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Harmful algae in aquaculture systems in Ngerengere Catchment, Morogoro, Tanzania: Descriptive community structure and environmental concerns

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ABSTRACT

Climate variability, anthropogenic activities, and hydrological shifts are fueling the nuisance of harmful algal blooms in water bodies. Unfortunately, cyanobacterial harmful algal blooms (CyanoHABs) dynamics have not received much attention in Tanzania. The study aimed to identify and characterize common species of cyanobacteria and examine their possible change in composition and succession in the Ngerengere catchment, Morogoro, Tanzania. Water samples from the selected reservoirs were collected quarterly between October 2017 and September 2018 for physico-chemical parameters in situ and in the laboratory. A benchtop FlowCAM was used for the identification of cyanobacteria and compared with the literature and available online databases. Principal component analysis (PCA) was used to examine the association between the physico-chemical variables and meteorological patterns. The study found common CyanoHABs such as *Microcystis*, *Cylindrospermopsis*, *Anabaena* (*Dolichospermum*), *Lyngbya* as well as other species such as diatoms and *Euglena* which are also considered nuisance. Virtually, a colonial cyanobacteria species dominated the fishponds, while Mindu Dam was more of filamentous species. The study suggest that Mindu dam, based on Carlson's Trophic State Index (TSI), falls under eutrophic while the fishponds were hypereutrophic. Associated physico-chemical conditions, heavy rainfall and prolonged dry conditions influenced cyanobacteria bloom dynamics. The hydrological connectivity between the fishponds and the Mindu Dam poses a threat to public health because a significant population in Morogoro depends on Mindu Dam for domestic water supply. There is a need for the development of a framework for mitigative and adaptive measures in the catchment, especially during pre-and post-occurrence of blooms.

1. Introduction

Climate variability, anthropogenic activities, and hydrological shifts are fueling the nuisance of harmful algae (CyanoHABs) in water bodies. Cyanobacterial harmful algal blooms are known for their ability to produce cyanotoxins and hypoxia condition, but also alters food web, which are problematic for humans, domestic animals, fish, and wildlife (Nyakairu et al., 2010). Impacts of CyanoHABs into the environment, humans, and pets have been previously studied (Barange et al., 2018; Brooks et al., 2016; Busch et al., 2013; Flores et al., 2018; Griffith and Gobler, 2019; Hazen and Sawyer, 2015; Ho and Michalak, 2015; Lopez et al., 2008; Paerl et al., 2018; Sanseverino et al., 2016; Suzane, 2016; Wells et al., 2015). For example, about 40–70% of cyanobacteria blooms reported worldwide are toxic (Turner et al., 2018). Majority of toxin-producers are planktonic (e.g., *Anabaena, Aphanizomenon, Planktothrix, and Cylindrospermopsis*) and benthic (e.g., *Lyngbya*) species, but also there are others (for instance *Gloeotrichia*) which have both planktonic and benthic properties (Watson et al., 2015). The tendency of CyanoHABs in freshwater ecosystems is to increase due to environmental and climatic changes (Graham et al., 2018) however that there is still a knowledge gap in understanding their interaction (Chen et al., 2016). Some previous studies (Cho et al., 2014; Chon, 2011) revealed a complex interplay between algal cyanobacteria communities and environmental conditions. The complexity has resulted in different types of metrics such as qualitative estimation of cyanobacteria, remotely sensed-based, toxins concentrations, biovolume, and impacts related

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metrics (Ho and Michalak, 2015).

Till now, there are about 2000 species in 150 genera of cyanobacteria (Vincent, 2009) and more than 55 species in thirty (30) genera have been confirmed to be toxin-producers (Table 1) (UNESCO et al., 2004). Morphologically, there are bloom-forming groups of cyanobacteria, such as, coccoid cells (e.g., *Synechococcus, Chroococcus* and *Microcystis* species), filaments of undifferentiated cells (e.g. *Oscillatoria* and *Planktothrix* species) and filaments with differentiated cells (e.g. *Anabaena, Aphanizomenon, Cylindrospermopsis*, and *Nodularia* species) (Paerl, 2014).

Cyanobacteria may survive and exploit a wide range of environmental conditions. For example, they have the ability to uptake phosphorus, fix atmospheric nitrogen, acquisition of inorganic carbon, dissipating excess light energy, and photo adaptive mechanism (Westermark and Steuer, 2016), (Berg and Sutula, 2015; Watson et al., 2015). Therefore understanding their dynamics is paramount important. The recent advances in imaging technologies, such as FlowCAM for morphological identification and quantification of cyanobacteria, proved to have a significant achievement over conventional techniques (Graham et al., 2018). FlowCAM combines both speed and statistical capabilities of a flow cytometer with imaging features of the microscope (Dashkova, Malashenkov, Poulton, Vorobjev and Barteneva, 2017a). The technology is among the global efforts for the identification and quantification of cyanobacteria biovolume in freshwaters that lack spatial monitoring data (Ko et al., 2017; Patiño et al., 2014; Wells et al., 2015).

Traditional methods for quantification of planktons community in the environment are slow, tedious, and laborious although they have contributed to the research. In Morogoro, Tanzania, previous studies have demonstrated the use of molecular methods for quantifying microbial communities. A comparison of microbial community structure from agriculture, urban, and pristine areas identified 8% species of cyanobacteria in which *Cylindrospermopsis* was the dominant (Mushi, 2015), while others (Mdegela et al., 2011) demonstrated the occurrence of *Microcystis* species. Both studies (Mdegela et al., 2011; Mushi, 2015) did not show the harmful potentials of the identified species nor the interaction with environmental factors. Some other previous works evidenced levels of water pollution (GLOWS-FIU, 2014b, 2014a; Mero, 2011) which might influence algal proliferation. Coupled effects of land use change, climate, and hydrological variation on water resources has also been reported in the previous studies (Natkhin et al., 2015). The hydrological connectivity of the catchment raise more concern and that there is a need to validate or contribute to the previous studies so as to assist in the management decision of the Ngerengere catchment.

Chlorophyll-a has been widely accepted rather a proxy for the estimation of Cyanobacteria (Merel et al., 2013). However, as stated earlier there are other metrics can be used to confidently identify the occurrences of cyanobacteria (Wang et al., 2015). Modern technologies, such as, FlowCAM has proved to be rapid, sophisticated, and useful for morphological identification of phytoplankton in water samples (Dashkova, Malashenkov, Poulton, Vorobjev and Barteneva, 2017b). With FLowCAM®, it is also possible to morphologically distinguish features of the specific cyanobacteria species (Busch et al., 2013). The present study aimed to identify and characterize common species of cyanobacteria with the up-to-date tool and examine their possible change in composition and succession in the Ngerengere catchment, Morogoro, Tanzania. The study also aimed to provides insight into the environmental factors that control cyanobacteria bloom in the catchment.

2. Material and methods

2.1. Description of the study site

Ngerengere Catchment is the sub-catchment of the Wami Ruvu basin situated in Morogoro, the United Republic of Tanzania (Fig. 1). Mindu

Table 1
Different orders, characteristics and genera for cyanobacteria ((UNESCO et al., 2004); (Vincent, 2009); and (Paerl et al., 2018)).

Order	Characteristics	Illustrative genera
1. Chroococcales	Coccoid cells that reproduce by binary fission (one, two or more planes) or budding Do not form true filaments	*Aphanocapsa, Aphanothece, Gloeocapsa, Merismopedia, Microcystis, Synechococcus, Synechocystis*
2. Pleurocapsales	Coccoid cells, aggregates or pseudo-filaments that reproduce by baeocytes	*Chroococcidiopsis, Pleurocapsa*
3. Oscillatoriales	Uniseriate filaments, without heterocysts or akinetes	*Lyngbya, Leptolyngbya, Microcoleus, Oscillatoria, Phormidium, Planktothrix*
4. Nostocales	Filamentous cyanobacteria that divide in only one plane, with heterocysts; false branching in genera such as Scytonema	*Anabaena, Aphanizomenon, Calothrix, Cylindrospermopsis, Nostoc, Scytonema, Tolypothrix*
5. Stigonematales	Division in more than one plane; true branching and multiseriate forms; heterocysts	*Mastigocladus (Fischerella), Stigonema*

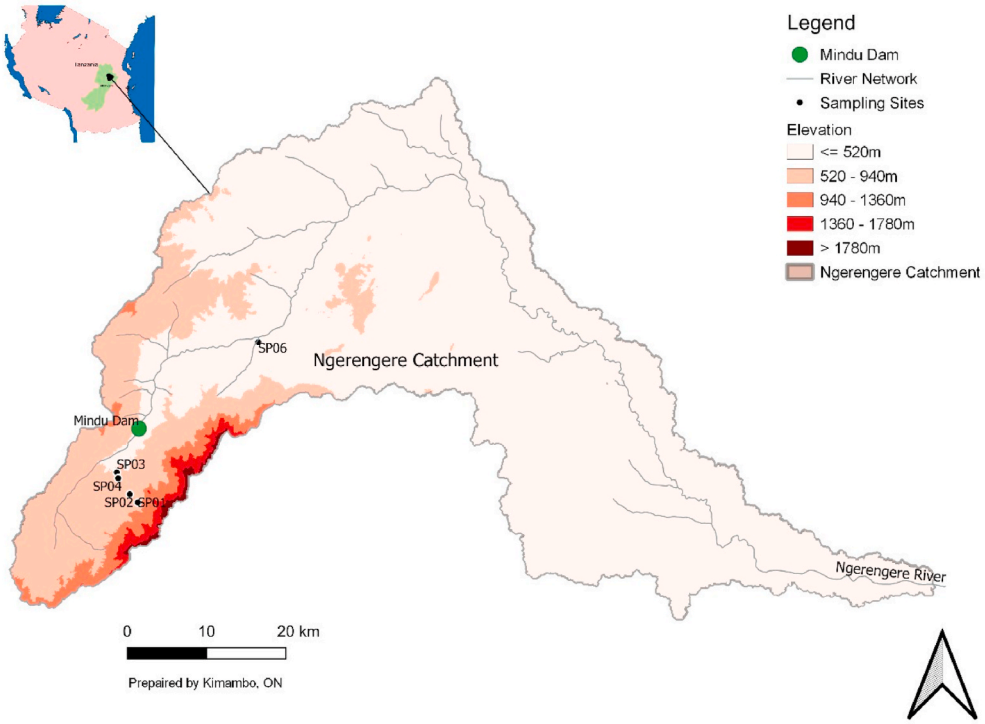

Fig. 1. A map showing sampling points namely SP01, SP02, SP03, SP04, SP05, and SP06 in the study area.

Dam is the main reservoir suppling water for domestic uses to a larger population in Morogoro Urban and fishery (Ngoye and Machiwa, 2004). Regarding the climate, daily maximum temperatures range between 18 and 33 °C and annual precipitation between 800 and 1500 mm (Kimambo et al., 2019). There is a noticeable hydrological connection between river tributaries in the upper Ngerengere catchment with active fishponds and the Mindu Dam.

Land use changes and climate variability and change in the Ngerengere catchment has been also studied deeply (Benjamin, 2017; Mbungu, 2016; Natkhin et al., 2015; Shagega, Munishi, & Kongo, 2019, 2020). These studies show that land use and climate variability and change are the key factors on the increasing pressure on water resources in the Ngerengere catchment. For example, a contribution of both climate variability and human activities to the changes on streamflow are 46% and 54% respectively (Mbungu, 2016).

Table 2
Description of the sampling points.

Label	Fishpond/Dam location	Latitude (degree) -	Longitude (degree) - East	Altitude (m) (AMSL[a])	Surface area (m^2)	Site description (See also Supplementary Fig. S1 for field images)
SP01	Tangeni- Chalinze	−6.93794	37.6164831	803	200	The pond is Located at Tangeni Village (Chalinze), in Mzumbe Ward, Morogoro with a depth of 1 m. Fish grown in the pond were Oreochromis *niloticus* (Tilapia). The farmer uses poultry manure as a nutrient enrichment to the pond and water is added twice a week (according to the farmer), from a nearby the Ngerengere River (less than 10 m from the river).
SP02	Tangeni-Kikoya	−6.92866	37.6072377	623	105	The pond is located at Tangeni Village (Kikoya). The owner uses cattle, poultry, and pig manure as a source of nutrients to his pond. The depth of the pond was 1 m (the pond was also at about 30 m from Ngerengere River)
SP03	Konga- Kidangawa	−6.90356	37.5925432	502	575	At this point, there are more than five fishponds. One pond was selected as the representative of all. The depth of the pond was 1.5 m. *Clarias gariepinus* (African catfish) and *O. niloticus* (Tilapia) are the two species of fish being farmed in these ponds. The pond uses water from Lukurunge River, a tributary of Ngerengere River
SP04	Konga-Kidangawa	−6.91039	37.5941065	515	600	Natural pond, with no outlet. Recharge is mainly runoff from nearby paddy fields. The pond is irregular in shape with an estimated depth of 1.5 m. A mixture of African catfish and Tilapia are farmed all together.
SP05	Mindu Dam	−6.85537	37.6144658	477	4.2×10^6	Public owned reservoir which supplies freshwater and freshwater fishery to a larger population in Morogoro municipality. The dam varies in depth from the center (11 m) to the shores (ranging between 1 and 2 m). The dam receives water from Ngerengere, Mzinga, Mgera and Lukulunge River tributaries.
SP06	Kingolwira National -Fish Farming Center	−6.75568	37.7543226	427	200	Government-owned fish farming Centre with several fishponds in series, with 2 m depth. The center is known to produce Fingerlets. The center tapped water from the source of Bigwa River which is a tributary of the Ngerengere River and downstream the Mindu Dam.

[a] Above Mean Sea Level (AMSL).

2.2. Sampling design and samples preparations

Samples were collected from five fishponds and a Mindu Dam in October 5, 2017, January 29, 2018, May 29, 2018, and September 9, 2018 (see a detailed description of the sampling points in Table 2 and Fig. S1 in the supplementary information). The first sampling point (SP01 at Tangeni, Village) was at the highest elevation which in the present study was assumed to be a control site since it is free from human interactions (e.g., agriculture and or domestic discharges). On the other hand, sampling point six (SP06) (Kingolwira National Fish Farming Center) although it is at the lowest elevation its pipes water from the source of River Bigwa which is also assumed to be free from human interactions. The sampling schedules considered both wet and dry seasons i.e., October 2017 (representing September October November - SON), January 2018 (representing December, January February - DJF), May 2018 (representing March April, May - MAM), and August 2018 (representing June July August - JJA).

2.3. Physico-chemical parameters

Water temperature (Tw), pH, and total dissolved solids (TDS) were measured in the field with a calibrated pH meter HM-30P, DKK-TOA Corporation. Electrical conductivity (EC) (μs/cm) was measured using a HACH conductivity meter. Dissolved oxygen (DO) (mg/L) was measured using self-calibrating DO-31P, DKK-TOA Corporation. Transparency (cm) was measured using a Secchi disk and turbidity (nephelometric turbidity unit-NTU) was measured using turbidity meter HI98703. All the instruments were calibrated a day before field campaigns. Meteorological data in the Ngerengere were also collected for linking it with the variation and shift in cyanobacteria. Weather data during the entire period of study were obtained from the automatic weather station located at the College of Science and Education, Sokoine University Mazimbu, Morogoro.

2.4. Total alkalinity, color, and total phosphorus concentrations

Total alkalinity, apparent color, and total phosphorus were determined in the laboratory. Water samples were collected in a polyethylene bottles and transported to the laboratory in a cooler box until analysis was done. Apparent color (mg/L Pt. Co) which considers both dissolved materials and suspended matter and total alkalinity (mg/L) were analyzed immediately after sampling to avoid agitation and prolonged exposure to air. The study used the APHA Platinum–Cobalt standard method for Colors determination while for the total alkalinity; a titrimetric method and thereafter estimated using equation (1) (American Public Health Association, 1999).

$$Total\ Alkalinity\ \left(\frac{mg}{L}\right) = \frac{B^{*}N^{*}50000}{ml\ of\ Sample\ used} \quad (1)$$

where B is the total volume (ml) of titrant used for a sample to reach endpoint and N is the normality of the titrant.

The total phosphorus (mg/L) was determined by the ascorbic acid colorimetric method using a Spectroquant® following the manufacture's directives (Merk KGaA, Darmstadt, Germany). In sulfuric solution, orthophosphate and molybdate ions form molybdophosphoric acid. The detection limit for the total phosphorous was 0.05 mg/L.

2.5. Chlorophyll-a estimation

Water samples were filtered using a Whatman glass fiber filter (GF/C) with a pore size of 0.47 μm. The filters were labeled and wrapped in aluminum foil within the Petri dish and frozen (at −20 °C) until shipping. The samples were shipped frozen in a dry ice cooler box to the University of Venda, South Africa for analysis. The filter papers were cut into five-six pieces and inserted into a 50 ml centrifuge tube, added 20 ml of methanol (95%), and mixed (shake and vortex) until the filter was broken up and then stored with plastic closure in the refrigerator overnight. After that, the solution was centrifuged at 3200 rpm for 10 min. The supernatant was then measured at 665 nm and 750 nm and the Chlorophyll-a concentrations were calculated according to equation (2) (Holm-Hansen and Riemann, 1978).

$$\mathrm{Chl-a}(\mu g / L) = ((Abs\ at\ 665\ nm - Abs\ at\ 750\ nm) * A * Vm) / (Vf * L) \quad (2)$$

where A is the absorbance coefficient of Chlorophyll-a in methanol (12.63); Vm is the volume of methanol used for extinction (ml), Vf is the volume of sample filtered, and L is the pass length of the cuvette (1 cm).

2.6. Phytoplankton samples processing

Water samples for morphological identification and classification of cyanobacteria species were immediately preserved with 1% (1mL/100 mL) Lugol's solution in a 50 ml polypropylene conical centrifuge tubes as previously described (Graham et al., 2018) and shipped in a cooler box (in wet ice) to the University of Venda, South Africa for analysis. A pre-filtered sample (Davis, 2015) was subjected to a dynamic imaging particle analyzer (FlowCAM®) (Fluid Imaging Technologies, Yarmouth, ME USA) under the auto image mode, with a magnification of 10× objective, flow cell of 100 μm (Descy and Sarmento, 2008) and (IOC-UNESCO et al., 2010). The morphological identification of common species of cyanobacteria includes cell arrangements such as the colonies and filaments, terminal cell shape in filaments, and the presence of unique geometric shapes as suggested by [20], [21] (Rosen et al., 2017) (Komárek and Hauer, 2013), [54]–[56]. Common geometric shapes are used to identify different species such as spheres (*Anabaena* and *Microcystis*), ellipsoid (*Anabaena*, *Anabaenopsis*), cylinder (*Aphanizomenon, Pseudanabaena, Cylindrospermopsis, Oscillatoria, Planktothrix,* and *Nodularia*), rod-shaped (*Synechococcus, Aphanothece, and Cyanonephron*) and cone shape. For estimating biovolume from each sampling point spherical diameter (ESD) and area-based diameter (ABD) were evaluated with VisualSpreadsheet 3.2.2 Software which comes with the FlowCAM® as previously described (Álvarez et al., 2012; Dashkova et al., 2017b; Wang et al., 2015).

2.7. Data analyses

A principal component analysis (PCA) was performed to examine the association between the observed physico-chemical and biological parameters. For meteorological data, a patterns analysis with a moving average (MA) was also performed to obtain a cumulative reading (48 points corresponding to a daily observation originating from every 30 min observation). The descriptive statistics, Pearson correlation, PCA, and test statistics were done using XLSTAT-Addinsoft 2019.1.3 (Addinsoft, 2019). Trophic status for all the sampling points and phases was estimated by using Carlson's Trophic State Index (TSI) (Sulis et al., 2014). 3.

3. Results

3.1. Physico-chemical characteristics

In the present study, total phosphorous concentration, turbidity, chlorophyll-a, and color showed a huge variation of 149%, 108, %, 80%, and 89% respectively. On the other hand, temperature and pH showed low variation 11% and 9% respectively (Table 3).

3.2. Morphological identification

Cyanobacterial species of Coccoid, filamentous, colonial (*Microcystis*) were found in nearly all sampling points (Supplementary Information Figs. S2–S7). In all the sampling points and phases,

Table 3
Descriptive statistics for all the environmental variables investigated.

Statistic	Chl-a µg/L	Colour (mg/L Pt. Co)	Alkalinity (mg/L)	DO (mg/L)	EC (µS/cm)	pH (unit)	SDD (cm)	TDS (mg/L)	Turbidity	Tw (°C)	TP (mg/L)
Minimum	9.4	16.3	20.9	1.6	35.3	6.5	4.7	17.7	4.0	22.6	0.1
Maximum	103.9	547.0	198.3	10.8	247.0	9.7	107.7	123.7	233.3	31.2	5.8
Range	94.5	530.7	177.4	9.2	211.7	3.2	103.0	106.0	229.3	8.6	5.7
1st Quartile	14.4	59.6	46.2	4.9	88.2	7.2	26.3	44.0	15.6	25.5	0.3
Median	23.1	123.2	68.6	5.9	139.5	7.6	34.5	69.8	28.3	27.7	0.4
3rd Quartile	37.6	230.8	103.2	7.3	176.9	8.4	50.3	88.8	53.8	29.9	0.6
Mean	33.0	173.3	79.5	6.3	137.9	7.8	39.5	68.4	45.6	27.8	0.9
Variance (n)	688.25	23772.55	1894.54	4.36	3135.04	0.73	492.50	838.37	2442.44	5.78	1.94
Variance (n-1)	718.17	24806.14	1976.92	4.55	3271.35	0.76	513.91	874.83	2548.63	6.03	2.02
Standard deviation (n)	26.23	154.18	43.53	2.09	55.99	0.86	22.19	28.95	49.42	2.40	1.39
Standard deviation (n-1)	26.80	157.50	44.46	2.13	57.20	0.87	22.67	29.58	50.48	2.45	1.42
Coefficient of variation	0.80	0.89	0.55	0.33	0.41	0.11	0.56	0.42	1.08	0.09	1.49

Chlorophyll-a (Chl-a) (µg/L), Color (mg/L Pt.Co), Dissolved Oxygen (DO) (mg/L), electrical conductivity (EC) (µS/cm), pH, Sechi Disk Depth (SDD in cm), total dissolved solids (mg/L), Turbidity, Water Temperature (Tw) (°C), and Total Phosphorus (TP) (mg/L).

cyanobacteria occurred together with other green algae species, such as diatoms, and *Euglenophytes*. At sampling point SP01 species identified were *Microcystis* (Fig. S2 A, B & C); *Lepocincilis acus* which resamples single-cell Euglena species) (Fig. S2 D); *Oscillatoria* (Fig. S2 E & G) which resembles (Huynh and Serediak, 2006)) and *Scenedesmus* (Fig. S2 F) (compares well with (S. J. Van Vuuren, 2006) and (Bellinger and Sigee, 2010)). Species observed at sampling point SP02 (Fig. S3) were *Anabaena cicrinalis (*cylindrical with rounded ends as described by (Komárek and Zapomělová, 2007)*)* (Figure S3 A), and *Cylindrospermopsis* (curved/coiled) (same as those reported by (UNESCO et al., 2004)) (Figure S3 B); Merismopedia (Figure S3 C); *Scenedesmus opoliensis* (Figure S3 D) (Prescott, 1954)*,* Collonial *Microsistis* (Fig. S3 E & S3 H)*; Lepocincilis acus* (Fig. S3 F & S3 G) *(*Order: *Euglenales,* genus: *Leponcinclis* - http://algaevision.myspecies.info/taxonomy/term/1799). Furthermore, at sampling point SP03 species identified were the filamentous *Anabaena bergii* (as reported by (Graham, Loftin, Ziegler and Meyer, 2008)) (A); *Chroococcus* (B), *Microcystis* (Fig. S4 C); *Merismopedia* (Fig. S4 D), *A. cicrinalis* (Fig. S4 E), *Scenedesmus* (Fig. S4 F) (elongated cylindrical cells joined side by side and form rectangular plate-like colonies of 2, 4, 8, 16 cells as in (Bellinger and Sigee, 2010) & (Huynh and Serediak, 2006)); *Anabaena* (Fig. S4 H, J, and P), *Pediastrum* species in different views (Fig. S4 G, I, and L). At sampling point SP04 species identified were *Anabaena* (Fig. S5 A); *Microcystis* (Fig. S5 B, C & D); *Merismopedia* (Fig. S5 F); *Euglena* spp. (Fig. S5 E), *Euglena (*these are single-cell showing content, some of the imaged resemble those in http://algaevision.myspecies.info/taxonomy/term/1799). At Mindu Dam (sampling ID SP05) species were more of filamentous (sometimes known as *Planktothrix* species in nature as per (Metcalf and Codd, 2014)). *Oscillatoria (*Fig. S6 *A); Lingbya* species *(*false branched*),* (Fig. S6 B and C), *Microcystis aeruginosa* (Fig. S6 F), *Cylindrospermopsis* (curved) (Fig. S6 D), and *Cylindrospermopsis* (Straights) *(*Fig. S6 E*) (*resembles those reported in (Newcombe et al., 2010) and (UNESCO et al., 2004)); *Nodularia (*Fig. S6 *G)*. Species observed at sampling point SP06 were *Anabaena (*as those available at https://planktonnet.awi.de/) (Fig. S7 A & M), *Leponcinclis* (Figure S7 B), *Nostoc* (Fig. S7 C), *Microcystis aeruginosa* (Fig. S7 D & K); *Microcystis warbegii* (Fig. S7 E), *Aphanizomenon* (Fig. S7 F), *Nodularia* (Fig. S7 G); *Oscillatoria* (Fig. S7 I), *Closterium Nitzsch* (Fig. S7 H elongated and crescent, sickle-brown shaped) and *Pediastrum*

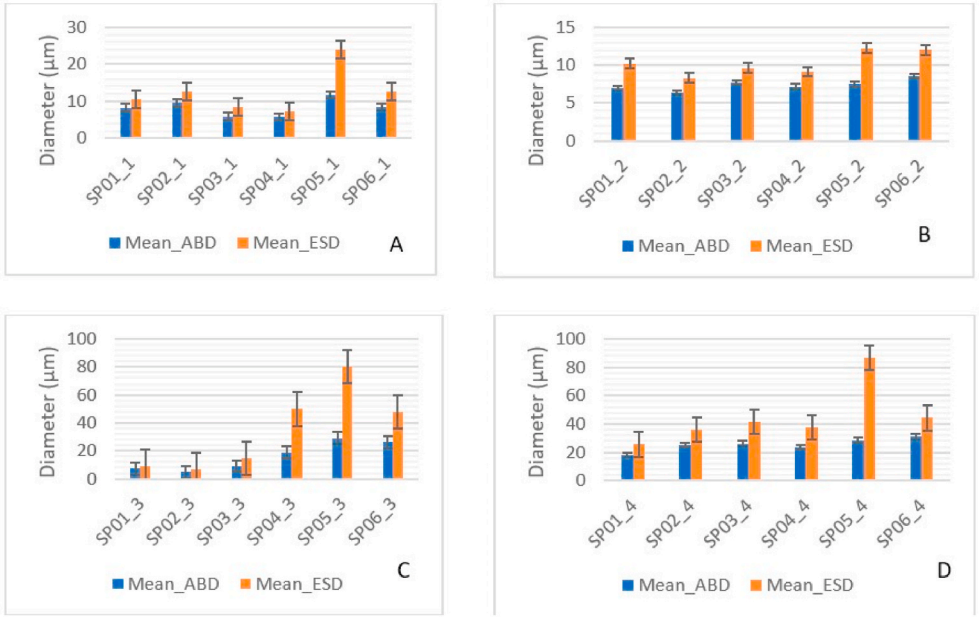

Fig. 2. Area-based diameter (ABD) and equivalent spherical diameter (ESD) for all the sampling points and sampling phases (A; represent phase one (October 2017), B; phase two (January 2018), C; phase three (May 2018) and D; phase four (September 2018)).

(Fig. S7 L disc-shaped and oval to circular colonies).

Regarding the biovolume, unlike other sampling phases (Fig. 2A, C, and 2D), sampling phase two (Fig. 2B) showed a relatively equal distribution of area-based diameter (ABD) all the sampling points and significantly different from other samplings phases. The equivalent spherical diameter in the current study showed a significant variation for both sampling phases and sampling points. For example, sampling phase two (February 2018) showed a significant reduction in ESD (Fig. 2) and sampling point SP05 (Mindu Dam) implying larger ESD than any other sampling point. The phenomenon might be attributed to the filamentous species which dominated the sampling site. The variations in ESD and ABD during phase two (February 2018) can be linked to the flash flood event which happened 18 days before our sampling schedule (supplementary information in Figure S8 E).

3.3. Correlation analysis

From Table 4 and Fig. 3 (i.e., PCA) the bolded figures indicate that at least one variable correlated with one another. The correlation table shows that there was a significant negative correlation between Secchi disk depth, color, and turbidity. The results also suggest that Secchi disc depth is in accordance with the basic principle (the higher the color or turbidity, the lower the Secchi disk depth). A significant ($p < 0.05$) positive correlation was gauged between the total dissolved solids, alkalinity, and electrical conductivity but with a negative correlation with total phosphorus concentration. Furthermore, there was a significant negative correlation between total phosphorus, pH, and turbidity.

Total alkalinity registered positive correlation with electrical conductivity and total dissolved oxygen. Total dissolved solids (TDS) and EC had a strong positive correlation while total phosphorous showed a negative association with pH and TDS but a positive correlation with turbidity.

The bootstrap biplot (Fig. 4) on the other hand summarizes the relationships between physico-chemical parameters and active observations (sampling points). It enables a two-dimensional map to identify trends and uniqueness of observations especially when the data re standardized (Forkman et al., 2019). For example, sampling five and phase three (SP05_3) indicate high value of sechi disk depth, SP02_1 indicate the high values on color, SP03_1, and SP02_3 had a unique value of total phosphorous. All these were significantly different from other observations and phases.

3.4. Trophic State Index (TSI)

The calculated Carlson's Trophic State Index (TSI) (Supplementary Information Table S1) values < 30 are common among lakes and reservoirs with oligotrophy, and between 50 and 70 correspond to eutrophic while hypereutrophic are common at TSI values > 70 (Pavluk and Vaate, 2017). The results suggest that SP05 (Mindu Dam) was eutrophic while all other sampling points were hypereutrophic.

3.5. Meteorological observations in the study area during the entire study period

Meteorological patterns (for observations taken after every 30 min) for the whole of the period of study (October 2017 to September 2018) was performed and examined. The meteorological parameters include air temperature (°C), relative humidity (%), atmospheric pressure (mmHg), rainfall (mm), and wind directions (Supplementary Information Figs. S8A–S8E). Air temperatures varied between 15 and 35 °C, and relative humidity (%) ranged between 0 and 80% with low humidity values occurring during the dry season. The atmospheric pressure was in the range of 951–968 mmHg with relatively high values during the dry season (June, July, September). For the wind patterns, a notable phenomenon was shift in wind direction i.e., from northeasterly (NE) to southeasterly (SE) during January backing to Southwesterly during

Table 4
Correlation matrix (Pearson) among the investigated environmental variables.

Variables	Chlorophyll-a (μg/L)	Alkalinity-Total (mg/L)	Colour (mg/L PtCO)	Dissolved Oxygen (mg/L)	Electrical Conductivity (μS/cm)	pH	Total Dissolved Solids (mg/L)	Turbidity (NTU)	Water Temperature (oc)	Secchi Disc Depth (cm)	Total Phosphorus (mg/L)
Chlorophyll *a* (μg/L)	1										
Alkalinity-Total (mg/L)	−0.002	1									
Colour (mg/L PtCO)	0.13	−0.12	1								
Dissolved Oxygen (mg/L)	−0.214	−0.132	−0.315	1							
Electrical Conductivity (μS/cm)	−0.068	0.627	−0.175	−0.024	1						
pH	0.008	−0.164	0.08	−0.108	0.296	1					
Total Dissolved Solids (mg/L)	−0.05	0.637	−0.188	−0.05	0.995	0.321	1				
Turbidity (NTU)	0.03	−0.307	0.317	0.166	−0.288	−0.252	−0.363	1			
Water Temperature (oc)	0.141	0.247	0.196	−0.131	0.04	0.069	0.05	0.11	1		
Secchi Disc Depth (cm)	−0.15	0.367	−0.583	0.033	0.152	−0.131	0.183	−0.509	0.009	1	
Total Phosphorus (mg/L)	−0.139	−0.348	0.186	0.318	−0.374	−0.473	−0.424	0.559	−0.304	−0.402	1

Values in bold are different from 0 with a significance level alpha = 0.05.

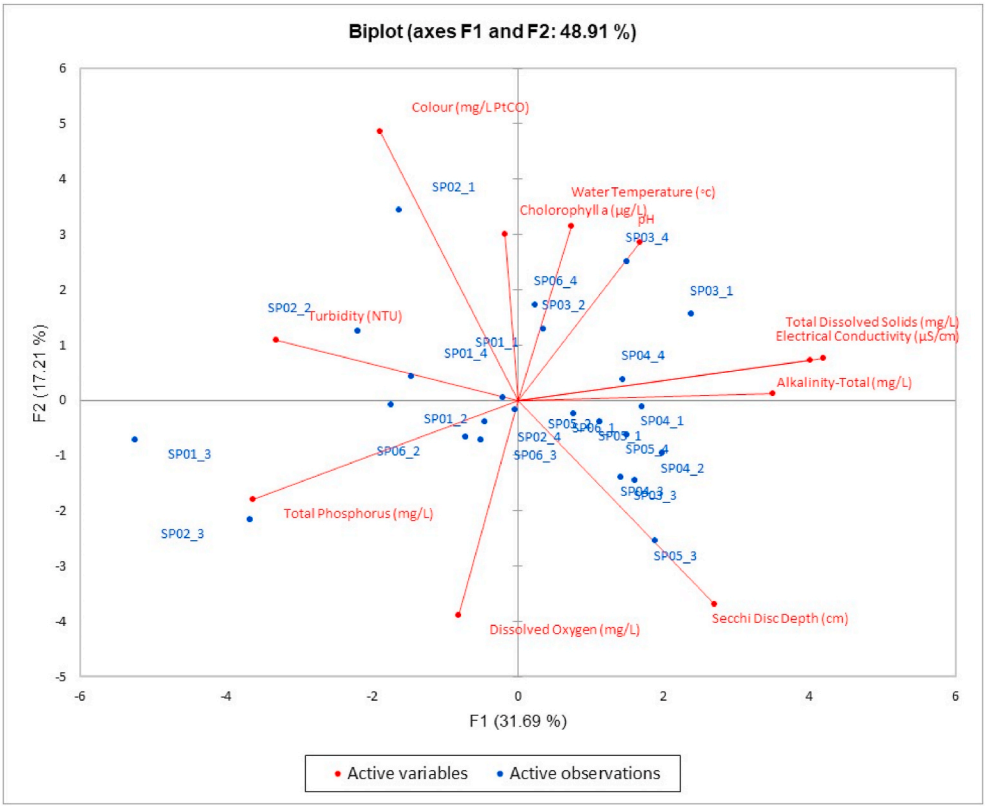

Fig. 3. Principal component analysis (PCA) ordination plot of active variables and the for sampling point and schedules combined within the components (F1 and F2).

MAM season.

4. Discussion

Stress factors such as climate, hydrological, extreme weather are known to control CyanoHABs dynamics (Sinoven, 2009). In a study conducted in the subtropical area in Brazil (Moura et al. 2017) suggests that extreme climatic events increase water temperatures and total phosphorous and promote harmful cyanobacteria. In the present study, between the first (October 2017) and second (February 2018) sampling, there was a case of heavy rain which is one among the episodic hydrological events that regulate dynamics of blooms in the region (Reichwaldt and Ghadouani, 2012). The flash flood event, might have influenced the variations of estimated cyanobacteria biovolumes (i.e., equivalent spherical diameter (ESD) and the area-based diameter (ABD) as seen in Fig. 2A to D). The results of this study support the view that, heavy rainfall tends to suppress occurrences of cyanobacteria bloom through the transport of nutrients, mixing of water and/or increased turbidity (Havens et al., 2016).

Water turbidity ranged between 4 and 233.3 NTU and Secchi disk depth values ranged between 4.7 and 107.7 cm. The two parameters had a significant negative correlation (−0.509). In the present study, pH ranged between 6.5 and 9.7 while alkalinity ranged between 20.9 and 198.3 mg/L with the sampling sites SP03 and SP04 registering relatively high values of alkalinity. The reason could be due to their location because the two sampling sites are close to a rice paddy. However, in fishponds, pH and alkalinity values were within the ranges reported by (Boyd, 1998; Sallenave, 2012). Otherwise, the rest showed no significant correlations. Some similar findings were also reported in Brazil (Figueredo and Giani, 2009). Total dissolved solids and EC registered significant positive association with alkalinity triangulate well with the existing of rice paddy near the fishponds.

From Table 3, total phosphorus concentrations levels ranged between 0.1 and 5.8 mg/L. The higher values were observed from sampling sites SP01 and SP02. The high values could be due application of animal manures to enrich nutrients in the fishponds. In the current study total phosphorus levels were found to be higher than the threshold values, which are considered to favor cyanobacterial growth. According to World Health Organization (WHO, 2015) high concentration of nutrients particularly phosphorous (>25–50 µg/L), high water temperatures (>25 °C), long hydraulic retention time (>1 month) and stable water body stratification favors cyanobacteria growth. Total phosphorous is the limiting factor and any small amount can lead to the rapid growth of algal blooms (Gatz, 2018). Although it is still debatable, Harke (Harke et al., 2016) argued that phosphorus control is the central core issue.

In the current study species of *Microcystis, Anabaena, Lyngbya*, and *Cylindrospermopsis* species were identified. The study findings confirms that cyanobacteria occur together with other green algae species such as Diatoms and *Euglena* (Supplementary Figs. S2–S7). The observation also corroborates with other reservoirs where other algal species are dominant such as green algae, diatom, blue-green algae (Cho et al., 2014). In the present study species of *Microcystis* were observed in all the sampling points. Unlike the temperate region, blooming in the tropics occurs at any time of the year [67]. The tropical characteristics are species-specific, for example, Microcystis blooms occurs during the wet season due to elevated nutrient levels but also it may not restrict other dominant species such as Anabaena and Cylindrospermopsis [76]. Previous studies have indicated that *Microcystis* spp. alone in tropical Africa account for 66% of toxic blooms (Mowe et al., 2015). This implies that there a need to systematically and analytically investigate the toxicity levels of the identified species in the Ngerengere catchment. Virtually, a filamentous species of cyanobacteria dominated sampling point SP05 (Mindu Dam) than any other sampling point. This sampling point also showed a dominance of species of larger equivalent spherical diameter (Fig. 2) which might be attributed to filamentous species than the other

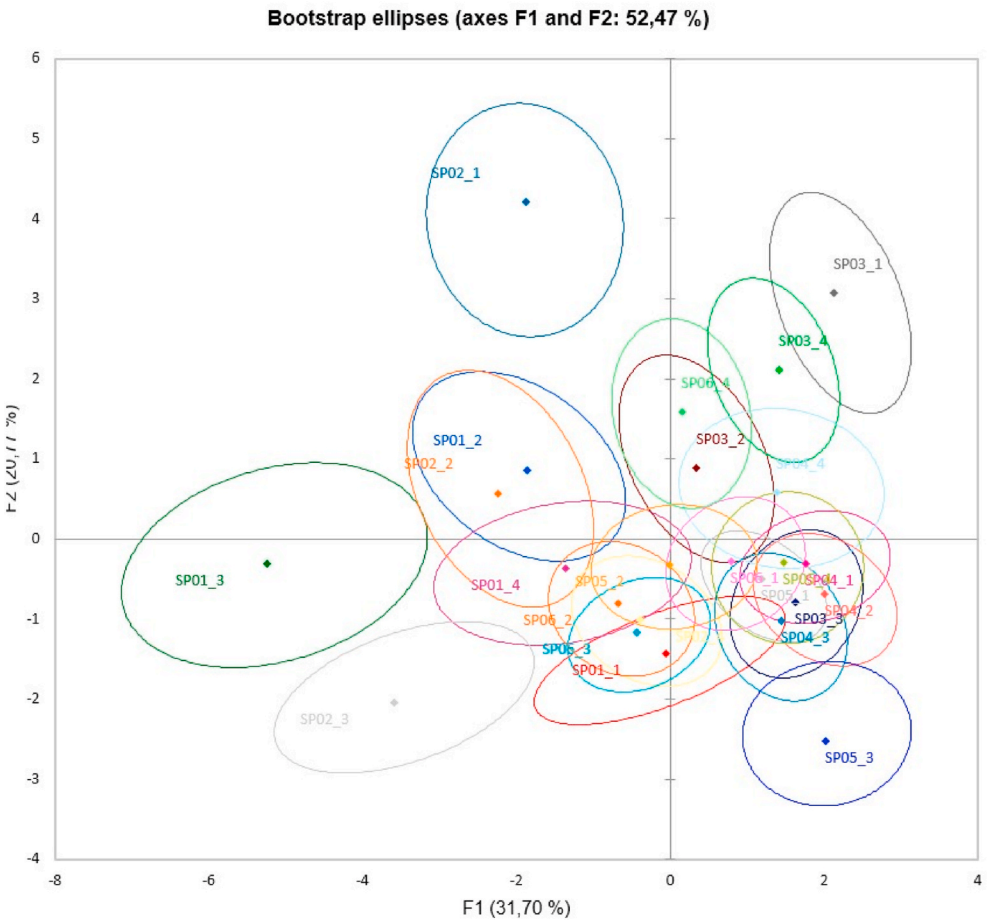

Fig. 4. Bootstrap ellipses for active sampling points and schedules. Herein, the sampling points are grouped based on their characteristics and or uniqueness at 95% confidence intervals.

sampling sites. The difference between this dominance of species in the fishponds and the Mindu Dam can be attributed to constant withdrawal of water from the Dam while in fish ponds the water is relatively stagnant. Dominance also raises a concern about catchment management. The dominance is consistent with the findings in Ethiopia by (Tilahun and Kifle, 2019) whereas limited nitrogen could have triggered the unusual dominance of filamentous species of cyanobacteria genus *Cylindrospermopsis* over the dominant persistence genus *Microcystis* in the same environment (Dam).

Chlorophyll-a registered values ranging between 9.4 and 103.9 μg/L for all the sampling points, implying that they can be categorized as a eutrophic reservoirs (Istvánovics, 2009). As noted earlier, chlorophyll-a is widely used as an indicator for algal blooms, the predictability of bloom in the temperate region allows for a preventive or control measure, unlike tropical algal blooms where they tend to be controlled by temperature, nutrient input, and periods of drought or heavy rains.

Algae and suspended particles make the water cloudy which in turn reduces Secchi disk depths (see the correlations in Table 3). From the derived Trophic State Index (STI) (Supplementary Table S1) showed that most of the sampling points were eutrophic to hypereutrophic status for all the sampling phases. Mindu Dam (SP05) was the only sampling point with a score of less than 70 (eutrophic status) at times. Generally, the finding in the study agrees with findings reported elsewhere in the tropical reservoirs (Te and Gin, 2011). The STI status supports algal bloom proliferation which were also observed in the morphological findings.

5. Conclusion

The present study aimed to identify and characterize common species of cyanobacteria with the up-to-date tool and examine their possible change in composition and succession in the Ngerengere catchment, Morogoro, Tanzania. The study contributes to the morphological identification of potential CyanoHABs in the region with knowledge and data gaps. The study identified common species of cyanobacteria namely *Microcystis, Anabaena, Cylindrospermopsis, Aphanizomenon,* and *Lyngbya* but also other algal species such as Diatoms, and *Euglenas*. Most blooming occurred throughout the study duration (i.e., October 2017 to September 2018). Mindu Dam showed to be dominated by filamentous species of cyanobacteria. With exception of Mindu dam, all other sampled reservoirs were in the hypereutrophic state. Mindu Dam was eutrophic for all the sampled phases implying a threat to the public health since it is used for domestic water supply. The results implies that proactive measures are necessary due to the interconnectivity between the fishponds, river tributaries, and the Mindu Dam. Moreover, Morogoro population is at risk of consuming CyanoHABs through drinking water and or fishery. Further investigation particularly in epidemiological, ecotoxicological, and their mobility to the higher energy levels is therefore recommended for more informed management strategies.

Authors contribution

KON idea conceptualization, design, data analysis, and manuscript writing; JRG & HC idea conceptualization, design, funding acquisition, review, and editing; TNM review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2021.103103.

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