Temporal patterns in phytoplankton, zooplankton and fish composition, abundance and biomass in Shirati Bay, Lake Victoria, Tanzania

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Abstract

Shirati Bay is among the important breeding and nursery sites for major fish species in Lake Victoria. Weekly samplings were conducted to assess the temporal patterns in phytoplankton, zooplankton and fish composition, abundance and biomass in relation to prevailing water quality parameters. The study also determined the influences of plankton dynamics and water quality on the fish catch composition and biomass. It was hypothesized that temporal patterns in the composition, abundance and biomass in the plankton in the bay are controlled by water quality parameters that, in turn, affect the composition and biomass of fish catches. The phytoplankton comprised mainly cyanophytes and bacillariophytes, while the zooplankton were dominated by copepods. The heavy rain season exhibited a significantly higher plankton abundance and biomass than the dry season. The plankton abundances in both seasons exhibited significant positive correlations with water temperature and transparency. The phytoplankton community was controlled by calanoid and cyclopoid species. At higher trophic levels, *Lates niloticus* juveniles, *Oreochromis niloticus* juveniles and haplochromines controlled Cladocera and Cyclopoid copepods, while *Tilapia rendalli* juveniles controlled the Rotifera. This study revealed that Cyanophyta and Bacillariophyta are the dominant phytoplankton, whereas cyclopoids dominate the zooplankton species in the bay. These dominant plankton groups are partly controlled by rainfall, water temperature and transparency. Fish biomass, zooplankton and phytoplankton exhibit a typical predator–prey inverse relationship. Thus, evaluation of the plankton composition, abundance and biomass should be mandatory during fisheries stock assessments to effectively manage the fishery resources in the bay.

Key words

Bacillariophyta, biomass, copepod, predation, transparency.

INTRODUCTION

Zooplankton are recognized as the major primary consumers in most aquatic ecosystems, feeding mainly on phytoplankton, bacteria, protozoa, detritus and other zooplankton (Irvine & Waya 1992; Wanink *et al.* 2002; Waya *et al.* 2014). They also play an important ecological role in transferring the energy from primary producers (phytoplankton) to higher trophic levels as they are preyed upon by fish (e.g. juveniles of Nile perch and Nile tilapia, haplochromines and *Rastrineobola argentea*) and macroinvertebrates (Peters & Downing 1984; Irvine & Waya 1995; Wanink *et al.* 2001, 2002; Waya *et al.* 2014). As such, the abundance, survival, recruitment and eventual catch composition of various fish species in aquatic ecosystems are largely dependent on the temporal abundance and biomass of phytoplankton and zooplankton (Wanink *et al.* 2001; Semyalo *et al.* 2009).

The composition, abundance and biomass of phytoplankton and zooplankton in freshwater bodies are highly dependent on both abiotic and biotic factors and their

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interactions (Makarewicz *et al.* 1998; Badsi *et al.* 2010). Main abiotic factors include water temperature, transparency, electrical conductivity and pH (Shayestehfar *et al.* 2010). Biotic factors, in turn, include seasonal variations in food (phytoplankton) and top-down control by fish and other predators (Isumbisho *et al.* 2006). Since 1990s, Lake Victoria has exhibited wide fluctuations in such abiotic factors as nutrient loading (Vincent *et al.* 2012). The lake has experienced extensive eutrophication manifested with the occurrence of low dissolved oxygen concentrations in deep water layers during the thermal stratification period (Hecky *et al.* 1994). In regard to biotic factors, disruption of the food web through introduced species has been reported (Downing *et al.* 2012). All these changes imply temporal variability in phytoplankton and zooplankton abundance and biomass, thereby leading to variations in fish catch biomass.

Previous studies focused on studying phytoplankton and zooplankton composition, abundance and biomass as separate groups, without considering their ecological interactions. Phytoplankton studies for Lake Victoria include those by Lung'ayia *et al.* (2000), Machiwa *et al.* (2005), Mbonde *et al.* (2004), Sekadende *et al.* (2005a), Ngupula *et al.* (2011) and Sitoki *et al.* (2012), while zooplankton studies have been conducted by Mavuti and Litterick (1991), Mwebaza-Ndawula (1994), Waya and Chande (2004), Waya and Mwambungu (2004), Ngupula *et al.* (2010), Vincent *et al.* (2012), Ngupula (2013) and Waya *et al.* (2014). Despite the importance and interactions of phytoplankton with zooplankton in fisheries production, there is a paucity of information regarding their composition, abundance and biomass, and their relationship in the inshore waters of Lake Victoria, particularly in Shirati Bay. Understanding their spatial and temporal dynamics in relation to fish composition and abundance is important for testing the hypothesis that there exists trophic cascades among phytoplankton, zooplankton and fish in the inshore waters of Lake Victoria.

This study was conducted to investigate the composition, abundance and biomass of phytoplankton and zooplankton in Shirati Bay in relation to fish species catch composition and biomass. It was hypothesized that phytoplankton and zooplankton composition, abundance and biomass are regulated by water quality parameters such as water temperature, transparency, pH and electrical conductivity, and the seasonal input of nutrients from rainfall, leading to their temporal variability. It was also assumed that the temporal variabilities in phytoplankton, zooplankton and water quality parameters affect the composition and biomass of fish catches.

MATERIALS AND METHODS

Study site

This study was conducted in Shirati Bay, which is located in the Tanzanian waters of Lake Victoria near the border with Kenya, at a latitude of 1°09′ 00″ S and a longitude of 33°58′00″ E (Fig. 1). It is among the important breeding and nursery sites of the major fish species in Lake Victoria. Samples were collected on a weekly basis between March 2005 and March 2006 at three sampling sites, including Nyangoge (15 m deep), Nyasobu (5 m deep) and Michire (7 m deep). These three sites were strategically chosen to include varying depths to capture phytoplankton, zooplankton and fish at various depths.

The climate of the Lake Victoria basin is characterized by two distinct seasons: a dry season from July to September and two wet seasons involving light rain from October to December and heavy rains between March and May.

Sampling strategy and analysis

Phytoplankton composition, abundance and biomass

Water samples for the analysis of phytoplankton species composition and abundance were collected from the same stations at 5–15 m depths using a one-litre JT-1 Lamotte water sampler. A water sub-sample of 100 mL was preserved with Lugol's solution and formaldehyde (0.7% and 2.5% final concentrations, respectively) and transported to the laboratory at Sota Centre for analysis. In the laboratory, samples for numerical abundance were allowed to settle for 48 h to a final volume of 20 mL. This was homogenized by gently shaking the sample bottles by hand to obtain a uniform mixture. A final volume of two millilitres (2 mL) was analyzed for species composition using a Leica inverted microscope (model number 090-135.001) at 400× magnification. Identification of phytoplankton was done based on taxonomic keys by Van Meel (1954), Mosille (1984) and John *et al.* (2002). All specimens were distributed over at least two transects from the sedimentation chamber and counted. Phytoplankton were counted as numbers of filaments, colonies or cells, depending on the species. At least 10 fields were counted from each sample. The counts made from these samples were used for calculating percentage species composition. The phytoplankton numerical abundance was calculated according to Greenberg *et al.* (1992) using the formula:

$$\text{Abundance} = \frac{C \times At \times v}{Af \times F \times V \times Vi} \quad (1)$$

where C = number of organisms counted; At = total bottom area of settling chamber (mm^2); Af = area of field

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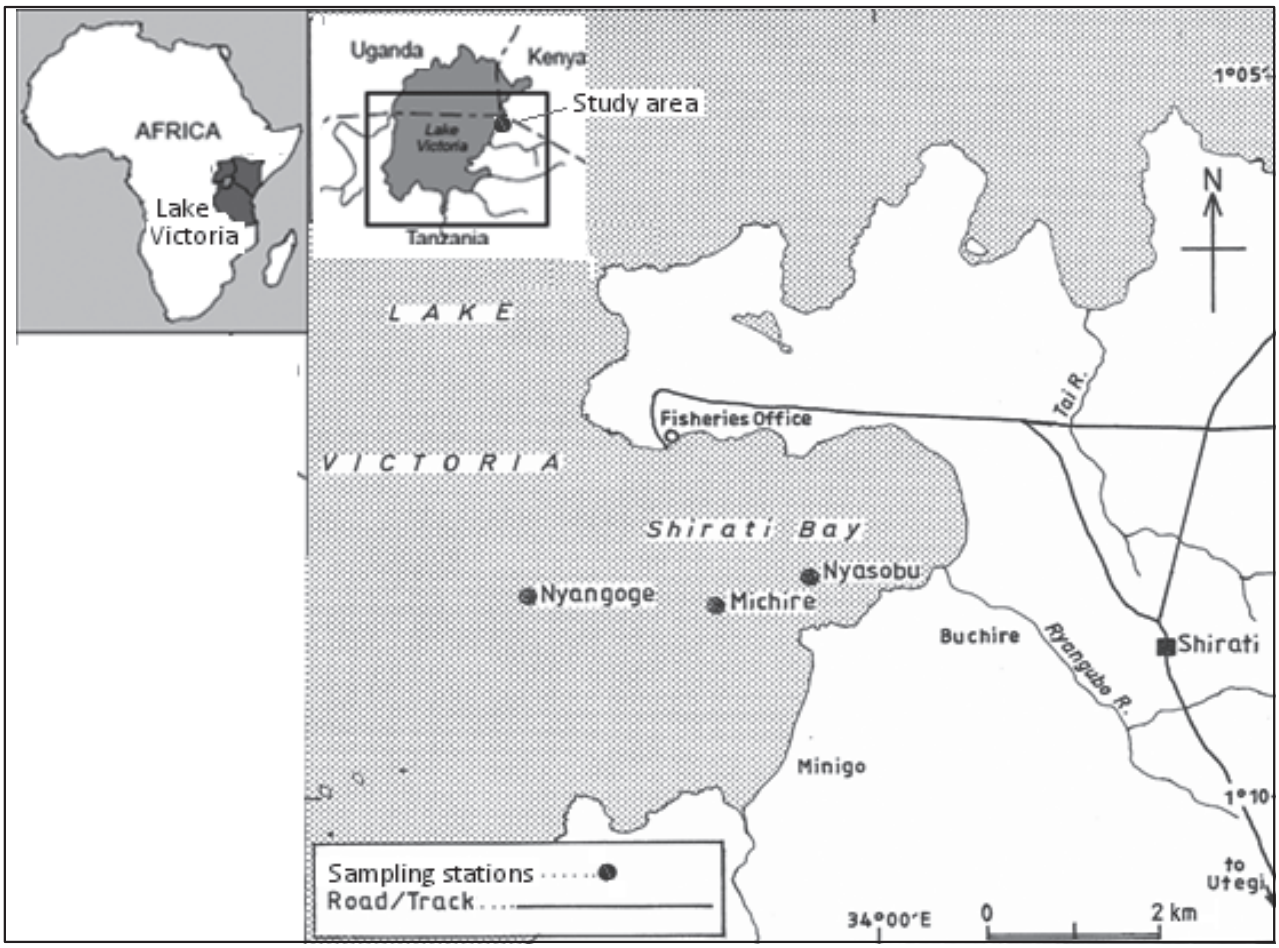


Fig. 1. Map of Shirati Bay showing three sampling sites.

(mm^2); F = number of fields counted; Vi = volume of sedimented sample; V = volume of sample observed (2 mL); and v = volume of concentrated sample (20 mL).

Phytoplankton biomass was estimated indirectly using chlorophyll-*a* analysis (Vörös & Padisák 1991). Water samples were filtered through a 0.45 μm Millipore membrane filters and extracted in 90% acetone overnight at 4 °C. Chlorophyll-*a* concentration was measured using a Shimadzu 1201 Spectrophotometer according to Parsons *et al.* (1984).

Zooplankton composition, abundance and biomass

Triplicate zooplankton samples were collected by vertically hauling 65-μm mesh size plankton net (30 cm diameter and one m length) from one metre above the sediment surface. Samples were filtered through a 90-μm-mesh plankton sieve (Sethi Standard Test Sieves, Ambala Cantt, India). They were preserved with 4% formaldehyde and transported in a cool box to the laboratory at the Sota Centre. In the laboratory, samples were diluted and homogenized by gently shaking the sample bottles by hand, with at least 10 mL of each homogenized sample being examined. The identification was carried out with taxonomic keys and manuals by Ruttner-Kolisko (1974), Korinek (1984), Maas (1993) and Korovchinsky (1993), as deemed appropriate. Identified zooplankton species were counted under a light microscope (model number XSZ-10BN) at 40× magnification. The data (number/subsample) were used to calculate the zooplankton numbers per sample, depending on the split factor and numbers per m^2, using the Microsoft Excel software according to IFMP (2003-2008), with the formulae:

$$\text{Abundance (no. sample}^{-1}) = \frac{\text{Dilution volume} \times \text{number in a subsample} \times \text{split factor}}{\text{Count volume}} \quad (2)$$

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and

$$\text{Abundance (no. m}^{-2}) = \frac{\text{Number per sample}}{\text{Area of net mouth opening}} \quad (3)$$

with a net opening of 30 cm, and area = 0.0855 m^2.

For biomass determination, the copepod body length was measured from the top of the head to the tip of the furcal rami. Cladocera and rotifers were measured from the top of the head to the tip of the abdomen, excluding spines and other projections. The biomass (mg wet wt m^{-2}) was determined on the basis of the length–weight relationship (Herzig 1984) using the formula:

$$\text{Biomass (mg wet wt m}^{-2}) = \left[\frac{(4/3 * \pi ab^2)}{10^6}\right] * \text{Numerical abundance of taxa} \quad (4)$$

where $\pi = 3.14$; $a = 0.5$ length; and $b = 0.5$ width.

Although developed for temperate zooplankton species, this method is appropriate for use on Lake Victoria because it was previously applied by Waya and Chande (2004) for the same lake and was found to be acceptable.

Fish composition and biomass

Fish sampling was carried out with a beach seine with cod-end nets of 2, 1 and 0.5 inches. The seine nets were set to ensure fish were caught within an area covering 5, 10 and 15 m. The nets were set starting from the shallower towards the deeper part of the water and vice versa for three hauls per day at each site. The seine nets were set to cover an area of approximately 200 m^2, being left for two hours before hauling on each sampling run. The nets were hauled three times a day at 0500, 1000 and 1800 hours, with the hours chosen to reflect the common practice by local fishers and convenience for the researchers. The fish caught from the three hauls at each site were pooled for calculating the catch per day to normalize longitudinal variations in the catch attributable to the different depths within a site.

Stomach content analysis of juvenile fish species

Eight juvenile fish species samples (*L. niloticus; O. niloticus; T. rendalli*) per week with relatively similar sizes and haplochromine species from each haul were analysed for stomach contents. A total of 1536 stomachs were removed soon after capture and preserved in specimen bottles containing 4% formalin and subsequently transferred to the laboratory for analysis. In the laboratory, the stomachs were analysed for food content on the basis of the modified point method described by Amundsen *et al.* (1996). Each individual fish was dissected, its stomach opened and the content emptied into a Petri dish and uniformly mixed with some freshwater. The mixture was then transferred to a slide for microscopic examination with a Leica inverted laboratory microscope (model number 090-135.001). Identification of food and plankton biomass was performed as previously explained. The identified food items were assigned percentage values on the basis of their relative abundance in the fish stomachs.

Water quality parameters

Water temperature, pH, electrical conductivity and water transparency were measured using a multimeter probe (model KTO, HQ, 40D PHC 101-LD 101-01 by Hach Company Ltd, USA) and a 21-cm black and white Secchi disc, respectively.

Data analyses

The results are presented as the means ± standard error of means, and the data were tested using Levene's test and Shapiro–Wilk test to guard against violation of parametric statistics assumptions. After confirming the homogeneity of variances and normality, one-way analysis of variance (ANOVA) was applied to test for significant differences in temporal variations in zooplankton, phytoplankton and fish abundance and biomass. Specific significant differences were detected using Tukey's multiple comparisons test. Correlations among phytoplankton, zooplankton and fish abundance and biomass were analysed using Pearson's correlation coefficient. Similarly, Pearson's correlation was used to examine any correlation among water quality parameters and zooplankton, phytoplankton and fish abundance. Results with P values ≤ 0.05 were considered statistically significant (Zar 2010). All statistical analyses were performed using SPSS version 20 (IBM, Armonk, NY, USA) for Windows.

RESULTS

Phytoplankton species composition, abundance and biomass

A total of 55 phytoplankton species classified into 31 genera were identified (Table 1). The phytoplankton species composition was mainly dominated by cyanophytes (44.83%) and bacillariophytes (44.72%; Table 1).

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Table 1. Phytoplankton percentage composition in Shirati Bay, March 2005 to March 2006

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% per taxa and species
Chlorophyta															
Ankistrodesmus falcatus	1.40	–	–	–	4.00	–	–	–	–	1.80	–	–	4.30	11.50	15.01
Ankistrodesmus sp.	–	–	1.00	–	–	–	–	–	–	0.90	1.30	–	–	3.20	4.18
Closterium sp.	–	–	–	–	–	1.00	1.30	–	–	–	1.30	–	–	3.60	4.70
Cosmarium sp.	0.70	–	–	–	1.30	–	1.30	–	–	–	1.30	1.80	–	6.40	8.36
Oocystis lacustris	–	–	–	–	–	–	–	–	–	–	–	0.90	–	0.90	1.17
Pediastrum simplex	0.70	1.10	1.00	1.10	–	1.00	–	–	–	–	–	–	–	4.90	6.40
Scenedesmus acuminatus	–	–	–	–	–	–	1.30	–	–	–	–	–	–	1.30	1.70
Scenedesmus armatus	1.80	1.10	–	–	–	–	–	–	–	–	1.30	–	–	4.20	5.48
Scenedesmus bijugatus	–	–	–	–	–	–	–	–	–	–	1.30	–	–	1.30	1.70
Scenedesmus curvatus	–	–	–	–	–	–	1.30	–	–	–	–	–	–	1.30	1.70
Scenedesmus incrassatulis	–	–	–	–	–	–	–	–	–	3.60	1.30	1.80	4.30	11.00	14.36
Scenedesmus obliquus	–	1.10	–	–	–	–	–	–	–	0.90	–	–	–	2.00	2.61
Scenedesmus perforatus	0.70	–	–	–	–	–	–	–	–	–	–	–	–	0.70	0.91
Scenedesmus quadricauda	0.70	1.10	–	1.10	–	2.00	–	–	–	–	–	–	–	4.90	6.40
Scenedesmus sp.	1.40	2.10	2.10	2.20	–	–	–	–	–	–	–	0.90	-	8.70	11.36
Selenastrum gracile	-	1.10	-	-	-	-	-	1.00	-	0.90	-	-	-	3.00	3.92
Sphaerozosma granulatum	0.70	–	–	–	–	–	–	–	–	–	–	–	–	0.70	0.91
Sphinctosiphon polymorphus	–	–	–	–	–	–	–	–	–	–	–	0.90	-	0.90	1.17
Staurastrum anatinum var. subglabrum	–	–	–	–	–	1.00	–	–	–	0.90	–	–	–	1.90	2.48
Staurastrum cambricum	-	1.10	–	–	–	–	–	–	–	–	–	–	–	1.10	1.44
Staurastrum gracile var. nyassae	–	–	–	–	–	1.00	–	–	–	–	–	–	–	1.00	1.31
Staurastrum gracile var. protractum	–	–	–	–	–	1.00	–	–	–	–	–	–	–	1.00	1.31
Staurastrum sp.	–	1.10	–	–	–	–	–	–	–	–	–	–	–	1.10	1.44
Total per month and taxa	**8.10**	**9.80**	**4.10**	**4.40**	**5.30**	**7.00**	**5.20**	**1.00**	**0.00**	**9.00**	**7.80**	**6.30**	**8.60**	**76.60**	**5.89**
Cyanophyta															
Anabaena flos-aquae	29.70	13.80	36.90	31.70	23.50	19.20	28.80	78.00	17.20	16.00	11.30	14.70	4.30	325.10	55.76
Anabaena sp.	–	1.10	–	–	–	–	–	–	–	–	–	–	–	1.10	0.19
Anabaena spiroides var. crassa	–	–	–	–	–	–	1.30	–	–	–	–	–	–	1.30	0.22

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Table 1. (Continued)

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% per taxa and species
Anabaenopsis tanganyikae	–	–	–	–	–	–	–	–	–	0.90	3.80	0.90	-	5.60	0.96
Lyngbya circumcreta	5.00	7.90	5.10	2.20	6.70	4.60	5.00	–	3.90	3.60	-	0.90	4.30	49.20	8.44
Lyngbya conkorta	0.70	1.10	-	1.10	2.70	3.00	2.50	-	1.60	–	5.00	4.40	8.70	30.80	5.28
Lyngbya sp.	–	–	–	–	–	–	–	–	–	0.90	–	–	–	0.90	0.15
Merismopedia punctata	–	–	–	–	–	1.00	–	–	–	–	–	–	–	1.00	0.17
Merismopedia tenuissima	3.60	3.70	2.60	1.10	1.30	3.00	1.30	–	4.70	0.90	1.30	1.80	4.30	29.60	5.08
Microcystis aeruginosa	3.60	6.30	1.00	6.60	1.30	2.50	3.80	–	3.10	1.30	1.30	–	–	30.80	5.28
Microcystis flos-aquae	3.90	7.40	5.10	1.10	–	10.10	3.80	2.00	6.30	7.20	7.50	6.20	4.30	64.90	11.13
Romeria sp.	2.90	5.30	2.10	1.10	2.70	3.00	1.30	–	6.30	2.70	3.80	2.70	6.50	40.40	6.93
Spirulina sp.	–	–	–	–	–	–	–	1.00	–	–	–	–	–	1.00	0.17
Stichococcus minutissimus	–	–	–	–	–	–	1.30	–	–	–	–	–	–	1.30	0.22
Total per month and taxa	**49.40**	**46.60**	**52.80**	**44.90**	**38.20**	**46.40**	**49.10**	**81.00**	**43.10**	**33.50**	**34.00**	**31.60**	**32.40**	**583.00**	**44.83**
Bacillariophyta															
Aulacoseira nyassensis	0.70	–	–	–	2.70	3.30	1.30	–	1.60	1.80	3.80	4.00	–	19.20	3.30
Chodatella subsalsa	0.70	–	–	–	1.30	1.00	2.50	–	–	–	–	–	–	5.50	0.95
Cyclotella sp.	–	–	–	–	–	1.00	2.50	–	1.60	3.60	5.00	2.70	4.30	20.70	3.56
Navicula sp.	1.40	1.10	–	–	–	–	–	–	1.60	0.90	–	2.70	6.50	14.20	2.44
Nitzchia acicularis	27.20	28.60	28.70	37.30	43.00	29.90	31.30	16.00	39.70	22.90	28.60	30.20	26.10	389.50	66.97
Nitzchia lacustris	5.70	4.20	9.20	2.20	1.30	3.00	5.00	1.00	6.30	6.30	11.30	9.80	8.70	74.00	12.72
Nitzschia asterionelloides	–	1.10	–	2.20	1.30	2.00	2.50	–	1.60	18.90	3.80	4.40	4.30	42.10	7.24
Nitzschia sp.	–	–	–	–	–	–	–	–	–	0.90	–	0.90	–	1.80	0.31
Rhizosolenia victoriae	–	–	–	1.10	1.30	–	–	–	–	–	–	0.90	–	3.30	0.57
Surirella cuspidata	–	–	–	1.10	–	–	–	–	–	–	–	–	–	1.10	0.19
Synedra acus	–	1.10	–	–	–	–	–	–	–	–	–	–	–	1.10	0.19
Synedra cunningtonii	2.20	3.20	–	1.10	–	1.00	–	–	1.60	–	–	–	–	9.10	1.56
Total per month and taxa	**37.90**	**39.30**	**37.90**	**45.00**	**50.90**	**41.20**	**45.10**	**17.00**	**54.00**	**55.30**	**52.50**	**55.60**	**49.90**	**581.60**	**44.72**
Euglenophyta															
Euglena sp.	-	–	1.00	–	–	–	–	–	–	–	–	–	–	1.00	11.36
Trachelomonas volvocina	-	2.10	3.10	–	1.30	–	–	–	–	–	1.30	–	–	7.80	88.64
Total per month	**-**	**2.10**	**4.10**	**–**	**1.30**	**–**	**–**	**–**	**–**	**–**	**1.30**	**–**	**–**	8.80	**0.68**
Dinophyta															
Peridinium sp.	0.70	1.60	–	1.10	–	–	–	–	–	0.90	–	1.80	4.30	10.40	35.49

Table 1. (Continued)

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% per taxa and species
Glenodinium sp.	2.20	1.10	–	2.20	1.30	1.00	–	–	1.60	–	2.50	2.70	4.30	18.90	64.51
Total per month and taxa	**2.90**	**2.70**	–	**3.30**	**1.30**	**1.00**	–	–	**1.60**	**0.90**	**2.50**	**4.50**	**8.60**	29.30	**2.25**
Chrysophyta															
Mallomonas sp.	0.70	–	–	1.10	2.70	4.10	1.30	1.00	1.60	1.30	2.50	2.20	0.00	18.50	86.85
Trachelomonas volvocina	0.70	–	1.00	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.80	13.15
Total per month and taxa	**1.40**	–	**1.00**	**2.20**	**2.70**	**4.10**	**1.30**	**1.00**	**1.60**	**1.30**	**2.50**	**2.20**	–	**21.30**	**1.64**
Grand total for all taxa														**1300.60**	**100.00**

Symbol '–' means species was not identified in a particular month.

Bacillariophyta was the most diverse group, followed by Cyanophyta. *Nitzchia acicularis* (Bacillariophyta) and *Anabaena flos-aquae* (Cyanophyta) were the dominant species, followed by *Nitzschia lacustris* (Bacillariophyta), *Microcystis flos-aquae* and *Lyngbya circumcreta* (Cyanophyta). A low abundance of *Aulacoseira nyassensis* (Bacillariophyta) was also found in the bay. While *Nitzschia* species contributed 87.24% of the bacillariophytes, *Anabaena* species accounted for 56.17% of the cyanophytes by numbers (Table 1).

The phytoplankton abundance exhibited three peaks: namely April and October in 2005, and February 2006 (Fig. 2). The phytoplankton abundance for April and October 2005 was significantly higher than for all other months ($P < 0.05$), but exhibited a similar abundance for the months of March and September 2005, and February 2006 ($P > 0.05$). The heavy rain season produced a comparatively higher phytoplankton abundance ($0.93 \pm 0.05 \times 10^6$ individuals L^{-1}) than the light rain season ($0.81 \pm 0.17 \times 10^6$ individuals L^{-1}) and the dry season ($0.73 \pm 0.85 \times 10^6$ individuals L^{-1}). The abundance of phytoplankton among the seasons, however, was statistically comparable ($F = 0.961$, $P = 0.428$).

The temporal phytoplankton biomass (measured indirectly as chlorophyll-*a* concentration) exhibited two peaks, one in March 2005 and one in October 2005 (Fig. 3). The phytoplankton biomass for March 2005 was significantly higher than for all other months ($P < 0.05$). October 2005 exhibited a significantly higher phytoplankton biomass than all the other months ($P < 0.05$). The months of May, August and December 2005 had statistically similar phytoplankton biomass ($P > 0.05$).

The heavy rain season exhibited a comparatively higher phytoplankton biomass (30.22 ± 3.37 $\mu g L^{-1}$) than the light rain season (25.34 ± 2.64 $\mu g L^{-1}$) and dry season (18.91 ± 0.53 $\mu g L^{-1}$). The phytoplankton biomass differed significantly among the seasons ($F = 4.424$, $P = 0.014$). The heavy rain season produced a significantly higher phytoplankton biomass than the dry season ($P = 0.010$). The phytoplankton biomasses observed during the heavy and light rain seasons, however, were statistically comparable ($P = 0.407$).

Zooplankton composition, abundance and biomass

A total of 25 genera and 43 species of zooplankton were identified for Shirati Bay (Table 2). The rotifers contributed 25 species, while the copepods had nine species (seven cyclopoids, one calanoid and one harpacticoid) and the cladocerans accounted for nine species. Other invertebrate organisms in the bay included chaoborid

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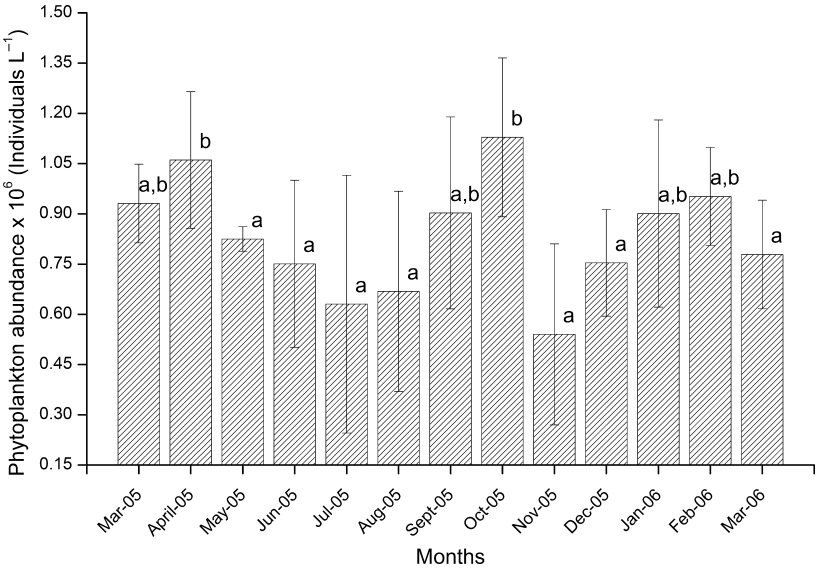


Fig. 2. Abundance of phytoplankton $\times 10^6$ (individuals L^{-1}) in Shirati Bay during the study period (different letters above bars indicate significant difference ($P \leq 0.05$)).

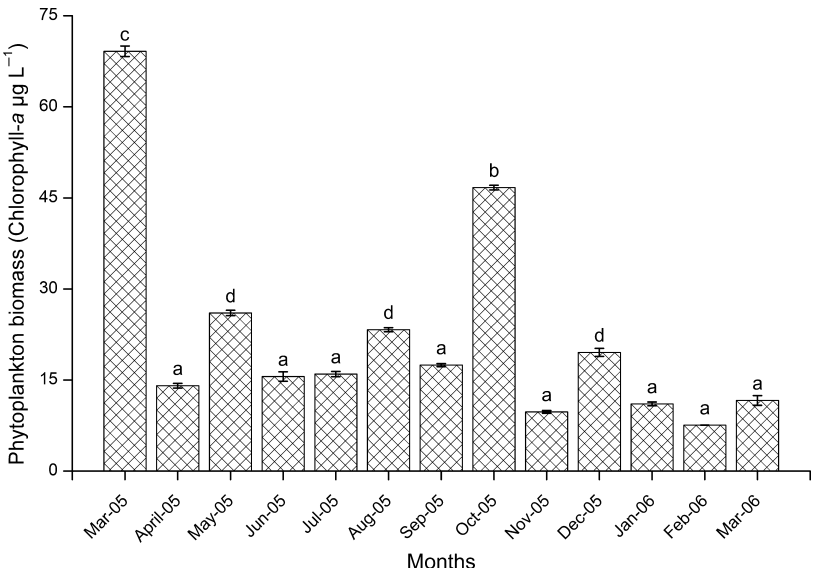


Fig. 3. Biomass of phytoplankton (chlorophyll-*a*) in Shirati Bay, March 2005 to March 2006 (different letters above bars indicate significant difference ($P \leq 0.05$)).

larvae, trichopterans, ostracods and the decapod *Caridina nilotica*. The diversity indices (H′) were 2.321, 1.679 and 0.878 for the rotifers, copepods and cladocerans, respectively.

Copepods were the dominant zooplankton group, contributing 94% of the total zooplankton abundance (Table 2). Among the copepods, cyclopoid copepod comprised about 75% of the total zooplankton abundance. The most common cyclopoid copepods were *Thermocyclops neglectus* and *Thermocyclops emini*. Next in abundance were the calanoid copepods, while the harpacticoid copepods were very rare. Rotifers and cladocerans were generally fewer in number, contributing 4.04 and 1.64% of the total mean zooplankton abundance, respectively (Table 2).

The zooplankton community in Shirati Bay exhibited seasonal variations in abundance. The highest ($11\,992 \pm 4858$ individuals m^{-2}) and lowest (1333 ± 425 individuals m^{-2}) abundances were recorded in February 2006 and June 2005, respectively (Fig. 4). The zooplankton abundance differed significantly among the various sampling months ($F = 2.390$, $P = 0.006$). Significantly higher zooplankton abundances were observed in November 2005, and February and March 2006 than for June, July and August 2005 and December 2005 ($P < 0.05$). They were similar, however, in March and October 2005 and January 2006 ($P > 0.05$). The month of February 2006 exhibited significantly higher zooplankton abundances than the months of April, May and September 2005 ($P < 0.05$).

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Table 2. Zooplankton abundance (number m^{-2}) in Shirati Bay, March 2005 to March 2006

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% (taxa and species)
COPEPODS															
Calanoida															
Thermodiaptomus galeboides	10 939	9679	13 881	10 204	5934	7442	9675	24 305	56 576	4907	6393	7632	9070	176 636	9.24
Calanoid copepodite	4209	1719	3738	1596	866	635	19 087	22 342	7454	1746	3255	8187	4535	79 369	4.15
Calanoida nauplius larvae	15 637	7631	13 782	5822	6256	3215	17 095	17 885	11 004	4880	25 219	47 204	40 816	216 447	11.32
Cyclopoida															
Eucyclops sp.	–	–	91	5	–	–	–	–	–	–	567	227	-	889	0.05
Mesocyclops sp.	3973	1065	1100	1099	1125	1383	337	454	3129	395	1335	1029	907	17 329	0.91
Thermocyclops emini	15 347	9284	18 274	3420	4916	4778	7602	11 200	29 404	7411	20 681	26 099	8163	166 579	8.71
Thermocyclops incisus	3120	2126	2672	455	159	354	159	465	1456	544	503	3951	907	16 870	0.88
Thermocyclops neglectus	9270	7567	16 010	2068	2621	12 621	9975	11 720	75 638	10 499	10 873	29 239	10884	208 986	10.93
Tropocyclops confinnis	10 050	6386	7581	1208	2091	3825	7501	6816	8121	2372	6647	11 409	10 884	84 890	4.44
Tropocyclops tenellus	7547	4359	8307	1525	907	5574	9032	7443	6628	2358	8280	13 652	2721	78 332	4.10
Cyclopoid copepodite	50 503	20 578	36 304	7930	8766	13 429	19 107	14 311	46 815	10 544	46 419	114 495	41 723	430 923	22.54
Cyclopoid nauplius larvae	37 261	21 989	29 064	6968	9329	11 835	44 892	47 110	32 279	4717	30 673	78 884	78 005	433 005	22.65
Harpactocoid	363	–	227	–	91	220	–	–	113	–	242	-	-	1256	0.07
Total per month and taxa	**168 218**	**92 381**	**151 032**	**42 298**	**43 061**	**65 311**	**144 461**	**164 051**	**278 616**	**50 372**	**161 085**	**342 007**	**208 617**	**1 911 510**	**94.32**
CLADOCERA															
Alona spp.	91	–	–	–	–	–	–	–	–	–	-	-	-	91	0.27
Bosmina longirostris	91	86	298	24	23	143	6	1	–	62	381	57	227	1400	4.21

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Table 2. (Continued)

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% (taxa and species)
Ceriodaphnia cornuta	–	431	726	95	–	–	–	302	227	–	-	-	-	1781	5.35
Chydorid sp.	363	408	36	2	–	–	–	–	–	–	-	-	-	809	2.43
Daphnia barbata	–	–	–	–	–	–	–	499	–	–	-	907	-	1406	4.23
Daphnia lumhortzi (helm.)	–	–	227	–	68	91	–	–	–	–	-	-	-	386	1.16
Diaphanosoma excisum	3918	942	5787	408	544	989	1383	2506	3238	703	1710	1421	1814	25 364	76.22
Moina micrura	181	–	454	59	–	41	–	–	–	–	-	-	-	735	2.21
Macrothrix sp.	–	–	1034	29	–	–	–	–	–	–	242	-	-	1305	3.92
Total per month and taxa	**4644**	**1868**	**8562**	**617**	**635**	**1263**	**1389**	**3308**	**3465**	**765**	**2333**	**2386**	**2041**	**33 275**	**1.64**
ROTIFERA															
Ascomorpha sp.	363	145	29	2	–	45	–	–	–	–	189	-	-	773	0.94
Asplanchna sp.	181	853	132	384	660	179	975	476	980	662	2721	3900	1814	13 917	17.01
Brachionus angularis	1832	1578	917	1105	1059	1050	1162	1528	3017	2522	4397	2579	-	22 743	27.80
Brachionus bidendata inermis ROUSSELET	181	73	15	1	–	–	–	–	–	–	-	-	-	269	0.33
Brachionus bidendata testudinarius	181	–	–	–	–	–	–	–	–	–	-	-	-	181	0.22
Brachionus calyciflorus	1324	321	110	152	–	91	–	–	181	–	189	726	-	3094	3.78
Brachionus caudatus	–	431	227	–	272	272	23	5	681	–	1209	45	907	4072	4.98
Brachionus falcatus	363	–	–	–	181	222	136	27	5	–	242	45	-	1222	1.49
Brachionus falcatus falcatus ZACHARIAS	363	–	–	–	–	–	73	–	–	–	-	-	-	435	0.53

Table 2. (Continued)

Taxa	March 2005	April 2005	May 2005	June 2005	July 2005	August 2005	September 2005	October 2005	November 2005	December 2005	January 2006	February 2006	March 2006	Total per taxa and species	% (taxa and species)
Brachionus forficula	–	–	–	–	181	–	–	–	–	–	-	-	-	181	0.22
Brachionus patulus	–	–	–	–	–	–	153	–	–	–	-	-	-	153	0.19
Brachionus leydig var. rotundus ROUSSELET	1723	–	–	–	–	–	73	–	–	–	-	-	-	1796	2.20
B. urceolaris urceolaris O.F.M	218	–	–	45	–	136	73	–	–	–	-	-	-	472	0.58
Euclanis sp.	–	–	–	–	102	–	–	–	–	–	-	-	-	102	0.12
Filinia longiseta	–	998	–	–	–	–	23	5	1	59	189	454	1814	3541	4.33
Filinia opoliensi	272	1206	241	1	91	–	–	166	–	–	-	170	-	2148	2.62
Keratella cochlearis	–	–	–	147	–	–	73	314	2041	–	242	1621	-	4437	5.42
Keratella tropica	435	79	952	335	181	581	912	1377	192	–	1028	2408	-	8481	10.37
Lecane bulla	363	–	191	114	–	–	–	–	–	–	302	-	-	969	1.18
Lecane inermus	–	–	–	–	–	–	45	–	–	91	-	-	-	136	0.17
Polyarthra sp.	–	–	–	–	220	181	–	–	680	181	378	227	-	1868	2.28
Proales sp.	363	–	–	–	–	–	–	–	–	–	-	-	-	363	0.44
Synchaeta sp.	–	–	–	91	272	177	186	113	–	–	-	218	-	1057	1.29
Trichocerca cylindrica	–	–	91	5	–	181	–	–	–	363	-	-	-	639	0.78
Trichocerca sp.	145	58	737	37	515	163	181	1361	36	68	673	2982	1814	8770	10.72
Total per month and taxa	**8308**	**5741**	**3641**	**2417**	**3735**	**3279**	**4087**	**5371**	**7815**	**3946**	**11 759**	**15 375**	**6349**	**81 822**	**4.04**
Grand total for all taxa														**2 026 606**	**100.00**

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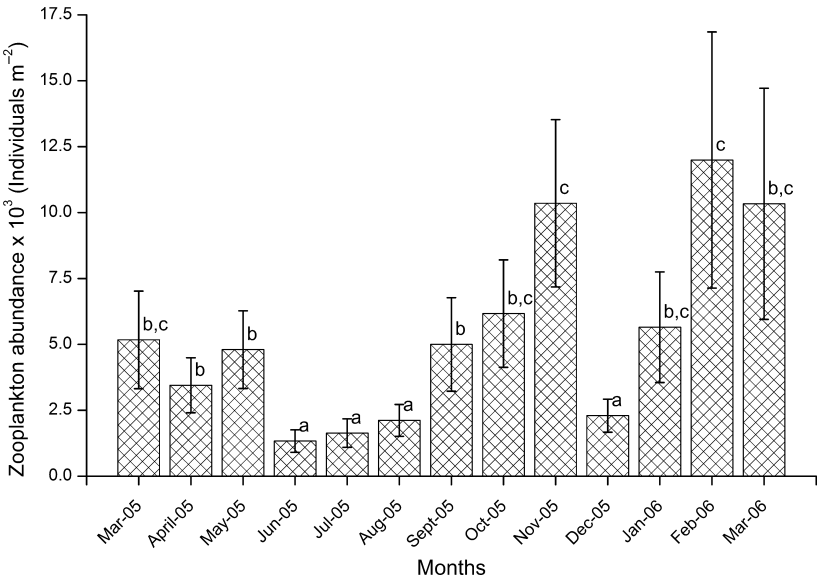


Fig. 4. Abundance of zooplankton in Shirati Bay, March 2005 to March 2006 (different letters above bars indicate significant difference ($P \leq 0.05$)).

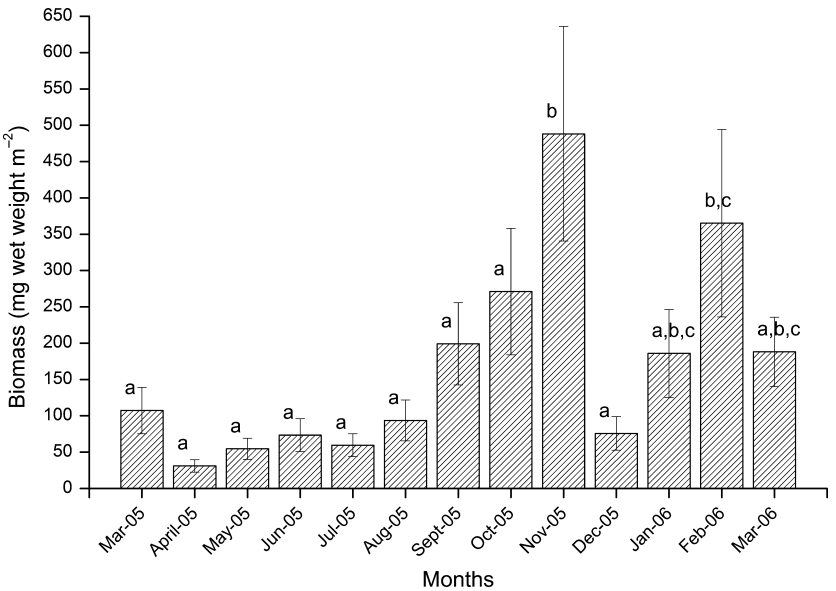


Fig. 5. Biomass of zooplankton in Shirati Bay, March 2005 to March 2006 (different letters above bars indicate significant difference ($P \leq 0.05$)).

Zooplankton abundance differed significantly among the seasons ($F = 5.734$, $P = 0.003$). The heavy rain season exhibited the highest zooplankton abundance (6471 ± 963 individuals m^{-2}), followed by the light rain season (5651 ± 768 individuals m^{-2}). The dry season exhibited the lowest values (2905 ± 460 individuals m^{-2}). The dry season also exhibited significantly lower zooplankton abundance than the heavy rain ($P = 0.005$) and light rain ($P = 0.021$) seasons. The abundance was similar, however, between the light rain and dry seasons ($P = 0.725$).

The zooplankton biomass patterns were comparable to those of the numerical abundance. The highest biomass (488 ± 148 mg wet wt m^{-2}) and the lowest biomass (31 ± 9 mg wet wt m^{-2}) were observed in November and April 2005, respectively (Fig. 5). The zooplankton biomass differed significantly among the different months during the study period ($F = 4.141$, $P < 0.001$). The zooplankton biomass was significantly higher in November 2005 than in all the other months ($P < 0.05$), but exhibited a statistically comparable biomass in October 2005 and February 2006 ($P > 0.05$). Similarly, the month of February 2006 exhibited a significantly higher zooplankton biomass than for all the other months ($P < 0.05$) except for September and October 2005 and January 2006 ($P > 0.05$). Likewise, the month of October 2005 exhibited a significantly higher biomass than all the other months ($P < 0.05$) except for September 2005, and

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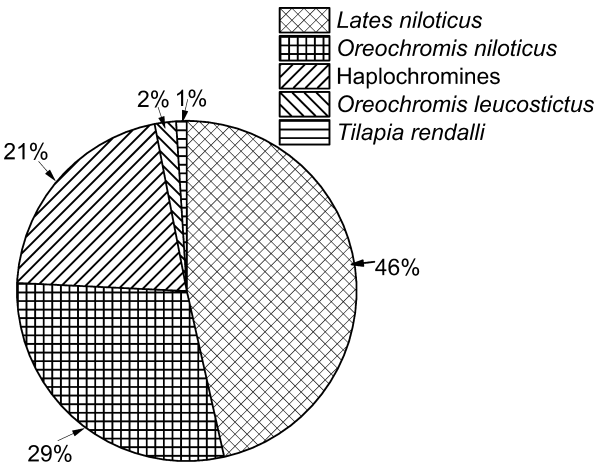


Fig. 6. Fish composition in Shirati Bay, March 2005 to March 2006.

January and March 2006 ($P > 0.05$). The month of April 2005 exhibited a significantly lower biomass than all the other months ($P < 0.05$). March 2005 exhibited a significantly higher biomass than May 2005 ($P = 0.046$) and July 2005 ($P = 0.048$). The months of March, June, August and December 2005 exhibited statistically comparable biomass ($P > 0.05$). Similarly, May, June, July, August and December 2005 also exhibited a statistically comparable zooplankton biomass ($P > 0.05$).

Generally, the heavy rain season exhibited a comparatively higher zooplankton biomass (278 ± 62 mg m^{-2}) than the light rain season (118 ± 23 mg m^{-2}) and the dry season (95 ± 17 mg m^{-2}). The zooplankton biomass exhibited significant differences between the three seasons ($F = 7.378$, $P = 0.001$). A significantly higher zooplankton biomass was observed during the heavy rain season than for the light rain ($P = 0.009$) and dry seasons ($P = 0.001$). The light rain and dry seasons, however, exhibited a statistically comparable zooplankton biomass ($P = 0.899$).

Fish catch composition and biomass

Fish catches in Shirati Bay comprised mainly *Lates niloticus* (Nile perch), *Oreochromis niloticus* (Nile tilapia), *Oreochromis leucostictus, Tilapia rendalli* and haplochromines (Fig. 6). Juvenile and adult fish of a particular species were combined to estimate their composition. *L. niloticus* dominated (46%) the total catches, followed by *O. niloticus* (29%) and haplochromines (21%). The *O. leucostictus* (2%) and *T. rendalli* (1%) were the least dominant fish species (Fig. 6).

The biomass of the fish catches differed significantly among the species ($F = 33.781$, $P < 0.001$; Fig. 7). Nile perch adults exhibited a significantly higher catch than all the other species ($P < 0.05$). Its juveniles also had a significantly higher biomass than *O. leucostictus* ($P < 0.001$) and *T. rendalli* adults and juveniles ($P < 0.001$). Similarly, *O. niloticus* adults were a significantly higher biomass than haplochromines ($P = 0.009$), *O. leucostictus* ($P = 0.024$), *T. rendalli* adults ($P = 0.003$) and *T. rendalli* juveniles ($P = 0.003$). Its juvenile's biomass differed significantly from that of *O. leucostictus*, *T. rendalli* adults and *T. rendalli* juveniles ($P < 0.001$). The haplochromine biomass was different from all the other species catches ($P < 0.05$), except for *L. niloticus* juveniles ($P = 0.357$) and *O. niloticus* juveniles ($P = 0.902$).

Monthly variations in fish catches at the Shirati Bay indicated September 2005 exhibited the highest catch

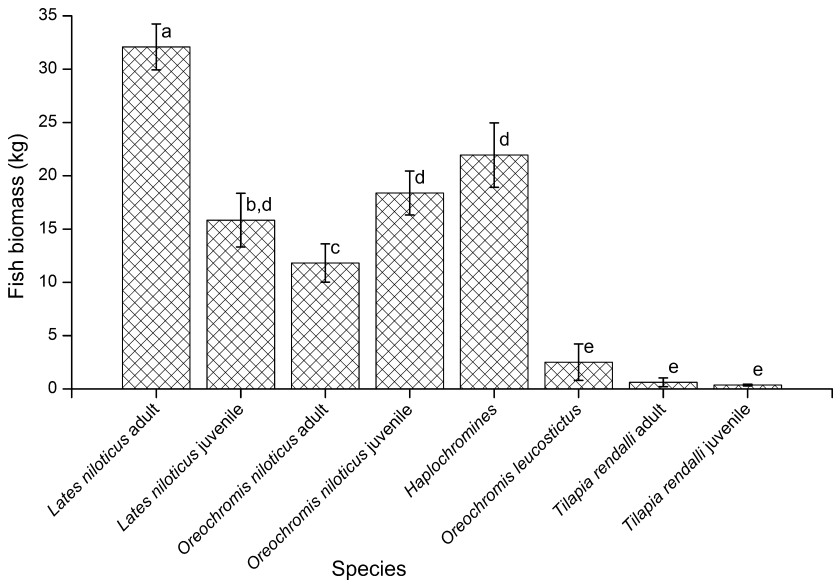


Fig. 7. Biomass of fish catches in Shirati Bay, March 2005 to March 2006 (different letters above bars indicate significant difference ($P \leq 0.05$)).

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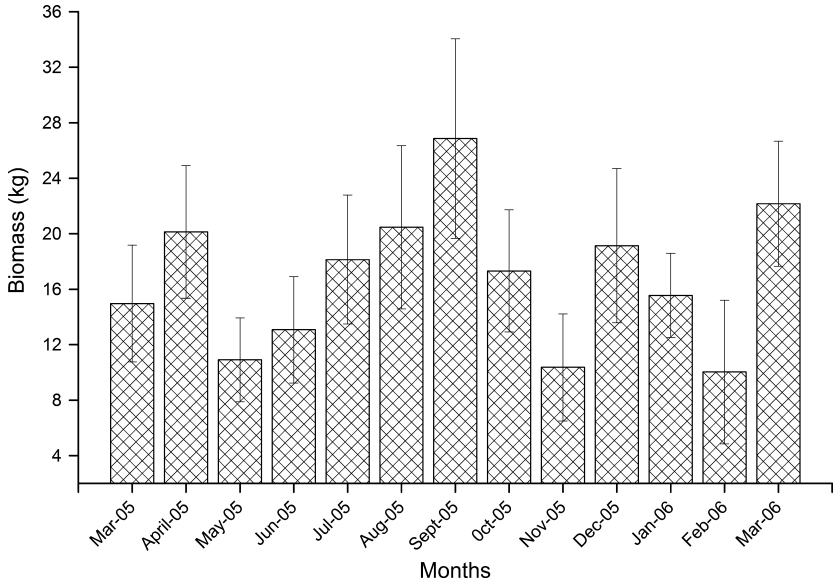


Fig. 8. Monthly variations of fish catches in Shirati Bay, March 2005 to March 2006.

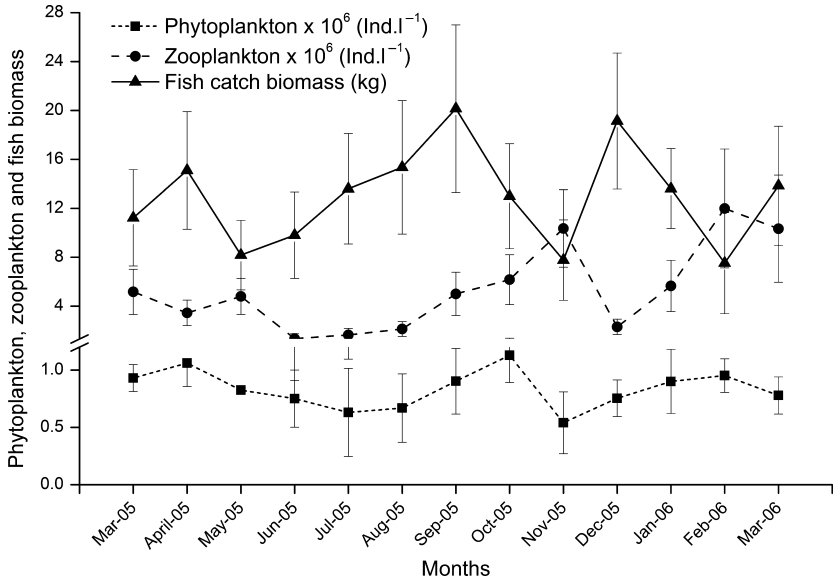


Fig. 9. Relationships among phytoplankton, zooplankton and fish catch biomass in Shirati Bay during the study period.

(26.86 ± 7.19 kg), with the lowest catch (10.03 ± 5.18 kg) seen in February 2006 (Fig. 8). The monthly fish catches, however, were not significantly different among the sampling months ($F = 1.055$, $P = 0.411$).

The fish catches were higher (21.82 ± 3.38 kg) during the dry season than for the heavy rain (16.82 ± 2.15 kg) and light rain seasons (15.96 ± 2.83 kg). The biomass of fish catches was statistically comparable, however, among the seasons ($F = 1.239$, $P = 0.297$).

Phytoplankton–zooplankton–fish correlation trends

The phytoplankton and zooplankton biomass exhibited an alternating trend, with the latter lagging behind the former by one month, except for the months of August to October 2005, and February to March 2006, during which time the trends coincided (Fig. 9). Phytoplankton and zooplankton biomass for the entire sampling period indicated that Chlorophyta, Cyanophyta, Bacillariophyta, Euglenophyta, Dinophyta and Chrysophyta were all insignificantly negatively correlated with calanoid copepods ($r = -0.105$, $P = 0.733$) and cyclopoid copepods ($r = -0.101$, $P = 0.743$; Table 3). Conversely, cladocerans were significantly negatively correlated with *L. niloticus* juveniles ($r = -0.553$, $P = 0.050$), *O. niloticus* juveniles ($r = -0.664$, $P = 0.013$) and haplochromines ($r = -0.592$, $P = 0.033$). Calanoid copepods were insignificantly negatively correlated with *L. niloticus* juveniles ($r = -0.333$,

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Table 3. Phytoplankton abundance and zooplankton and fish biomass correlation coefficient and *P* values

Independent variable	Dependent variable	Correlation coefficient (*r*)	*P*
Chlorophyta (48 990 ± 2756)	Calanoid copepods (328 ± 96)	−0.105	0.733
Cyanophyta (373 662 ± 21 018)		−0.105	0.733
Bacillariophyta (371 967 ± 20 922)		−0.105	0.733
Euglenophyta (5628 ± 317)		−0.105	0.733
Dinophyta (18 739 ± 1054)		−0.105	0.733
Chrysophyta (13 622 ± 766)		−0.105	0.733
Calanoid copepods (328 ± 96)	*Lates niloticus* juveniles (16 ± 3)	−0.333	0.266
	Oreochromis niloticus juveniles (18 ± 2)	−0.425	0.148
	Haplochromines (22 ± 3)	−0.290	0.337
	Oreochromis leucostictus (3 ± 2)	−0.226	0.457
	Tilapia rendalli adult (1 ± 0.4)	−0.193	0.528
	Tilapia rendalli juveniles (0.4 ± 0.1)	−0.133	0.664
Chlorophyta (48 990 ± 2756)	Cyclopoid copepods (427 ± 107)	−0.101	0.743
Cyanophyta (373 662 ± 21 018)		−0.101	0.743
Bacillariophyta (371 967 ± 20 922)		−0.101	0.743
Euglenophyta (5628 ± 317)		−0.101	0.743
Dinophyta (18 739 ± 1054)		−0.101	0.743
Chrysophyta (13 622 ± 766)		−0.101	0.743
Cyclopoid copepods (427 ± 107)	*Oreochromis niloticus* juveniles (18 ± 2)	−0.680	0.010
	Haplochromines (22 ± 3)	−0.601	0.030
	Lates niloticus adult (32 ± 2)	−0.005	0.987
	Lates niloticus juveniles (16 ± 3)	−0.510	0.075
	Oreochromis leucostictus (3 ± 2)	−0.024	0.938
	Tilapia rendalli juveniles (0.4 ± 0.1)	−0.501	0.081
Cladocerans (23 ± 4)	*Lates niloticus* juveniles (16 ± 3)	−0.553	0.050
	Oreochromis niloticus juveniles (18 ± 2)	−0.664	0.013
	Haplochromines (22 ± 3)	−0.592	0.033
Rotifera (12 ± 3)	*Tilapia rendalli* juveniles (0.4 ± 0.1)	−0.618	0.025
	Lates niloticus juveniles (16 ± 3)	−0.267	0.378
	Oreochromis niloticus adult (12 ± 2)	−0.019	0.951
	Oreochromis niloticus juveniles (18 ± 2)	−0.449	0.083
	Haplochromines (22 ± 3)	−0.503	0.080

Numbers in brackets indicate mean abundance for phytoplankton and biomass ± SE for zooplankton and fish during the study period.

$P = 0.266$), *O. niloticus* juveniles ($r = -0.425$, $P = 0.148$), haplochromines ($r = -0.290$, $P = 0.337$), *O. leucostictus* ($r = -0.226$, $P = 0.457$), *T. rendalli* adult ($r = -0.193$, $P = 0.528$) and *T. rendalli* juveniles ($r = -0.133$, $P = 0.664$). Cyclopoid copepods were significantly negatively correlated with *O. niloticus* juveniles ($r = -0.680$, $P = 0.010$) and haplochromines ($r = -0.601$, $P = 0.030$), and negatively insignificantly correlated with *L. niloticus* adults ($r = -0.005$, $P = 0.987$) and juveniles ($r = -0.510$, $P = 0.075$), *O. leucostictus* ($r = -0.024$, $P = 0.938$) and *T. rendalli* juveniles ($r = -0.501$, $P = 0.081$). The rotifers (Rotifera) were significantly negatively correlated with *T. rendalli* juveniles ($r = -0.618$, $P = 0.025$). However, they were insignificantly negatively correlated with *L. niloticus* juveniles ($r = -0.267$, $P = 0.378$), *O. niloticus* adults ($r = -0.019$, $P = 0.951$) and juveniles ($r = -0.499$, $P = 0.083$) and haplochromines ($r = -0.503$, $P = 0.080$).

Stomach content analysis of juvenile fish and haplochromine species

Analysis of the stomach contents of juvenile fish species (*L. niloticus*, *O. niloticus*, *T. rendalli*) and haplochromines indicated the presence of zooplankton in their diet. The common food items of *L. niloticus* were copepods and *Caridina nilotica*, while those of *O. niloticus* were copepods and phytoplankton. The gut content of *T. rendalli*

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Table 4. Gut contents of juvenile planktivorous fish in Shirati Bay, March 2005 to March 2006

Food items	*Lates niloticus*	*Oreochromis niloticus*	Haplochromines	*Tilapia rendalli*
Asplanchna sp.	+	-	+	-
Caridina nilotica	+	-	-	-
Cyclopoid	+	+	+	+
Calanoid	+	+	+	+
Ceriodaphnia cornuta	–	–	+	–
Chaoborid larvae	–	–	+	–
Chironomid larvae	–	–	+	+
Filiniao poliensis	–	–	+	–
Insects	–	–	+	+
Lecane spp.	–	–	+	+
Macrothrix spp.	–	–	+	–
Moina micrura	–	–	+	–
Nauplii	–	–	+	+
Ostracods	–	–	+	–
Phytoplankton	–	+	+	+

+, Present, –, Absent.

gut was mainly comprised of cyclopoid copepods, phytoplankton and chironomid larvae, while the haplochromines fed almost entirely on zooplankton (Table 4).

Rainfall patterns

The rainfall values at the study sites exhibited a temporal variability (Fig. 10). There was a significant difference in the rainfall among the different sampling months ($F = 3.499$, $P = 0.006$). The months of March, April and October 2005 and March 2006 exhibited significantly higher rainfall values than for all the other months ($P < 0.05$). The month of June 2005 had the lowest quantity of rainfall ($P < 0.05$) than all the other months, except for January 2006 ($P > 0.05$).

The heavy rain season exhibited comparatively higher rainfall value (13.00 ± 0.94 mm) than the light rain (7.81 ± 0.89 mm) and dry (4.70 ± 0.22 mm) seasons. The rainfall values differed significantly among the seasons ($F = 28.450$, $P < 0.001$). The heavy rain season exhibited a significantly higher quantity of rainfall than the light rain ($P < 0.001$) and dry ($P < 0.001$) seasons.

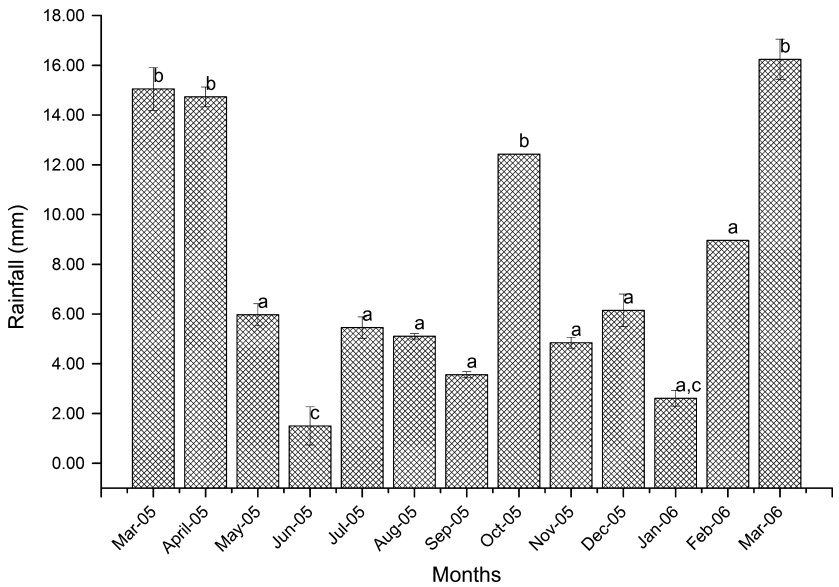


Fig. 10. Quantity of rainfall recorded at study site during the sampling period.

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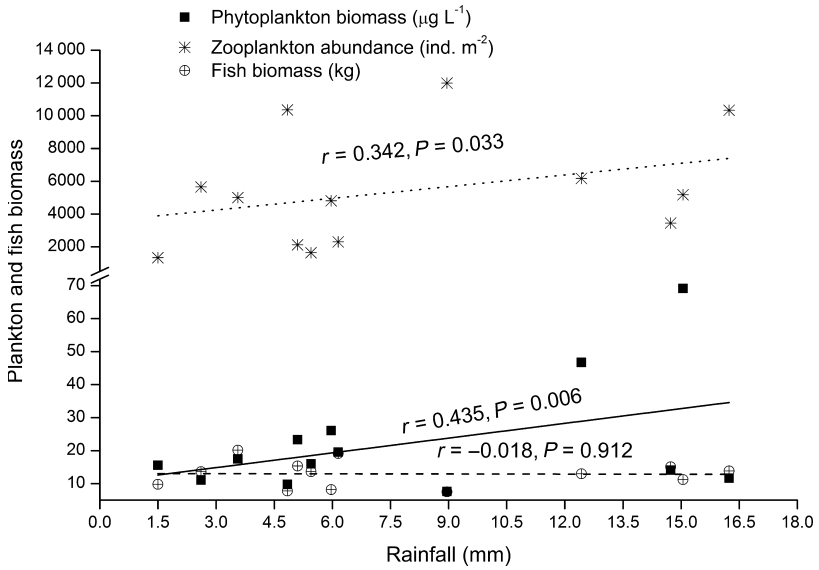


Fig. 11. Relationship among rainfall and plankton and fish biomass at study site during the sampling period.

Furthermore, the light rain season exhibited a significantly higher quantity of rainfall than the dry season ($P = 0.034$). The quantity of rainfall was significantly positively correlated with phytoplankton biomass ($r = 0.435$, $P = 0.006$) and zooplankton abundance ($r = 0.342$, $P = 0.033$; Figure 11). The rainfall quantity, however, was insignificantly negatively correlated with fish biomass catch ($r = -0.018$, $P = 0.912$).

Water quality parameters

The values of the water quality parameters determined during the study period are summarized in Table 5. The water temperatures differed significantly among the sampling months ($F = 3.426$, $P = 0.004$). The water temperature for March 2005 was significantly higher than in September 2005 ($P = 0.032$). Furthermore, the water temperature for November 2005 was significantly lower than for March ($P = 0.003$) and April 2005 ($P = 0.008$). The water transparency also differed significantly among the sampling months ($F = 4.347$, $P = 0.001$). November 2005 and February 2006 exhibited comparable ($P > 0.05$) water transparency values [(2.20 ± 0.40 m) and (2.20 ± 0.21 m), respectively]. Their values were significantly higher than those for March ($P = 0.050$), April ($P = 0.050$), June ($P = 0.009$), July ($P = 0.013$), August ($P = 0.019$) and October 2005 ($P = 0.013$). The electrical

Table 5. Water quality parameters variations during sampling months in Shirati Bay during the study period

Months	Temperature (°C)	Transparency (m)	Conductivity ($\mu S\ cm^{-1}$)	pH
March 2005	27.40 ± 0.06[a]	1.40 ± 0.12[a]	81.43 ± 0.23[a]	9.40 ± 0.21[a]
April 2005	27.20 ± 0.26[a]	1.40 ± 0.20[a]	83.10 ± 0.06[a]	9.40 ± 0.29[a]
May 2005	26.73 ± 0.15[a,b]	1.50 ± 0.10[a,b]	138.93 ± 5.62[b,c]	9.50 ± 0.12[a]
June 2005	26.13 ± 0.82[a,b]	1.23 ± 0.12[a]	118.97 ± 8.71[b]	8.83 ± 0.41[a]
July 2005	25.93 ± 0.09[a,b]	1.27 ± 0.09[a]	133.70 ± 11.75[b]	9.13 ± 0.38[a]
August 2005	26.03 ± 0.15[a,b]	1.30 ± 0.06[a]	115.53 ± 3.49[b]	9.30 ± 0.32[a]
September 2005	25.30 ± 0.00[b]	1.53 ± 0.07[a,b]	108.87 ± 7.33[a,b]	9.20 ± 0.12[a]
October 2005	26.17 ± 0.03[a,b]	1.27 ± 0.03[a]	149.00 ± 5.598[b,c]	9.87 ± 0.15[a]
November 2005	24.77 ± 1.23[b]	2.20 ± 0.40[b]	134.47 ± 6.12[b]	9.76 ± 0.06[a]
December 2005	25.97 ± 0.03[a,b]	1.53 ± 0.09[a,b]	130.77 ± 2.30[b]	9.40 ± 0.15[a]
January 2006	25.90 ± 0.15[a,b]	1.77 ± 0.03[a,b]	149.30 ± 0.00[b,c]	9.50 ± 0.29[a]
February 2006	26.03 ± 0.32[a,b]	2.20 ± 0.21[b]	106.2 ± 0.31[a]	9.60 ± 0.15[a]
March 2006	25.50 ± 0.29[a,b]	1.70 ± 0.10[a,b]	100.63 ± 0.32[a]	9.40 ± 0.12[a]

Different superscript letters within each column indicate significant differences ($P \leq 0.05$).

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Table 6. Relationships among water quality parameters and phytoplankton abundance and zooplankton and fish biomass correlation coefficient and *P* values

Independent variable	Dependent variable	Correlation coefficient (*r*)	*P*
Water temperature (25.35 ± 0.22 °C)	Phytoplankton abundance (22.14 ± 4.81)	0.156	0.610
	Zooplankton biomass (5408± 976)	0.656	0.015
	Fish biomass (12.94 ± 1.12)	−0.069	0.823
Water transparency (1.60 ± 0.100 m)	Phytoplankton abundance (22.14 ± 4.81)	−0.344	0.250
	Zooplankton biomass (5408 ± 976)	0.680	0.011
	Fish biomass (12.94 ± 1.12)	−0.220	0.470
Water conductivity (121.58 ± 6.14 μS cm^{-1})	Phytoplankton abundance (22.14 ± 4.81)	−0.191	0.531
	Zooplankton biomass (5408 ± 976)	−0.210	0.491
	Fish biomass (12.94 ± 1.12)	0.149	0.626
Water pH (9.49 ± 0.06)	Phytoplankton abundance (22.14 ± 4.81)	0.183	0.550
	Zooplankton biomass (5408 ± 976)	0.161	0.600
	Fish biomass (12.94 ± 1.12)	0.062	0.840

Numbers in brackets indicate mean abundance for phytoplankton and biomass ± SE for zooplankton and fish during the study period.

conductivity also differed significantly between the sampling months ($F = 17.136$, $P = 0.000$). March and April 2005 exhibited similar ($P > 0.05$) water conductivity values (81.43 ± 0.23 Ms cm^{-1} and 83.10 ± 0.06 μS cm^{-1}, respectively). These values were significantly lower than the conductivity values for May, June, July, August, October, November and December 2005 and January 2006 ($P < 0.05$). They were, however, comparable to September and February 2005, and March 2006 ($P > 0.05$). The water pH was statistically comparable among the different sampling months ($F = 1.251$, $P = 0.304$).

Water quality–phytoplankton–zooplankton–fish correlation trends

The correlation between the water quality parameters and the phytoplankton, zooplankton and fish measured parameters is summarized in Table 6. The water temperature depicted a significant positive correlation with zooplankton biomass ($r = 0.656$, $P = 0.015$), while it was insignificantly positively correlated with phytoplankton abundance ($r = 0.156$, $P = 0.610$). However, the water temperature exhibited an insignificant negative correlation with fish biomass ($r = -0.069$, $P = 0.823$). The water transparency also exhibited a significant positive correlation with the zooplankton biomass ($r = 0.680$, $P = 0.011$). In contrast, the water transparency was insignificantly inversely correlated with the phytoplankton abundance ($r = -0.344$, $P = 0.250$) and the fish biomass ($r = -0.220$, $P = 0.470$). The electrical conductivity was insignificantly negatively correlated with the zooplankton biomass ($r = -0.210$, $P = 0.491$) and the phytoplankton abundance ($r = -0.191$, $P = 0.531$). It was insignificantly positively correlated, however, with the fish biomass ($r = 0.149$, $P = 0.626$). The water pH was insignificantly positively correlated with the zooplankton biomass ($r = 0.161$, $P = 0.600$), fish biomass ($r = 0.062$, $P = 0.840$) and phytoplankton abundance ($r = 0.183$, $P = 0.550$).

DISCUSSION

The phytoplankton species in Shirati Bay are comprised mainly of cyanophytes and bacillariophytes. Cyanobacteria were reported to dominate the phytoplankton community in Lake Victoria (Lung'ayia *et al.* 2000; Mbonde *et al.* 2004; Machiwa *et al.* 2005; Sekadende *et al.* 2005a,b; Hecky *et al.* 2010; Haande *et al.* 2011; Ngupula *et al.* 2011; Cornelissen *et al.* 2014). Similar results indicating the dominance of bacillariophytes in other water bodies has also been reported by Soylu and Gonulol (2010), Zakariya *et al.* (2013) and Gulecal and Temel (2014). The high abundances of cyanophytes and bacillariophytes are apparently attributable to the eutrophic status of Shirati Bay, which favours the existence of only a few groups (Ngupula *et al.* 2011). Based on the Carlson and Simpson (1998) eutrophication guide, lakes containing chlorophyll-*a* concentrations between 20 and 56 μgL^{-1} are deemed eutrophic. The values of chlorophyll-*a* obtained in the present study ranged from 7.57 ± 0.01 to 69.14 ± 0.87 μgL^{-1}, with an average of 22.14 ± 5.14 μgL^{-1}, indicating a eutrophic condition. Eutrophication favours the preferential thriving of Cyanobacteria through a competitive advantage for light. Cyanobacteria also have buoyant vesicles that enable them to remain in the surface waters, facilitating the

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ability to utilize more sunlight for photosynthesis than other phytoplankton groups (Reynolds *et al.* 1987). Furthermore, Cyanobacteria are more efficient light harvesters than other eukaryotic algae, thereby furthermore highlighting their dominance. However, bacillariophytes are tolerant to environmental variables, including nutrient concentrations, suspended sediments and different types of human disturbances (Brucet *et al.* 2013). Thus, the eutrophic nature of Shirati Bay favoured the flourishing of cyanophytes and bacillariophytes.

The existence of higher phytoplankton abundance and biomass for the month of March 2005 obtained in the present study was previously reported by Sekadende *et al.* (2005a) in the satellite lakes of Lake Victoria, Regina *et al.* (2012) for Kariba Lake, Sitoki *et al.* (2012) for Nyanza Gulf in Lake Victoria and Darchambeau *et al.* (2014) for Lake Kivu. During the study period, the months of March to May fall within the heavy rain season, a period characterized by water stratification in Lake Victoria (MacIntyre *et al.* 2014). The months of July to September were a dry season period characterized by lake water mixing. November to December was a light rain season with thermal re-establishment and moderate water stratification.

The higher abundance and biomass of phytoplankton during the heavy rain season is likely attributable to nutrient inputs from rainfall and catchment area run-off (Cornelissen *et al.* 2014). The nutrients provided in the rainfall and water run-off may have triggered an increased phytoplankton abundance and biomass by utilizing warmer water temperatures, as water temperature was significantly positively correlated with phytoplankton abundance. Thus, the heavy rain season seemed to cause higher phytoplankton abundance and biomass in Shirati Bay attributable to nutrient inputs from rainfall and water run-off.

The dominance of zooplankton species by cyclopoid copepods in Shirati Bay agrees with the results reported by Waya and Mwambungu (2004), Ngupula *et al.* (2010), Vincent *et al.* (2012) and Waya *et al.* (2014), indicating cyclopoid copepods constitute the most dominant zooplankton group in Lake Victoria waters. The observed dominance of cyclopoid copepods is associated with their versatile feeding habits and efficient ability to escape from fish predators (Bradley *et al.* 2012). Cyclopoid copepods utilize different feeding habits (Anraku & Omori 1963). Some freshwater cyclopoid copepods are known to be carnivorous, mostly feeding on animals of their body size or larger (Brandl 1998, 2005). Others are herbivorous, however, feeding mainly on filamentous algae and diatoms. Many copepod species also are omnivorous, consuming phytoplankton and zooplankton (Sarma *et al.* 2013).

Furthermore, the dominance of cyclopoid copepods in turbid habitats is attributed to their ability to escape from fish predators (Omondi *et al.* 2011). Copepods are known to possess the toughest exoskeleton and the longest and strongest appendages among all zooplankton (Savitha & Yamakanamardi 2012). This body form helps them swim faster during predator avoidance than other zooplankton. The ability to swim faster enables them to avoid visual fish predators, increasing their chances of survival (Waya & Mwambungu 2004; Waya *et al.* 2014). Thus, their versatile feeding habits and predator avoidance strategy in the eutrophic environment of Lake Victoria could explain their dominance in the bay.

The results indicating higher zooplankton abundance and biomass during the heavy rain than during the light rain and dry seasons are comparable with those of Waya and Chande (2004) and Okogwu (2010). Such results are explained by the fact that, at a local scale, zooplankton abundance and biomass are known to be controlled by phytoplankton abundance and biomass attributable to nutrient inputs from rainfall and run-off (Masson *et al.* 2001; Imam & Balarabe 2012; Pinel-Alloul *et al.* 2013). Higher zooplankton abundance and biomass during the heavy rain season coincided with the period of higher inflows of water coinciding with rainfall and surface run-off. Considering the significant positive correlation between the quantity of rainfall and both the phytoplankton biomass and zooplankton abundance, the higher zooplankton abundance and biomass were presumably attributable to nutrients directly entering the bay from rainfall, run-off and water from rivers and drained agricultural lands. These nutrients possibly triggered increased phytoplankton production, consequently resulting in higher zooplankton abundance and biomass.

Significant positive correlations between zooplankton abundance and water temperature and transparency were previously obtained by Hart (1986), Akbulut (2004), Shurin *et al.* (2010), Messner *et al.* (2013) and Akindele (2013). The positive correlation of zooplankton with water temperature is due to its effect on the general life cycle of living organisms. Although little variation exists in the water temperature in the tropics, it still has a major influence on zooplankton reproductive rates, feeding, movements and longevity (Cruz *et al.* 2013; Messner *et al.* 2013). Furthermore, water transparency plays a significant role on the diel vertical movement and feeding (Williamson *et al.* 2011) and visual predator avoidance of zooplankton (Hu *et al.* 2014). To some extent, therefore, the zooplankton abundance in the present study

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appeared to be controlled by water temperature and transparency.

The correlation results indicated that all the phytoplankton species were controlled by the existence of calanoid and cyclopod copepods. In the higher trophic level of the food chain, *L. niloticus* juveniles, *O. niloticus* juveniles and haplochromines controlled Cladocera and cyclopoid copepods, while *T. rendalli* juveniles controlled the Rotifera. The results regarding the inverse relationship of phytoplankton with zooplankton are similar to those obtained by Kleppel (1993) and Balseiro *et al.* (2001). Calanoid copepods are known to feed on diverse microplanktonic organisms and selectively consume phytoflagellates. Furthermore, Rollwagen-Bollens *et al.* (2013) reported that cyclopoid copepods have an indirect role in modulating phytoplankton, such as Cyanobacteria blooms. Thus, calanoid and cyclopoid copepod grazing could have determined the phytoplankton biomass.

The results regarding the control of Cladocera and cyclopoid copepods by *L. niloticus* and *O. niloticus* juveniles are similar to those reported by Mwebaza-Ndawula (1998), who maintained that these two species incorporate zooplankton in their diets during their juvenile stages. Katunzi *et al.* (2006) also found that *L. niloticus* had a size selective predation on both calanoid and cyclopoid copepods, a finding also supported by the results of Kishe-Machumu *et al.* (2012), who reported that *L. niloticus* changes its diet, with juveniles consuming zooplankton, while adults prey on haplochromines. Furthermore, Njiru *et al.* (2004) found that the major diet for *O. niloticus* juveniles <5 cm total length was zooplankton. The inverse relationship between haplochromines and zooplankton is also corroborated by Witte *et al.* (1991), who classified the former as zooplanktovirous. The haplochromines diet is known to contain 65% to 91% zooplankton (van Rijssel *et al.* 2015). The control of rotifers by *T. rendalli* is similar to the results reported by Meschiatti and Arcifa (2002), who showed that rotifers contribute 40.80% by volume and 42% occurrence in its diet. *T. rendalli* adults are mainly phytoplanktivorous, although they also consume zooplankton (Arcifa & Meschiatti 1996). The present study indicated a trophic level interaction whereby phytoplankton species were kept in check by calanoid and cyclopoid copepods and Cladocera. The latter were, in turn, controlled by *L. niloticus* juveniles, *O. niloticus* juveniles and haplochromines, while *T. rendalli* juveniles controlled the rotifers.

The typical predator–prey inverse relationship between zooplankton and fish obtained in the present study is similar to observations of Tiberti and Iacobuzio (2013). The negative correlation indicates a strong fish predation on zooplankton in eutrophic lakes (Iglesias *et al.* 2011; Vanderploeg *et al.* 2012). The stomach content analysis of the sampled fish species indicated the presence of zooplankton such as cyclopoid and calanoid copepods, which were consumed by almost all the fish caught, indicating zooplankton abundance affects fish catch biomass at the site. Fish catch, however, is a complex aspect affected by other factors, including season, net mesh size and fish availability.

CONCLUSIONS AND RECOMMENDATIONS

It is clear Shirati Bay in Lake Victoria (Tanzania) contains diverse plankton species. Cyanophyta and Bacillariophyta are the dominant phytoplankton groups because of the eutrophic nature of the Bay, whereas cyclopoids dominate the zooplankton species because of their versatile feeding habits and efficient ability to escape from predators. Among other factors, these dominant plankton species are partly controlled by rainfall, water temperature and transparency. This study reveals trophic dynamics whereby phytoplankton species abundance and biomass were regulated by calanoid and cyclopoid copepods and Cladocera. The latter were, in turn, controlled by *L. niloticus* juveniles, *O. niloticus* juveniles and haplochromines, while *T. rendalli* juveniles regulated the rotifers. The fish biomass, zooplankton and phytoplankton in Shirati Bay exhibited a typical predator–prey inverse relationship. Thus, phytoplankton and zooplankton should be included as mandatory groups, meriting consideration by fishery managers during fish stock assessments to more effectively manage the bay's fishery resources.

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