

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/368846297>

# From benthic to floating: phytoplankton dynamics in African freshwater lakes and reservoirs

Chapter · January 2023

DOI: 10.1016/B978-0-323-95527-0.00012-9

CITATIONS

0

READS

227

4 authors, including:



**Takudzwa Comfort Madzivanzira**  
University of Mpumalanga

22 PUBLICATIONS 182 CITATIONS

[SEE PROFILE](#)



**Chipso Perseverance Mungenge**  
Zimbabwe Parks and Wildlife Management Authority

11 PUBLICATIONS 11 CITATIONS

[SEE PROFILE](#)



**Tatenda Dalu**  
University of Mpumalanga

242 PUBLICATIONS 3,882 CITATIONS

[SEE PROFILE](#)

## CHAPTER 4

# From benthic to floating: phytoplankton dynamics in African freshwater lakes and reservoirs

Takudzwa C. Madzivanzira<sup>1,2</sup>, Chipso P. Mungenge<sup>3</sup>,  
Timothy Dube<sup>4</sup>, Tatenda Dalu<sup>1,2</sup>

<sup>1</sup>Aquatic Systems Research Group, School of Biology and Environmental Sciences, University of Mpumalanga, Nelspruit, South Africa

<sup>2</sup>South African Institute for Aquatic Biodiversity, Makhanda, South Africa

<sup>3</sup>Department of Zoology and Entomology, Rhodes University, Makhanda, South Africa

<sup>4</sup>Institute of Water Studies, Department of Earth Sciences, University of the Western Cape, Bellville, South Africa

### 4.1 Introduction

Freshwater ecosystems are among the most biologically diverse systems per unit habitat volume on Earth, with more than 140,000 species compressed into just 2% of the world's surface area [1–3]. They have inestimable economic, cultural, health, scientific, and educational values [4]. Beyond these ecosystem services, understanding the resident species of an ecological system and how they are being exploited and threatened is vital to conserve important and rare species [5].

Among the biotic components of aquatic systems are phytoplankton (i.e., algae) which are ubiquitous, unicellular autotrophic microorganisms adapted to live partly or continuously in open water and are major primary producers of organic carbon [6]. Phytoplankton species are grouped into 15 legitimate phyla, covering both bacterial and eukaryotic protist domains consisting of a wide diversity of size, morphology, and colony formations [6]. The various phytoplankton groups which are well described in John et al. [7] and Reynolds [6] include Bacillariophyta (diatoms), Chlorophyta (green algae), Chrysophyta (golden algae), Cryptophyta (cryptomonads), Cyanophyta (Cyanobacteria), Euglenophyta (euglenoids), Eustigmatophyta, Glaucophyta, Haptophyta (Prymnesiophyta), Prasinophyta, Pyrrophyta (dinoflagellates), Phaeophyta (brown algae), Raphidophyta, Rhodophyta (red algae), and Xanthophyta (yellow-green

algae), with the Chlorophyta and Bacillariophyta being the most diverse groups [8]. These seemingly inconspicuous primary producers are extremely abundant and are found throughout the  $\sim 1$  billion  $\text{km}^3$  of living space in aquatic ecosystems [9], and form the base of aquatic food webs, on which almost all aquatic fauna directly or indirectly rely on [10]. In addition, as part of the photosynthetic process of converting light into energy and oxygen which is released into the environment, it is thought that phytoplankton are responsible for more oxygen production than tropical rainforests such as the Amazon (see [11]). Phytoplankton growth depends on the availability of light, carbon dioxide, and nutrients. They, like terrestrial plants, require nutrients such as nitrate, phosphate, calcium, and silicate at various growth levels depending on the species [6]. Phytoplankton help in water purification by taking up nutrients and pollutants [8,12], and transforming nutrients from inorganic to organic forms, for example, converting atmospheric nitrogen into ammonium (Lee et al., 2013).

Given their basal role in the food web of aquatic systems and their importance in atmospheric processes, phytoplankton are among the most important aquatic biota group, although their role is often overlooked by the public [8]. The importance of phytoplankton can be seen in fisheries, with African lakes being havens for diverse endemic fish fauna of immense ecological and scientific importance that are dependent on sustained phytoplankton growth [13]. Most African livelihoods are dependent directly on fish and their products for both food and nutritional security, as well as many social, cultural, and economic benefits gained from the biodiverse freshwater resources [14,15]. Any stressor that affects phytoplankton cascades through the trophic chain affecting zooplankton (that graze on phytoplankton) and fish production and ultimately threatening the viable fisheries that sustain the livelihoods of riparian communities [13]. Unfortunately, the poor communities are at the most risk as they depend on the natural resources provided by many African lakes, yet policies around these resources do not benefit them much [13].

Although phytoplankton are integral biotic components of aquatic ecosystems, they can cause serious adverse effects [6,16]. When present in very large numbers, they can produce “*blooms*” that, on decomposition, deoxygenate the aquatic systems causing fish deaths. This increases the costs of water purification and reduces biodiversity. Some phyto-

plankton are harmful or toxic as a result of their biotoxins, physical damage they cause, anoxia, irradiance reduction, and nutritional unsuitability [6,16]. Harmful phytoplankton species (e.g., Cyanobacteria) can produce toxins that may alter the physiology of both invertebrates and vertebrates [16]. Dinophyta and Cyanophyta stand out among the particularly problematic phytoplankton groups in forming harmful blooms and having noxious properties [17]. The proliferation of harmful phytoplankton is mainly caused by changes in local environmental factors, especially nutrients (nitrogen and phosphorous) and temperature which have been shown to regulate phytoplankton community structure ([18,19]; see Box 4.1).

Since phytoplankton are primary producers living in dispersive environments, abiotic and biotic factors exert strong controls on their composition and dynamics [21]. In the African continent with different climatic conditions, phytoplankton assemblages are likely to vary across geographic regions, and species richness has been shown to increase from the poles to the Equator according to the latitudinal diversity gradient (LDG) [22,23]. To date, very little is known about the geographic diversity and structuring of phytoplankton. Although many species of phytoplankton have been identified, the question of where they occur is largely unexplored; in light of the current biodiversity crisis, this represents a serious knowledge gap [24]. As the world's biological diversity faces unprecedented threats, the urgent challenge facing the concerned biologists is to understand ecological processes and biotic components well enough to maintain their functioning in the face of the pressures resulting from human population growth.

This chapter summarizes phytoplankton communities in African freshwater lakes and reservoirs and further assesses the LDG which has been used to explain species variations in other higher taxonomic groups. Current knowledge of phytoplankton species diversity, distribution, and ecology is still too limited to make far-going conclusions on geographical patterns of richness and levels of endemism among African regions. Knowledge of phytoplankton composition is vital for evaluating the ecological status of freshwater ecosystems and is essential for understanding the structure and dynamics of aquatic ecosystems [25,26]. This chapter also identifies freshwater lakes and reservoirs on the continent that have been heavily impacted by anthropogenic impacts and assesses how these have led to variation and/or changes in phytoplankton communities.

**BOX 4.1**

The annual cycle of stratification and phytoplankton growth in Lake Victoria [20].

Lake Victoria although relatively shallow is the second largest lake in the world and the largest in the equatorial regions. Its stratification shows pronounced seasonal changes and can vary between inshore (bay and gulfs) and offshore (open lake) regions. This stratification is important for the seasonal cycles in phytoplankton growth. The pH values range from 7 to 8.9. Distributions of three nutrients, that is, nitrate, phosphate, and dissolved silicone (expressed as silica) had several features in common. High concentrations were generally present near the mud surface and low concentrations in the uppermost 20 m or photosynthetic zone. An appreciable increase in  $\text{PO}_4^{3-}$  did not occur during the mixing associated with temporary isothermal conditions in January and March 1961. However, there was a pronounced increase during the almost isothermal conditions of August 1961. During most of the year, the exceptionally low concentrations of nitrate ( $<10 \mu\text{g/L NO}_3\text{-N}$ ) and phosphate ( $<7 \mu\text{g/L PO}_4\text{-P}$ ) in the surface layers were undetectable. By contrast, dissolved silica was present in relatively large and rather uniform concentrations (4.0–4.5 mg/L) during most of the year. During most of the year, a large part of the offshore plankton was composed of colonial coccoid Myxophyceae. In total, 24 species were counted and these included 5 diatoms, 4 blue-green algae, 7 desmids, 7 chlorococcalean and other green algae, and 1 dinoflagellate. The taxonomy of other algae was not clear, but they resembled *Aphanocapsa elachista* and *Aphanocapsa delicatissima*. These algae and another *Microcystis* sp. were present in July 1961 but could not be readily counted. Diatoms were most abundant in the offshore open lake during the periods of isothermal mixing of the water column. *Aulacoseira agassizii*, *Aulacoseira nyassensis*, *Surirella nyassae*, and *Nitzschia acicularis* were the most important diatom species. Cyanophyta dominated during periods of thermal stratification with *Anabaenopsis tanganyikae*, *Anabaena flos-aquae*, *Planktolyngbya circumcreta*, and *Microcystis wesenbergii* as the most abundant. The green algae were present in low numbers throughout the year as well as the dinoflagellate *Ceratium brachyceros*. Inshore, longer periods of vertical mixing were associated with a more prolonged abundance of diatoms particularly *Melosira* sp. and *N. acicularis*. Although the temperature is an important indirect factor, a direct effect in limiting algal growth is unlikely given the small annual temperature range (approx.  $23^\circ\text{C}$ – $26^\circ\text{C}$ ) in Lake Victoria and the widespread geographical occurrence of most of the species. Another consequence of the equatorial position is the small seasonal variation of solar radiation which is very unlikely to affect algal growth directly. The production of phytoplankton is, however, related to the stratification cycle. The patterns of seasonal occurrence of individual species differ chiefly in the amplitude of variation and the response to in-

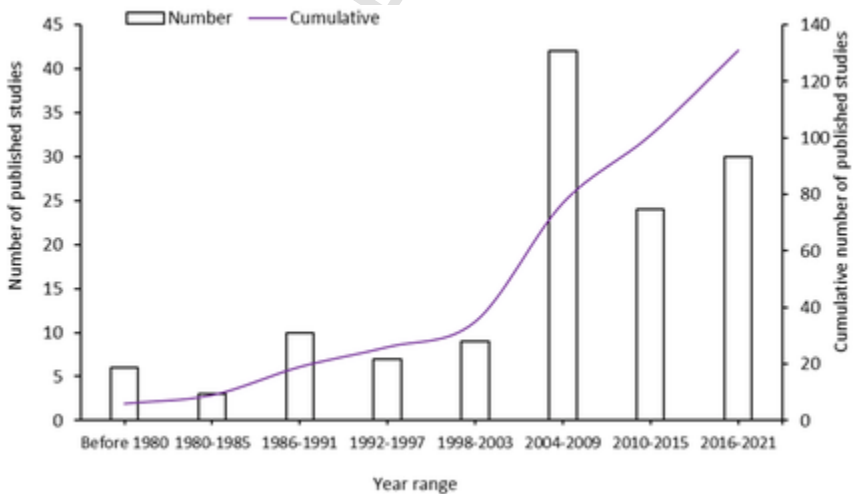
creased vertical mixing. Of the nutrients measured, nitrates were the most likely to limit algal growth.

Lastly, the chapter assesses how environmental managers and policymakers are addressing eutrophication and climate-based problems as a result of human anthropogenic impacts.

## 4.2 Phytoplankton studies in Africa

The earliest paper was published in 1879 describing the phytoplankton from Lake Malawi. Since then, the number of articles studying phytoplankton in African lakes and reservoirs has been increasing, with a steady increase, especially after 1997, and with most papers being published in 2004–09 (Fig. 4.1).

Phytoplankton information is available for 51 reservoirs in Africa (Table 4.1). While the number of reservoirs analyzed in this study is minimal, when compared to the number of reservoirs on the African continent, phytoplankton information for major reservoirs is available. Concerning the spatial distribution of the reservoirs, phytoplankton informa-



**Figure 4.1** The number of papers (and the cumulative number of papers) referring to phytoplankton in African lakes and reservoirs between 1879 and 2021.

**Table 4.1** List of reservoirs per geographical location reviewed in the current study chapter.

System	Region	References
Lake Mefou	Northern	Ndjouondo et al. (2020)
Lake Ahémé	Northern	Olodo et al. (2019)
Awba Reservoir	Northern	Akin-Oriola (2003)
Lake Ehoma	Northern	Okogwu and Ugwumba (2012)
Lake Iyieke	Northern	Okogwu and Ugwumba (2012)
Lake Guiers	Northern	Bouvy et al. (2006); Berger et al. (2006); Ka et al. (2006)
Lake Qarun	Northern	Fathi and Flower (2005)
Lake Lago Biao	Northern	Schabetsberger et al. (2004)
Lake Lago Loreto	Northern	Schabetsberger et al. (2004)
Lake Tana	Northern	Wondie and Mengistu (2017); Wondie et al. (2007)
Lake Chitu	Northern	Ogato and Kifle (2017)
Lake Shala	Northern	Ogato and Kifle (2017)
Lake Volta	Northern	Karikari et al. (2013)
Lake Arenguade	Northern	Belachew (2010)
Sennar Reservoir	Northern	Sinada and Abdelrahman (2019)
Roseires reservoir	Northern	Sinada and Abdelrahman (2019)
Lake Nasser	Northern	Goher et al. (2021)
Lake Chala	Equator	Cocquyt and Ryken (2016)
Lake Edward	Equator	Cocquyt et al. (2019); Stoyneva-Gartner and Descy (2018)
Lake Victoria	Equator	Nozaki et al. (2019); Gikuma-Njuru et al. (2013); Sekadende et al. (2005); Lung'Ayia et al. (2000); Gophen et al. (1995)
Lake Kivu	Equator	Rugema et al. (2019); Stoyneva et al. (2012); Sarmiento et al. (2007); Sarmiento et al. (2006)
Lake Chad	Equator	Toyosi et al. (2018); Carcea et al. (2015); Compere and litis (1983)
Lake Kyanninga	Equator	Cocquyt et al. (2010)
Lake Nakuru	Equator	Kaggwa et al. (2013); Okoth (2009)
Lake Bukoni	Equator	Nyakoojo (2010)
Lake Naivasha	Equator	Ballot et al. (2009)

System	Region	References
Lake Oloidien	Equator	Ballot et al. (2009); Cocquyt (2004)
Lake Baringo	Equator	Schagerl and Oduor (2003)
Lake Albert	Equator	Evans (1997)
Lake Kyoga	Equator	Evans (1962)
Lake Turkana	Equator	Kallqvist et al. (1988)
Malilangwe Reservoir	Southern	Dalu et al. (2013); Dalu and Wasserman [18]
Mazvikadei Reservoir	Southern	Mhlanga et al. [27]
Tugwi-Mukosi Reservoir	Southern	Mhlanga et al. (2020)
Swakoppoort Reservoir	Southern	Sirunda et al. (2021a, b)
Von Bach Reservoir	Southern	Sirunda et al. (2021a, b)
Vaalkop Reservoir	Southern	Swanepoel et al. (2017)
Lake Loskop	Southern	Oberholster et al. (2010); Oberholster and Botha (2011)
Lake Tanganyika	Southern	Stoyneva et al. (2007); Cocquyt and Vyverman (2005); Stoyneva et al. (2005)
Lake Tswaing	Southern	Oberholster et al. (2009)
Loch Logan Reservoir	Southern	Vos and Roos (2004)
Lake Chivero	Southern	Tendaupenyu [28]; Brendonck et al. (2003)
Wagendrift Reservoir	Southern	Hart and Bychek [29]
Lake Malawi	Southern	Higgins et al. (2003); Haberya and Mhone (1991)
Hartbeespoort Reservoir	Southern	Zohary et al. (1996)
Lake Kariba	Southern	Cronberg (1997); Ndebele-Murisa et al. [30]
Lake Gariiep	Southern	Venter (2000)
Lake Manyame	Southern	Tendaupenyu [28]
Lake Zeekoevlei	Southern	Harding and Paxton [31]
Lake Rukwa	Southern	Moto and Maghembe (2021)
Lake Liambezi	Southern	Seaman et al. (1978)



tion is available for 19 reservoirs in the northern region; 13 reservoirs in the Equator region; and 20 reservoirs in the southern region (Table 4.1; Fig. 4.2).

#### 4.2.1 Latitudinal diversity gradient of phytoplankton species

Lakes and reservoirs on the African continent are estimated to contain a total of 1633 freshwater phytoplankton species belonging to nine taxonomic groups (Bacillariophyta, Chlorophyta, Chrysophyta, Cryptophyta, Cyanophyta, Dinophyta, Euglenophyta, Synurophyta, and Xanthophyta) (Table 4.2). Bacillariophyta (642 species) are the most abundant taxo-

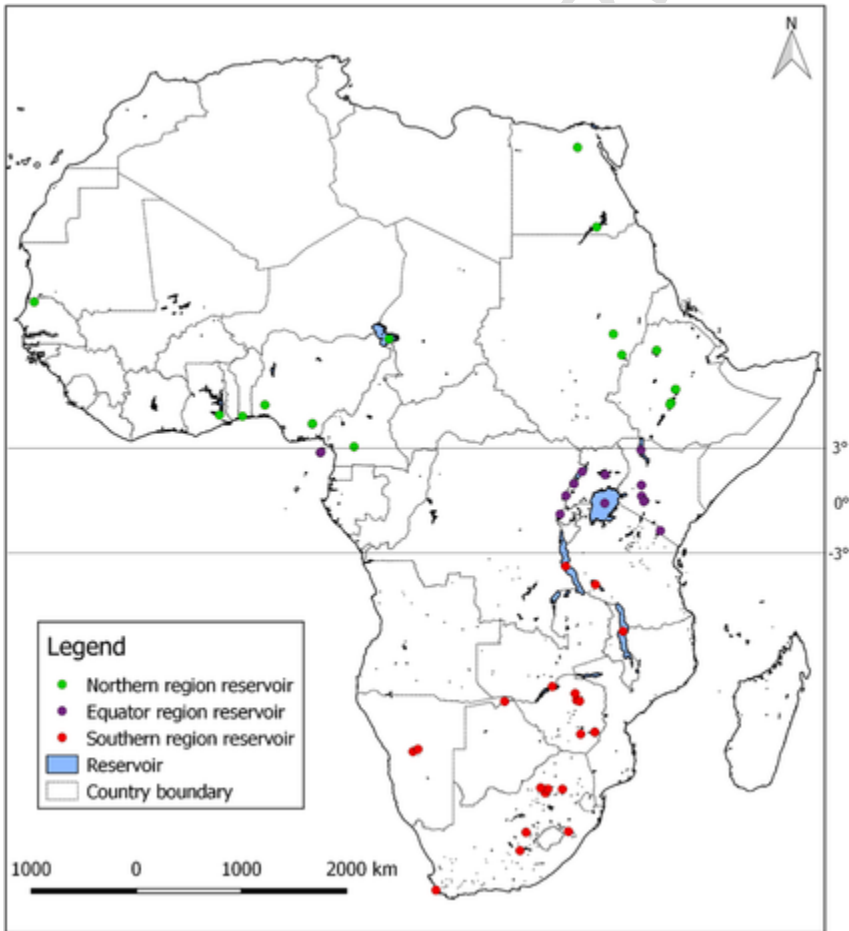


Figure 4.2 Spatial distribution of African reservoirs studied in this chapter.

**Table 4.2** Total number (N) of phytoplankton species recorded from different African study regions.

Group	Northern region	Equator region	Southern region	Total N
Bacillariophyta	213	330	89	632
Chlorophyta	123	215	157	495
Chrysophyta	6	6	9	21
Cryptophyta	8	5	4	17
Cyanophyta	83	198	69	350
Dinophyta	11	10	11	32
Euglenophyta	21	30	15	66
Synurophyta	0	1	0	1
Xanthophyta	1	18	0	19
Total N	466	813	354	1633

onomic group while Synurophyta were the least abundant (1 species). However, it is important to note that this might be a huge underestimation of the phytoplankton species diversity as some of the taxa are only identified to genus level making the counts unreliable. There is strong evidence that supports LDG for phytoplankton species richness. The number of taxa, species richness, and abundances increased from the poles toward the Equator region. A high number of species (i.e., 813 taxa) was recorded from lakes and reservoirs in the Equator region, while the low species richness (i.e., 354 taxa) was recorded from the southern region (Table 4.2). Nine phytoplankton taxonomic groups were recorded from reservoirs in the Equator region while eight and seven phytoplankton taxonomic groups were recorded from the northern and southern regions, respectively. The most abundant and dominant phytoplankton groups: Bacillariophyta, Chlorophyta, and Cyanophyta (in order of abundance) also supported the LDG hypothesis as their abundance decreases from the Equator region (Table 4.2). Like other taxonomic groups, three explanations have been proposed for LDGs: (1) ecological hypotheses that focus on the mechanisms of species coexistence and maintenance of species diversity; (2) evolutionary hypotheses that focus on diversification rates; and (3) historical hypotheses that focus on the period and extent of tropical environments in Earth's history [23]. The taxonomic group Bacillariophyta is abundant in the northern and Equator regions,

while, Chlorophyta is the abundant group in the southern region (Fig. 4.3). Only one taxonomic group, Synurophyta, was unique in the Equator region and absent in the other regions (Fig. 4.3).

#### 4.2.2 Highly occurring phytoplankton species

The occurrence of phytoplankton species in the reservoirs was detected when an individual species was present, thereby, indicating the number of reservoirs with that particular species.

The Cyanophyta *Merismopedia tranquilla* and *Anabaena* sp. highly occurred in lakes and reservoirs from the Equator (62%) and southern regions (60%), respectively, while, the Bacillariophyta *Cyclotella meneghiniana* highly occurred in the northern lakes and reservoirs (58%) (Table 4.3). Species that highly occurred in reservoirs from the three regions include *Microcystis aeruginosa*, *C. meneghiniana*, *M. tranquilla*, and *Aulacoseira granulata*.

As few species were common between the regions, the Jaccard similarity index was low (Fig. 4.4). The northern versus the Equator, north-

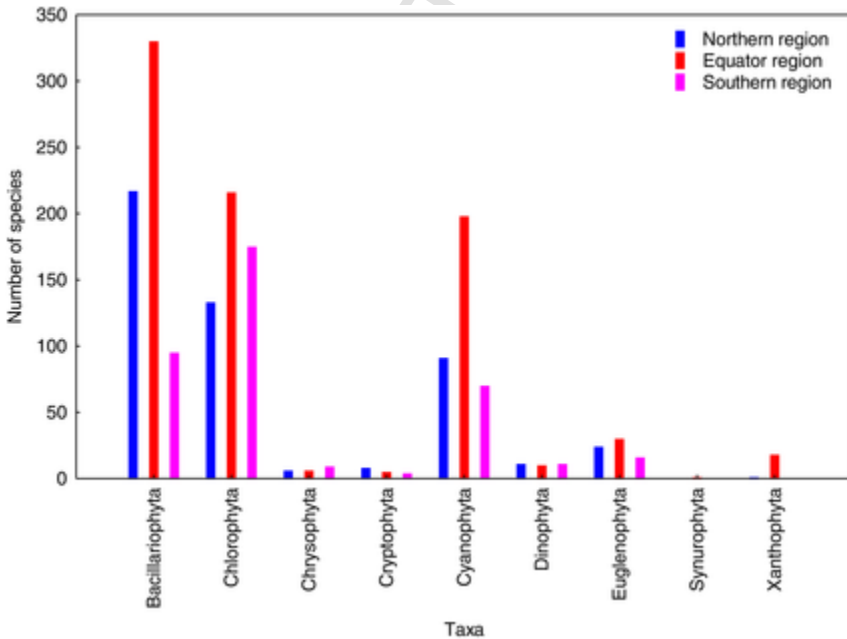


Figure 4.3 Phytoplankton taxonomic richness between reservoirs in regions on the African continent.

**Table 4.3** Phytoplankton species that highly occurred in different reservoirs in the northern, Equator, and southern regions analyzed using the Frequency of Occurrence (% F.O) index.

Northern region	% FO	Equator region	% FO	Southern region	% FO
<i>Cyclotella meneghiniana</i>	57.89	<i>Merismopedia tranquilla</i>	61.54	<i>Anabaena</i> sp.	60.00
<i>Microcystis aeruginosa</i>	54.34	<i>Cosmarium subtumidum</i>	46.15	<i>Microcystis aeruginosa</i>	59.00
<i>Navicula</i> sp.	47.37	<i>Aulacoseira granulata</i>	38.46	<i>Ankistrodesmus falcatus</i>	55.00
<i>Merismopedia tenuissima</i>	42.11	<i>Anabaenopsis cunningtonii</i>	38.46	<i>Aulacoseira granulata</i>	50.00
<i>Oscillatoria</i> sp.	42.11	<i>Aphanothece microscopica</i>	38.46	<i>Merismopedia</i> sp.	50.00
<i>Nitzschia</i> sp.	36.84	<i>Merismopedia convoluta</i>	38.46	<i>Cyclotella meneghiniana</i>	50.00
<i>Aulacoseira granulata</i>	31.58	<i>Cyclotella meneghiniana</i>	30.77	<i>Amscottia</i> sp.	45.00
<i>Pleurosigma</i> sp.	31.58	<i>Ankistrodesmus falcatus</i>	30.77	<i>Micrasterias furcate</i>	45.00
<i>Fragilaria</i> sp.	31.58	<i>Microcystis aeruginosa</i>	30.77	<i>Oscillatoria</i> sp.	45.00
<i>Gyrosigma acuminatum</i>	26.32	<i>Coelastrum astroideum</i>	30.77	<i>Melosira</i> sp.	40.00

ern versus southern, and southern versus Equator regions had a similarity index of 0.12, 0.25, and 0.20, respectively (Fig. 4.4).

#### 4.2.3 Phytoplankton importance in African reservoirs

A highly diverse system is more productive, stable, and resilient to anthropogenic stressors. Different phytoplankton taxa are specialized to perform several functions that are important for the functioning of an ecosystem. Cyanophyta, for example, can take up toxic nitrogenous compounds in reservoirs such as nitrite, nitrate, ammonium, and urea, which they can directly assimilate [32]. Cyanophyta are the only photosynthetic microorganisms capable of fixing and utilizing atmospheric nitrogen ( $N_2$ ) in the free-living state and symbiosis [33]. Nitrogen fixation occurs inside special transformed, vegetative cells, the heterocytes, which are

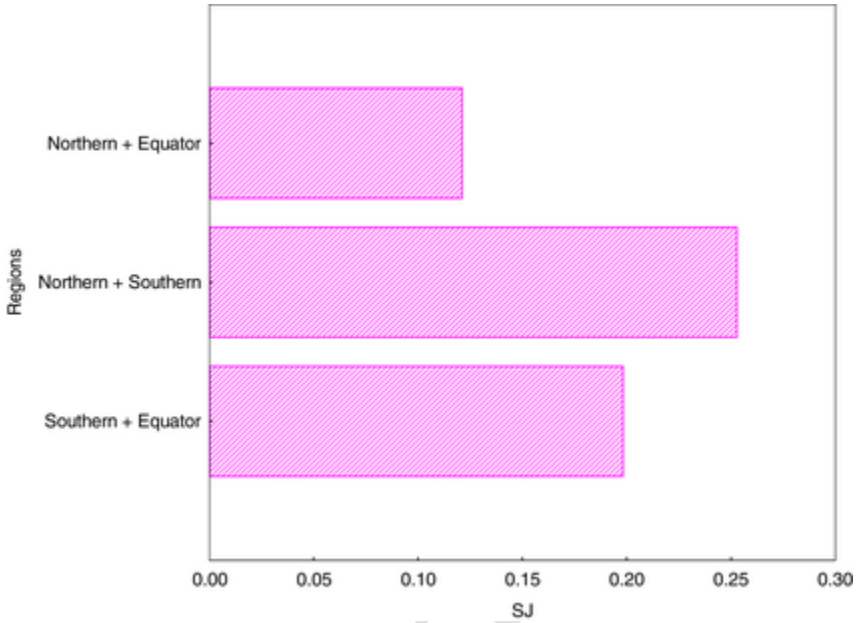


Figure 4.4 The Jaccard index of similarity between regions of Africa concerning phytoplankton species.

thick-walled [34], formed in some filamentous Cyanobacteria, but the process is also observed in nonheterocystous filamentous and unicellular forms [35]. Examples of  $N_2$ -fixing Cyanophyta include *Calothrix* sp., *Fischerella* sp., *Nodularia* sp., *Anabaena* sp., *Trichodesmium* sp., *Nostoc* sp., *Rivularia* sp., *Symploca* sp., *Lyngbya* sp., sp., *Crocospaera* sp., *Cyanothece* sp., and *Gloeothece* sp [36]. Most of these  $N_2$ -fixing Cyanophyta species are present in African lakes and reservoirs, except for Cyanophyta *Fischerella* sp. and *Symploca* sp., which have been recorded in Brazil and Australia. The presence of these  $N_2$ -fixing Cyanophyta species in African freshwater lakes and reservoirs facilitates the functioning of ecosystems and production [34].

Lakes and reservoirs' pelagic food webs are mainly based on phytoplankton primary production. Herbivorous zooplankton diet consists of various phytoplankton species, which differ in nutritional quality and their grazing resistance (e.g., armor, size, shape, toxins) [37–39]. The phytoplankton composition and abundance are vital in defining secondary and primary production since phytoplankton synthesize many essential biomolecules (e.g., amino acids, fatty acids, sterols), which con-

sumers are not able to synthesize de novo [40–44]. The relative carbon (C) and nitrogen (N) contents are similar in all phytoplankton species, and therefore, are not often considered limiting nutrients for zooplankton [45]. Phytoplankton are often assumed to be a homogenous group and a uniform food source for higher trophic levels (Karlsson et al., 2003; [46]). The dietary quality of distinct phytoplankton classes for consumers is known to vary primarily due to the different availability of omega-3 ( $\omega$ -3) and omega-6 ( $\omega$ -6) fatty acids as they are the only source of long-chain polyunsaturated fatty acids (PUFAs) in pelagic food webs [37,47,48]. Thus, the availability of essential fatty acids in aquatic food webs depends on phytoplankton community composition [37,49,50]. The availability and quality of the  $\omega$ -3 and  $\omega$ -6 fatty acids affect the somatic growth of consumer species, which is important since the consumer body size is directly reflected in its fitness and reproductive output [29]. This is ecologically important for consumers, particularly zooplankton, which have a key position in pelagic food webs by linking the flow of dietary energy and essential fatty acids from phytoplankton (primary producers) to fish (upper trophic levels) [51].

Fatty acid composition, particularly PUFAs, and the long-chain  $\omega$ -3 fatty acids like eicosapentaenoic acid (EPA, 20:5  $\omega$ 3) and docosahexaenoic acid (DHA, 22:6  $\omega$ 3) of freshwater taxa are strongly related to that of their phytoplankton diets. These are vital for growth and reproduction (see [43,44,49,50,52–55]). However, only certain phytoplankton taxa can synthesize EPA and DHA fatty acids, whereas all phytoplankton taxa can synthesize shorter-chain  $\omega$ -3 and  $\omega$ -6 PUFA. Further, it has been shown that high  $\omega$ -3 compared to  $\omega$ -6 PUFA ( $\omega$ -3:6 ratio) is beneficial for *Daphnia* [37,47]. Among freshwater phytoplankton, Cryptophyta, Dinophyta, Chrysophyta, Bacillariophyta, and Raphidophyta have been identified as EPA-synthesizing taxa, and Cryptophyta, Dinophyta, Chrysophyta, and Euglenophyta as DHA-synthesizing taxa [37,38,51]. Even though Cyanophyta and Chlorophyta cannot synthesize EPA or DHA, some Cyanophyta species and all Chlorophyta can synthesize alpha-linolenic acid and stearidonic acid (18:4 $\omega$ 3) [51,56] and can contribute much or all to their fatty acids. In addition to long-chain and medium-chain PUFA, Chlorophyta and Bacillariophyta can synthesize 16 PUFA, which does not have physiological importance for aquatic consumers [57].

It is with no doubt, that phytoplankton play a major role in food security and human health in Africa through the consumption of fish and other aquatic products which will be high in essential fatty acids that will have come mostly from phytoplankton and transferred along the food chain up to humans [58]. Fish are one of the cheapest sources of quality animal protein and play an important role in quenching the protein requirements within the developing world [59,60].

#### 4.2.4 Phytoplankton problems in African reservoirs

Several aquatic ecosystems have undergone substantial changes over the last five decades due to the introduction of exotic species, eutrophication, and climate change (see [61–63]). Eutrophication can occur naturally over centuries as reservoirs age and are filled in with sediments [64]. However, human activities (e.g., agriculture, industry, and municipal sewage disposal) have accelerated the rates and extent of eutrophication through both point-source discharges and nonpoint loadings of limiting nutrients, such as nitrogen (N) and phosphorus (P), into aquatic ecosystems, with dramatic consequences for drinking water sources, fisheries, and recreational water bodies [65].

High nutrient loading results in the overall increase in phytoplankton biomass (e.g., recorded in Lake Chivero, Lake Victoria, Lake Nasser, Hartbeespoort Reservoir, see Ndebele-Murisa et al. [30]) in the inshore and offshore areas, and a notable decrease in water transparency [63]. The classic sign of eutrophication in reservoirs is blooms of Cyanophyta such as *Microcystis* sp., *Cylindrospermopsis* sp., *Anabaena* sp., *Planktothrix* sp., *Aphanizomenon* sp., and *Nodularia* sp. [66] which cause notable decreases in water transparency ([67]; see Box 4.2). Cyanophyta species have all been recorded from African reservoirs and are anticipated to increase with climate change [28]. Increased phytoplankton biomass as a result of Cyanophyta blooms in the epilimnion also results in increased phytoplankton decomposition rates which ultimately depress dissolved oxygen (DO) concentration to  $\leq 1$  mg/L, similar to the observation in Lake Victoria [68]. The impact of hypoxia (i.e., lack of oxygen) can be twofold: on a macro-scale in the environment hypoxia constrains the distribution of species in the water column and forces them to depart from their normal behavior; and on a micro-scale, it causes physiological changes and shifts, and thus, alters lifecycle performance, reproductive capacity, growth capacity, and the vulnerability to diseases [69]. Hypoxic

**BOX 4.2**

Cyanobacteria dynamics in a small tropical reservoir: Understanding spatio-temporal variability and influence of environmental variables [18].

Malilangwe reservoir is in the south-eastern lowveld of Zimbabwe. Rainfall occurs between November and March and the area is prone to droughts due to the erratic rainfall patterns. Summer temperatures are high, with a daily maximum of  $>32^{\circ}\text{C}$  and peak temperatures of  $>45^{\circ}\text{C}$ . Thermal stratification was established during the hot-wet season. In the cool and hot dry seasons, the reservoir was not stratified but was completely mixed. The reactive and total phosphorus, ammonium and total nitrogen were generally high at the bottom ( $<8$  m depth) during the hot-wet season. During the cool-dry season when the reservoir mixed, the nutrient concentrations were generally low. A total of 15 Cyanobacteria taxa belonging to 9 families were recorded from the Malilangwe Reservoir over three seasons. The most abundant species during the hot-wet season when the reservoir was well stratified were *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya and Subbaraju, *Merismopedia* sp., *Chroococcus* sp. and unidentified filamentous Cyanophyta. Three species dominated the cyanobacterial blooms in the cool-dry season when the reservoir was weakly stratified, and these were *Anabaena circinalis* Rabenhorst ex Bornet and Flahault, *M. aeruginosa* (Kützing) Kützing and *Chroococcus* sp. Macrophyte cover, DO, water transparency, reactive phosphorus, water level depth, chemical oxygen demand were found to have a significant effect on the Cyanobacteria community structure. The Malilangwe Reservoir as a model of a small reservoir shows that certain conditions are conducive for key Cyanobacteria proliferation in semiarid subtropical environments. Cyanobacteria blooms in the cool-dry season came after an increase in phosphorus in May which likely drove the increase in nitrogen-fixing species such as *Chroococcus* sp., *M. aeruginosa*, and *A. circinalis*. This could also have been partially attributed to the decrease in the destabilizing effects of river inflows and increased reservoir mixing. Overall, the high pH, low nitrogen and nitrate concentration, and low transparency in the reservoir were associated with increased Cyanobacteria abundance. However, the period associated with the most animal and human risk was the cool-dry season as Cyanobacteria were the most abundant taxa, and known cyanotoxin producers, such as *Anabaena*, *Microcystis*, and *Cylindrospermopsis*, were among the most prevalent bloom-forming taxa found. Their high occurrence suggests a high risk of potential exposure to toxigenic Cyanobacteria and associated cyanotoxins to animals and humans through recreational activities and drinking with serious socioeconomic costs.



conditions in the hypolimnion of reservoirs fundamentally affect the community structure and diel vertical migration patterns of zooplankton [69].

Zooplankton play a vital role in regulating water quality in reservoirs because of their crucial position in the food chain. They are the dominant phytoplankton grazers and are in turn consumed by fish [70]. Zooplankton commonly exhibit diel vertical migration in which most populations reside in the hypolimnion during the day to avoid visual predation from fish [71,72]) or damaging ultraviolet (UV) radiation from the sun [73,74], at the cost of reduced growth and reproduction in the colder hypolimnion [75]. Furthermore, zooplankton need oxygen for respiration and exhibit decreased growth rates, fecundity, and increased mortality under low-oxygen conditions (e.g., [76]). Hypoxic conditions in the hypolimnion because of high phytoplankton decomposition rates result in zooplankton experiencing a trade-off during the day between experiencing increased metabolic stress and mortality due to low hypolimnion DO versus mortality and increased zooplankton cellular damage due to increased fish predation and UV radiation exposure in the oxic epilimnion. Low zooplankton densities result in increases in phytoplankton blooms as zooplankton regulate phytoplankton by grazing on them [77].

Under eutrophic conditions, Cyanophyta dominate the phytoplankton community and disrupts food web processes due to their high abundance, toxicity, and reduced food quality for grazers [78–80]. For example, the zooplankton in Lake Chivero were drastically reduced by eutrophication which promoted the proliferation of the inedible Cyanophyta *M. aeruginosa* which are currently dominating the phytoplankton composition in the reservoir [19]. The failure of zooplankton to regulate Cyanophyta blooms lies within key attributes that can reduce zooplankton growth and abundance [66]. The production of water-soluble toxic metabolites, including hepato- or neurotoxins, and various other less known metabolites cause lethal and sublethal effects when ingested by the zooplankton [81]. The Cyanophyta species release toxins as their defense mechanism, when disturbed, grazed, and/or in competition with other phytoplankton [82]. *Cylindrospermopsis raciboskii*, which dominates in Lake Kariba [19], can affect the aquatic ecosystem in three ways. (1) Its toxicity to zooplankton and vertebrates [83,84]. *C. raciboskii* produces hepatotoxins and nephrotoxins and is among the most commonly recognized toxigenic Cyanophyta associated with harmful algal blooms (HAB) in freshwater

systems, being specifically associated with multiple water-soluble toxins [85]; (2) allelopathy, in which it suppresses the growth of other phytoplankton and macrophytes [86,87], and (3) inducing teratogenic effects to the fish embryos as recorded on zebrafish *Danio rerio* [88], which could also be happening in other African lakes and reservoirs dominated by *C. raciboskii*. Although Cyanophyta dominate most phytoplankton blooms globally, other species in other taxonomic groupings (e.g., Dinophyta) have also been shown to produce HAB (see the complete list in [89]). Cyanophyta also limit zooplankton fitness because they are deficient in sterols and PUFAs, vital for regulating cell function in animals [47,90]. Finally, the aggregation of Cyanophyta cells into large, inedible filaments or colonies provides a grazer refuge, and the filaments can inhibit grazing by large daphniids by clogging the filtration apparatus [91,92].

It is clear from several studies globally that phytoplankton blooms often have devastating effects on fisheries [89]. Reduced zooplankton affects fisheries as zooplankton provide the crucial trophic link between phytoplankton and fish. Harmful phytoplankton have caused considerable damage by depleting fish stocks, restricting harvests resulting in great losses to the fishing industry, and having significant economic impacts [89]. Phytoplankton blooms cause the sudden and unexpected death of several fish over a short time and often within a particular area in the wild, often referred to as “fish kills” [93]. Fish kills are attributed in some cases to hypoxic conditions when blooms decay, while in others, there is clear evidence of the involvement of water-soluble toxic metabolites [89]. There is either a direct action of the phytoplankton on the fish itself, especially on sensitive organs such as the gills, liver, and tissue of the nervous system causing asphyxiation and eventually death, or indirect death of predators which have consumed herbivores by feeding on blooms [89,94]. Fish kills in Lake Chivero resulted from hypoxic conditions caused by the high oxygen demand from the massive algal die-off and released algal toxins [27]. Lake Chivero is hypereutrophic with sewage and industrial effluent discharged into the reservoir through the Mukovisi and Marimba rivers [95]), with *M. aeruginosa* being the dominant algal group [27,96]. Approximately 100 tons of greenhead tilapia *Oreochromis macrochir* in Lake Chivero in March/April 1996 were lost to deoxygenation that was compounded by ammonia toxicity which was unacceptably high at 3.5 mg/L [27]. Depressed DO levels (< 1.9 mg/L)

are lethal for cichlid fish species that dominate fisheries catches in Africa [95]). In the Nyanza Gulf of Lake Victoria, Cyanophyta blooms have been observed since 1980 which are associated with massive fish kills [94,97,98]. In South Africa, fish kills (as well as the death of mammals) attributed to Cyanophyta toxins have been recorded from several reservoirs [31]. It is therefore important to distinguish between natural events and anthropogenic activities so that remedial measures are implemented to address the cause and prevent future fish kills. This is particularly important for other human activities (e.g., agriculture, mining, urban expansion) which could be the first to be blamed when a fish kill occurs.

#### **4.2.5 Impact of phytoplankton on human health**

Human exposure to cyanotoxins is likely to occur through direct consumption of toxin-contaminated drinking water [89]. In Lake Victoria, cylindrospermopsin and microcystin were detected in the lakeshore sites although none were detected in wells or treated drinking water samples [99]. The existence of multiple toxins in the lake may lead to synergistic effects and increase the toxicological risk to humans [99]. In South Africa, water used for domestic purposes (including drinking) by communities around the Hartbeespoort reservoir had microcystins averaging 4.3  $\mu\text{g/L}$  in communal tap water and 4.8  $\mu\text{g/L}$  in the water stored in tanks [100]. This is of concern as the Hartbeespoort reservoir is a major water source in the northwest province of South Africa. The decaying of Cyanophyta emits a strong septic odor; this has also been reported in areas around the Hartbeespoort reservoir [100]. In Lake Embu, Kenya, there are unconfirmed reports of hundreds of deaths attributable to cyanotoxin exposure in 2001 [101]. In Zimbabwe, circumstantial evidence linked the seasonal increase of gastroenteritis cases in Harare to algal blooms in Lake Chivero [102,103]. Between 1991 and 2001, gastrointestinal infections and liver cancer cases in Harare rose by over 300% [96]. Documented cases of gastroenteritis rose from <100 to 300 per 1000 people, whereas, liver cancers rose from 30 to 130 per 1000 people [96]. Microcystin concentrations in Lake Chivero were  $\leq 13.9 \mu\text{g/L}$  and were also detected in the city's drinking water [96]. This observation is a matter of concern, mainly because microcystin has been linked to hepatocellular carcinomas, a major type of primary liver cancer ([104]; Welker et al., 2004). The high incidences of cancer in Africa could, therefore, also be attributed to the consumption of fish and water with high

microcystin levels. Despite the dangers of cyanotoxins to human health, the risks posed by exposure to cyanobacterial toxins through water and fish consumption remain poorly described [105].

Consumption of agricultural plants following irrigation with toxin-contaminated water is also another route of cyanotoxin intake by humans [106]. The uptake and accumulation of three different hepatotoxic cyanotoxins in lettuce *Lactuca sativa*, ryegrass *Lolium perenne*, clover *Trifolium repens*, and rape *Brassica napus* were demonstrated (see [106]) which poses a serious health concern, especially in Africa, where agricultural production is highly reliant on irrigation water from Cyanophyta-dominated lakes and reservoirs. Although oral exposure is the main route of human cyanotoxin intake, dermal exposure may occur [107]. Dermal exposure can be through recreational, sport, and water activities (e.g., fishing, swimming) in infested waters, or through the domestic use of cyanotoxin-containing water (in the case of showering) [107], causing dermatitis and mild to severe allergic reactions or maybe a systemic toxic effect [106]. Case reports and anecdotal references dating from as early as 1949 describe a range of illnesses associated with recreational exposure to Cyanophyta: hay fever-like symptoms and pruritic skin rashes are most frequently reported, while others describe more serious acute illnesses, with symptoms such as severe headache, fever, pneumonia, myalgia, vertigo, and blistering in the mouth [108]. Although not much has been documented in Africa with regards to cyanotoxin dermal exposure, communities living around reservoirs who often come in contact with the water might be experiencing these symptoms, hence, further studies are warranted.

The quality of fish meat is defined based on the sensory characteristics, chemical composition, and physical properties which influence how the fish are perceived by the consumer [109]. Fish quality also involves safety aspects such as being free from parasites, harmful bacteria, pesticide chemicals, heavy metals, biotoxins, and many other substances [110]. Accumulation of biotoxins in fish muscle and viscera render the fish unsafe for human consumption [89] as toxins produced by Cyanophyta can be biomagnified along the food chain from lower to higher trophic levels [111]. For instance, the potent microcystins, which are hepatotoxins, may cause liver damage and promote tumor growth in animals as well as humans through the inhibition of protein phosphatase 1 and 2A [112,113]. These toxins are highly water-soluble and are also

resistant to boiling, thus, posing a huge threat to water and food quality if not properly monitored [113]. In the Loskop reservoir in South Africa, extremely high microcystin levels were observed in the liver and muscles of *Labeo rosae* and *Oreochromis mossambicus*, indicating that the consumption of high fish biomass might cause severe adverse effects in humans [111]. Microcystins were also detected in *Rastrineobola argentea*, a small planktivorous fish in Lake Victoria [105]. In the Koka reservoir, Ethiopia, the liver and muscle tissues of *Oreochromis niloticus*, *Cyprinus carpio*, and *Clarias gariepinus* had high levels of microcystins [114]. Most studies in Africa, however, have only looked at the presence of Cyanophyta in the fish guts, and not the presence of cyanotoxins in fish tissues. Some studies on tilapia diets in Lake Victoria demonstrated that Cyanophyta (especially *Microcystis* sp.) constitute about 30% of the phytoplankton community [115,116]. The few examples we have of the presence of cyanotoxins in fish tissues are of concern as globally more than 2000 cases of human poisoning through either fish or shellfish consumption are reported every year with a mortality rate of 15% [117].

#### 4.2.6 Impact of phytoplankton on other animals

The impact of Cyanophyta blooms on piscivorous birds as well as terrestrial mammals has been well documented [89]. This observation was first reported over a century ago, when dogs, horses, pigs, and sheep were seen to die within hours of drinking from a waterbody contaminated and dominated by Cyanophyta *Nodularia spumigena* [108]. Cyanotoxins have frequently been the suspected cause of mass deaths of medium- and large-sized terrestrial mammals in Africa, including livestock (i.e., cattle, goats, sheep) as well as nonwading wild mammals (i.e., rhinoceros, wildebeests, giraffes, zebras, impalas) [118]. Interestingly, due to the vigilance against predators, many of these wild mammals drink at the downwind edge of waters where dense Cyanophyta scum tends to accumulate, thus, exposing them to high levels of cyanotoxins [118]. In Kruger National Park, South Africa, several clustered, multispecies, wildlife mortality events occurred in the vicinity of two reservoirs [119]. On investigation, heavy Cyanophyta blooms were visible in these reservoirs and microscopic analysis of water samples showed the dominance of *M. aeruginosa*. Laboratory toxicity tests confirmed the presence of significant levels of microcystins in water from the two reservoirs. The postmortem of the dead animals showed macroscopic le-

sions and histopathological lesions which were compatible with a diagnosis of Cyanophyta intoxication. The recent mass mortality event of 350 African elephants in Botswana was attributed to biotoxins produced by Cyanophyta [118]. Cyanotoxins were indeed the most likely cause of this tragic event, which would be the first confirmed case of cyanotoxin-induced elephant mass mortality. Thus, increasing exposure to cyanotoxins in polluted reservoirs will inevitably be harmful to the health and livelihoods of humans who consume livestock and wildlife [118].

### 4.3 Phytoplankton and climate change

In moderate emission scenarios that feature little change from present global-development patterns, for instance, average global temperatures are projected to rise by 2.1°C–3.5°C [120], which is way above the 1.5°C–2°C limit laid out as a goal by signatories that signed the 2015 Paris climate agreement. The most obvious and easily measured indicator of warming in aquatic systems is a change in water temperature with the thermal cycle being the ecological driver which is most likely to be directly affected by changing temperatures [121]. African reservoirs are known to be sensitive and vulnerable to climate change, as small variations can cause wide fluctuations in their thermal dynamics and their aquatic environment [13,122–124]. Surface temperatures in the Hartbeespoort and Roodeplaat reservoirs in South Africa rose by about 0.14°C/year between 1980 and 2000, rose by about 5°C between 1962 and 1995 in Lake Albert, and the epilimnion temperature of Lake Kivu increased by about 0.5°C–1.0°C since the mid-1970s, and by about 0.5°C at the depth of the temperature inversion. Deeper water temperatures in Lake Malawi increased by about 0.7°C over six decades and the surface temperatures of Lake Victoria increased by 0.05°C per decade between 1927 and 2000, and 0.92°C between 2000 and 2009, while its deep waters warmed by 0.08°C and 1.09°C over the same period [121], and Lake Kariba increased by 2.0°C in the 50 years since its creation [30,95].

Increased water temperatures associated with climate warming are likely to cause a shift in phytoplankton species composition from a balanced ecosystem to a Cyanophyta-dominated ecosystem, which is competitively superior at high temperatures [30]. The growth rate of Chlorophyta declined at temperatures above 24°C, becoming negative after 28°C [125]. In contrast, Cyanophyta increased almost exponentially up

to 34°C [125]. As water temperatures increase, phytoplankton succession follows a progression from Bacillariophyta to Chlorophyta to Cyanophyta [126]. The results corroborated several reports from various lakes and reservoirs globally where Cyanophyta is the dominant phytoplankton group thriving under the changing climate. For example, in a study of 188 lakes and reservoirs exhibiting a wide range of trophic status, it was concluded that lake warming strongly favors phytoplankton species such as Cyanophyta [127]. The same scenario is happening in African lakes and reservoirs that are already experiencing the impacts of climate change such as Lake Kariba (with average temperatures of the epilimnion > 25°C), where *C. raciboskii* is now dominating the phytoplankton community (see [19]). In Lake Victoria, the phytoplankton blooms observed during February and August comprised over 90% *Microcystis* sp. at concentrations of 34,000 colonies/mL. The blooms corresponded with high temperatures, discharge of nutrients, nutrient upwelling, and nutrient release from sediments [98].

Besides the effects of climate warming on phytoplankton communities in African lakes and reservoirs as described above, warming also affects the thermal stratification of lakes [13]. Stratification is the tendency of reservoirs to form separate and distinct thermal layers during warm weather [13]. Stratification is prevalent in many deep African lakes and reservoirs such as Albert, Cahora Bassa, Chad, Kariba, Malawi, Niger, Tanganyika, and Turkana. A fairly stable stratification is established during the wet season, characterized by increased water temperatures and diminished wind intensities, however, currents and internal waves, as well as coastal jets and return flows, can cause localized upwelling, which may partly disrupt this stratification [13]. Global warming is likely to cause many reservoirs to exhibit prolonged stratification with decreased nutrient concentrations in the epilimnion and prolonged hypoxia in hypolimnion [128] leading to overall productivity reductions in lakes and reservoirs [95]. There is evidence that global warming is already affecting African lakes and reservoirs [129]. Lakes Malawi [130], Kivu, [131] and Tanganyika [124] appear to have strengthened stratifications. Lake Kariba still becomes isothermal in winter, and mixing occurs despite its warming [129]. This mixing releases nutrients from the hypolimnion to the epilimnion, indicated by a general increase in primary production and nutrients during the winter season. It is essential that regular monitoring

be carried out in African lakes and reservoirs as all systems might not respond to climate change in the same way [129].

#### **4.4 Management of reservoirs in Africa**

Africa is exceptionally well endowed with river basins and large inland lakes and reservoirs that extend over the territories of several countries with both crisis-prone hotspots and a good number of promising approaches to transboundary water management [132]. In Africa, there are international agreements in effect for 20 of the continent's 63 river basins. There are institutionalized forums that have the task of coordinating national initiatives in 16 river basins. Despite this limited number of formal coordination forums on the African continent, transboundary water management has made considerable progress, especially in southern Africa. The Southern African Development Community provides an overarching political framework in southern Africa conducive to efforts aimed at transboundary cooperation with regard to the management of water basins in the region. Other transboundary river basin organizations in Africa include the Lake Chad Basin Commission, Organization pour la mise en valeur du fleuve Sénégal, the Niger Basin Authority, Zambezi Watercourse Commission, and the new initiatives for cooperation being undertaken on Lake Victoria. The founding of the African Ministers' Council on Water also established a continent-wide cooperation context that has placed transboundary water cooperation on its agenda and is receiving external support and funding for the purpose [132]. These organizations have put in frameworks that work to promote cooperation, security, social and economic development, and poverty eradication among the member states through the effective management of the continent's water resources and provision of water supply services. As lakes and reservoirs in Africa have been subjected to various anthropogenic pressures, the frameworks aid in management as usage of the lakes and reservoirs are governed by the national, regional as well as international frameworks although it is proving to be difficult to manage threats to biodiversity like pollution of aquatic ecosystems and climate change, both of which have negative impacts on phytoplankton communities.

Wastewater disposal is becoming a problem in African countries as large quantities of municipal waste and industrial effluent (both containing extremely high nutrients) are being produced due to increased indus-



trialization and urbanization [133]. In the Kisumu District in Kenya, all three of the existing pump stations are broken down resulting in the overflow of sewage at manholes upstream of the pump stations and direct discharge of raw sewage into Lake Victoria [133]. The hypereutrophic Lake Chivero receives raw sewage from the City of Harare which contains alarmingly high nutrients, more than the applicable Zimbabwean nutrient limits for effluents discharged into sensitive waters (which are 10 mg/L total N and 0.5 mg/L total P) (Government of Zimbabwe Statutory Instrument 274 of 2000). Population growth, frequent breakdowns, and no maintenance of wastewater treatment plants contribute to untreated wastewater discharged into receiving aquatic ecosystems [134].

The deteriorating state of sewage and wastewater treatment facilities or infrastructure management in Africa is one of the largest factors contributing to the numerous pollution problems experienced in most parts of the continent and a major contributor to human and environmental problems [135]. Of the 824 treatment plants in South Africa, it is estimated that only 60 release water within the recommended limits. Raw or partially treated sewage flows directly into rivers and reservoirs throughout the country, turning reservoirs green, laying waste to sensitive aquatic ecosystems, and harming people who drink the polluted water. From large cities, such as Johannesburg, to smaller rural towns, wastewater from domestic industries frequently either escapes out of broken pipes or from the wastewater treatment plants into the natural environment [135].

The Nkolbisson reservoir in Cameroon receives untreated wastewater from the Abiergue and Mintotomo rivers of the Mefou watershed flowing across Cité Verte which has gradually degraded its quality and environment [136]. Not only is wastewater the only contributor of high nutrients into reservoirs, but other human activities such as agriculture also contribute the same [137]. Excessive use of various agrochemicals in the nearby lands around watersheds, lack of well-planned development on the riverbanks, and population growth are increasingly polluting lakes and reservoirs. Areas surrounding Lake Edward are used for agricultural activities and water from the reservoir is generally used for irrigation purposes, washing clothes, bathing, and for the domestic animals which lead to the degradation of water quality [137]. This is also being experienced in several reservoirs across the continent. This results in a massive proliferation of undesirable phytoplankton, and this coupled with other

anthropogenic stressors (e.g., climate change), further strains our lakes and reservoirs.

#### **4.4.1 Controlling phytoplankton blooms**

Nitrogen and phosphorous are the major nutrients governing phytoplankton primary production and biomass in African lakes and reservoirs with warm temperatures playing a huge role in the proliferation of phytoplankton blooms [138,139]. Theoretically, to prevent eutrophication and phytoplankton blooms, environmental managers must control the three factors (N, P, and temperature). This, however, has been difficult for various African states besides having sound regulations for anthropogenic stressors. Policymakers and principal government service providers who are supposed to be spearheading the prevention of pollution are neglecting their oversight role, resulting in the local municipalities and governments being the largest polluters of aquatic ecosystems [135]. As discussed in the previous section, most local municipalities in African states are disposing of untreated sewage into aquatic ecosystems resulting in increased nutrient levels which promote algal blooms. Local municipalities should invest in sound sewage treatment systems that efficiently reduce nutrient loads to aquatic ecosystems. Constructed wetlands can also be used and these consist of a shallow depression in the ground with a level bottom designed and built like natural wetlands to treat wastewater [140,141]. The flow is controlled so the water is spread evenly among the wetland plants, thereby, allowing natural processes to occur and clean the wastewater more efficiently [140–143]. Constructed wetlands provide a simple and effective option and have proven to be effective in the treatment of domestic, industrial, agricultural, and municipal wastewater [140–143]. Constructed wetlands, a promising green technology, are also very effective in treating toxic metal-contaminated water, pharmaceuticals and personal care products contaminated waters, oil refinery wastewater, diesel, and agricultural drainage water (see [144]). Their construction and operational costs are much less than conventional systems. Some statistics show that the cost of subsurface constructed wetlands in Africa for wastewater treatment is approximately US\$ 5 per person compared to mechanical wastewater treatment (i.e., activated sludge system used by municipalities), which costs approximately US\$ 50 per person [145]. Constructed wetlands also provide scenery, are pleasant to look at, attract desired wildlife, and provide environmental education op-

portunities [141]. Natural wetlands are more desirable to perform the treatment of wastewater, but these are being developed as well as being affected by agriculture which affects the water cycle. Constructed wetlands, therefore, could be a better option that offers a low-cost and low-maintenance treatment alternative for wastewater to prevent African lakes and reservoirs from receiving high nutrient loads which affect phytoplankton communities.

Climate change experts have been researching ways to counter the increasing global temperatures which are presently being reflected in the proliferation of undesirable phytoplankton in some reservoirs. A holistic approach is required when dealing with the issues of climate change. The emission of greenhouse gases from anthropogenic activities must decline substantially by greatly reducing our dependency on fossil fuels, which is the largest challenge of our time [120]. Reducing deforestation and massive planting of trees is something citizens can easily get involved with which could help in mitigating the effects of climate change.

#### **4.5 Remote sensing in the monitoring of phytoplankton: key research strides, challenges, and opportunities**

Although, the use of in situ methods for phytoplankton assessment and monitoring is considered to be accurate, limited financial resources for routine monitoring and malfunctioning equipment, restricted aerial coverage, and the existing data gaps have resulted in the lack of proper understanding of phytoplankton distribution and occurrence in most African lakes and reservoirs. This has prompted the need to integrate in situ and remote sensed datasets to achieve a holistic understanding of the phytoplankton taxonomic richness in African lakes and reservoirs. As such, the remote sensing of phytoplankton has increased drastically over the years since the emergence of Earth observation satellite platforms over the past four decades. This has been largely motivated by the need for lake-scale spatial explicit information on phytoplankton distribution and occurrence.

To date, various remotely sensed datasets have been used ranging from Advanced Very-High-Resolution Radiometer, Hyperspectral, Landsat Series, MERIS, MODIS, SPOT, and Sentinel data [146–149]. However, the results varied significantly depending on the trade-offs between the sensor type and lake size variations. For instance, some of the lakes

or reservoirs are small in size which makes the use of broadband and coarse multispectral satellite datasets challenging due to spectral mixing [147]. In addition, the return time (temporal scale) for the majority of these satellite data sensors ranges between 10 and 20 days [150–152], except for MERIS and MODIS data which have a daily coverage. It is important to note that because of these limitations, the use of MERIS and MODIS data remains largely restricted to big lakes such as Kariba in Zimbabwe, Lake Malawi, and Lake Naivasha, Kenya, although several attempts have been observed in Lake Chivero among others. Despite the limitations, numerous remotely sensed models (e.g., the maximum peak-height algorithm after Matthews and Bernard [149] and the FLH algorithms [153]) have been developed for estimating and predicting phytoplankton concentrations or presence in freshwater ecosystems and these have proved to be accurate based on the validation results conducted in some lakes and reservoirs in Africa. The majority of these models focused on the chl-a estimation and high accuracies have been reported [152, 154].

Overall, the use of remotely sensed data in monitoring and assessing phytoplankton is gaining significant traction in Africa. This is further motivated by the development of new generation sensors with unique strategically positioned spectral bands such as the 10 m Sentinel 2 data with a repeated temporal coverage of 5 days [155]. The introduction of these data has opened new avenues for data fusion with other readily available remotely sensed datasets such as Sentinel 3 (OLCI), Landsat 8, the newly introduced Landsat 9 using machine learning and artificial intelligence, and Google Earth Engine clouding computing techniques [156]. New research breakthroughs have been reported in southeast Asia [157], Europe [158, 159], and America [160]. There is, therefore, a need to test the transferability of some of these research advancements and methodologies on inland freshwater ecosystems (lakes and reservoirs) in Africa.

#### **4.6 Conclusions**

The absence of information on phytoplankton from hundreds of reservoirs on the African continent clearly shows there is considerable limited research and necessary infrastructure to enable and/or facilitate research (see [161]). The LDG is supported as more species are found in the

Equator region, with diversity decreasing toward the poles, with the Bacillariophyta group being the most dominant in terms of species. Of concern is the highly occurring *M. aeruginosa* among other Cyanophyta species in almost all the lakes and reservoirs, which form blooms that affect various levels of aquatic ecosystem structure. Apart from its negative impacts on the trophic structure of aquatic ecosystems, cyanotoxins produced by *M. aeruginosa* have been detected in the water and fish of the lakes and reservoir that are consumed by humans, with significant detrimental impacts on the indigenous local communities' livelihoods and health.

Nutrient enrichment is the primary water quality issue that is leading to nuisance Cyanophyta blooms, with many African lakes and reservoirs being recipients of untreated wastewater which is causing nutrient enrichment and proliferation of bloom formations. To control algal blooms, this review calls on municipalities in respective states to ensure that wastewater is adequately treated before being discharged into reservoirs to prevent biodiversity loss as well as serious human health issues. This chapter further makes recommendations for local municipalities to construct wetlands as a cost-effective and environmentally friendly option for treating wastewater. Climate change is predicted to cause further increases in Cyanophyta blooms as they have a competitive advantage at elevated temperatures (see [28]). For this, a holistic approach is required when dealing with the issues of climate change to reduce the emission of greenhouse gases from human activities.

Management of reservoirs against eutrophication and associated cascading impacts promotes the attainment of Sustainable Development Goals:

**1. SDG 1 No poverty**

Productive reservoirs are beneficial to livelihoods when they harvest ecosystem services that can generate income (e.g., selling fish).

**2. SDG 2 Zero hunger**

Similar to SDG 1. Productive reservoirs are beneficial to livelihoods when they harvest ecosystem services that they use for family consumption or can generate income (e.g., selling fish), which they will use to buy food for family consumption.

**3. SDG 3 Good health and well being**

When a reservoir is well managed (including the watershed), the reservoir will have nutrients within acceptable ranges, with diverse

phytoplankton composition and less cyanotoxic phytoplankton which can cause serious health issues.

#### 4. SDG 6 Clean water and sanitation

Similar to SDG 3. When a reservoir is well managed (including the watershed), the water can be consumed in households without causing serious health issues.

#### 5. SDG 14 Life below water

Managing reservoirs promotes the conservation of biotic components below water to maintain biodiverse aquatic systems

Periodic phytoplankton biodiversity monitoring and assessments should be carried out in African aquatic systems to provide insights into the changes (biotic, physical, or chemical) of aquatic ecosystems over time. The assessments indicate the status of these ecosystems. Monitoring and assessment also provide evidence-based documentation of the state of these reservoirs as a result of human disturbances and interventions. Furthermore, monitoring and assessment programs provide insights into whether management actions and/or strategies are effective in reducing or preventing further aquatic ecosystem degradation. Overall, monitoring and assessment facilitate decision-making, supports policy development, and provide information to stakeholders which may encourage their participation in decision-making and implementation processes. Lastly, monitoring and assessment programs are essential for the sustainable development and management of water resources.

## References

- [1] A.J. Reid, A.K. Carlson, I.F. Creed, E.J. Eliason, P.A. Gell, P.T.J. Johnson, et al., Emerging threats and persistent conservation challenges for freshwater biodiversity, *Biol. Rev.* 94 (2019) 849–873, <https://doi.org/10.1111/brv.12480>.
- [2] T. Dalu, R.J. Wasserman (Eds.), *Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management*, Elsevier, Cambridge, 2022, p. 864.
- [3] D. Dudgeon, A.H. Arthington, M.O. Gessner, Z.-I. Kawabata, D.J. Knowler, C. Lévêque, et al., Freshwater biodiversity: importance, threats, status and conservation challenges, *Biol. Rev.* 81 (2006) 163–182, <https://doi.org/10.1017/S1464793105006950>.
- [4] J.S. Albert, G. Destouni, S.M. Duke-Sylvester, A.E. Magurran, T. Oberdorff, R.E. Reis, et al., Scientists' warning to humanity on the freshwater biodiversity crisis, *Ambio* (2020), <https://doi.org/10.1007/s13280-020-01318-8>.
- [5] E.G.E. Brooks, R.A. Holland, W.R.T. Darwall, F. Eigenbrod, Biodiversity versus fisheries productivity, *Glob. Ecol. Biogeogr* 25 (2016) 553–562, <https://doi.org/10.1111/geb.12435>.
- [6] C.S. Reynolds, *The Ecology of Phytoplankton*, Cambridge University Press, Cambridge, 2006, <https://doi.org/10.1017/CBO9780511542145>.
- [7] D.M. John, B.A. Whitton, A.J. Brook, *The Freshwater Algal Flora of the British Isles*, Cambridge University Press, Cambridge, 2002.

- [8] T. Dalu, T. Mwedzi, R.J. Wasserman, Phytoplankton dynamics, in: T. Dalu, R.J. Wasserman (Eds.), *Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management*, Elsevier, Cambridge, 2022, pp. 189–219.
- [9] S.D. Batten, R. Abu-Alhajib, S. Chiba, M. Edwards, G. Graham, R. Jyothibabu, et al., A global plankton diversity monitoring program, *Front. Mar. Sci.* (2019) 6, <https://doi.org/10.3389/fmars.2019.00321>.
- [10] R.N. Cuthbert, R.J. Wasserman, Keates, T. Dalu, Foodwebs, in: T. Dalu, R.J. Wasserman (Eds.), *Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management*, Elsevier, Cambridge, 2022, pp. 517–547.
- [11] Brannen, P. The Amazon is not earth's lungs. *The Atlantic*. <<https://www.theatlantic.com/science/archive/2019/08/amazon-fire-earth-has-plenty-oxygen/596923/>>, 2019 (accessed 18.01.22).
- [12] Biggs, B.J. F., & Kilroy, C. *Stream Periphyton Monitoring Manual*. Ministry for the Environment. Christchurch, N. Zealand, NIWA. 226 p., 2000.
- [13] M.R. Ndebele-Murisa, C. Musil, L. Raitt, A review of phytoplankton dynamics in tropical African lakes, *South. Afr. J. Sci.* 106 (1/2) (2010) 13–18, <https://doi.org/10.4102/sajs.v106i1/2.64>.
- [14] J.D. Olden, J.R.S. Vitule, J. Cucherousset, M.J. Kennard, There's more to fish than just food: exploring the diverse ways that fish contribute to human society, *Fisheries* 45 (2020) 453–464, <https://doi.org/10.1002/fsh.10443>.
- [15] T.C. Madzivanzira, O.L.F. Weyl, J. South, Ecological and potential socioeconomic impacts of two globally-invasive crayfish, *NeoBiota*. (2021), <https://doi.org/10.3897/neobiota.@@0.71868>.
- [16] N.Ž. Gladan, F. Matic, J. Arapov, S. Skejic, M. Bužančić, A. Bakrač, et al., The relationship between toxic phytoplankton species occurrence and environmental and meteorological factors along the Eastern Adriatic coast, *Harmful Algae* 92 (2020) 101745, <https://doi.org/10.1016/j.hal.2020.101745>.
- [17] C.A. Amorim, A.do N. Moura, Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning, *Sci. Total Environ.* (2021) 758, <https://doi.org/10.1016/j.scitotenv.2020.143605>.
- [18] T. Dalu, R.J. Wasserman, Cyanobacteria dynamics in a small tropical reservoir: understanding spatio-temporal variability and influence of environmental variables, *Sci. Total Environ.* 643 (2018) 835–841.
- [19] C.H.D. Magadza, T.C. Madzivanzira, P.C. Chifamba, Decline of zooplankton food resources of *Limnothrissa miodon* fishery in Lake Kariba: global warming induced ecosystem disruption by *Cylindrospermopsis raciborskii*, *Lakes Reserv.* 25 (2020) 117–132, <https://doi.org/10.1111/lre.12318>.
- [20] J. Talling, The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa), *Int. Rev. Ges. Hydrobiol. Hydrogr.* 51 (4) (1966) 545–621.
- [21] J.B. Deemy, A.F. Besterman, B.M. Hall, K.N. Tyler, K.K. Takagi, Nutrient cycling, in: T. Dalu, R.J. Wasserman (Eds.), *Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management*, Elsevier, Cambridge, 2022, pp. 133–160.
- [22] N.L. Kinlock, L. Prowant, E.M. Herstoff, C.M. Foley, M. Akin-Fajjiye, N. Bender, et al., Explaining global variation in the latitudinal diversity gradient: meta-analysis confirms known patterns and uncovers new ones, *Glob. Ecol. Biogeogr.* 27 (1) (2017) 125–141, <https://doi.org/10.1111/geb.12665>.
- [23] G.G. Mittelbach, D.W. Schemske, H.V. Cornell, A.P. Allen, J.M. Brown, M.B. Bush, et al., Evolution and the latitudinal diversity gradient: speciation, extinction and biogeography, *Ecol. Lett.* 10 (4) (2007) 315–331, <https://doi.org/10.1111/j.1461-0248.2007.01020.x>.

- [24] E.T.H. Zurich, Mapping the global distribution of phytoplankton. *Science Daily* (2019). <<http://www.sciencedaily.com/releases/2019/05/190522120509.htm>> (accessed 02.01.22).
- [25] S. Birk, W. Bonne, A. Borja, S. Brucet, A. Courrat, S. Poikane, Three hundred ways to assess Europe's surface waters: an almost complete overview of biological methods to implement the water framework directive, *Ecol. Indic.* 18 (2012) 31–41, <https://doi.org/10.1016/j.ecolind.2011.10.009>.
- [26] P.V. McCormick, J. Cairns, Algae as indicators of environmental change, *J. Appl. Phycol.* 6 (1994) 509–526, <https://doi.org/10.1007/BF02182405>.
- [27] L. Mhlanga, J. Day, M. Chimbari, N. Siziba, G. Cronberg, Observations on limnological conditions associated with a fish kill of *Oreochromis niloticus* in Lake Chivero following collapse of an algal bloom, *Afr. J. Ecol.* 44 (2) (2006) 199–208, <https://doi.org/10.1111/j.1365-2028.2006.00625.x>.
- [28] P. Tendaupenyu, Nutrient limitation of phytoplankton in five impoundments on the Manyame River, Zimbabwe, *Water SA* 38 (1) (2012) 97–104.
- [29] R.C. Hart, E.A. Bychek, Body size in freshwater planktonic crustaceans: an overview of extrinsic determinants and modifying influences of biotic interactions, *Hydrobiologia* 668 (1) (2011) 61–108, <https://doi.org/10.1007/s10750-010-0400-y>.
- [30] M.R. Ndebele-Murisa, E. Mashonjowa, T. Hill, The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, *Trans. R. Soc. South. Afr.* 66 (2) (2011) 105–119, <https://doi.org/10.1080/0035919X.2011.600352>.
- [31] W.B. Harding, B. Paxton, Cyanobacteria in South Africa: a review. Report to the Water Research Commission. WRC Report No: TT 153/01, 2001.
- [32] E. Flores, A. Herrero, Nitrogen assimilation and nitrogen control in cyanobacteria, *Biochem. Soc. Trans.* 33 (Pt 1) (2005) 164–167, <https://doi.org/10.1042/BST0330164>.
- [33] H. Bothe, Nitrogen fixation, in: N.G. Carr, B.A. Whitton (Eds.), *The Biology of Cyanobacteria*, University of California Press, Berkeley, CA, 1982, pp. 87–104.
- [34] L.C. Stal, Nitrogen fixation in cyanobacteria, eLS, John Wiley and Sons, Ltd, Chichester, 2015, <http://doi.org/10.1002/9780470015902.a0021159.pub2>.
- [35] E. Philips, P. Hansen, T. Velardi, Effect of the herbicide diquat on the growth of microalgae and cyanobacteria, *Bull. Environ. Contam. Toxicol.* 49 (5) (1992) 750–756, <https://doi.org/10.1007/bf00200790>.
- [36] R. Stancheva, R.G. Sheath, B.A. Read, K.D. McArthur, C. Schroeffer, J.P. Kociolek, et al., Nitrogen-fixing cyanobacteria (free-living and diatom endosymbionts): their use in southern California stream bioassessment, *Hydrobiologia* 720 (1) (2013) 111–127, <https://doi.org/10.1007/s10750-013-1630-6>.
- [37] S. Taipale, U. Strandberg, E. Peltomaa, A.W. Galloway, A. Ojala, M.T. Brett, Fatty acid composition as biomarkers of freshwater microalgae: analysis of 37 strains of microalgae in 22 genera and in seven classes, *Aquat. Microb. Ecol.* 71 (2013) 165–178, <https://doi.org/10.3354/ame01671>.
- [38] S.J. Taipale, M. Hiltunen, K. Vuorio, E. Peltomaa, Suitability of phytosterols alongside fatty acids as chemotaxonomic biomarkers for phytoplankton, *Front. Plant. Sci.* 7 (2016) 212, <https://doi.org/10.3389/fpls.2016.00212>.
- [39] S.H. Jónasdóttir, A.W. Visser, K. Richardson, M.R. Heath, Seasonal copepod lipid pump promotes carbon sequestration in the deep North Atlantic, *Proc. Natl Acad. Sci.* 112 (39) (2015) 12122–12126, <https://doi.org/10.1073/pnas.1512110112>.
- [40] J. Sargent, G. Bell, G.L. McEvoy, L.D. Tocher, D.A. Estevez, Recent developments in the essential fatty acid nutrition of fish, *Aquaculture* 177 (1999) 191–199, [https://doi.org/10.1016/S0044-8486\(99\)00083-6](https://doi.org/10.1016/S0044-8486(99)00083-6).
- [41] M.T. Brett, D.C. Müller-Navarra, J. Persson, Crustacean zooplankton fatty acid



- composition, in: M.T. Arts, M.T. Brett, M.J. Kainz (Eds.), *Lipids in Aquatic Ecosystems*, Springer, New York, 2009, pp. 115–146.
- [42] K.E. Harrison, The role of nutrition in maturation, reproduction and embryonic development of decapod crustaceans: a review, *J. Shellfish. Res.* 9 (1990) 1–28.
- [43] D. Martin-Creuzburg, E. Von Elert, Ecological significance of sterols in aquatic food webs, in: M.T. Arts, M.T. Brett, M.J. Kainz (Eds.), *Lipids in Aquatic Ecosystems*, Springer, New York, 2009, pp. 25–42.
- [44] D. Martin-Creuzburg, E. Von Elert, Good food versus bad food: the role of sterols and polyunsaturated fatty acids in determining growth and reproduction of *Daphnia magna*, *Aquat. Ecol.* 43 (4) (2009) 943–950, <https://doi.org/10.1007/s10452-009-9239-6>.
- [45] D.O. Hessen, J.J. Elser, R.W. Sterner, J. Urabe, Ecological stoichiometry: an elementary approach using basic principles, *Limnol. Oceanogr.* 58 (6) (2013) 2219–2236, <https://doi.org/10.4319/lo.2013.58.6.2219>.
- [46] C.T. Solomon, S.R. Carpenter, M.K. Clayton, J.J. Cole, J.J. Coloso, M.L. Pace, et al., Terrestrial, benthic, and pelagic resource use in lakes: results from a three-isotope Bayesian mixing model, *Ecology* 92 (5) (2011) 1115–1125, <https://doi.org/10.1890/i0012-9658-92-5-1115>.
- [47] D.C. Müller-Navarra, M.T. Brett, A.M. Liston, C.R. Goldman, A highly unsaturated fatty acid predicts carbon transfer between primary producers and consumers, *Nature* 403 (2000) 74–77, <https://doi.org/10.1038/47469>.
- [48] E. von Elert, Determination of limiting polyunsaturated fatty acids in *Daphnia galeata* using a new method to enrich food algae with single fatty acids, *Limnol. Oceanogr.* 47 (6) (2002) 1764–1773, <https://doi.org/10.4319/lo.2002.47.6.1764>.
- [49] S.J. Taipale, M.J. Kainz, M.T. Brett, Diet-switching experiments show rapid accumulation and preferential retention of highly unsaturated fatty acids in *Daphnia*, *Oikos* 120 (11) (2011) 1674–1682, <https://doi.org/10.1111/j.1600-0706.2011.19415.x>.
- [50] S.J. Taipale, M.J. Kainz, M.T. Brett, A low  $\omega$ -3: $\omega$ -6 ratio in *Daphnia* indicates terrestrial resource utilization and poor nutritional condition, *J. Plankton Res.* 37 (3) (2015) 596–610, <https://doi.org/10.1093/plankt/fbv015>.
- [51] S.J. Taipale, K. Vuorio, U. Strandberg, K.K. Kahilainen, M. Järvinen, M. Hiltunen, et al., Lake eutrophication and brownification downgrade availability and transfer of essential fatty acids for human consumption, *Environ. Int.* 96 (2016) 156–166, <https://doi.org/10.1016/j.envint.2016.08.018>.
- [52] S. Park, M.T. Brett, D.C. Müller-Navarra, C.R. Goldman, Essential fatty acid content and the phosphorus to carbon ratio in cultured algae as indicators of food quality for *Daphnia*, *Freshw. Biol.* 47 (2002) 1377–1390, <https://doi.org/10.1046/j.1365-2427.2002.00870.x>.
- [53] J.L. Ravet, M.T. Brett, D.C. Müller-Navarra, A test of the role of polyunsaturated fatty acids in phytoplankton food quality for *Daphnia* using liposome supplementation, *Limnol. Oceanogr.* 48 (5) (2003) 1938–1947, <https://doi.org/10.4319/lo.2003.48.5.1938>.
- [54] M.T. Brett, D.C. Müller-Navarra, A.P. Ballantyne, J.L. Ravet, C.R. Goldman, *Daphnia* fatty acid composition reflects that of their diet, *Limnol. Oceanogr.* 51 (5) (2006) 2428–2437, <https://doi.org/10.4319/lo.2006.51.5.2428>.
- [55] A.W.E. Galloway, S.J. Taipale, M. Hiltunen, E. Peltomaa, U. Strandberg, M.T. Brett, et al., Diet-specific biomarkers show that high-quality phytoplankton fuels herbivorous zooplankton in large boreal lakes, *Freshw. Biol.* 59 (9) (2014) 1902–1915, <https://doi.org/10.1111/fwb.12394>.
- [56] D.A. Los, K.S. Mironov, Modes of fatty acid desaturation in cyanobacteria: an update, *Life (Basel, Switz.)* 5 (1) (2015) 554–567, <https://doi.org/10.3390/>

- life5010554.
- [57] S. Taipale, E. Peltomaa, P. Salmi, Variation in  $\omega$ -3 and  $\omega$ -6 polyunsaturated fatty acids produced by different phytoplankton taxa at early and late growth phase, *Biomolecules* 10 (4) (2020) 559, <https://doi.org/10.3390/biom10040559>.
- [58] N. Abd Aziz, A. Azlan, A. Ismail, S. Mohd Alinafiah, M.R. Razman, Quantitative determination of fatty acids in marine fish and shellfish from the warm water of Straits of Malacca for nutraceutical purposes, *BioMed. Res. Int.* 2013 (2013) 1–13, <https://doi.org/10.1155/2013/284329>.
- [59] O.L.F. Weyl, W. Potts, Q. Rouhani, P. Britz, The need for inland fisheries policy in South Africa: a case study of the North West Province, *Water SA* 33 (4) (2007) 497–504.
- [60] B.E. Marshall, M. Maes, Small water bodies and their fisheries in southern Africa. CIFA Technical Paper No. 29. FAO, 1994.
- [61] R.E. Hecky, The Eutrophication of Lake Victoria, *Verh. Int. Ver. Limnol. Stuttgart* 25 (1993) 39–48.
- [62] D. Verschuren, T.C. Johnson, H.J. Kling, D.N. Edgington, P.R. Leavitt, E.T. Brown, et al., History and timing of human impact on Lake Victoria, East Africa, *Proc. R. Soc. B: Biol. Sci.* 269 (1488) (2002) 289–294, <https://doi.org/10.1098/rspb.2001.1850>.
- [63] S. Haande, T. Rohrlack, R.P. Semyalo, P. Brettum, B. Edvardsen, A. Lyche-Solheim, et al., Phytoplankton dynamics and cyanobacterial dominance in Murchison Bay of Lake Victoria (Uganda) in relation to environmental conditions, *Limnologica* 41 (1) (2011) 20–29, <https://doi.org/10.1016/j.limno.2010.04.001>.
- [64] L.R.D. Human, M.L. Magoro, T. Dalu, R. Perissinotto, A.K. Whitfield, J.B. Adams, et al., Natural nutrient enrichment and algal responses in near pristine micro-estuaries and micro-outlets, *Sci. Total Environ.* 624 (2018) 945–954, <https://doi.org/10.1016/j.scitotenv.2017.12.184>.
- [65] S.R. Carpenter, N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, V.H. Smith, Nonpoint pollution of surface waters with phosphorus and nitrogen, *Ecol. Appl.* 8 (3) (1998) 559–568, [https://doi.org/10.1890/1051-0761\(1998\)008\[0559:N POSWW\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1998)008[0559:N POSWW]2.0.CO;2).
- [66] K.A. Ger, L.-A. Hansson, M. Lüring, Understanding cyanobacteria-zooplankton interactions in a more eutrophic world, *Freshw. Biol.* 59 (9) (2014) 1783–1798, <https://doi.org/10.1111/fwb.12393>.
- [67] R. Mugidde, The increase in phytoplankton primary productivity and biomass in Lake Victoria (Uganda), *SIL Proceedings, 1922–2010: Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen* 25 (2) (1993) 846–849. doi: 10.1080/03680770.1992.11900264.
- [68] R.E. Hecky, F.W.B. Bugenyi, P.B.O. Ochumba, J.F. Talling, R. Mugidde, M. Gophen, et al., Deoxygenation of the deep water of Lake Victoria, East Africa, *Limnol. Oceanogr.* 39 (6) (1994) 1476–1481, <https://doi.org/10.4319/lo.1994.39.6.1476>.
- [69] W. Ekau, H. Auel, H.-O. Portner, D. Gilbert, Impacts of hypoxia on the structure and processes in the pelagic community (zooplankton, macro-invertebrates and fish), *Biogeosci. Discuss.* 6 (2009) 5073–5144.
- [70] J.A. Downing, F.H. Rigler (Eds.), A manual on methods for the assessment of secondary production in fresh waters, *IBP Handbook*, 2nd ed., Blackwell Scientific Publications, Oxford, 1984, p. 500 No. 17.
- [71] J.P. Doubek, K.L. Campbell, K.M. Doubek, K.D. Hamre, M.E. Lofton, R.P. McClure, et al., The effects of hypolimnetic anoxia on the diel vertical migration of freshwater crustacean zooplankton, *Ecosphere* 9 (7) (2018) e02332, <https://doi.org/10.1002/ecs2.2332>.

- [72] W. Lampert, The adaptive significance of diel vertical migration of zooplankton, *Funct. Ecol.* 3 (1) (1989) 21–27, <https://doi.org/10.2307/2389671>.
- [73] S.C. Rhode, M. Pawlowski, R. Tollrian, The impact of ultraviolet radiation on the vertical distribution of zooplankton of the genus *Daphnia*, *Nature* 412 (6842) (2001) 69–72, <https://doi.org/10.1038/35083567>.
- [74] D.M. Leech, C.E. Williamson, In situ exposure to solar UV radiation alters the depth distribution of *Daphnia*, *Limnol. Oceanogr.* 46 (2001) 416–420.
- [75] C.J. Loose, P. Dawidowicz, Trade-offs in diel vertical migration by zooplankton: the costs of predator avoidance, *Ecology* 75 (8) (1994) 2255–2263, <https://doi.org/10.2307/1940881>.
- [76] L.C. Stalder, N.H. Marcus, Zooplankton responses to hypoxia: behavioral patterns and survival of three species of calanoid copepods, *Mar. Biol.* 127 (1997) 599–607, <https://doi.org/10.1007/s002270050050>.
- [77] M.N. Gusha, T. Dalu, R.J. Wasserman, C.D. McQuaid, Zooplankton grazing pressure is insufficient for primary producer control under elevated warming and nutrient levels, *Sci. Total Environ.* 651 (1) (2019) 410–418, <https://doi.org/10.1016/j.scitotenv.2018.09.132>.
- [78] H.W. Paerl, V.J. Paul, Climate change: links to global expansion of harmful cyanobacteria, *Water Res.* 46 (5) (2012) 1349–1363, <https://doi.org/10.1016/j.watres.2011.08.002>.
- [79] C. Wiegand, S. Pflugmacher, Ecotoxicological effects of selected cyanobacterial secondary metabolites a short review, *Toxicol. Appl. Pharmacol.* 203 (3) (2005) 201–218, <https://doi.org/10.1016/j.taap.2004.11.002>.
- [80] W.W. Carmichael, Cyanobacteria secondary metabolites—the cyanotoxins, *J. Appl. Bacteriol.* 72 (6) (1991) 445–459, <https://doi.org/10.1111/j.1365-2672.1992.tb01858.x>.
- [81] J. Leflaive, L. Ten-Hage, Algal and cyanobacterial secondary metabolites in freshwaters: a comparison of allelopathic compounds and toxins, *Freshw. Biol.* 52 (2) (2007) 199–214, <https://doi.org/10.1111/j.1365-2427.2006.01689.x>.
- [82] E.S. Reichwaldt, A. Ghadouani, Effects of rainfall patterns on toxic cyanobacterial blooms in a changing climate: between simplistic scenarios and complex dynamics, *Water Res.* 46 (5) (2012) 1372–1393, <https://doi.org/10.1016/j.watres.2011.11.052>.
- [83] I.C.G. Nogueira, M.L. Saker, S. Pflugmacher, C. Wiegand, V.M. Vasconcelos, Toxicity of the cyanobacterium *Cylindrospermopsis raciborskii* to *Daphnia magna*, *Environ. Toxicol.* 19 (5) (2004) 453–459, <https://doi.org/10.1002/tox.20050>.
- [84] M.L. Saker, I.C.G. Nogueira, V.M. Vasconcelos, Distribution and toxicity of *Cylindrospermopsis raciborskii* (cyanobacteria) in Portuguese freshwaters, *Limnetica* 22 (3–4) (2003) 129–136.
- [85] A. Jaja-Chimedza, C. Saez, K. Sanchez, M. Gantar, J.P. Berry, Identification of teratogenic polymethoxy-1-alkenes from *Cylindrospermopsis raciborskii*, and taxonomically diverse freshwater cyanobacteria and green algae, *Harmful Algae* 49 (2015) 156–161, <https://doi.org/10.1016/j.hal.2015.09.010>.
- [86] C.F. Cleber, G. Allesandria, D.F. Bird, Does allelopathy contribute to *Cylindrospermopsis raciborskii* (cyanobacteria) bloom occurrence and geographic expansion?, *J. Phycol.* 43 (2) (2007) 256–265, <https://doi.org/10.1111/j.1529-8817.2007.00333.x>.
- [87] E. Grineli, M. Werberg, P.S. Salomon, Harmful algal blooms of allelopathic microalgal species: the role of eutrophication, *Harmful Algae* 8 (1) (2008) 94–102, <https://doi.org/10.1016/j.hal.2008.08.011>.
- [88] C.A.N. Moraes, S.H.V.F. Magalhães, H.R. Habibi, *Cylindrospermopsis* impairs

- zebrafish (*Danio rerio*) embryo development, *Mar. Environ. Res.* 175 (2022) 105567, <https://doi.org/10.1016/j.marenvres.2022.105567>.
- [89] J. Bruslé, *The Impact of Harmful Algal Blooms on Fish—Mortality, Pathology and Toxicology*, IFREMER, Brest, 1995.
- [90] R. Gulati, W. Demott, The role of food quality for zooplankton: remarks on the state-of-the-art, perspectives and priorities, *Freshw. Biol.* 38 (3) (1997) 753–768, <https://doi.org/10.1046/j.1365-2427.1997.00275.x>.
- [91] W.R. DeMott, R.D. Gulati, E. Van Donk, Daphnia food limitation in three hypereutrophic Dutch lakes: evidence for exclusion of large-bodied species by interfering filaments of cyanobacteria, *Limnol. Oceanogr.* 46 (8) (2001) 2054–2060, <https://doi.org/10.4319/lo.2001.46.8.2054>.
- [92] Z.M. Gliwicz, W. Lampert, Food thresholds in Daphnia species in the absence and presence of blue green filaments, *Ecology* 71 (2) (1990) 691–702, <https://doi.org/10.2307/1940323>.
- [93] A.C. Jarvis, Ecological problems in Hartbeespoort Dam, *J. Limnol. Soc. South. Afr.* 14 (2) (1988) 82–86.
- [94] D.M. Onyango, P.S. Orina, R.C. Rsamkat, C. Kowenje, C.M. Githukia, D. Lusweti, et al., Review of current state of knowledge of microcystin and its impacts on fish in Lake Victoria, *Lakes Reserv.* 25 (2020) 350–361, <https://doi.org/10.1111/lre.12328>.
- [95] C.H.D. Magadza, Indications of the effects of climate change on the pelagic fishery of Lake Kariba, Zambia-Zimbabwe, *Lakes Reserv.: Res. Manag.* 16 (1) (2011) 15–22, <https://doi.org/10.1111/j.1440-1770.2011.00462.x>.
- [96] M.R. Ndebele, C.H.D. Magadza, The occurrence of microcystin-LR in Lake Chivero, Zimbabwe, *Lakes Reservoirs: Res. Manag.* 11 (2006) 57–62, <https://doi.org/10.1111/j.1440-1770.2006.00287.x>.
- [97] L.L. Ndlela, P.J. Oberholster, J.H. Van Wyk, P.H. Cheng, An overview of cyanobacterial bloom occurrences and research in Africa over the last decade, *Harmful Algae* 60 (2016) 11–26, <https://doi.org/10.1016/j.hal.2016.10.001>.
- [98] O.P. Ochumba, D.I. Kibaara, Observations on blue-green algal blooms in the open waters of Lake Victoria, Kenya *Afr. J. Ecol.* 27 (1989) 23–34.
- [99] G.J. Mchau, R. Machunda, M. Kimanya, E. Makule, Y.Y. Gong, E. Mpolya, et al., First report of the co-occurrence of cylindrospermopsin, nodularin and microcystins in the freshwaters of Lake Victoria, Tanzania, *Expos. Health* 13 (2021) 185–194, <https://doi.org/10.1007/s12403-020-00372-7>.
- [100] M.M. Mokoena, M.S. Mukhola, Current effects of cyanobacteria toxin in water sources and containers in the Hartbeespoort Dam Area, South Africa, *Int. J. Environ. Res. Public Health* 16 (22) (2019) 4468, <https://doi.org/10.3390/ijerph16224468>.
- [101] G.A. Codd, S.M.F.O. Azevedo, S.N. Bagchi, M.D. Burch, W.W. Carmichael, W.R. Harding, et al. CYANONET: a global network for Cyanobacterial bloom and toxin risk management: initial situation assessment and recommendations, International Hydrological Programme (IHP) of the United National Educational, Scientific and Cultural Organization (UNESCO). IHP-VI. Technical Documents in Hydrology. Working Series SC-2005/WS/55, 2005.
- [102] B. Zilberg, Gastro-enteritis in Salisbury European children—a five-year study, *Cent. Afr. J. Med.* 12 (9) (1966) 164–168.
- [103] B.E. Marshall, Toxic cyanobacteria in Lake Chivero: a possible health hazard?, *Trans. Zimb. Sci. Assoc.* 65 (1991) 16–19.
- [104] Y. Ueno, S. Nagat, T. Tsutsumi, A. Hasegawa, M.F. Watanabe, H.-D. Park, et al., Detection of microcystins, a blue-green algal hepatotoxin, in drinking water sampled in Haimen and Fusui, endemic areas of primary liver cancer in China, by

- highly sensitive immunoassay, *Carcinogenesis* 17 (6) (1996) 1317–1321.
- [105] B.M. Simiyu, S.O. Oduor, T. Rohrlack, L. Sitoki, R. Kurmayer, Microcystin content in phytoplankton and in small fish from eutrophic Nyanza Gulf, Lake Victoria, Kenya, *Toxins* 10 (7) (2018) 275, <https://doi.org/10.3390/toxins10070275>.
- [106] M.F. Abdallah, W.H.R. Van Hassel, M. Andjelkovic, A. Wilmotte, A. Rajkovic, Cyanotoxins and food contamination in developing countries: review of their types, toxicity, analysis, occurrence and mitigation strategies, *Toxins* 13 (2021) 786, <https://doi.org/10.3390/toxins13110786>.
- [107] E. Funari, E. Testai, Human health risk assessment related to cyanotoxins exposure, *Crit. Rev. Toxicol.* 38 (2) (2008) 97–125, <https://doi.org/10.1080/10408440701749454>.
- [108] I. Stewart, P.M. Webb, P.J. Schluter, G.R. Shaw, Recreational and occupational field exposure to freshwater cyanobacteria-A review of anecdotal and case reports, epidemiological studies and the challenges for epidemiologic assessment, *Environ. Health* 5 (2006) 6, <https://doi.org/10.1186/1476-069X-5-6>.
- [109] M.G. Klanian, M.G. Alonso, Sensory characteristics and nutritional value of red drum *Sciaenops ocellatus* reared in freshwater and seawater conditions, *Aquac. Res.* 46 (7) (2015) 1550–1561, <https://doi.org/10.1111/are.12307>.
- [110] V.R. Hamandishe, P.T. Saidi, V.E. Imbayarwo-Chikosi, T. Nhwatiwa, A comparative evaluation of carcass quality, nutritional value, and consumer preference of oreochromis niloticus from two impoundments with different pollution levels in Zimbabwe, *Int. J. Food Sci.* 2018 (2018) 1–10, <https://doi.org/10.1155/2018/7862971>.
- [111] T. Nchabeleng, P. Cheng, P. Oberholster, A.-M. Botha, W. Smit, W. Luus-Powell, Microcystin-LR equivalent concentrations in fish tissue during a post bloom Microcystis exposure in Loskop Dam, South Africa, *Afr. J. Aquat. Sci.* 39 (4) (2014) 459–466, <https://doi.org/10.2989/16085914.2014.973830>.
- [112] C. MacKintosh, K.A. Beattie, S. Klumpp, P. Cohen, G.A. Codd, Cyanobacterial microcystin-LR is a potent and specific inhibitor of protein phosphatases 1 and 2A from both mammals and higher plants, *FEBS Lett.* 264 (2) (1990) 187–192, [https://doi.org/10.1016/0014-5793\(90\)80245-e](https://doi.org/10.1016/0014-5793(90)80245-e).
- [113] I.R. Falconer, A.R. Humpage, Tumour promotion by cyanobacterial toxins, *Phycologia* 35 (1996) 74–79.
- [114] T.W. Zewde, J.A. Johansen, D. Kifle, T.B. Demissie, J.H. Hansen, Z. Tadesse, Concentrations of microcystins in the muscle and liver tissues of fish species from Koka reservoir, Ethiopia: a potential threat to public health, *Toxicon* 153 (2018) 85–95, <https://doi.org/10.1016/j.toxicon.2018.08.013>.
- [115] R. Semyalo, J.K. Nattabi, P. Larsson, Diel vertical migration of zooplankton in a eutrophic bay of Lake Victoria, *Hydrobiologia* 635 (2009) 383–394, <https://doi.org/10.1007/s10750-009-9931-5>.
- [116] S. Haande, A. Ballot, T. Rohrlack, J. Fastner, C. Wiedner, B. Edvardsen, Diversity of *Microcystis aeruginosa* isolates (Chroococcales, Cyanobacteria) from East-African water bodies, *Arch. Microbiol.* 188 (2007) 15–25, <https://doi.org/10.1007/s00203-007-0219-8>.
- [117] K. Sivonen, G. Jones, Cyanobacterial toxins, in: I. Chorus, J. Bartram (Eds.), *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*, E & FN Spon, London, 1999.
- [118] H. Wang, C. Xu, Y. Liu, E. Jeppesen, J.-C. Svenning, J. Wu, et al., From unusual suspect to serial killer: cyanotoxins boosted by climate change may jeopardize megafauna, *The Innovation* 2 (2) (2021) 100092, <https://doi.org/10.1016/j.xinn.2021.100092>.

- [119] R. Bengis, D. Govender, E. Lane, J. Myburgh, P. Oberholster, P. Buss, et al., Eco-epidemiological and pathological features of wildlife mortality events related to cyanobacterial bio-intoxication in the Kruger National Park, South Africa, *J. South. Afr. Vet. Assoc.* 87 (1) (2016) 1–9, <https://doi.org/10.4102/jsava.v87i1.1391>.
- [120] IPCC, Summary for policymakers, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2021.
- [121] B.E. Marshall, An assessment of climate change and stratification in Lake Kariba (Zambia-Zimbabwe), *Lakes Reserv.: Res. Manag.* 22 (3) (2017) 229–240, <https://doi.org/10.1111/lre.12185>.
- [122] L.A. Olaka, E.O. Odada, M.H. Trauth, D.O. Olago, The sensitivity of East African rift lakes to climate fluctuations, *J. Paleolimnol.* 44 (2010) 629–644, <https://doi.org/10.1007/s10933-010-9442-4>.
- [123] S. Stenuite, S. Pirlot, M.A. Hardy, H. Sarmento, A.-L. Tarbe, B. Leporcq, et al., Phytoplankton production and growth rate in Lake Tanganyika: evidence of a decline in primary productivity in recent decades, *Freshw. Biol.* 52 (11) (2007) 2226–2239, <https://doi.org/10.1111/j.1365-2427.2007.01829.x>.
- [124] P. Verburg, R.E. Hecky, The physics of the warming of Lake Tanganyika by climate change, *Limnol. Oceanogr.* 54 (6part2) (2009) 2418–2430, [https://doi.org/10.4319/lo.2009.54.6\\_part\\_2.2418](https://doi.org/10.4319/lo.2009.54.6_part_2.2418).
- [125] P. Tendaupenyu, C.H.D. Magadza, Possible effects of global warming on the growth of five species of algae, *J. Appl. Sci. South. Afr.* 17 (1) (2011) 17–25.
- [126] L. Ramberg, Phytoplankton succession in the Sanyati basin, Lake Kariba, *Hydrobiologia* 153 (1987) 193–202.
- [127] B.M. Kraemer, T. Mehner, R. Adrian, Reconciling the opposing effects of warming on phytoplankton biomass in 188 large lakes, *Sci. Rep.* 7 (2017) 10762, <https://doi.org/10.1038/s41598-017-11167-3>.
- [128] A.D. Ficke, C.A. Myrick, L.J. Hansen, Potential impacts of global climate change on freshwater fisheries, *Rev. Fish. Biol. Fish.* 17 (4) (2007) 581–613, <https://doi.org/10.1007/s11160-007-9059-5>.
- [129] T. Mahere, M. Mtsambiwa, P. Chifamba, T. Nhiwatiwa, Climate change impact on the limnology of Lake Kariba, Zambia–Zimbabwe, *Afr. J. Aquat. Sci.* 39 (2) (2014) 215–221, <https://doi.org/10.2989/16085914.2014.927350>.
- [130] M.K. Vollmer, H.A. Bootsma, R.E. Hecky, G. Patterson, J.D. Halfman, J.M. Edmond, et al., Deep-water warming trend in Lake Malawi, East Africa, *Limnol. Oceanogr.* 50 (2005) 727–732.
- [131] A. Lorke, K. Tietze, M. Halbwachs, A. Wüest, Response of Lake Kivu stratification to lava inflow and climate warming, *Limnol. Oceanogr.* 49 (3) (2004) 778–783, <https://doi.org/10.4319/lo.2004.49.3.0778>.
- [132] Scheumann, W., Neubert, S. (Eds.) *Transboundary water management in Africa: challenges for development cooperation (DIE Studies, 21)*. Bonn: Deutsches Institut für Entwicklungspolitik gGmbH, 2006. <https://nbn-resolving.org/urn:nbn:de:0168-ssoar-109930> (accessed 12.02.22).
- [133] H. Wang, T. Wang, B. Zhang, F. Li, B. Toure, I.B. Omosa, et al., Water and wastewater treatment in Africa—current practices and challenges, *Clean. Soil Air Water* 42 (2014) 1029–1035, <https://doi.org/10.1002/clen.201300208>.
- [134] I. Nhapi, M.A. Siebel, H.J. Gijzen, A proposal for managing wastewater in Harare, Zimbabwe, *Water Environ. J.* 20 (2) (2006) 101–108, <https://doi.org/10.1111/j.1747-6593.2006.00018.x>.
- [135] F.J.W. Herbig, Talking dirty—effluent and sewage irreverence in South Africa: a

- conservation crime perspective, *Cogent Soc. Sci.* 5 (2019) 1, <https://doi.org/10.1080/23311886.2019.1701359>.
- [136] J. Ndjama, G. Ajeagah, N. Nkoue, W. Jude, N. Birama, G. Eyong, et al., Physico-chemical and biological characteristics of the Nklobisson Artificial Lake in Yaounde, Cameroon, *J. Water Resour. Prot.* 9 (2017) 1547–1563, <https://doi.org/10.4236/jwarp.2017.912098>.
- [137] K. Karume, M. Bagalwa, E. Bagula, M. Yalire, P. Habakaramo, J. Byamukama, et al., Water quality in and around Lake Edward Basin of the Greater Virunga Landscape, D.R. Congo Side, *J. Environ. Prot.* 10 (2019) 1174–1193, <https://doi.org/10.4236/jep.2019.109070>.
- [138] J.F. Talling, I.B. Talling, The chemical composition of African lake waters, *Int. Rev. Ges. Hydrobiol. Hydrogr.* 50 (1965) 421–463.
- [139] A.B. Viner, Relationships of nitrogen and phosphorus to a tropical phytoplankton population, *Hydrobiologia* 52 (1977) 185–196.
- [140] M. Prajapati, J.J. van Bruggen, T. Dalu, R. Malla, Assessing the effectiveness of pollutant removal by macrophytes in a floating wetland for wastewater treatment, *Appl. Water Sci.* 7 (8) (2017) 4801–4809, <https://doi.org/10.1007/s13201-017-0625-2>.
- [141] S.A.A.A.N. Almuktar, S.N. Abed, M. Scholz, Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review, *Environ. Sci. Pollut. Res.* 25 (24) (2018) 23595–23623, <https://doi.org/10.1007/s11356-018-2629-3>.
- [142] M. Bouali, I. Zrafi, F. Mouna, Bakhrouf, A. Pilot study of constructed wetlands for tertiary wastewater treatment using duckweed and immobilized microalgae, *Afr. J. Microbiol. Res.* 6 (32) (2012), <https://doi.org/10.5897/ajmr12.455>.
- [143] S.E. Agarry, K.M. Oghenejoboh, G.K. Latinwo, C.N. Owabor, Biotreatment of petroleum refinery wastewater in vertical surface-flow constructed wetland vegetated with *Eichhornia crassipes*: lab-scale experimental and kinetic modelling, *Environ. Technol.* 41 (14) (2020) 1793–1813, <https://doi.org/10.1080/09593330.2018.1549106>.
- [144] I. Hassan, S.R. Chowdhury, P.K. Prihartato, S.A. Razzak, Wastewater treatment using constructed wetland: current trends and future potential, *Processes* 9 (2021) 1917, <https://doi.org/10.3390/pr9111917>.
- [145] C.C. Azubuikwe, C.B. Chikere, G.C. Okpokwasili, Bioremediation techniques—classification based on site of application: principles, advantages, limitations and prospects, *World J. Microbiol. Biotechnol.* 32 (2016) 180, <https://doi.org/10.1007/s11274-016-2137-x>.
- [146] M.E. Smith, G.C. Pitcher, Saldanha Bay, South Africa I: the use of ocean colour remote sensing to assess phytoplankton biomass, *Afr. J. Mar. Sci.* 37 (4) (2015) 503–512, <https://doi.org/10.2989/1814232x.2015.1093023>.
- [147] T. Dube, O. Mutanga, K. Seutloali, S. Adelabu, C. Shoko, Water quality monitoring in sub-Saharan African lakes: a review of remote sensing applications, *Afr. J. Aquat. Sci.* 40 (1) (2015) 1–7, <https://doi.org/10.2989/16085914.2015.1014994>.
- [148] T. Lamont, R.J.W. Brewin, R.G. Barlow, Seasonal variation in remotely-sensed phytoplankton size structure around southern Africa, *Remote. Sens. Environ.* 204 (2018) 617–631, <https://doi.org/10.1016/j.rse.2017.09.038>.
- [149] M.W. Matthews, S. Bernard, Characterizing the absorption properties for remote sensing of three small optically-diverse South African reservoirs, *Remote. Sens.* 5 (9) (2013) 4370–4404, <https://doi.org/10.3390/rs5094370>.
- [150] M.G. Tulbure, M. Broich, Spatiotemporal dynamic of surface water bodies using Landsat time-series data from 1999 to 2011, *ISPRS J. Photogramm. Remote. Sens.* 79 (2013) 44–52.

- [151] M.A. Wulder, T.R. Loveland, D.P. Roy, C.J. Crawford, J.G. Masek, C.E. Woodcock, et al., Current status of Landsat program, science, and applications, *Remote. Sens. Environ.* 225 (2019) 127–147, <https://doi.org/10.1016/j.rse.2019.02.015>.
- [152] T. Dalu, T. Dube, P.W. Froneman, M.T. Sachikonye, B.W. Clegg, T. Nhiwatiwa, An assessment of chlorophyll-a concentration spatio-temporal variation using Landsat satellite data, in a small tropical reservoir, *Geocarto Int.* 30 (10) (2015) 1130–1143.
- [153] S. Mollae, Estimation of phytoplankton chlorophyll-a concentration in the western basin of Lake Erie using Sentinel-2 and Sentinel-3 data. Master's thesis, University of Waterloo, 2018.
- [154] M. Chawira, T. Dube, W. Gumindoga, Remote sensing based water quality monitoring in Chivero and Manyame lakes of Zimbabwe, *Phys. Chem. Earth* 66 (Parts A/B/C) (2013) 38–44.
- [155] N. Pahlevan, B. Smith, J. Schalles, C. Binding, Z. Cao, R. Ma, et al., Seamless retrievals of chlorophyll-a from Sentinel-2 (MSI) and Sentinel-3 (OLCI) in inland and coastal waters: a machine-learning approach, *Remote. Sens. Environ.* (2020) 111604, <https://doi.org/10.1016/j.rse.2019.111604>.
- [156] S. Li, K. Song, S. Wang, G. Liu, Z. Wen, Y. Shang, et al., Quantification of chlorophyll-a in typical lakes across China using Sentinel-2 MSI imagery with machine learning algorithm, *Sci. Total Environ.* 778 (2021) 146271, <https://doi.org/10.1016/j.scitotenv.2021.146271>.
- [157] J. Delegido, J. Verrelst, L. Alonso, J. Moreno, Evaluation of sentinel-2 red-edge bands for empirical estimation of green LAI and chlorophyll content, *Sensors* 11 (7) (2011) 7063–7081, <https://doi.org/10.3390/s110707063>.
- [158] M.P. Sandoval, E.P. Urrego, A. Ruiz-Verdu, N.C.T. Gil, J. Delegido, X.S. Perpinyà, et al., Calibration and validation of algorithms for the estimation of chlorophyll-a concentration and Secchi depth in inland waters with Sentinel-2, *Limnetica* 38 (1) (2019) 471–487, <https://doi.org/10.23818/limn.38.27>.
- [159] A. Ansper, K. Alikas, Retrieval of chlorophyll a from Sentinel-2 MSI data for the European Union water framework directive reporting purposes, *Remote. Sens.* 11 (1) (2019) 64, <https://doi.org/10.3390/rs11010064>.
- [160] C. Cairo, C. Barbosa, F. Lobo, E. Novo, F. Carlos, D. Maciel, et al., Hybrid chlorophyll-a algorithm for assessing trophic states of a tropical Brazilian reservoir based on msi/sentinel-2 data, *Remote. Sens.* 12 (1) (2020) 40, <https://doi.org/10.3390/rs12010040>.
- [161] T. Dalu, P.W. Froneman, Diatom-based water quality monitoring in southern Africa: challenges and future prospects, *Water SA* 42 (4) (2016) 551–559.