highly mechanised and performed by light attraction and lift nets from pontoon rigs. On the Zimbabwean side of the lake, each company returns monthly statistics with landings and numbers of nights fished. The Kapenta catch is expressed in mean metric tons per boat-night which was then transposed to months and years in catches. Catch per unit effort (CPUE) in the experimental fishery is expressed as catch (kg wet weight) per standard unit per setting of individual panels (mesh sizes). The standard unit is a net panel of 45.7 m long. It was assumed that the landings declared by the Kapenta fishermen were reflective of fish production in the lake but there is evidence that some fishermen declare fewer catches than actually caught as they often trade illegally, selling off part of the stock before landing (Madamombe, 2002) and the presence of poachers in the lake (I. Tendaupenyu, pers. comm.).

Similarly, the weekly experimental gillnet data accumulated at Lake Kariba Fisheries Research Institute (LKFRI) from the Lakeside station sampling programme, is the longest and probably one of the most reliable data series from Lake Kariba. The routine is well incorporated in the activities of LKFRI and the sampling methodology and design have remained constant. Thus it was assumed that this substantial database truly represents the relative changes in the artisanal fish populations in the lake. The Kapenta and artisanal fish catches data collected were up to the year 2002, as the records after 2002 were inconsistent or could not be retrieved from old computers that broke down at LKFRS (N. Siziba, pers. comm.; I. Tendaupenyu, pers. comm.).

The daily climatic data and lake level recordings from the Zimbabwe Meteorological Services and the Zambezi River Authority (ZRA) must be considered reliable. Water levels are measured daily at the dam site by ZRA while daily readings of the evaporation rates, temperature and rainfall are taken at the Kariba Weather Station. Nonetheless, quality control of the data was performed and all the data conformed to normality under the Anderson-Darling test. The secondary data collected are summarised in Table 1. Permission to use all data for this study was duly sought and granted.

Analyses of secondary data

All data were tested for normality using the Anderson-Darling test before applying any statistical tests and tested positive. Seasonal rainfall anomalies were used to characterise years into wet and dry years. The anomalies were calculated as standardised (division by standard deviation) differences between annual rainfall amounts and their long-term averages according to Tumbo (2007). That is:

$$X_{an,i} = \frac{X_i - \overline{X}}{\sigma_x}, \qquad (1)$$

where $X_{an,i}$ is rainfall anomaly in year *i*, and X_i is rainfall for year *i*, X and σ_x are the long-term mean annual (or seasonal) rainfall and standard deviation of the annual (or seasonal) rainfall totals for the weather station.

Table 1. Sources of secondary data.

Data	Source	Years
Fish and Kapenta catches (daily and monthly)	Lake Kariba Fisheries Research Station	1974–2002
Climate (daily evaporation rates*, total rainfall; maximum and minimum temperature)	Zimbabwe Meteorological Services; Kariba Weather Station	1964–2007
Lake water levels (daily and monthly)	Zambezi River Authority (ZRA); Hydrology Unit	1959–2008

*Evaporation rates record available for the period 1963 to 1999; and not from 1964 to 2007 as indicated.

In addition, the coefficient of variation (CV) was calculated as:

$$CV = \frac{\sigma_x}{\overline{X}} \times 100(\%)\,, \tag{2}$$

where symbols are as defined above.

The anomalies were used to classify years according to rainfall abundance or deficit. Plots of series of rainfall anomalies were visually analysed to provide limits that appropriately define different levels of wetness and dryness of the year that reflect actual observations. The procedure established five classes (Table 2).

Droughts were classified using the Standardized Precipitation Index (SPI) data calculated from the monthly rainfall totals for Kariba (McKee *et al.*, 1993, 1995; Edwards & McKee, 1997). The SPI is an index that is used to provide assessment of drought severity and is based on the probability of the observed cumulative precipitation deviating from the climatological average for any time scale (1 month, 3 months, 6 months, 12 months, etc). In this study the time scale chosen was 12 months. The 12-month time scale avoids intra-annual frequency variations and allows the identification of the main hydrological droughts. The drought classification used in this study is given in Table 3.

Table 2. Criteria for characterisation of hydrological years from the normalised anomalies (after Tumbo, 2007).

Criteria	Level
Extreme wet year	$X_{an} > 2.0$
Wet year	$2.0 \geq X_{an} > 1.0$
Normal	$1.0 \geq X_{an} \geq -1.0$
Dry year	$-1.0 > X_{an} \geq -2.0$
Extreme dry year	$X_{an} > -2.0$

Table 3. Classification of drought using the SPI values (source: McKee *et al.*, 1993).

Category	SPI Values
Extremely wet	≥2.00
Severely wet	1.50 to 1.99
Moderately wet	1.00 to 1.49
Near normal	0.99 to –0.99
Moderately dry	–1.00 to –1.49
Severely dry	–1.50 to –1.99
Extremely dry	≤–2.00

A time series analysis was employed to ascertain any trends in the climate, lake water levels and Kapenta catches. Regression analyses were performed to investigate the relationships among the environmental factors and the fish catches. A general linear model (GLM) was used to predict Kapenta production levels using the environmental data. Linear regression attempts to model the relationship between two variables by fitting a linear equation to the observed data; in this case the environmental variables were the exploratory variables while the fish catches were the dependent variables; assuming that the relationship is linear. Homoscedasticity as well as independence of all variables from each other was assumed. All statistical analyses were performed in S-Plus (Version 45, Microsoft Corp., Redmond, WA, USA).

RESULTS

Climate

Kariba's mean climate as calculated from the available mean monthly data from 1964 to 2007 are summarised in the climatogram in Figure 1. The climate of Kariba during this period was characterised by consistently high temperatures with a seasonal variation. October, November and September were the hottest months (monthly means ≥28 ± 0.8°C), while July and June were the coldest (monthly means of ≤22° ± 0.8°C) and overall the mean temperature was 25.7 ± 0.7°C. Rainfall patterns were consistent with the expectations of a semi-arid region with a mean annual total of 677 mm ± 214.2 mm for the period 1964 to 2007. The coefficient of variation for rainfall in Kariba for the same period was 31%. The rainy season, from October to April, was characterised by high temperatures while the cool, dry season occurred from May to July while August and September were hot and dry.

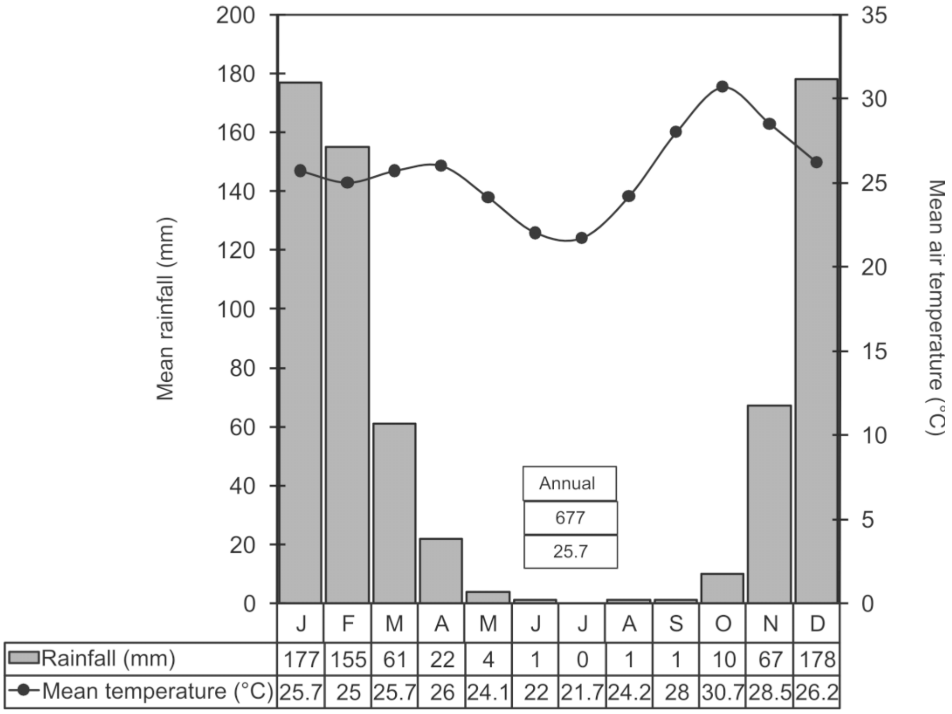
Observed climate trends

Analyses of the trends of the observed mean annual rainfall, mean annual temperatures, mean minimum and maximum temperatures and evaporation rates were conducted in order to investigate whether or not the climate of the study area has changed since 1964. The observed trends in rainfall, temperature and evaporation rates will enable the establishment of possible links between Kapenta fish stocks and observed climatic trends in Kariba.

Rainfall

As shown in Figure 2, Kariba experiences high inter-annual rainfall variability, with the years after 1980 showing higher tendency of below average rainfall than before. The lowest annual total rainfall recorded between 1964 and 2007 was 272 mm (received in 1995), and the highest total amount recorded during the same period was 1299 mm (received in 1978). With the exception of 1969 and 1986, the majority of the wet conditions were experienced in the 1970s.

Over the 43 years in which the rainfall records were available, 22 years (50%) received below average rainfall (Figure 3) and of these six were drought years (Table 4) with one year (1995)



	J	F	M	A	M	J	J	A	S	O	N	D
▨Rainfall (mm)	177	155	61	22	4	1	0	1	1	10	67	178
-●-Mean temperature (°C)	25.7	25	25.7	26	24.1	22	21.7	24.2	28	30.7	28.5	26.2

Figure 1. Mean monthly temperature and rainfall experienced around Lake Kariba, 1964–2007.

exhibiting severely dry and one year, extremely dry conditions. Wet conditions were experienced in seven years with four moderately wet years and three severely wet years, but none of the years was extremely wet (Table 4).

Dry conditions occurred at an average frequency of 4.5 years but the majority of the drought events were clustered between 1983 and 1995, with droughts (SPI ≤ –1) occurring in the years 1968, 1983–1984, 1990, 1992 and 1995. The frequency of occurrence of drought intensified between 1990 and 1995 at an average frequency of two years. Extremely dry conditions (SPI ≤ –2) were recorded in 1995. Since 1996, the Lake Kariba area has experienced near normal rainfall conditions. Figure 3 shows the annual SPI series for Kariba.

The greatest proportion of years (70%) exhibited near normal rainfall conditions, while the total percentage of the dry years was 11% and of wet years was 19% with the majority of the wet years (60%) occurring in the 1970s. Figure 4 shows the frequency of the annual SPI index. Further analysis using time series demonstrated a 2-year moving average of –0.63 mm per year, illustrating that rainfall has declined by an average of 27.1 mm since 1964 with a declining rate of 6.3 mm per decade. Figure 5 illustrates the trend in rainfall patterns over time.

Temperature

Figures 6–8 show the observed trends in mean annual temperature, temperature anomalies (departure from normal)

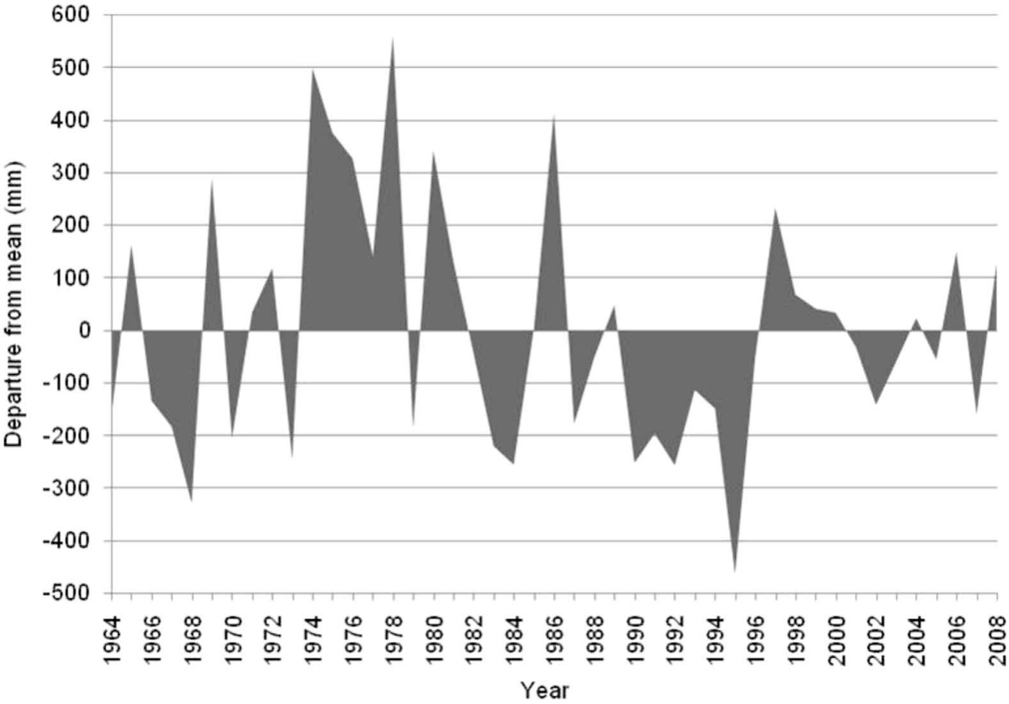


Figure 2. Deviation from the mean annual rainfall from 1964–2007.

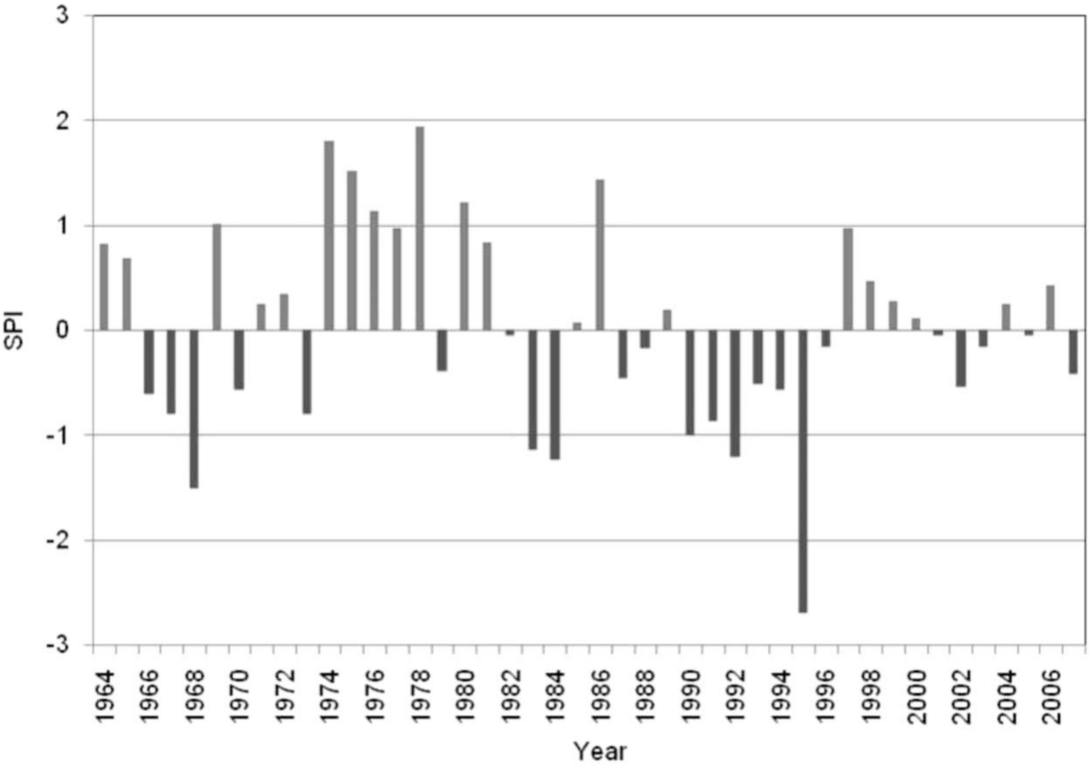


Figure 3. The annual SPI series for Lake Kariba. The positive SPI values indicate greater than average precipitation while the negative SPI values indicate less than average precipitation.

and the mean minimum and maximum temperature for Kariba. Air temperatures were high, ranging between 18.4 and 38.1°C. The highest temperatures were recorded in the hot, dry season (August–October) while the minimum temperatures were recorded in the winter period (May–July). On average, the hottest year was 1995 with an annual mean of 26.4°C, closely followed by 1992 (26.1°C), which was on par with 1983 (26.1°C), then 1987 (26.0°C) and 2005 (26.0°C), 1984 and 1998 (both at 25.8°C) then 2002 (25.7°C). These years' average temperatures were above (some nearly a degree and more) the average 25.7°C calculated for the entire 44 year period from 1964 to 2008. In addition, the years highlighted above were all dry years which received below average rainfall, while 1983, 1984, 1992 and 1995 were drought years (Figure 2). A time series analysis showed a significant ($P \leq 0.05$), linear increase in both the minimum ($R^2 = 0.32$, $n = 44$) and particularly the maximum ($R^2 = 0.43$, $n = 44$) yearly average since 1964 as well as a significant upward trend in the mean annual temperature in Kariba ($R^2 = 0.39$, $n = 44$). Figure 6 shows the variation in annual mean temperature around Kariba.

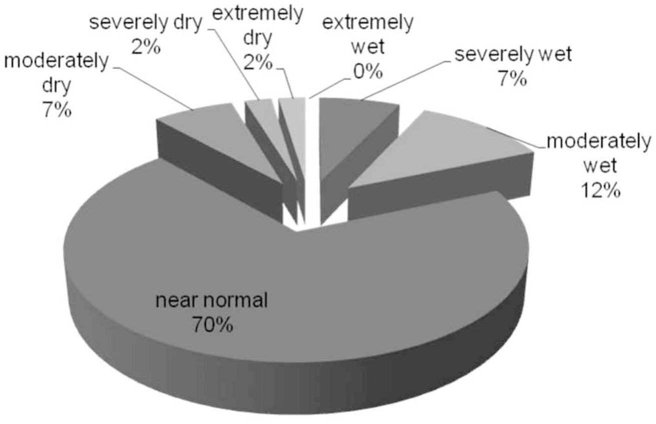


Figure 4. Percentages of the wet and dry years for Lake Kariba based on the SPI classifications for the period 1964–2007.

The mean temperature is shown to increase linearly by an average of 3.43°C over the entire period and at an average rate of 0.78°C per decade. The temperature data suggest detectable, significant ($R^2 = 0.39$, $P \leq 0.05$, $n = 44$) warming at an average increase of 3.58°C for the maximum and 3.29°C for the minimum temperatures over the four decades. In general, the period of cooler than normal temperatures span the 1970s, while most of the warming in Kariba occurred during the period after 1980, which is also the period with higher than usual occurrences of droughts. This suggests that the presence or absence of cloud cover may have played a significant role in modulating the observed temperature anomalies. This is shown in Figures 4–8, in which the trends of temperature and rainfall anomalies can be seen to be out of phase with each other. Periods of above normal rainfall generally coincide with cooler than normal temperatures, and *vice versa.*

The mean annual diurnal temperature range (DTR) was calculated as the difference between the maximum and the minimum temperatures. It was found that the DTR has been increasing significantly ($R^2 = 0.32$, linear, $P \leq 0.05$, $n = 29$) in the Kariba area (Figure 9). This increase has been at an average rate of 0.017°C per year from 1968 to 2007.

Evaporation rates

Evaporation rates were obtained for the period 1963 to 1999 and varied from 0 to 23.4 mm per day. On a monthly average, the rates ranged from 4.86 to 8.72 mm per day in each year with a mean of 6.80 ± 1.0 mm per day for the entire period analysed; giving a total average of 2483 mm loss of water per year from 1963 to 1999. The increase in the evaporation rate (Figure 10) has been at an average rate of 0.014 per day. A time series analysis showed a 2 year moving average of 0.14 mm per year and at this rate the evaporation rate had increased significantly by 1999 ($R^2 = 0.31$, $P < 0.05$, $n = 36$; linear). An extrapolation of this

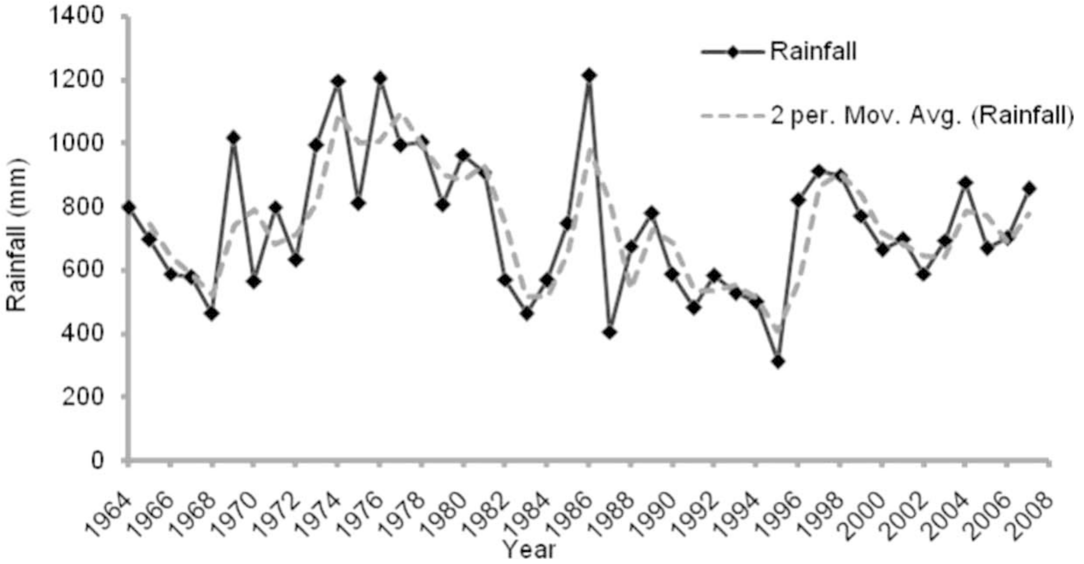


Figure 5. Variation in annual rainfall (mm) around Lake Kariba, 1964–2007.

trend from 1999 onwards to date; suggests that the evaporation rates of Lake Kariba would have reached an annual average of 9.1 mm per day by 2010 and that it would continue to rise if all conditions remain the same. The highest annual evaporation rates were recorded in 1995 which was also the hottest year. The second highest annual evaporation rates were recorded in 1987 followed by 1992 and both these years were hot and dry (drought) years.

The highest evaporation rates occurred during the hot dry season (August to November) and particularly in the month of October in which most levels (>80%) exceeded 10 mm on each day of this month in each year. When the evaporation data were split into two phases, one with a range from 0–7.5 mm and the other from 7.5 mm and above, hot, dry-spell years and phases (1983–84; 1987–88; 1990–1995) fall into the second category of high evaporation rates of ≥7.5 mm.

Water levels

Lake water levels varied between 458 m and 487 m from 1959 to 2008 (Figure 11). There is a 23 m range in the water levels among the years reflecting high variability in the water levels. However, if the initial levels (1959–1964) are treated as outliers considering that the lake was filling up in this period, the variance in water levels is reduced and shows that the lake has ebbed between 477.1 and 486.6 m since 1965 with an average water level of 482 ± 2.8 m and an annual range of 9.5 m. Figure 11 shows the trend in the water levels over time. The highest variation in water levels occurred between 1981 and 1996 when levels dropped by 9.5 m. However, despite the 'normalised' rainfall from 1996 to 2007, the lake recorded low water levels in this period and the last five years in the water levels data (2003 to 2007) witnessed an unprecedented decrease in the water levels that is comparable to the 1981–85

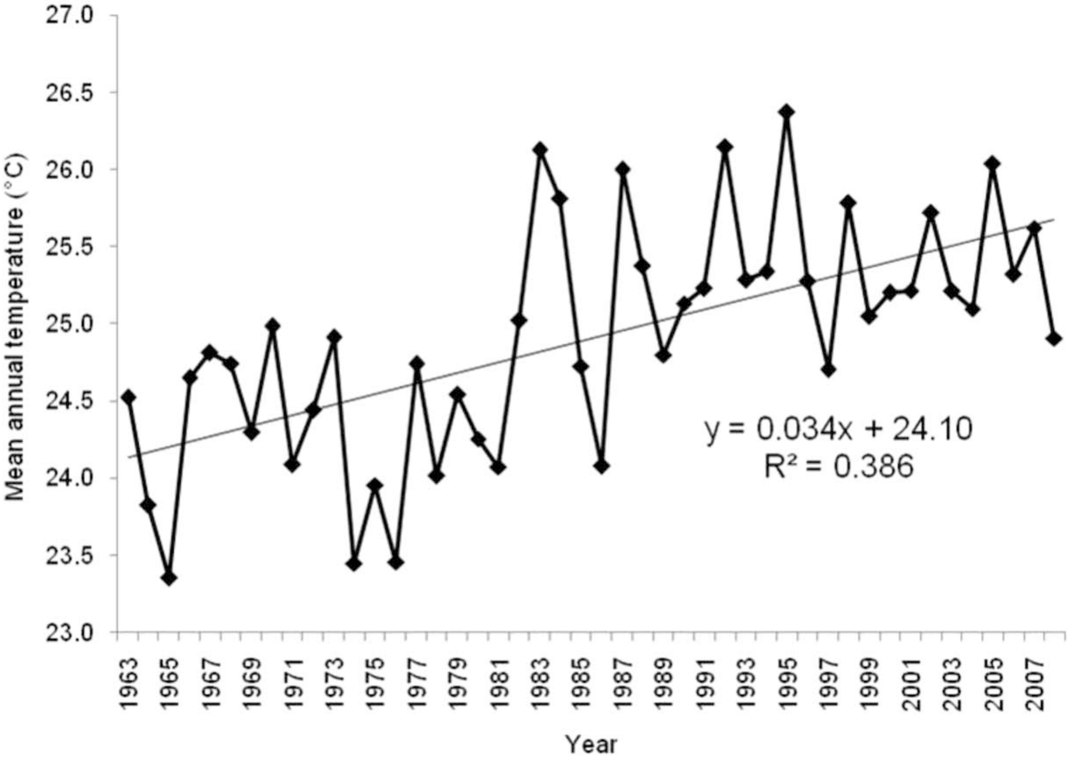


Figure 6. Observed trends in mean annual temperatures for Lake Kariba, 1963–2007.

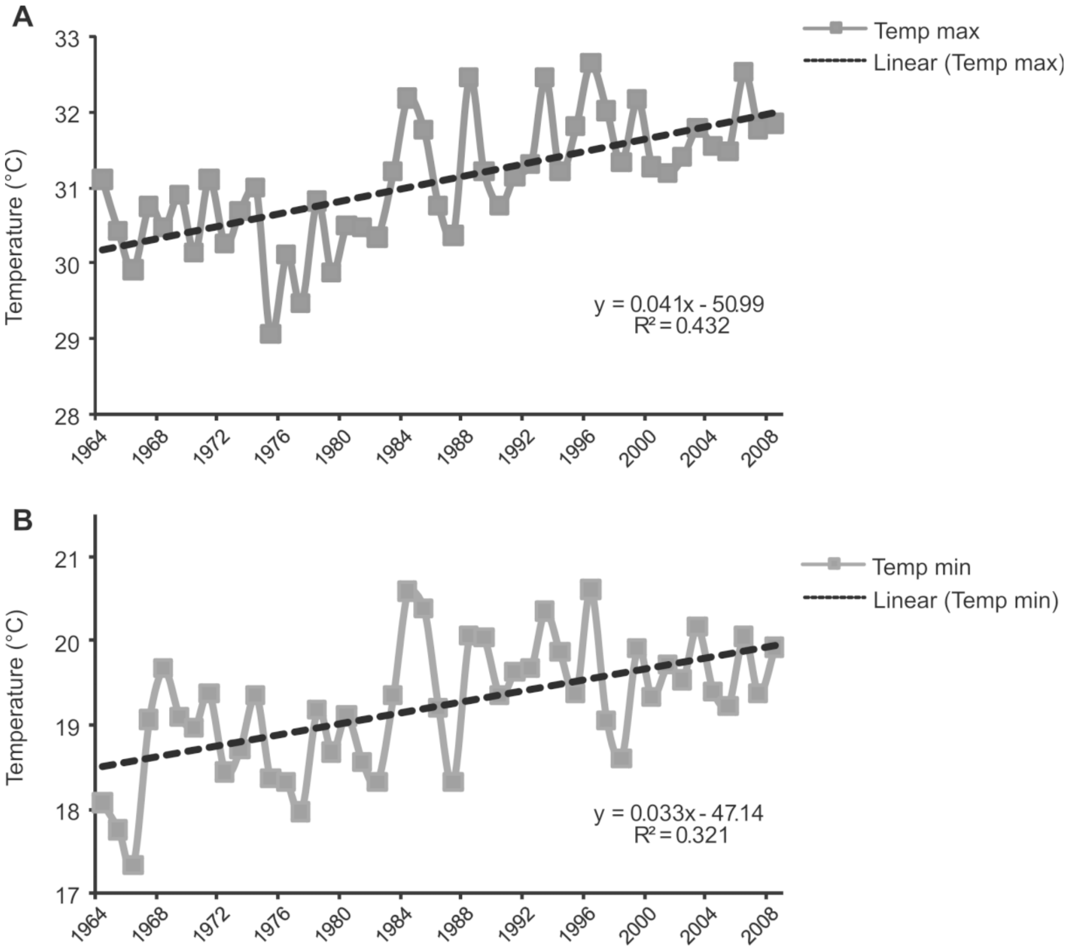


Figure 7. Average annual **A**. maximum and **B**. minimum temperature levels for Lake Kariba, 1964–2008.

declines (Figure 12). Low water patches coincide with hot spells and low rainfall years that have plagued the South African region more frequently in the past 30 years since the 1982–1984 drought.

Kapenta and artisanal fish catches

Since their successful introduction in 1968 and first commercial catches of 1974, Kapenta production trends have followed a polynomial distribution (R^2 = 0.84, polynomial order 3, $P \leq 0.05$) with an initial increase and lag phase (1974–1983), preceding growth (1984–1992); and a decline (1992–2002). Overall, there has been a decline in the Kapenta fish stocks at an average rate of 29.58 metric tons per year; notably the rate of decline was much steeper (37.26 metric tons per year) from 1992 onward. Similarly, the artisanal fish stocks have been declining significantly (R^2 = 0.95, logarithmic, $P \leq 0.05$) in the lake and

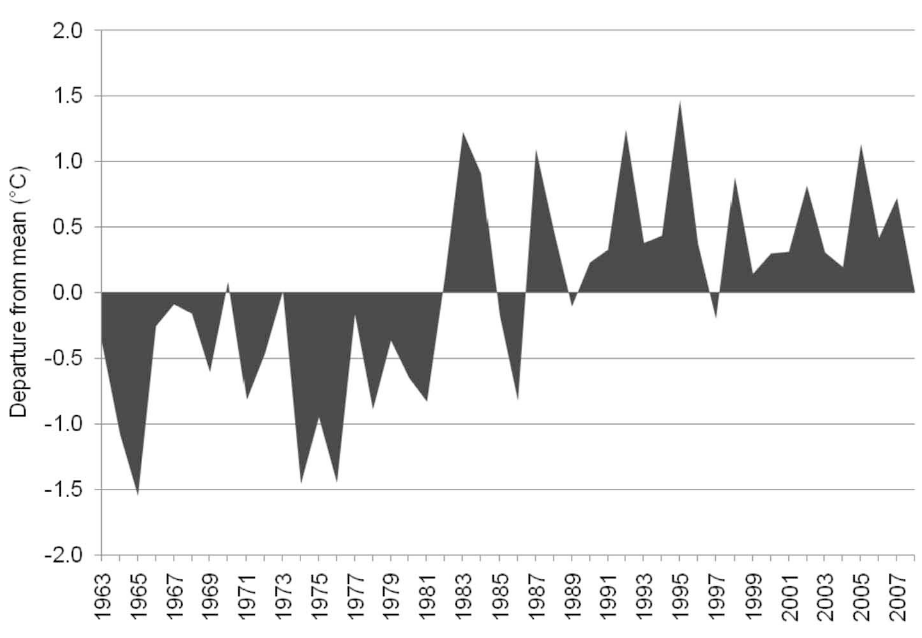


Figure 8. Annual temperature anomalies (departure from mean) for Lake Kariba, 1963–2007.

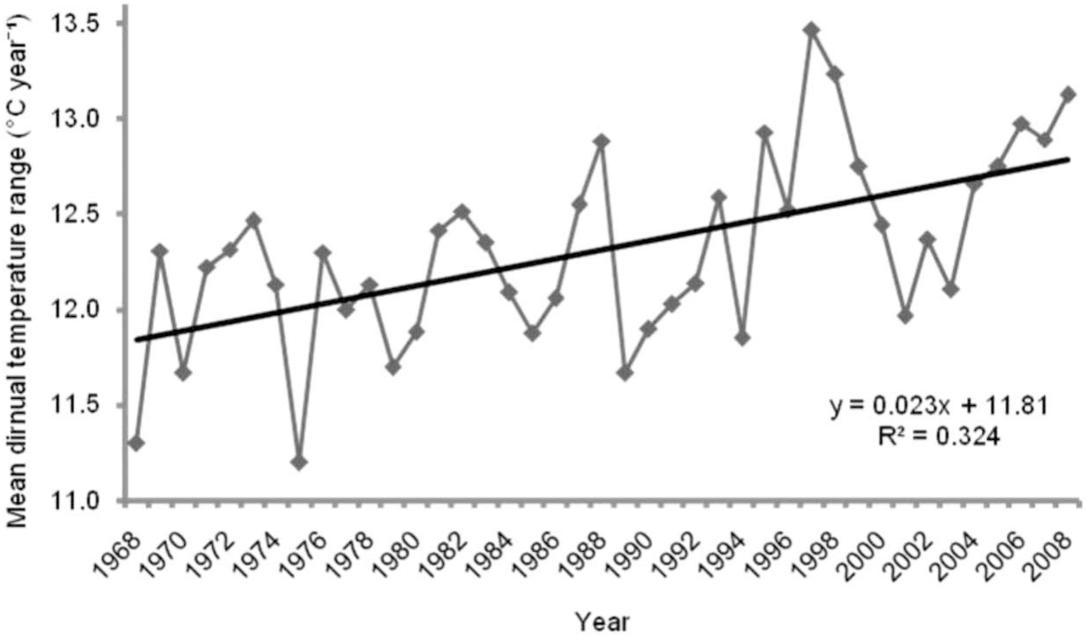


Figure 9. Increasing trend in the annual diurnal temperature range around Lake Kariba, 1968–2007.

follow a trend when they were initially high from 1974 to 1978 but started to decline up to 1983. From then (1983) on, the artisanal fish stocks revived and increased up to 1990 but not to the high levels of the 1970s. Low Kapenta catches coincide with high (maximum) temperatures and low rainfall and of particular note in this trend were the years 1982, 1987, 1992, 1995 and 1998 which were the hottest (mean, maximum temperature above 32°C) and driest years with 1992 and 1995 as drought years. Similarly, low fish (artisanal) production also coincides with the dry years (1983, 1992, 1995–1996 and 1999–2001) and hot spells. Figure 13 shows the trends in Kapenta fish development over time.

In the Sanyati basin (B5) where the majority of the Kapenta fishermen operate in and where a significant (60%) portion of the fish is caught, trends in the sardine production mimic those of the whole lake. However, more comprehensive records of the fish landings are available from B5 and thus a detailed analysis of the Kapenta fish development in this basin was possible. The Kapenta fish production in the basin varied synchronously with the patterns observed in the whole lake and inversely with lake water levels (Figure 14). In fact, a regression analysis of the environmental and Kapenta data in the basin reflects that water levels are the primary significant ($P \leq 0.05$) determinant of the sardine catches, followed closely by maximum temperature, minimum temperature and with rainfall bearing a moderate impact (Table 4). When the Kapenta production within the Sanyati Basin was divided into seasons, a consistent decline in the sardine catches from 1986 to 2003 was noted, regardless of season (Figure 15). However, when regression analysis was applied to the data, the steepest linear decline in the sardine fish catches occurred mostly in the summer ($R^2 = 0.51$) followed by autumn ($R^2 = 0.44$), winter ($R^2 = 0.25$) and spring ($R^2 = 0.22$).

Comprehensive fishing records from the Lake Kariba Fisheries Research Station show that there has been a decrease in the number of vessels and fishermen involved in *Kapenta* fishing by a factor of 2 from 1974 to 2002. However, even though the number of *Kapenta* fishermen have decreased in time, it has been noted that the catch per unit effort (CPUE) of the *Kapenta* sardines has increased significantly ($R^2 = 0.83$ poly order 3, $P < 0.05$, $n = 28$) with a peak around 1994 from where CPUE began to decrease (Figure 16). Interestingly, the distribution of

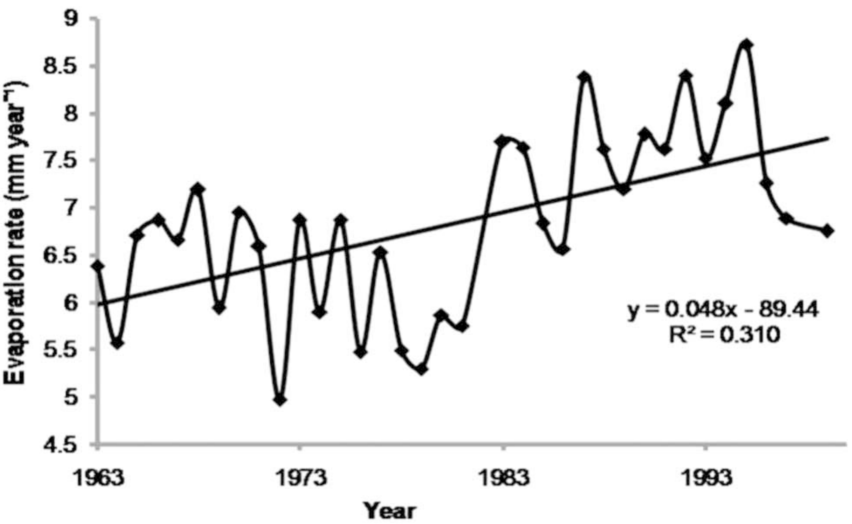


Figure 10. Variation of annual average evaporation rates (mm d^{-1}) from Lake Kariba, 1963–1999.

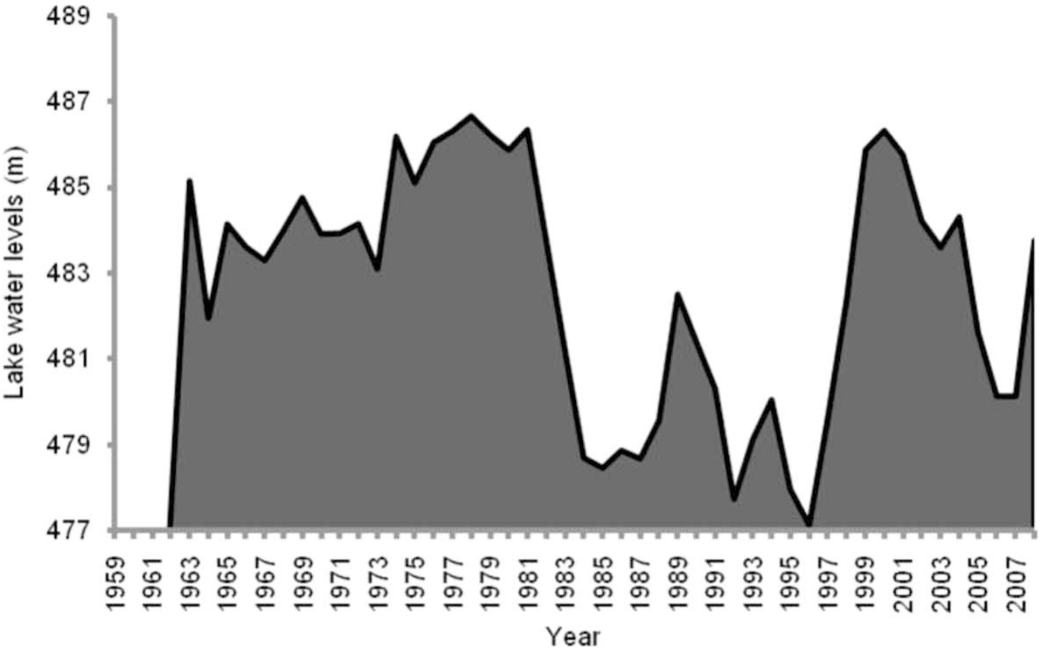


Figure 11. Measured annual water levels in Lake Kariba, 1964–2008.

CPUE closely mimics that of the *Kapenta* catches. However, it was expected that these two variables would be associated in a negative linearly manner thus these results suggest that other factors other than fishing pressures may be influencing the fish production.

Regression analysis

General Linear Models were superimposed on the climatic parameters and fish catch data. Strong linear relationships ($R^2 > 0.90$, $P \leq 0.05$) were found between rainfall and temperature (both maximum and minimum) and between the two temperature ranges and the water levels (Table 4). The maximum temperature had the highest correlation coefficients, being significantly and positively related to all the climate parameters and *Kapenta* variables. Rainfall was also positively and significantly related to all the other environmental variables but to a lesser extent than the maximum temperature. The minimum temperature exerted the least influence on the Kapenta production and among the environmental variables while water levels could explain the most variation in the Kapenta fish catches ($R^2 = 0.84$, $P \leq 0.05$); followed by maximum temperature ($R^2 = 0.72$, $P \leq 0.05$), evaporation and rainfall (Table 4). A high degree of association was found between the fitted GLM when all the exploratory variables were com-

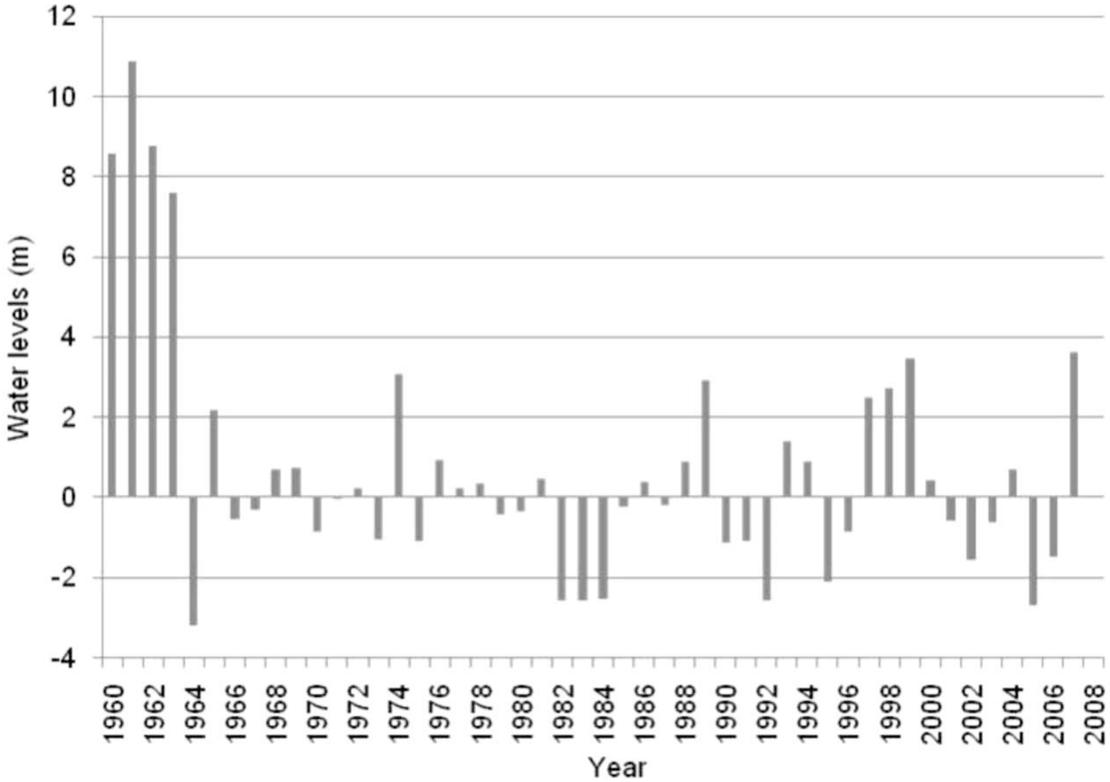


Figure 12. Differences in annual water levels in Lake Kariba, 1959–2008.

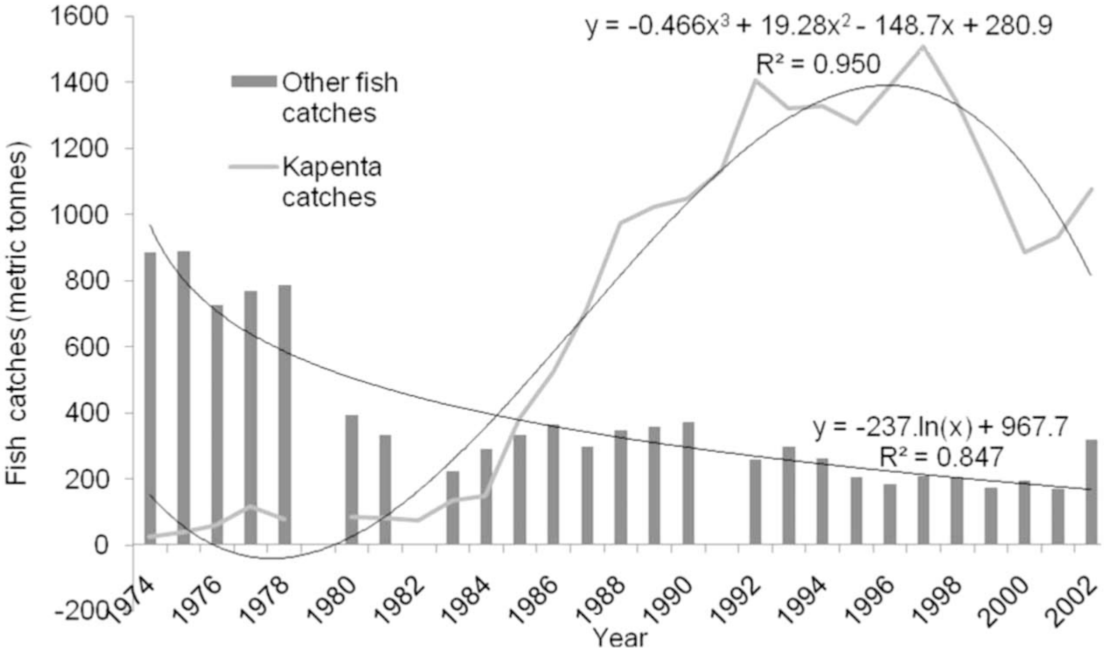


Figure 13. Mean annual variation in Kapenta and other fish catches in Lake Kariba, 1974–2002.

Table 4. Characterisation of years according to rainfall levels (SPI 12 months classification).

Year classification	Frequency	Years
Extreme wet	0	
Severely wet	3	1974–1975, 1978
Moderately wet	4	1969, 1976, 1980, 1986
Near normal	31	1964–1967, 1970–1973, 1977, 1979, 1981–1982, 1985, 1987–1989, 1991, 1993–1994, 1996–2007
Moderately dry	4	1983–1984, 1990, 1992
Severely dry	1	1968
Extremely dry	1	1995

bined as the model accounted for 94% of the observed Kapenta catches in the lake.

The water levels were related to the Kapenta catches and CPUE in a perfect negative linear manner while the maximum temperature also had a strong linear correspondence with the Kapenta CPUE and total catches in particular (Table 5). In addition, the minimum temperature could explain a great proportion of the variation in the Kapenta stocks and CPUE in a negative linear relationship for the total catches while the rainfall bore a moderate influence on the fish catches at R^2 of –0.57 for both the total Kapenta catches and CPUE (Table 6).

DISCUSSION

The climate around Lake Kariba is changing and our study reflected these changes as trends above the natural variability and acquiescent with predicted trends. The rainfall was very variable but this variability of 31% was expected and is compliant with the 30% of semi-arid regions (Sayce, 1998). In comparison to Arnell's (1999) model estimates of the southern African region of a 10 to 20% decline in precipitation, the rainfall data conformed to the predicted range, as a decrease of 3.67% over the 44 years. Similarly, the decreasing rainfall rate of 6.3 mm per decade is consistent with that of Magadza (1994), whose findings reflected a decreasing trend ranging from 1 to 15 mm per decade in the Zambezi Valley. This reflects that rainfall around Kariba oscillates closely with regional trends and this is further supported by the coincidence in the occurrence of dry spells and notably the four major droughts in the seasons 1982/83, 1987/88, 1991/92 and 1994/95 in the region as well as around Kariba.

The rate of increase in temperature around Kariba is compliant with Unganai's (1996) analysis of a 60-year temperature record (1933 to 1993) of Zimbabwe which suggested an average warming of 0.8°C. However, warming around Kariba is higher than the predicted average regional rise of 1.6 to 2.5°C by 2050 (IPCC, 2001) for the semi-arid regions of Africa and even the long-term projections of 1 to 3.5°C by 2100 (Hulme *et al.*, 2001; IPCC, 2007) suggesting that warming around Lake Kariba is occurring at a faster rate than is predicted for the region. Such a divergence is expected as microclimates vary at local levels and thus the ground measurements of a local station may vary and not tightly fit regional estimates, hence the need to downscale model predictions from regional to local level (Prudhomme *et al.*, 2002).

Though there has been an increase in the diurnal temperature range (DTR), the average DTR rate of increase is lower than the rate that Hulme *et al.* (2001) calculated as they indicated that the DTR across Zimbabwe has increased by 0.5 to 1°C since the 1950s. This divergence is expected as the Kariba area experiences higher temperature ranges than most parts of Zimbabwe. However, if the average DTR in the present analysis is extrapolated, DTR around Kariba may increase cumulatively to

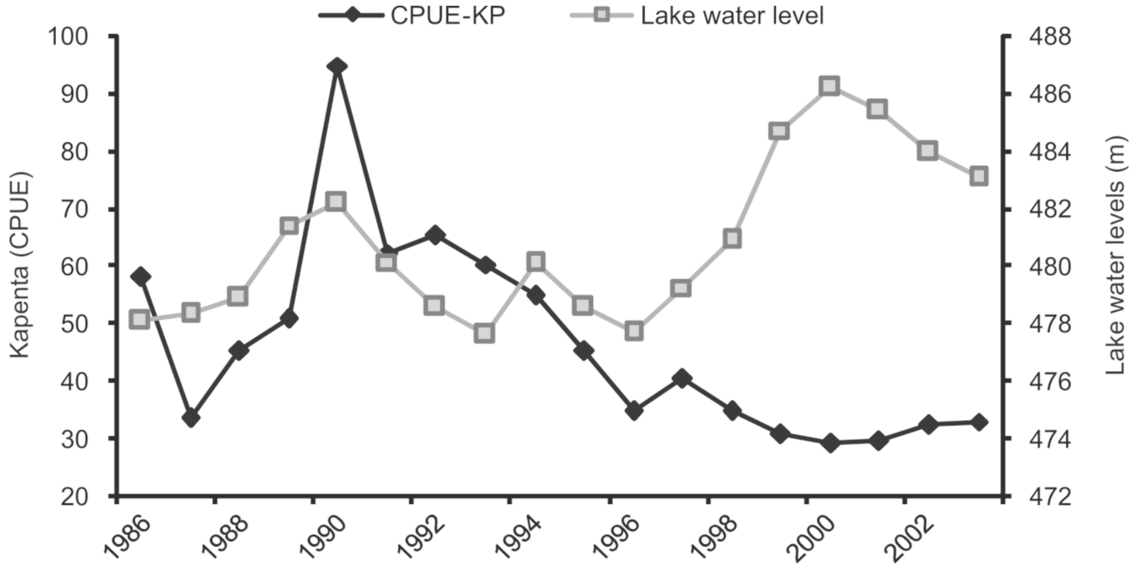


Figure 14. Annual variation in the Kapenta CPUE and lake water levels in the Sanyati Basin of Lake Kariba, 1986–2003.

0.79°C by 2050, a rate much closer to the figures in the Hulme *et al.* study. This implies that the maximum temperatures may continue to increase at a faster rate than the minimum temperatures with the overall effect of warmer winters and therefore a reduction in the cooling effect of winter and less mixing of the lake waters at turn-over in the winter season. Such conditions have immense implications for the lake production as increased water temperatures augment the stability of thermal stratification and lead to slower mixing of the waters thereby sharpening the density gradient and slowing vertical mixing and ultimately reducing primary production and in turn, the fish production. By contrast, the present warming trend observed around Kariba are divergent from the regional trends as Magadza (2008) observed that the winter seasons (March to August) in the Gwembe Valley within the Zambezi Valley have a higher decadal mean warming rate (0.62°C) than the warmer months of September to February (0.45°C) while the minimum (night) temperatures for the winter season (June to August) have been warming faster than the seasonal maxima (0.65°C against 0.47°C, respectively). Presently, the temperature Kariba data present increased warming rates of 3.7° C by 2050 if all conditions remain the same. Such an increase in temperature would be compliant with the temperature projections for Zimbabwe of a 1–4° C temperature rise by 2050 (Unganai, 1996) but would be higher than the predictions from IPCC (2007) models.

Similarly, the increase in water loss due to evaporation around Kariba is higher than the projected 15–25% potential loss around the Zambezi River. Magadza (2008) attributes the higher evaporation rates around Kariba to global warming which has implications on the water levels and nutrient availability while increasing the ionic composition of the waters, a condition that is not favourable for fish production. The annual water loss is slightly below the range of 2500 to 3600 mm recorded by Coche (1974) but higher than the ZRA estimate of 1500 mm from records of the Chirundu and Livingstone stations (WCD, 2000) as well as Sayce's (1998) annual estimate of 1700 mm. The water levels of the lake varied widely and it is important to note that the effects of rainfall on lake water levels are reflected a season after the rainy period and with the onset

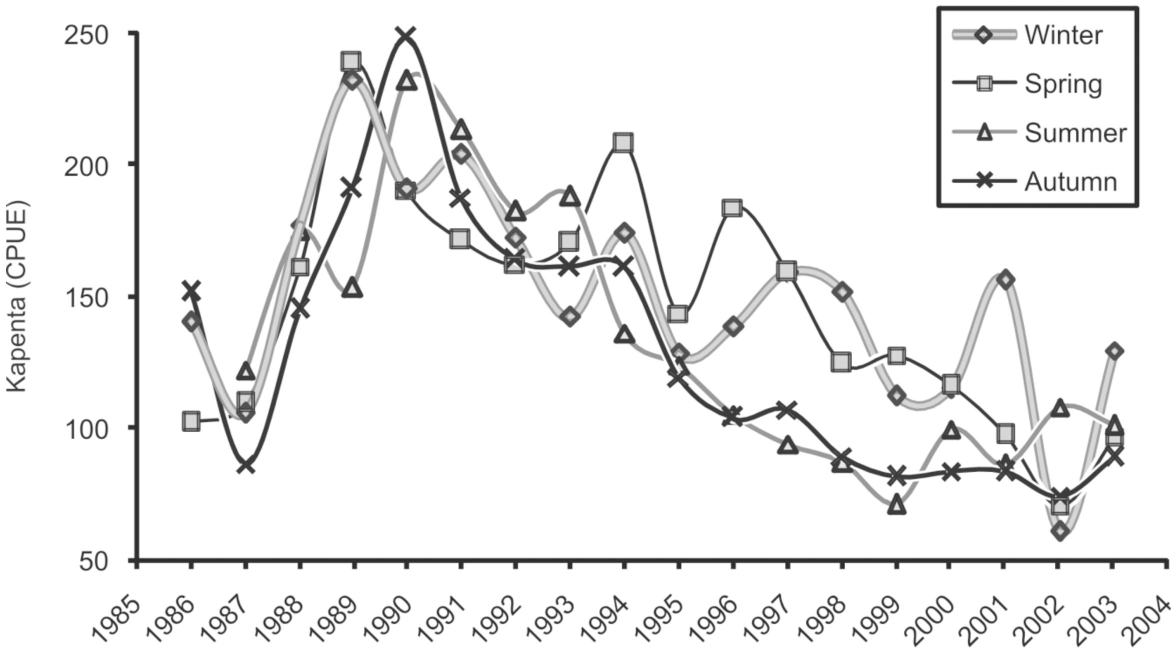


Figure 15. Annual variation in the Kapenta CPUE across seasons in the Sanyati Basin of Lake Kariba, 1986–2003.

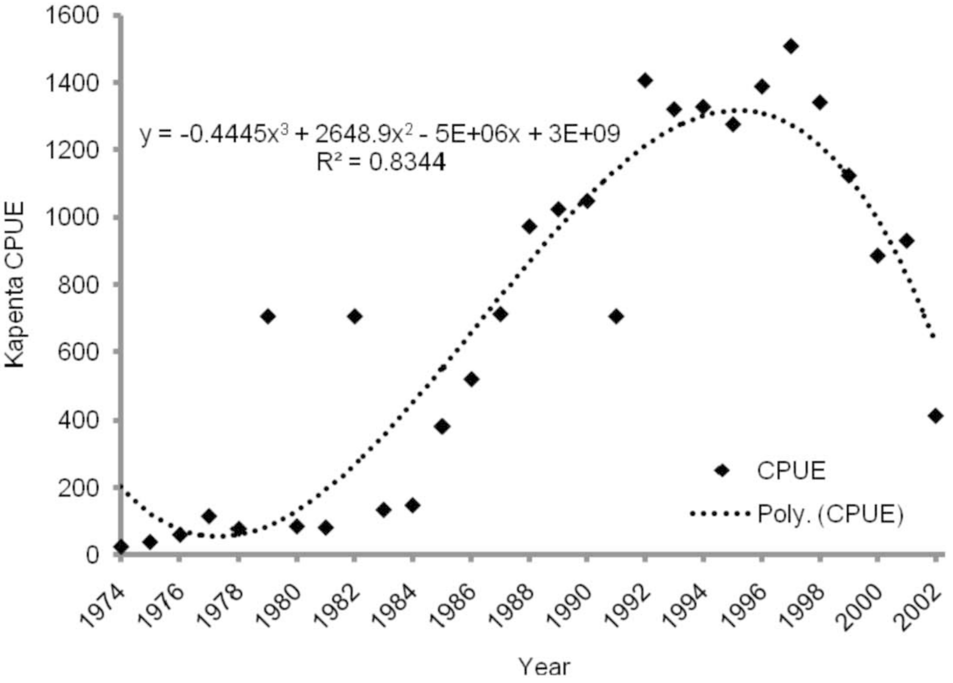


Figure 16. Annual variation in Kapenta catch per unit effort (CPUE), 1974–2002.

Table 5. Regression matrix of climatic factors and fish catch characteristics in Lake Kariba showing R^2 values; significant values are in boldface.

Parameters	Evaporation	Rainfall	Max temp	Min temp	Fish catch	Water levels	Kapenta catch	Kapenta CPUE
Evaporation	1							
Rainfall	0.14	1						
Max temp	0.05	**0.92**	1					
Min temp	0.02	**0.92**	**0.99**	1				
Fish Catch	0.25	**0.65**	**0.74**	0.16	1			
Water levels	0.22	**0.93**	**0.99**	0.19	0.05	1		
Kapenta Catch	**0.58**	**0.54**	**0.72**	0.12	0.13	**0.84**	1	
Kapenta CPUE	0.14	**0.50**	**0.68**	0.14	0.23	0.21	**0.81**	1

of the flooding regime of the Zambezi River. This was often reflected in the water levels as increased levels from April to August of each year reflecting a high variability associated with the different sources of water, namely the contribution from precipitation (10%) and river discharge and the flooding regime of the Zambezi River. Low water levels were recorded from 1982 to 1997 when some of the severest droughts were experienced during these periods (90%). This was also noted by Madamombe (2002) who also reported that the lowest levels recorded were in December 1992 and January 1997 at 476 m and these years still hold the record for the lowest water level in the lake as observed in the present study.

This study established that climate and hydrological factors around Kariba are changing; the question, however, is how the changes in these factors influence the Kapenta production in Lake Kariba. Our results were consistent with previous research (Marshall, 1982; Magadza, 1996; Chifamba, 2000) which showed the strong relationships between climate, hydrological factors and Kapenta fish production in the lake. However, the present study reflects that overall, the declines in the Kapenta are unprecedented since the last two long-term studies (Chifamba, 2000; Madamombe, 2002). Magadza (2008) postulated that the breaking point in the decline of the Kapenta was 1987 and in the present study Kapenta declines started to decline considerably from 1990 in the Sanyati Basin and 1992 for the whole lake. The year 1987 was one of the hottest years experienced in the region with the second highest yearly average evaporation rates and was only second to 1995 as the year with the lowest recorded rainfall while 1990 and 1992 were moderately dry years and 1992 was hotter than normal (>25.7°C). In investigating the Kapenta fish catches and climate as well as hydrological factors for the period 1970 to 1996, Chifamba (2000) found that all the environmental variables had a significant relation with CPUE and fish condition, but the relations of the environmental variables to the mean length of Kapenta were weak and mostly insignificant. In comparison,

Table 6. Regression matrix of climatic factors and fish catch characteristics in the Sanyati Basin of Lake Kariba showing R^2 values; significant values are in boldface.

Parameters	Rainfall	Max temp	Min temp	Water levels	Kapenta catch	Kapenta CPUE
Kapenta Catch	–0.57	–0.99	–0.96	–1	1	
Kapenta CPUE	–0.57	0.83	**0.98*****	**–1*****	0.81	1

Chifamba (2000) found that the maximum temperature was the best predictor of CPUE and this was consistent with the present study as maximum temperature had the strongest relationship with CPUE and this suggests that as the temperature continues to increase, Kapenta fish production may continue to decrease in the lake. Although the maximum temperature was second to water levels in predicting the total Kapenta catches, CPUE is a better indicator of the actual fish stocks in the lake as the total Kapenta catches depend on the number of fishermen operating at a given time as well as the number of hauls.

Temperature is an important factor in determining fish productivity in Lake Kariba and other tropical lakes through its effect on nutrient cycling *via* the stratification cycle. The higher the temperatures, the more stable the stratification and the more locked up nutrients are in the hypolimnion. In turn, phytoplankton production is adversely affected in the nutrient-deprived epilimnion and this decrease in production cascades up the trophic level through zooplankton to the Kapenta and other fish. The established rise in temperature could therefore be the main cause of the Kapenta fish decline in Lake Kariba among other factors. Such an assertion is supported by the strong relationship of temperature, the maximum range in particular, with CPUE and average fish catches demonstrated in this study. The positive correlation between temperature and fish production is expected as enzyme-catalysed biochemical reactions positively increase with increase in temperature according to the Q^{10} factor. These trends in fish production are compliant with the results of Mtada (1987) who found a strong negative correlation ($R^2 = 0.94$, $n = 32$) between thermal stratification and the monthly yields of the sardines and that fish catch is not uniform throughout the year, being reduced during periods of strong thermal stratification and increased during circulation in Lake Kariba. This was demonstrated in our analysis as Kapenta catches peaked around September/October of each year during the period just after the overturn – when the lake would have undergone mixing and during the latter months of the rainy season when strong winds and thundershowers tend to mix the lake. The increase in nutrients during these two periods has been documented as phosphorous increases; following overturn in winter indicating the release of nutrients from the deeper waters and in the rainy season (Magadza, 2006).

Evaporation rates had a moderate relationship with the fish catches and this can be explained by the fact that the relationship between evaporation and fish production is quite complex, following a chain of interacting processes such as light radiation and temperature (Vörösmarty *et al.*, 2000). The warmer the temperatures, the higher the evaporation rates and the lower the lake water levels, this bearing negative impacts on the fish production. Of concern is the possibility that continued temperature increase may consequently increase evaporation rates, and this may further adversely impact the pelagic fishery if all conditions remain the same. The results also reflected the strong link between the water levels and fish catches. This can be attributed to the water's role in transporting nutrients into the lake, which was demonstrated by Marshall (1982) as a strong link between water levels and the sardine catches while Chifamba (2000) showed the good correlation between the two factors. Concurrently, though lake water levels showed the strongest relationship with the Kapenta catches, variation in the water levels were in turn, are strongly related to temperature which also influences rainfall significantly. This then reflects the central role that temperature plays in determining the climate as well as Kapenta production in the lake.

The association between hydrological factors and fish parameters is a result of the link between rainfall, water inflow, water levels and nutrient fluxes in Lake Kariba. The spatial distribution of fish is associated with areas of river inflow (Magadza, 1980) and the timing of the peaks in the phytoplankton biomass (Ramberg, 1987) and zooplankton production (Masundire, 1989, 1991, 1992) coincides with the nutrient fluxes caused by river inflow and water levels as well as turnover. This trend in turn, is followed by peaks in fish production in the lake (Marshall, 1982). By contrast, Karenge and Kolding (1995) found little or no correspondence of the fish catches with absolute water levels even during periods of drought while Karange and Kolding (1995) showed that the changing hydrological regime, explained a large proportion of the variability in catch rates (CPUE). They concluded that Lake Kariba was an allotropic, riverine lake where productivity was largely driven by the nutrient pulses carried by the annual floods and therefore, hydrological factors and this influence was reflected by the strong correlation between the lake water levels and Kapenta catches and CPUE.

The analysis ruled out the possibility of overfishing as a significant causal factor of the Kapenta declines as the number of fishermen has declined over time while the fishing effort also declined in the decade from 1992 to 2002. Previously, the decline in Kapenta production was attributed predominantly to the increase in fishing effort in the sardine fishery (Marshall, 1988). This explanation fitted the data from 1974 to 1985 but could not fully account for the observed trend in CPUE from 1985 to 2002 when the CPUE and fishing stocks declined simultaneously. This is unexpected as CPUE and fish stocks are normally inversely related. By contrast, Chifamba (1995) suggested that the increase in the effective fishing effort due to vessel improvement could account for some of the initial increase in CPUE from 1985 to 2000 but the same cannot be suggested since the Chifamba study. In a separate study, Madamombe (2002) concluded that fishing effort levels were close to the maximum sustainable yield (MSY) effort levels and could explain the lowering CPUE levels. However, in a latter study, Madamombe (2004) showed that there was a decrease in the fishing effort and concluded that the Open Access (OA) was not a threat to the Lake fishery. The decreasing CPUE is reflective of the developments in the fishery industry as the number of rigs on the Zimbabwean side of the lake has been decreasing since 1994 (Madamombe, 2000); this corresponding with our findings and suggesting that the fish stock decline is due to other factors other than overfishing. The decrease in commercial fishing activities was exacerbated by the slump in the Zimbabwean economy which started in the late 1990s (Madamombe, 2000). Kapenta fishing is capital intensive and requires a large investment as well as daily inputs such as fuel. Observations made between 2007 and 2009 of yields of both small and large-scale fishermen operating in the lake indicate that there is still a substantive stock of the sardine but the catches are smaller and this is of concern (I. Tendaupenyu, pers. comm.).

The association of climate with declining fish production through the reduction of nutrient levels observed in Lake Kariba has been implied in other tropical African lakes. In Lake Tanganyika, for instance observations since 1974 document decreases in phytoplankton abundance and increase in dissolved Silica (Si), both indicative of declining primary productivity with negative implications for the pelagic fishery (Bergamino *et al.*, 2007; Stenuite *et al.*, 2007; Verburg *et al.*, 2007). O'Reilly *et al.* (2003) reported that the decrease in primary production was mainly due to regional climate change which has reduced primary production by 60% in Lake Tanganyika in the past 80 years. These findings, corroborated by another study which used satellite based reflectances to determine anomalies in chlorophyll over a seven-year period demonstrated a close correspondence between phytoplankton biomass and climate in Lake Tanganyika (Bergamino *et al.,* 2007, 2010). Decreasing primary productivity in Tanganyika will likely reduce the relative abundances of endemic fish species but possible effects on fish species richness are unknown although it has been predicted that climate change is likely to reduce primary production and possible fish yields by roughly 30% (IPCC, 2007). It has been demonstrated that the relative strengths of year classes in many fish correlate with weather conditions during the spawning and early life history stages while relatively modest changes in the weather can dramatically increase variability in recruitment (Tripple *et al.,* 1991) and thus temperature influences fish development directly and indirectly to a large extent.

The changes observed in Lake Tanganyika are mimicked in Lakes Albert, Edward, Malawi and Kivu (Patterson *et al.,* 2000; Sarmento *et al.,* 2006; Guilford *et al.,* 2007). This is because in these deep lakes, along with warming surface waters, deep-water temperatures (which reflect long-term trends) of the large East African lakes have warmed by between 0.2 and 0.7°C since the early 1900s (IPCC, 2007) while Lake Kariba's waters have warmed by 1.9°C since the 1960s (Ndebele-Murisa, 2011). In turn, lake fisheries in the region already experience high levels of climatic variability, which cause fluctuations in primary production and fish yield. For instance, high evaporation rates as a consequence of global warming have reduced water levels more than four meters in depth of Lake Victoria. This could be the cause of the declining fish production in the world's second largest freshwater lake (Fryer, 1997). However, Awange *et al.* (2008) argue that the 1°C increase in temperature could have contributed to increased evaporation but not at a scale to cause rapid decline of the lake water levels and therefore decreased nutrient and fish levels.

The fear is that increased warming rates may continue leading to slower mixing of the waters thereby sharpening the density gradient in African lakes such as Kariba and slowing vertical mixing ultimately reducing primary production and consequently fish production (IPCC, 2007). Underlying these fluctuations in many parts of Africa is a trend of declining rainfall and surface water availability (Arnell, 1999, 2004) and other factors that affect productivity such as changing wind regimes and evaporation rates (Magadza, 1994; Hulme, 1996, DeSanker & Magadza, 2001). However, it is important to note that other factors such as breeding patterns and predation affect the fish production alongside climate and the hydrological cycles. Thus the dynamics of fish production are complex, bearing in mind that the various factors are also interlinked. For instance, in Lake Kariba, during the summer (September to March) the kapenta sardines move inshore to protected waters to breed and this causes a decline in the open water population during this period (Karenge & Kolding, 1992) and thus many factors have to be considered in order to conclusively reflect on the causal factors of fish production.

However, the study demonstrated that the climate around Lake Kariba is changing – both the maximum and minimum temperatures are rising and this warming has resulted in higher evaporation rates and an erratic rainfall regime with an overall declining trend in the area around the lake which in turn caused fluctuating lake water and therefore nutrient levels in the Kariba waters. In addition, the study demonstrated the close correspondence between climatic factors and Kapenta fish catches with the water levels seemingly influencing the sardine catches to the greatest extent followed by maximum temperature. Climate variability is known to play an influential role in Kapenta production. Of concern is the fact that continual warming around the lake may continue to further the adverse effects of the climate changes on the Kapenta production which has declined by 50% since the 1970s as observed in other African lakes. There is an urgent need to circumvent the effects of the changing climate and temperature increases on the fish production in the lake if adequate mechanisms and remedial measures are to be effectively implemented in the fishery management. Therefore, continued long-term data collection is advocated for if decadal and multi-decadal cycles are to be understood.

ACKNOWLEDGEMENTS

We thank Nqobizitha Siziba, formerly a Researcher at the Kariba Fisheries Research Institute, Department of National Parks and Wildlife Management, Zimbabwe, and Itai Tendaupenyu of the Kariba Fisheries Research Institute, Department of National Parks and Wildlife Management, Zimbabwe, for valuable personal communications. We gratefully acknowledge funding of this research by IDRC/CDRI and DFID under the African Climate Change Fellowship Program 2009–2010.

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