UNIVERSITY OF VENDA

IMPACTS OF CLIMATE VARIABILITY AND HYDROLOGICAL MODIFICATIONS ON CYANOBACTERIA POTENTIALS IN AQUACULTURE SYSTEMS IN THE NGERENGERE CATCHMENT, MOROGORO, TANZANIA

By

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A PhD thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy in Environmental Science at the Department of Ecology and Resource Management, School of Environmental Sciences, University of Venda

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Declaration

I, **Offoro Neema Kimambo** (candidate number **17019501),** hereby declare that the thesis entitled "**IMPACTS OF CLIMATE VARIABILITY AND HYDROLOGICAL MODIFICATIONS ON CYANOBACTERIA POTENTIALS IN AQUACULTURE SYSTEMS IN THE NGERENGERE CATCHMENT, MOROGORO, TANZANIA"** for a PhD degree at the University of Venda, hereby submitted by me**,** has not previously been submitted for a degree at this or any university, and that it is my work in design and excursion and that all reference material contained therein has been dully acknowledged.

Signature Date **April 15, 2021**

Abstract

The scientific consensus is that the global increase in cyanobacterial harmful algal blooms (CyanoHABs) is attributed to eutrophication, hydrological variations, and anthropogenic activities compounded by climate change. Cyanobacteria are known to produce a wide range of toxins (cyanotoxins) and hypoxia conditions that can alter the food web. Besides the fact that Tanzania is rich in water resources such as the ocean, lakes, rivers, dams, and ponds and shreds of evidence of environmental constraints, climate and hydrological variations (episodic events and altered river flows), on HABs, much is yet to be done. Their growth is not spatially homogenous, and that there is an information gap on their dynamics. CyanoHABs have registered impacts on food security, tourism, water resources, fishery, and human health. The only recorded incidences (recurrence) are the mass fatalities of Lesser flamingo in Lake Manyara, Arusha. Some recent reports, for instance, gauged the rapid growth of the aquaculture sector as a result of livelihood diversification, but the sector is facing management and environmental constraints. Since the aquaculture farms/fishponds are hydrologically connected with the domestic water reservoirs in the Ngerengere catchment, there is a need for a thorough analysis. The study explored the impacts of climate variability and hydrological modification on cyanobacteria potentials in aquaculture systems in the Ngerengere catchment in Morogoro, in the United Republic of Tanzania.

In this study, a review of the literature (i.e., historical reconstruction) on CyanoHABs occurrences in Tanzania and their link with climate and hydrological variation was conducted. A stakeholders' perception and experience (questionnaire, focus group discussions, and key informant interviews) and anecdotal observations were also conducted and examined. Water samples were collected and analyzed for the identification and characterization of common species of cyanobacteria and in-situ measurements of physicochemical characteristics. Also, case studies were also diagnosed to examined how CyanoHABs link with other key environmental observations. The study also involved obtaining online data for chlorophyll-a to analyze their trends and how they are teleconnected with climate and hydrological variation in Mindu, Dam situated in the Ngerengere catchment. The methods and procedures followed in the study are detailed under the specific chapters.

The study found that on HABs, the field is still at its nascent stage in Tanzania, and research

in the field is lagging. Most studies are events driven, for example, post-mortem analysis and that there is no limnological data to perform time series analysis. Regarding the survey on stakeholders' perception of CyanoHABs in the Ngerengere catchment, 95% of the respondents could recognize blooms as displayed to them, with 70% noting that algal blooms proliferate more during the dry season. On the other hand, respondents were uncertain about any health effects associated with blooms. During the survey, farmers revealed that they sometimes feel itching during and after fishing, which is linked to toxic effects from CyanoHABs.

The morphological assessment shows the occurrences of common species of CyanoHABs in the Ngerengere catchment, such as *Microcystis, Cylindrospermopsis, Anabaena, Lyngbya,* as well as other species such as diatoms and *Euglenophytes,* which at times might be a nuisance to the environment. It was further observed that colony-forming cyanobacteria dominated the fishponds while filamentous species were dominant in Mindu Dam (a domestic water supply in the catchment). However, the eutrophic state of the sampling points varied from eutrophic to hypereutrophic state for all the sampling schedules. Moreover, Mindu Dam was eutrophic, becoming hypereutrophic toward the end of sampling (September 2018, usually the dry season).

During the study period, two unique cases, namely, heavy rainfall, which caused flash flood (in this study defined as an episodic hydrological event) and unusual observation of reddish colouration (red algae) fishponds at Kingolwira National Fish Farming Centre were gauged and examined. The heavy rainfall event happened between the first (October 2017) and the second (February 2018) sampling phases, which showed to be affecting the equivalent spherical diameter (ESD) and area-based diameter (ABD) of the community structure. The heavy rain phenomenon was localized (enhanced by the orographic nature of the place) but also steered by the presence of the Intertropical Convergence Zone (ITCZ) and the tropical cyclone Berguitta (which was the dominant weather over the Indian Ocean). Regarding the unusual observation of reddish bloom in the fishpond, the associated physicochemical characteristics during the event were also studied. To the best of our knowledge, the observed red algae is the first to be reported in fishponds in Tanzania. These results show that the fishponds were significantly ($p<0.05$) different from each other except for water temperatures. *Microcystis* and euglenophytes species respectively dominated non-reddish and reddish fishponds. The study findings demonstrate the dynamics of harmful cyanobacterial blooms in the study area. The use of case studies and observations synergistically can be utilized in understanding the local context hence studying the dynamics of CyanoHABs.

A retrospective analysis of chlorophyll-a was conducted in Mindu Dam, which demonstrated increasing Chlorophyll-a trends (defined as a chlorophyll-a index and a ratio between bands characteristics using Landsat 7 surface reflectances), minimum and maximum temperatures, and solar radiation. While rainfall trends were neutral, wind speed and directions and water levels for the Mindu Dam showed a significant decreasing trend with time. However, there was a strong correlation between wind speed and maximum temperature but weak with minimum temperature. There was also a significant weak correlation between Nino-3.4 monthly rainfall as well as water levels. The study area is to the leeward side of the Uluguru mountains. The patterns suggest links and causality between the CyanoHABs variations and meteorological parameters such as temperatures, solar radiations, and water levels.

Findings in this study contribute to the understanding of CyanoHABs with climate and hydrological variation in a region in the face of data paucity. The study further provides an insight into state of the art, cause of CyanoHABs, and their link with climate and hydrological variation hence informing policies and practices and professional development. The findings also provide a basis for the development of the CyanoHABs management framework and health risk assessment.

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(*Offoro Neema Kimambo*)

Table of contents

List of figures

List of tables

List of acronyms and abbreviation

ARSET	Applied Remote Sensing Training Program
CyanoHABs	Cyanobacteria Harmful Algal Blooms
EPA	Environmental Protection Agency
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
FDG	Focus Group Discussion
GEE	Google Earth Engine
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms
GF/F	Glass Fiber Filter
GWP-SA	Global Water Partnership-Southern Africa
GLOWSFIU	Global Water for Sustainability - Florida International University
GPS	Global Position System
HABs	Harmful Algal Blooms
IPCC	Intergovernmental Panel for Climate change
ITCZ	Intertropical Convergence Zone
JASP	Jaffrey's Amazing Statistics Program
KNMI	Koninklijik Nederlands Meteorologisch Instituut (Royal Netherland Meteorological Institute)
LC-MS	Liquid Chromatography Coupled Mass Spectrometer

MORUWASA	Morogoro Urban Water Supply Authority
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Statistics
NFM	National Field Manual
NIR	Near Infra-Red
NOAA-GFS	National Oceanic and Atmospheric Administration Global Forecast System
NPSG	North Pacific Subtropical Gyre
OLI	Operational Land Imager
PCA	Principle Component Analysis
REC	Research Ethics Committee
SADC	Southern Africa Development Community
SPEI	Standardized Precipitation and Evapotranspiration Index
SST	Sea Surface Temperature
SUA	Sokoine University of Agriculture
TDS	Total Dissolved Solids
TMA	Tanzania Meteorological Agency
TN	Total Nitrogen
TOA	Top of Atmosphere
TP	Total Phosphorus
UK	United Kingdom
USA	United State of America

USGS	United States Geological Survey
VS-MPR	Vovk-Sellke Maximum P-Ratio
WARFSA	Water Research Fund for Southern Africa
WCI	Water Cycle Integrator
WHO	World Health Organization
WMO	World Meteorological Organization
WRBO	Wami Ruvu Basin Office

Academic Outputs

Published articles

i. **Kimambo, O. N.,** Chikoore, H., Gumbo, J. R., & Msagati, T. A. M. (2019). Retrospective analysis of Chlorophyll-a and its correlation with climate and hydrological variations in Mindu Dam, Morogoro, Tanzania. *Heliyon*, 5, e02834. https://doi.org/10.1016/j.heliyon.2019.e02834

ii. **Kimambo, O. N.,** Gumbo, J. R., & Chikoore, H. (2019). The occurrence of cyanobacteria blooms in freshwater ecosystems and their link with hydro-meteorological and environmental variations in Tanzania. *Heliyon*, *5*(3), e01312. https://doi.org/10.1016/J.HELIYON.2019.E01312

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Conferences attended

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ii. Kimambo, O. N., Gumbo, J. R., & Chikoore, H. (2018). Harmful algal blooms occurrence and perception in the Upper Ngerengere Catchment, Morogoro, Tanzania. *First International Conference in Sustainable Management of Natural Resources*. Polokwane, South Africa.
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iv. Participated in an Online Course on Processing Satellite Imagery for Monitoring Water Quality, organized by NASA's Applied Remote Sensing Training Program (ARSET), September 5-19, 2018.

v. Participated in an Online Course on Introduction to remote sensing on harmful algal blooms, organized by NASA's Applied Remote Sensing Training Program (ARSET), September 5-26, 2017.

vi. EartH2Observe-Open access global hydrological re-analysis data for locally relevant water resources decisions, organized by the Unesco-Ihe Delft and the Earth2Observe research project, Swakopmund Hotel and Entertainment Centre, Namibia, October 24 2017

Award Received

i. 2019 One Planet Fellowship recipient (https://awardfellowships.org/one_planet_community/offoro-kimambo)

"The destruction of aquatic ecosystem health and the increasing water scarcity, are in my opinion the most pressing environmental problems facing humankind" Maude Victoria Barlow

Chapter 1

Introduction

1.1 Background

The frequency and geographical distribution of cyanobacteria harmful algal blooms (CyanoHABs) have been increasing globally (Gatz, 2018). CyanoHABs are microscopic species of bacteria, which are photosynthetic, and are naturally occurring in marine and freshwater ecosystems (Elliott, 2012; O'Neil, Davis, Burford, & Gobler, 2012). CyanoHABs produce secondary metabolites (cyanotoxins), alter the food web, as well as creating a hypoxic condition that is harmful to the environment, animals, and human health (Sinha et al., 2012; Paerl, Meeks, & Haselkorn, 2014; EPA Office of Water., 2014). CyanoHABs can quickly multiply into dense algal blooms (Requintina, Mmochi, Msuya, 2008; Elliott, 2012). Several studies suggested that climate variability and change, hydrological fluctuations, and environmental factors (i.e., physical, biological, and physicochemical) have a direct and indirect influence on the frequency, intensity, and geographic extent of a harmful algae bloom. Regrettably, little is known about the synergies, and it is impractical to attribute CyanoHABs with a single factor (Moore et al., 2008; Nonga et al., 2011; Zhang et al., 2016; Griffith & Gobler, 2019). CyanoHABs are ubiquitous as can be found everywhere, such as in lakes, estuaries, dams, ponds and marine ecosystems (Berger et al., 2008); in the air with significant health effects (Chu, Tneh, & Ambu, 2013) and that their frequency and severity are predicted to increase globally (Beaver, Tausz, Scotese, Pollard, & Mitchell, 2018). The most pressing fact is that cyanoHABs are widespread, and the rate of increase is alarming (Paerl, Hall & Calandrino, 2011) but also they can adapt to climatic changes (Moore et al., 2008).

In the United States of America (USA), the United Kingdom (UK), Australia, Canada, and Italy, there have been reports on fatalities of pets, fish, cattle, and humans which are linked to cyanotoxins (Lopez, Jewett, Dortch, Walton, & Hudnell, 2008). The World Health Organization (2003) still holds a view that about 60% of all samples investigated worldwide contain cyanotoxins. However, there are many studies and reports in the developed world and in Africa, where information regarding CyanoHABs is limited. A comprehensive review by

Ndlela, Oberholster, Van Wyk and Cheng (2016) established the occurrence of cyanobacteria in Africa. The authors report that some countries in Africa are exempted because of social unrest and or monitoring data. A study by Anderson (2014) noted that due to an increase in population, increased agriculture, and aquaculture productions in China, India, and Africa, these regions will be the hotspots of eutrophication related CyanoHABs outbreaks.

In the United Republic of Tanzania, there are water bodies such as lakes, rivers, dams, water reservoirs, ponds, and groundwater wells. Some are natural, and others were made for hydroelectricity generation irrigation and domestic water supply in major towns and municipalities. However, studies on cyanobacteria occurrence and its impacts on fisheries, aquatic ecology, and human are few. The available ones, for example, are post-mortem studies in Lake Manyara, Manyara Region, which confirmed cyanotoxins as the causes of massive deaths of flamingo (Lugomela, Pratap, & Mgaya, 2006; Nonga et al., 2011; Fyumagwa et al., 2013). These studies had no reliable conclusions or discussions on the associations between climate and or hydrological variability and change and cyanobacteria.

1.2 What causes CyanoHABs?

Cyanobacterial harmful algal blooms (CyanoHABs) occur when colonies of algae increase in the sea and or freshwater. Several factors are known to influence CyanoHABs proliferations such as hydrologic (e.g., after events like floods and droughts), climatic (e.g., warming, which results in warmer waters), geographic, and geologic, which interact with anthropogenic and natural nutrients (Paerl, Fulton, Moisander, & Dyble, 2001). CyanoHABs can sometimes be a non-native species (i.e., invasive species), which can be accelerated by the changing weather, wind, and or introduction of the species in the process of feeding (Zohdi & Abbaspour, 2019). Due to complexities involved in interactions between the drivers and the CyanoHABs, previous works have established links through theoretical frameworks as wells as a system analysis approach (Hudnell, Dortch, & Zenick, 2005). A recent study, for example, developed a framework that envisions water security from the perspective of the cyber-physical system (i.e., Cyber biosecurity) (Schmale, Ault, Saad, Scott, & Westrick, 2019). The approach might be more informative than laboratory experiments but also the inclusion of a human component that describes the socioeconomic and cultural impacts on CyanoHABs (i.e., cultural eutrophication).

1.3 Potential impacts of climate variability and change on CyanoHABs

The scientific consensus is that climate variability and change, as wells as hydrological variations, seem to favour cyanobacteria dominance (Griffith & Gobler, 2019). Global climate change will impact both drinking and irrigation water supplies, fishing, and recreational use of surface waters worldwide. Climate changes are likely to affect aquatic resources in two ways. Firstly, it is by episodic effects (frequency, duration, and magnitude extreme effects), and the second is a progressive change in average conditions (Conlan, Lane, & Wade, 2005). For example, in the United Republic of Tanzania, there has been a link between phytoplankton's biomass and cholera in Lake Tanganyika (Plisnier et al., 2015), which is among the symptoms of algal toxins exposure. A similar study (Mchau, Makule, Machunda, Gong, & Kimanya, 2019) in a small island of Ukerewe in Lake Victoria reported occurrences of species of *Microcystis* (ranging from $9*10^4$ to $3*10^6$ cell/mL) and *Anabaena* (ranging from $1*10^4$ to $5*10^6$ cell/mL) which were all above the WHO Standards. The authors concluded the symptoms (Gastrointestinal Illness) from the subjects. The studies report pertinent issues that needed to be confirmed by epidemiological analysis and risk assessments. It also shows a need for more investigation on the impact of CyanoHABs in the region.

Aquaculture plays a vital role in food security, which exists when "all the people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (Barange et al., 2018). Aquaculture contributes to food security by creating employment/jobs, supplier of nutritious food, and generating income and economic growth through harvesting, processing, and marketing of fish (Barange et al., 2018). Significant potential impacts on aquaculture include; global warming, water stress, and hydrological changes (De Silva & Soto, 2009). There are other environmental concerns in aquaculture such as land requirements, water demand, freshwater eutrophication, and greenhouse gases (Ahmed, Thompson, & Glaser, 2019). Some species of CyanoHABs exploit stratified conditions of the water body and forms gas vesicles, which allow for buoyancy regulation (e.g., red cyanobacterium *Planktpthrix rubescens*), which then can build a large population to create spectaculars red surface blooms known as the "Burgundy bloody phenomenon." according to Paerl & Huisman, (2009). The phenomenon has been reported to affect fishes and fish farming activities in areas where they have been reported.

1.4 Techniques used in studying harmful algae

The effects of climate and hydrological modifications have been studied in so many ways with different needs, and that has led to the formulation of policy documents, practice changes, and understanding of cyanobacteria dynamics (Hudnell et al., 2005). A recent review by Burford et al. (2020) provided an up-to-date summary of the pros and cons of different research approaches, methods, and techniques in studying harmful algae is due to cultural and geographical differences. Several studies demonstrated the use of palynological (the study of plant pollens), sedimentological, and geochemical records in the equatorial Atlantic and China to trace the variability of harmful algal blooms and the associated features (Cramwinckel et al., 2019; Zhang, Dong, Yang, Odgaard, & Jeppesen, 2019). Other techniques include simulations studies, social-ecological studies on CyanoHABs, and correlational studies. The complexity of algal blooms dynamics prompted some studies to recommend a holistic approach and case study approaches to be more informative. Zhang et al. (2019) narrate the use of cases that mimic climate change, for example, floods and drought.

Remote sensing technologies can also be used to investigate bloom dynamics in a remote area (Dörnhöfer & Oppelt, 2016a). Several algorithms (i.e., involving single bands and band ratios/combination) using different sensors in different geographical areas have been developed to estimate CyanoHABs in inland waters (Gholizadeh, Melesse, & Reddi, 2016). Although there are limitations, for example, most algorithms are region-specific and that their application should be considered and evaluated, but also remote sensing is just a tool to indicate the severity of blooms it does not determine the harmfulness of CyanoHABs (Schmale et al., 2019).

Recent advances in the field of remote sensing technology offer a mechanism to monitor water quality parameters, for example, the use of Google Earth Engine (GEE) (https://code.earthengine.google.com/) in assessing environmental changes, including drought, disaster, disease epidemics, and water surface changes over time (Gorelick et al., 2017; Kumar & Mutanga, 2018). A combination of GEE and Climate Engine (https://clim-engine.appspot.com/#) proved to be efficient in studying a broad spectrum of the changing environment. However, unlike the climate engine, GEE requires skills and knowledge of computing (Gorelick et al., 2017). In Tanzania, studies on HABs prediction using remote sensing techniques are lagging despite evidence of blooming in water bodies. Malahlela, Oliphant, Tsoeleng, Mhangara, and Malahlela (2018) found that anthropogenic activities play a significant role in promoting the rate of growth of algae blooms and that technology and data exchange could be limiting factors.

There are other techniques to understand CyanoHABs; for example, a study by Harvey (2012) used an ethnography of risk communication approach to study the communication of public health risk of cyanobacteria. Similarly, other researchers were involved in developing a social-ecological system, a framework that informs all interdisciplinary study of CyanoHABs (Van Dolah, Paolisso, Sellner, & Place, 2016). The inclusion of social research might help identify social drivers and consequences and that will prevent or mitigate CyanoHABs and significantly reduce associated impacts (Van Dolah et al., 2016).

There are research gaps that need to be filled in view of the above, such as an information gap that requires a reconstructive (empirical) approach. Furthermore, there is no limnological data to describe the time series of algal proliferation and environmental drivers. To address these gaps, case studies and retrospective analysis using remote sensing techniques might provide necessary information for understanding blooms dynamics in the region assisted with timely identification and characterization, and their link with the environmental drivers. Therefore, the study hypothesizes that climate variability (natural or anthropogenic) and hydrological modification increases the threat of harmful cyanobacteria in aquaculture systems in the Ngerengere catchment, Morogoro, Tanzania.

1.5 Study area

The present study was carried in the Ngerengere catchment, which is the sub-basin of the Wami/Ruvu basin in Morogoro, the United Republic of Tanzania (**Figure 1.1**). There are shreds of evidence of variations of hydrological flows in most of studied water catchments/basins in Tanzania (Hyandye, Worqul, Martz, & Muzuka, 2018; Kishiwa, Nobert, Kongo, & Ndomba, 2018; Näschen, Diekkrüger, Leemhuis, Seregina, & van der Linden, 2018). In the catchment, there is a domestic water reservoir (Mindu Dam), which is mainly for water supply but also freshwater fishery to the Morogoro Urban and Suburb areas (Mdegela et al., 2009). Maximum temperature ranges from 18 to 33℃ and rainfall from 800 to 1500 mm per year, much of it falling in the highland of the Uluguru Mountains part of eastern arch mountains. A survey of Global Water for Sustainability-Florida Institute - GLOWSFIU (2014a) in Wami/Ruvu Basin in Morogoro observed an increasing uncertainty of the start of rains and durations, distribution, and amounts as well as temperature changes. Some studies suggest that contaminated waters from streams, rivers, and reservoirs, are increasingly used by rural and urban communities for domestic, livestock, agriculture, and aquaculture (GLOWSFIU, 2014b; Hounmanou et al., 2016).

Mindu Dam receives water from tributaries with a source in the Uluguru Mountains. The area has experienced significant land-use changes; for example, the cultivated area increased from 16% in 1995 to 61% in 2000 (Natkhin, Dietrich, Schäfer, & Lischeid, 2015), which is also attributed to influence hydrologic and anthropogenic pollutant inputs into receiving waters. Apart from cultivated areas, there are also fishponds along the tributaries meaning that they are hydrologically connected with the receiving dam downstream. In the study area, small-scale farmers have realized the potentials of fish farming as livelihood diversification, which recently has also experienced a number of fish farming activities along and or nearby the river tributaries in the catchment. Recent statistics on people involved in aquaculture in Tanzania (including Morogoro) registered a significant increase from 9500 in 1998 to 18286 in 2013 (Drakenberg, Ek, & Fernqvist, 2016). The connectivity has been reported to affect hydrological patterns elsewhere in the world (Ahmed et al., 2019). Floods events and impacts resulting from riverbank being unable to accommodate the amount of water have been evidenced as well (Kimambo, Chikoore, & Gumbo, 2019). On the other hand, droughts and water scarcity, are also a common phenomenon in the study area, which also force pastoralists to move from the region to other parts of the country (Drakenberg et al., 2016).

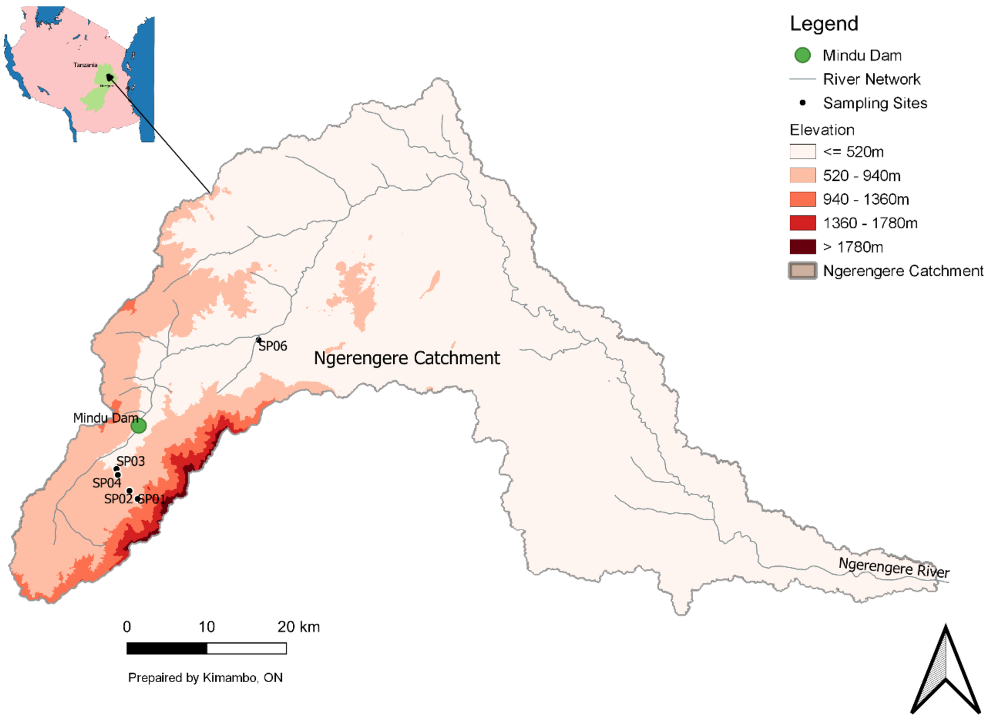

Figure 1.1 A map showing a Ngerengere catchment located in Morogoro, Tanzania.

A previous study claimed that water sources contaminated with algal blooms (an indicator for nutrient load) risks consumers from cyanotoxins (Mdegela et al., 2011). Herein, one may want to link the previous experiences with the health reports on burden diseases (https://vizhub.healthdata.org/lbd/diarrhea) in the region of interest (the study area). Consequently, studies of CyanoHABs in the study area, which are of paramount importance, are few or non-existing. This is due to the direct link between anthropogenic activities, climate, and hydrological regimes, which ultimately (for example, farming and fishing) affects water quality in reservoirs.

There is also an element of spatial coverage, for example, the study of Mdegela et al. (2011) on the effect of pond management on the prevalence of intestinal parasites in Nile Tilapia (*Oreochromis niloticus*) under small-scale fish farming systems in Morogoro, Tanzania surveyed 13 freshwater fishponds which most of them were near river tributaries. This study found that most ponds owners were using rice and maize bran, poultry, cattle, goat pig manures as a source of food for fishes, which are the source of nutrients in the ponds. Although the study was not directly investigating cyanobacteria, there are elements of contaminations that trigger further investigation because 16% of the collected fish samples were infected with intestinal parasites. Understanding the associations between algal bloom proliferation and physical, geological, and biological factors are vital for the control of their impacts. Previous studies suggest developing a tool that can break the synergy between nutrient load and the hydrological regime could be the best approach (Paerl et al., 2011).

1.6 Problem statement and justification

A comprehensive survey by GLOWSFIU (2014a) in Wami/Ruvu Basin situated in Morogoro observed an increasing uncertainty of the start of rains and durations, distribution and amounts, and temperature rises. Nakthin et al. (2015) noted anthropogenic modifications of aquatic environments (e.g., extensive water abstraction, increased cultivated land in turn nutrient over-enrichment and erosion), and increased water temperature. There is also evidence that rural and urban communities increasingly use contaminated waters from streams, rivers, and reservoirs for domestic, livestock, agriculture, and aquaculture (GLOWSFIU, 2014b; Hounmanou et al., 2016). However, monitoring and documentation (long term) of occurrence of CyanoHABs and the geographical extent of cyanobacteria with environmental changes and climate variability in aquaculture, waterlogged agriculture, and water bodies, remain a challenge. Additionally, the synergy between climate, hydrological variations, and cyanobacteria potentials (toxins, hypoxia production, and food web disruptions) in freshwater systems in Tanzania is less studied, and there is no enough information to characterize the threat of CyanoHABs. According to Niang *et al.* (2014), the impacts of climate change on freshwater systems and their management are mainly due to temperature and rainfall (timing and intensity) variability. The authors further noted that flood magnitudes and frequencies are likely to increase in most poorly and unmanaged freshwater systems and are expected to become more vulnerable. While noting the threat of climate change impacts, CyanoHABs are not only widespread, but they can also adapt to climatic changes (Moore et al., 2008).

With the notable varying climate and hydrological regimes, increased fish farming in freshwater reservoirs (dams, ponds, and lakes) as the means of diversification of livelihood (Paavola, 2008) and assurance of food security understanding of the threat of CyanoHABs is of paramount importance. Therefore, there is a need to examine the impacts of climate variability and hydrological modification (floods, drought, flushing, and flows) and environmental stressors on cyanobacteria potentials and distribution in aquaculture systems in the Ngerengere catchment.

1.7 Study motivation

Water quality assessment studies (Ngonyani & Nkotagu, 2007; Mero, 2011; GLOWS-FIU, 2014) and triggers of cyanobacteria proliferation, such as anthropogenic and climatic-induced effects and hydrological fluctuations such as a reduced flow (Natkhin et al., 2015), demonstrate the need for the study of CyanoHAB in the Ngerengere Catchment. The study area is on the leeward side of the Uluguru Mountain, which in principle, there would be times of high surface temperatures that are influenced by the topography (i.e., orographic effects). The hydrological interconnection between the domestic water reservoir (i.e., Mindu Dam) and the fishponds, which are along the tributaries and, more importantly, the lagging behind of studies in CyanoHABs in the catchment, are also among the motives. Finally, a push to contribute to policies, practices, and professional development, as well as the development of baselines for future studies on the impacts and risks associated with CyanoHABs.

1.8 Aim, scope, and objectives

The overarching aim of the study was to explore the impacts of climate variability and hydrological modification on cyanobacteria potentials in aquaculture systems in the Ngerengere Catchment in Morogoro, United Republic of Tanzania. The study, therefore, is addressed by the following specific objectives (research questions).

i. To survey the occurrence of cyanobacteria in freshwater ecosystems and their link with hydro-meteorological and environmental variations in Tanzania.
ii. To identify and characterise common cyanobacteria species, their community structure, and environmental concerns in aquaculture systems in the Ngerengere catchment, Morogoro.
iii. To examine the link between climate variability, hydrologic modification, and cyanobacteria potentials.
iv. To analyse the trend of chlorophyll-a and its correlation with climate and hydrological variations in Mindu Dam, Morogoro, Tanzania

1.9 Hypothesis

The hypothesis being tested is that climate variability and hydrological modification increases the threat of harmful cyanobacteria in aquaculture systems.

1.10 Methodologies followed in the study

The study involved field campaigns, laboratory works, and online research techniques (i.e., secondary information). Field campaigns were conducted four times (i.e., October 2017, February 2018, May 2018 and September 2018) considering seasonal durations (wet and dry). The following methods or research approaches were followed in the study, but also the detailed descriptions are in the individual chapters.

i. A scoping literature review (historical reconstruction) on the occurrence of CyanoHABs in Tanzania was performed by consulting peer-reviewed articles, reports, theses, and conference materials.

ii. A scoping survey for stakeholders' experiences and perceptions adopted quantitative (questionnaire) and qualitative methods of data collection (namely, field observation, meeting, key informant interviews, and focus group discussions) during field campaigns and the farmers' exhibition in Morogoro.

iii. Field campaigns included in situ measurements of the environmental variables (water quality parameters) and laboratory works (i.e., chlorophyll-a, nutrients, cyanobacteria species identification, and classification).

iv. Analysis of case studies (i.e., heavy rainfall event and unusual observation of red hue algae) as observed in the Ngerengere Catchment during the study period.

v. Retrospectively analysis of Chlorophyll-a concentration in the Ngerengere catchment and their link with climate and hydrological variations using advanced remote sensing technologies.

1.11 Significance of the study

The study demonstrated state of art on harmful algae in an area where there is data paucity and that both small-scale fish farmers, as well as water managers, can make use of the study as an awareness tool as well as for planning for monitoring, managing, and treatment. The study also provides an understanding of the threat that CyanoHABs have on water quality, human health, and the fishery industry. Since the study looks at algae in the catchment, it serves as a risk assessment tool to assist management strategies in the region of interest (Stevenson & Smol, 2003). The approaches used to conduct the study, which includes reviews (i.e., historical reconstruction) supplemented with field campaigns and observations, case studies, and the retrospective analysis of Chlorophyll-a, could link the trend of CyanoHABs with climate, hydrological and other environmental drivers in the region of interest. The present study adds to the targets of Sustainable Development Goal (SDG) 13 (https://www.globalgoals.org/13-climate-action) and Tanzania's government strategies on key priority sectors to combat the changing climate. The priority sectors of the national adaptations plan of actions include; agriculture, livestock, coastal and marine environment, fisheries, water resources, forestry, health, tourism, human settlement, and energy (Drakenberg et al., 2016).

1.12 Study Contribution to the body of knowledge

The impact of climate and hydrological modification on cyanobacteria potentials in Aquaculture systems in the Ngerengere catchment, Tanzania, is the central thesis. The study contributes to the understanding of CyanoHABs dynamics with climate and hydrological variation in a region where there is data paucity. The findings also provide insight into state of the art on CyanoHABs and their linkages with climate and hydrological variation that will inform the existing knowledge gaps, influence policy changes, and supports professional development.

1.13 Definition of key terms

Climate is defined as the measurement of the mean and variability of relevant quantities of certain variables (such as temperature, precipitation, or wind) over a period, ranging from months to thousands or millions of years. According to the World Meteorological Organization (WMO), the classical period is 30 years (IPCC, 2012).

Climate Variability is defined as variations in the mean state and other statistics of the climate on all temporal and spatial scales, beyond individual weather events (monthly and yearly) (IPCC, 2012).

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer) (IPCC, 2012).

Hydrological modification refers to alteration of streamflow (water levels, inflow and outflow of water in the receiving water body) and episodic events (heavy rainfall and droughts).

Aquaculture Systems refer to land-based systems, recycling systems, and integrated systems, as defined by Funge-Smith and Phillips (2001).

Cyanobacteria potentials refer occurrence of toxic cyanobacteria**,** blooms growth and concentration, and toxins concentration.

Harmful algal blooms (HABs/CyanoHABs) refers to Cyanobacteria species capable of producing toxins, those which alters the food web and creation of hypoxia (Paerl et al., 2011).

Cyanotoxin are secondary metabolites (toxins) that are produced by cyanobacteria

Hypoxia - Reduced dissolved oxygen concentration in water that stresses organisms (Chislock, Doster, Zitomer, & Wilson, 2013).

Internal nutrient load - releases of nutrients from sediments during low oxygen concentration conditions in water (Chislock et al., 2013).

1.13 Thesis structure

This thesis consists of eight chapters, including an introduction, chapters that are already published papers, those which are under review, and to be submitted to peer-reviewed journals for consideration and conclusion and recommendation for future studies. Since the adopted format of the thesis is by publication, there could be some minor repetition in the introduction, the experimental sections and references. However, the results and discussion and recommendations are specific to each chapter.

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Chapter 2

Review article: The occurrence of cyanobacteria blooms in freshwater ecosystems and their link with hydro-meteorological and environmental variations in Tanzania

This chapter has been published as Kimambo, O. N., Gumbo, J. R., and Chikoore, H. (2019). Review article: The occurrence of cyanobacteria blooms in freshwater ecosystems and their link with hydro-meteorological and environmental variations in Tanzania. Heliyon, 5(3), e01312. https://doi.org/10.1016/J.HELIYON.2019.E01312 (the chapter addresses objective i).

Abstract

Cyanobacteria (blue-green algae) are photosynthetic bacteria that, under favorable environmental conditions, produce secondary metabolites (cyanotoxins), which are harmful to the environment, including humans. The mass proliferation of harmful cyanobacteria is termed CyanoHABs. CyanoHABs can adapt to different climatic fluctuations; therefore, understanding their dynamics in freshwater systems is crucial. Variation in climatic and hydrological processes, changing land use, and economic growth all influence the occurrence and distribution of CyanoHABs. There have been inadequate CyanoHAB studies at local scales; therefore, their occurrence and dynamics cannot be generalized. This study reviews and synthesizes cases of CyanoHAB occurrence, magnitude, and timing and how these are linked with climatic and hydrological variations in the United Republic of Tanzania. In this study, a scoping review approach was adopted. Research articles, reports, and databases were consulted. The most common species of toxin-producing cyanobacteria were identified in different water bodies in Tanzania, as well as the record of mass fatality of birds (Lesser Flamingo) in Lake Manyara, which in almost all cases occurred during dry years. While previous studies on CyanoHAB dynamics and their links to climate, hydrological, and environmental changes have not been undertaken in Tanzania, there are studies in Lake Victoria and Tanganyika. Therefore, there should be an immediate response from water users,

managers, researchers, and water authorities to address and actively engage in monitoring and managing the risks associated with CyanoHABs in Tanzania.

1. Introduction

Cyanobacteria (blue-green algae) are oxygenic photosynthetic bacteria that occur naturally in fresh, brackish, and marine waters, and terrestrial environments (Codd, Louise, & Metcalf, 2005). Apart from their function as primary producers (Moorehead, Capelli, & Cysewski, 2011), cyanobacteria are now a global problem (Pham & Utsumi, 2018) because they can form massive blooms that produce a wide range of toxins (Codd, 2000; Codd et al., 2005; Zamyadi, Ho, Newcombe, Bustamante, & Prévost 2012 and Suzane, 2016). Over the past years, cyanobacteria were not regarded as water-borne pathogens (Codd et al., 2005), but recently the US Environmental Protection Agency (EPA, 2014) listed cyanobacteria on the Contaminant Candidate List (CCL), meaning that is an issue of public health concern. According to the World Health Organization (2003), 60% (worldwide) of samples from freshwater systems investigated had a mass occurrence of toxin-producing cyanobacteria.

The multiple environmental and health impacts of cyanobacteria have attracted researchers from different fields (Sanseverino, Conduto, Pozzoli, Dobricic, & Lettieri, 2016). One example is the development of models (Guven & Howard, 2006) studying occurrence, extent, and timing, while others have demonstrated the dynamics of cyanobacterial toxins in aquatic systems (Rodgers, 2008). Ho and Michalak (2015), for example, outlined several metrics for examining cyanobacterial proliferation. They include abundance, remotely sensed/spectral metrics, species-specific, toxicity, and qualitative metrics.

Harmful cyanobacteria, or CyanoHABs, are now a problem of global environmental concern, and efforts are being taken to prevent, predict, minimizes, and suppress their occurrences (Gatz, 2018). Triggers for CyanoHABs have been studied (Kubiak, Mazur, & Kotlarz, 2016; Paerl & Otten, 2016; Reichwaldt & Ghadouani, 2012; Schmidt, Wilhelm, & Boyer, 2014). These studies have demonstrated a scientific understanding of the dynamics of cyanobacteria. Despite all these efforts, geographical variation in CyanoHABs is not well explored, including the links between triggers and CyanoHAB proliferation. In the tropics, Tanzania is an example of insufficient studies on CyanoHAB. Of the few studies consulted, the reviews suggest the dominance of both *Microcystis* and *Cylindrospermopsis* species in the tropics, and their occurrence is throughout the year, unlike temperate regions in which their occurrences are confined to the warm summer months. In the nearby Lake Victoria, blooms of cyanobacteria have been observed since 1980, which are associated with massive fish kills (Ndlela, Oberholster, Wyk, & Cheng, 2016). Some reviews recommend preventive measures to be taken to combat cyanobacteria occurrences in major lakes (Ndlela, Oberholster, Wyk, et al., 2016).

Climate and hydrological variations are considered among the important factors promoting the occurrence and dominance of CyanoHABs aquatic environment (Ogashawara, Zavattini, & Tundisi, 2014; Reichwaldt & Ghadouani, 2012 and Havens, Fulton, Beaver, Samples, & Colele, 2016). Other studies (Ndlela, Oberholster, Van Wyk, & Cheng 2016 and Wells et al., 2015) suggest that little is known regarding climate variability and changes in cyanobacteria dynamics in Africa. In addition, there can be a conflict between the observation and experimental data. On the other hand, of the few studies, the genetic characterization of cyanobacteria isolated from Africa and Europe demonstrated the variation of cyanobacteria from different geographical regions (Haande et al., 2008, Harke et al., 2016). A study of Sinoven (2009) suggested that generalisation of CyanoHAB dynamics should be avoided because local climate and weather strongly impact contribution to and occurrence, as well as their extent. Sometimes cyanobacteria can withstand or adapt to changes or climatic fluctuations (El-Shehawy, Gorokhova, Fernández-Piñas, & del Campo, 2012). Studies (Lugomela, Pratap, & Mgaya 2006; Nonga et al. 2011; Mdegela, Omary, Mathew, & Nonga 2011; Fyumagwa et al., 2013; Kihwele, Lugomela, & Howell, 2014) in the United Republic of Tanzania have demonstrated the occurrence of toxin producing-cyanobacteria in specific regions. However, these studies are not sufficient to conclusively judge CyanoHABs dynamics and their link with climatic and hydrological variation, because most of them are event-driven, for example, post-mortem of Flamingo mortality in Lake Manyara. In this study, the goal was to review and synthesize cases of CyanoHABs (occurrence, extent, and timing) and how they have been linked with climate, hydrological variations, and or environmental (example, nutrients, and land use) changes in the United Republic of Tanzania. The study also aimed to provide the status as it stands to water managers, researchers, and policymakers in order to elucidate and plan the best management practices in water resources.

2.0 Study area description

The United Republic of Tanzania lies within 1–12 °S and 29–40 °E. Tanzania is blessed with a range of natural resources, for example, 6.4% of the country's area is water bodies (Lake Victoria in the North, Tanganyika to the west and Nyasa (Lake Malawi) to the south-west) and to the east lies the Indian Ocean (Basalirwa, Odiyo, Mngodo, & Mpeta, 1999). A large population depends on agriculture, including livestock and fisheries (Drakenberg, Ek, & Fernqvist, 2016). The country has a temporal climatic variation in both temperature and rainfall, and the trend is consistent (New et al., 2006). Tanzania's climate varies from tropical (along with the coast) to temperate (in the highlands), and there are two rainfall distribution types (unimodal and bimodal) (FAO, 2016). A well-detailed climate classification over Tanzania can be depicted from the previous climate studies (Kottek, Grieser, Beck, & Rudolf, Bruno, Rubel, 2006; Peel, Finlayson, & Mcmahon, 2007). Several weather systems are responsible for the observed climatic variation, including thunderstorms, Intertropical Convergence Zone (ITCZ) as it moves south and north and, tropical cyclones (which pool moisture from Congo forest), Sea Surface Temperature (SST) which enhance easterly to northeasterly winds resulting into moisture influx overland (Mbululo & Nyihirani, 2012; Kijazi & Reason, 2009; and Mafuru & Guirong, 2018).

In Tanzania, there has been no reports of fish kill or harm to domestic animals, including humans, are directly linked to specific cyanotoxins. Guidelines and standards for algal toxins are yet to be established (Miraji, Othman, Ngassapa, & Mureithi, 2016). Therefore, in view of the above, one can hypothesize that if a business, as usual, continues under a current climate change (warming, increase in carbon dioxide), CyanoHABs are likely to compromise water dependencies and in turn negatively affect our adaptation strategies.

In the current review, we considered all published articles and reports on HABs incidences in Tanzania and how they have been associated with climate and hydrological variations. A wide range of limnological, environmental, and scientific databases were also consulted for elucidating the theoretical aspects of HABs in the environment. Google search engine, webs, and journal databases were tools used in the current review study.

3.0 Factors influencing the proliferation of harmful algal blooms

There is no single factor that can describe the formation of cyanobacteria bloom (Te & Gin, 2011; Anderson, 2014) but rather a complex set of interactions (**Figure 2.1**) of several environmental factors (Wells et al., 2015) and optimal conditions should be met (Berger & Gobler, 2008; Descy & Sarmento, 2008). Factors such as light intensity and duration, temperature, nutrient availability, episodic hydrological events (droughts and floods events), bio-physiological and chemical characteristics and ecosystem structure are responsible for bloom formation (Moore et al., 2008; Paul 2008; Reichwaldt & Ghadouani, 2012; Merel et al., 2013; Hazen and Sawyer, 2015; Ndlela et al. 2016). Not much has been studied the impact or the mechanism that co-exists between cyanobacteria and carbon dioxide (CO_2) (Visser et al., 2016). Most studies suggest the use of chlorophyll-a as a proxy measure of algal blooms (Anderson, Moore, Tomlinson, Silke, & Cusack, 2015). Other studies (Elliott, 2012; Reichwaldt & Ghadouani, 2012; and Moore et al., 2008) have demonstrated the influences of major weather shifts on freshwater HABs dynamics. For example, a positive/negative correlation exists between rainfall intensity and length of dry periods, which in turn determine the occurrence of cyanobacteria blooms (Paerl et al., 2016). These studies establish how individual weather phenomena directly or indirectly influence CyanoHAB proliferation. In the same line of argument, Anderson (2014) suggests case studies, especially events that mimic future climate scenarios that, if studied, can be more informative than doing single parameters.

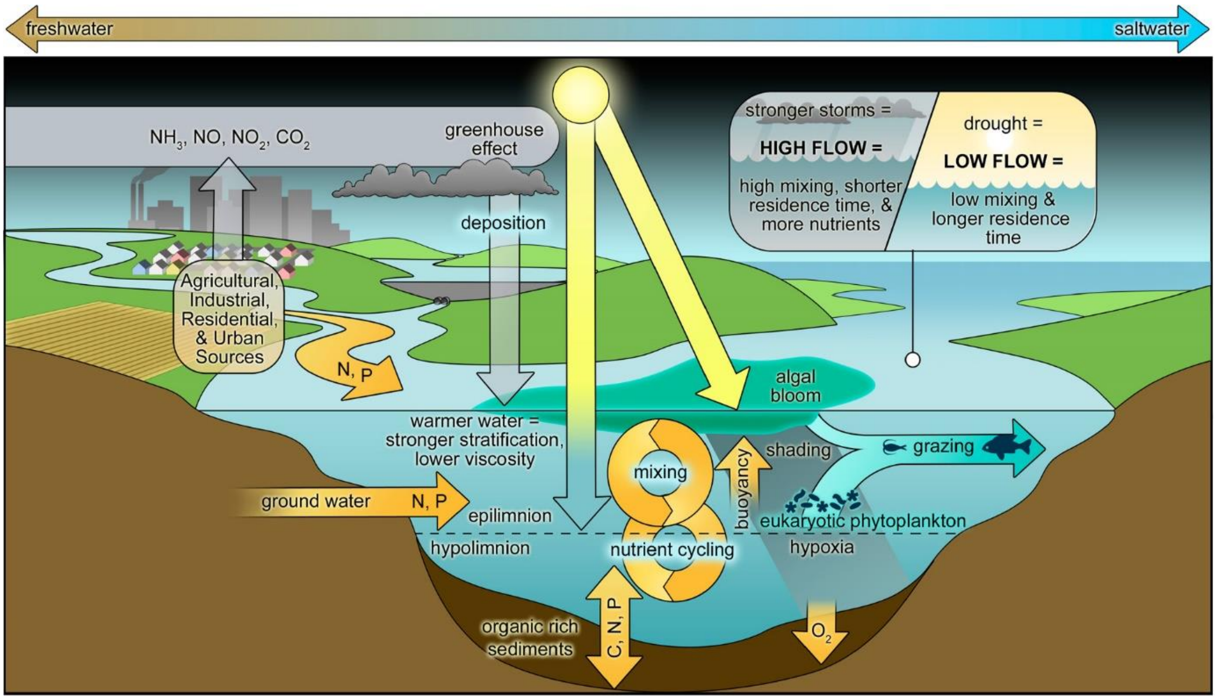


Figure 2.1 Schematic diagram of interactive physical, chemical and biological controls on harmful algal bloom formation and proliferation along the freshwater-to-marine continuum. Adopted with permission from "Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum," by Paerl et al. (2018).

Some studies have also investigated single or few factors and their influences on HABs. The factors are not standing alone because sometimes they may interact; therefore, the multifactor analysis should be done to critically highlight at what state (say mixing and pH) favors the growth or at what level (temperature, flushing, and nutrient inputs) CyanoHABs decrease. Another one, for example, Shen, Xu, and Guo, (2012) concluded a link between environmental factors and how their influence on HABs dynamics is neither well documented nor explained although there have been efforts in the understanding of HABs such as a recent scientific consensus (Heisler et al., 2008) highlight some doubts which need to be cleared.

Many studies have used methanol for the extraction of cyanotoxins (Codd, 2000; Fyumagwa et al., 2013; Kim, Huong Nguyen, Kim, Lee, & Yu, 2009; Mbukwa, Msagati, & Mamba, 2012; Merel et al., 2013; Metcalf & Codd, 2014). The approach was challenged by a recent study (Visser et al., 2016) that questions the validity of the previous findings, and this is still debatable.

3.1 Findings on Cyanobacteria (HABs) in Tanzania

In Tanzania, there have been reports on species of cyanobacteria and their toxins (Harke et al., 2016) in different water bodies. However, few studied harmful algal blooms and their link with climate and hydrology. Metcalf et al. (2012) reported species of *Oscillatoria amphibian* and O*scillatoria formosa* (0.125 ng mg^{-1} of dry weight) on their study on the analysis of microcystins and microcystins genes in 60-170 years' herbarium specimen of cyanobacteria which were collected in an aquatic and terrestrial environment in Zanzibar during 1988. As noted earlier, available literature asserts the occurrence of toxic strains of cyanobacteria and their impacts in some parts of the United Republic of Tanzania. To date, the only documented reports/incidences in Tanzania is the mass fatality of Lesser Flamingos in saline lakes in Arusha and Manyara Region (Kotut, Ballot, & Krienitz, 2006; Lugomela et al., 2006; Nonga et al., 2011; Fyumagwa et al., 2013; Kihwele, Lugomela, & Howell, 2014).

Following the mass fatalities of Flamingos in three soda lakes (Embakaai crater, Lake Natron, and Lake Manyara in Arusha Region) in the year 2000, 2002, and 2004, samples of both water and tissue were collected and analyzed for cyanotoxins. This is the same as the post-mortem study of Fyumagwa et al. (2013), which revealed that the impact was due to cyanobacterial toxins (Anatoxin-a and Microcystins). In these studies, no detailed analysis of the environmental factors responsible for the mortality rate was conducted. Furthermore, in this particular study, the findings (for example, pH) were more abstract (values not reported). The author (Fyumagwa et al., 2013) made a deduction that varying pH was due to prolonged drought out of no data, but it was good to speculate that anthropogenic activities could have triggered the proliferation of harmful blooms. This implies that if there were regular monitoring of all environmental parameters in the lake, it would have facilitated tracking the influences of individual causal effects on HABs.

Some other studies (Lugomela et al., 2006; Kihwele et al., 2014; Krienitz et al., 2016) in Lake Manyara found species of *Cylindrospermum* (701 cells/ml) and *Microcystis* (6043 cells/ml). These studies suggest repeated and unpredictable episodes of lesser flamingo fatalities, which are attributed to the exposure to cyanotoxins and that the toxification may be spread to other East African Lakes. Increased water abreaction, tourism developments, and degradation of the catchment were found to be negatively contributing to the ecohydrological health of Lake Manyara (Lugomela et al., 2006; Kihwele et al., 2014; Krienitz et al., 2016). According to

Kihwele et al. (2014), the change was constant with seasonal variability (more pronounced in a recent decade). However, the study could not demonstrate the magnitude of change and climate variability.

Several studies (Ndlela et al., 2016; Sinha et al., 2012 and Paerl & Paul, 2012) reported species of *Microcystis*, *Anabaena*, *Cylindrospermopsis raciborskii* and *Plantolyngbya* (Sekadende, Lyimo, & Kurmayer, 2005; Miles et al., 2013) in Lake Victoria. Another study, for example, Rumisha & Nehemia, (2013) on feeding selectivity of wild and cultured *Oreochromis niloticus* (Nile tilapia) registered high concentration of *Microcystis*, A*nabaena flos-aquae*, and *Lingbya circumcreta* species in Lake water than in fishponds. Changes in water quality in Lake Victoria is attributed to anthropogenic activities (Silsbe, Hecky, Guildford, & Mugidde, 2006). Other parts of the country, for example in Morogoro, *Microcystis* species were identified in ponds on the study of the effects of ponds management and the prevalence of intestinal parasites (Mdegela et al., 2011). Another recent study by Mushi (2015), which compared pristine, urban, and agricultural fields, also found species of cyanobacteria, including toxin-producing species of *Cylindrospermopsis*.

In Lake Babati in the central part of Tanzania, *Aphanizomenon* species, strains of *Chrysopsorum ovalisporum* were identified, and in Lake Rukwa in the South-eastern highlands, strains of *Sphaerospemopsis aphanizomenides* and *Sphaerospermopsis renifomis* were identified (Cire, 2016). These studies showed no direct link between physicochemical parameters and bloom occurrences. Along similar lines, species of *Anabaena flos-aqua* were reported to occur annually from October to November in Lake Tanganyika (Codd, Azevedo, et al., 2005). Communicating variations in the Lake Tanganyika, a study by Paul (2008) reported that cyanobacteria biomass dominated the lake over other phytoplankton during the period of March to April 2001 than how it was in 1975. The study suggests that in Lake Tanganyika, climate changes (warming) have been the driving factor, which was also observed by Paerl (2014). On a global scale, Paerl (2014) and Paerl et al. (2016) stated that climate change and hydrological modification might require modifying management strategies for controlling CyanoHABs.

4.0 General and predicted climate changes in Tanzania

Temperature is the most studied climate parameter when addressing CyanoHAB dynamics. In

Tanzania, pieces of evidence and projection of an increase in temperature can be deduced from models (as in **Figure 2.2**) and empirical studies (New et al., 2006 and World Wide Fund For Nature, 2006). To further highlight this, in Tanzania, there are climate change hotspots (Niang et al., 2014) such as Lake Tanganyika (directly linked with cyanobacteria dynamics and decrease in fish productivity) and Mountain Kilimanjaro (a good indicator of global warming). Changes in climate (for example, warming) have been attributed to the occurrence of blooms (Paul, 2008). While studies on climate variability and cyanobacteria dynamics are limited (Ndlela, Oberholster, Van Wyk, et al., 2016), existing ones (for example in Lake Tanganyika) indicate chlorophyll-a concentrations are constant throughout the year with the alteration of dry and wet seasons (De Senerpont Domis et al., 2013). Chlorophyll-a is used as a proxy for cyanobacterial biomass estimation in marine and freshwaters (Dörnhöfer & Oppelt, 2016). A study by Niang et al. (2014), which was based on more than 90 years of observation, suggests that increased stratification, nutrient fluxes, and decreased productivity was due to recent increases in surface temperatures. The effects have negatively affected the catches of sardines by 30-50% (Drakenberg et al., 2016). Predicted changes in climate (World Wide Fund For Nature, 2006) in the region require measures such as finding out the influence of both temperature and rainfall has on nutrients increases in the water bodies. (Paerl et al., 2016; and Paerl, Otten, & Kudela, 2018).

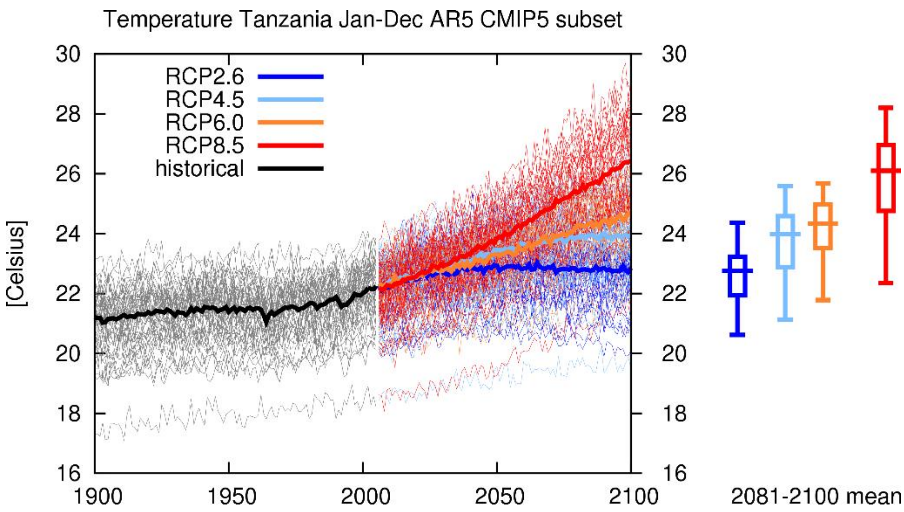
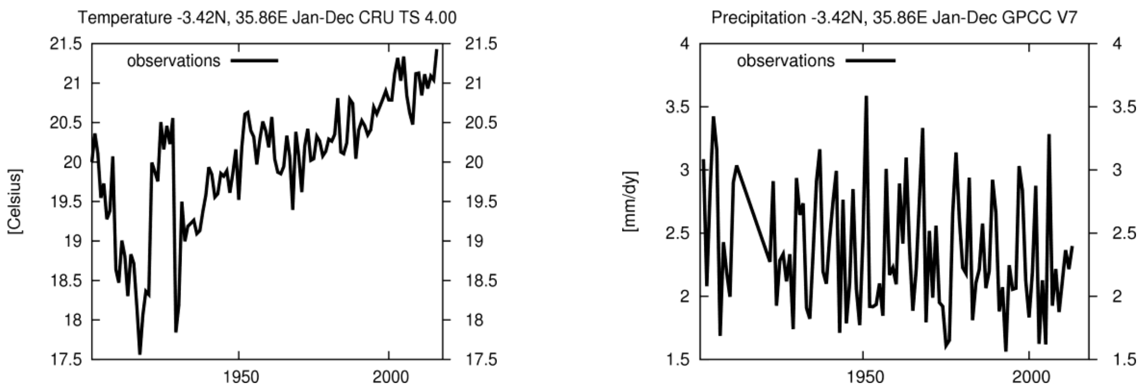


Figure 2.2 Projected changes in air temperatures (℃) for different climate scenarios in Tanzania (Data generated from "KNMI Climate Explorer").

4.1 Specific observations in selected areas

4.1.1 Manyara, Arusha

Plankton dynamics are system-specific (weather and hydrological); for example, temporal variability in precipitation can be an important driver of the seasonal development of plankton (De Senerpont Domis et al., 2013). Indirectly, increases in precipitation and warming are likely to impact water reservoirs stratification (Harke et al., 2016). The National Adaptation Programme (The United Republic of Tanzania, 2007) specifically for Lake Manyara emphasizes an increase in frequencies of floods, drought and land degradation, which reduces the frequency of recreational and tourism activities. The report further argues that it is the hydrological conditions in Lake Manyara that influence birds' (Flamingo) breeding patterns. Temperature is probably the most studied climatic parameters in relation to algal blooms (Wells et al., 2015). Generally, Manyara, for example, temperature indicates an increasing trend (**Figure 2.3a**), which was also demonstrated by New et al. (2006) and insignificant variations in precipitation (Fi**gure 2.3b**), which is a key driving factor of CyanoHABs.



(a) (b)

Figure 2.3 (a). An increasing air temperature trend (observed) (from Climate Research Unit TS 4.00) and (b) Observed Precipitation (mm/day) from Global Precipitation and Climate Centre version 7 (GPPCC V7) for Manyara (Data generated from "KNMI Climate Explorer,").

Standardized Precipitation and Evapotranspiration Index (SPEI) (Figure 2.4) obtained from Water Cycle Integrator (WCI) portal (available at http://wci.earth2observe.eu/) generally indicate drought conditions (negative values of SPEI) for most of the years (for example 1994, 2000, 2004, 2008). Some post-mortem studies in the same years (Lugomela et al., 2006; Nonga et al., 2011 & Kihwele et al., 2014) may confirm whether Lesser Flamingos were exposed to cyanotoxins. The hypothesis needs to be tested whether weather and hydrological changes contributed significantly to the changing of the concentration of CyanoHABs in Lake Manyara, which could have resulted in the deaths of birds. Case study analysis is an appropriate approach to investigate these events.

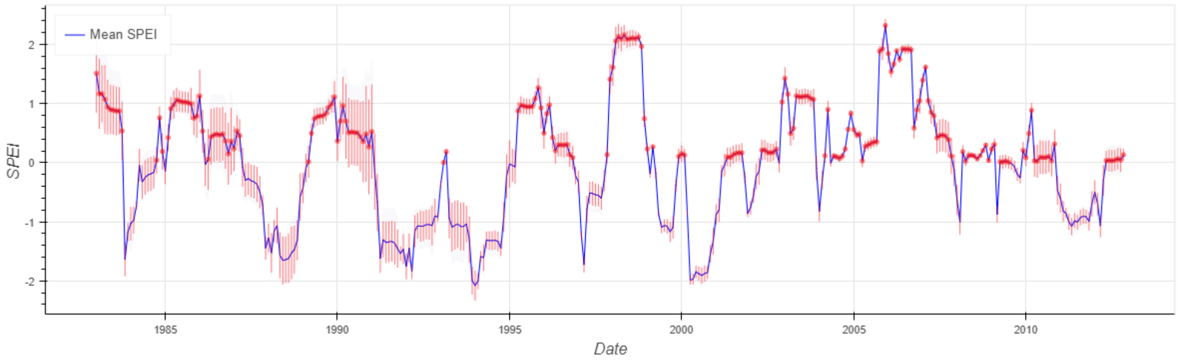


Figure 2.4 Standardized Precipitation and Evapotranspiration Index (SPI) for Manyara (Generated from "eartH2Observe Water Cycle Integrator," available online at http://wci.earth2observe.eu/)

4.2. Morogoro

4.2.1 Climatic and hydrological variation

It is widely accepted that local climate and weather variation, climate change, eutrophication, and hydrological variations are the key drivers of CyanoHABs (Paul 2008). Intertropical Convergence Zone (ITCZ) and El Niño Southern Oscillation (ENSO) cause greater than average rainfall in Tanzania in the short rainfall season (October to December) while the cold phase (La Niña) causes a dry condition than the average and these can work synergistically (GLOWS-FIU 2014; Kijazi & Reason, 2009). A study by Paavola (2008) on drought in the Morogoro region enumerated all the drought years, which indicates that Morogoro is a drought-prone area. Mean climatic conditions, for example, temperatures (New et al., 2006) of Morogoro, agrees with a threshold of more than 20-35°C air temperature (Elliott, 2012 and Sinha et al., 2012) which is the optimal temperature for CyanoHAB formations. However, a study by Baig et al. (2017) demonstrated a threshold of 24-28°C (water temperature), where the highest peak of cyanobacteria was observed. Moreover, the same study noted a decline of cyanobacteria blooms and chlorophyll-a when temperatures were 30°C. Another factor in Morogoro is drought (Paavola, 2008) which can be depicted (negative values of standardized precipitation index (SPEI)) from figure 2.5**,** which has the characteristics to prolong periods of surface temperatures, stabilizing water columns and increasing nutrient concentration indirectly (Reichwaldt & Ghadouani, 2012).

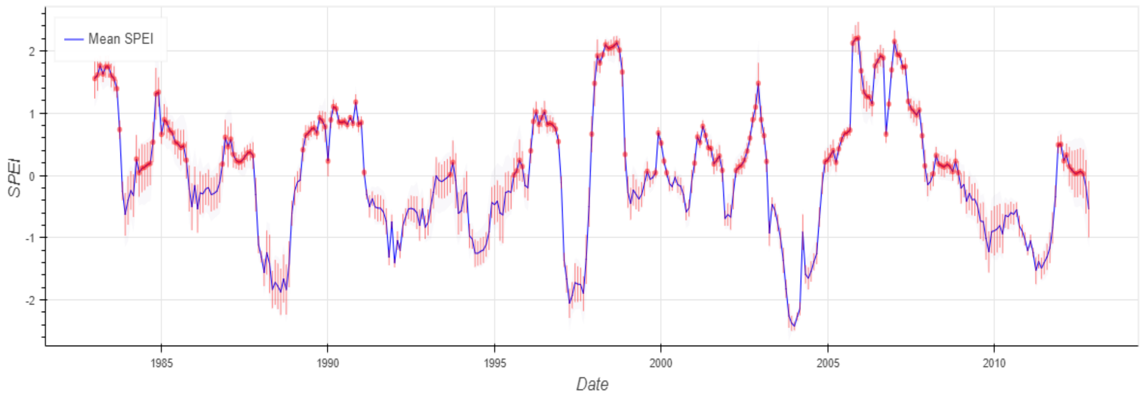


Figure 2.5 Standardized Precipitation and Evapotranspiration Index (SPEI) in Morogoro (Datapoint generated from “eartH2Observe Water Cycle Integrator,” available online at http://wci.earth2observe.eu/

4.2.2 Hydrological variations

In Mindu Dam, a Man-made Dam situated in the Ngerengere River Catchment, Morogoro Urban, there has been periodic maintenance of floodgates and other infrastructure to ensure that gates do not get jammed in the event of heavy rainfall and river flows (GLOWS-FIU 2014). The water level peaks (which is an indicator of hydrological variations) in figure 2.6 depicts some dry and wet years in Morogoro, which suggest the likelihood of severe drought and wet years which was also reported by Paavola, (2008). The dry and wet peaks in the (SPEI) in figure 2.5 also indicate negative values for dry and positive values for wet years, which corroborates with water level peaks variations in Mindu Dam (Figure 2.6). These variations are useful in describing the formation of algal blooms, as highlighted in the framework of Reichwaldt & Ghadouani (2012) and Zhang et al. (2016). Lack of monitoring of both climate, hydrological, and other environmental variables makes it impossible to study and ultimately manage CyanoHAB variations in this study area.

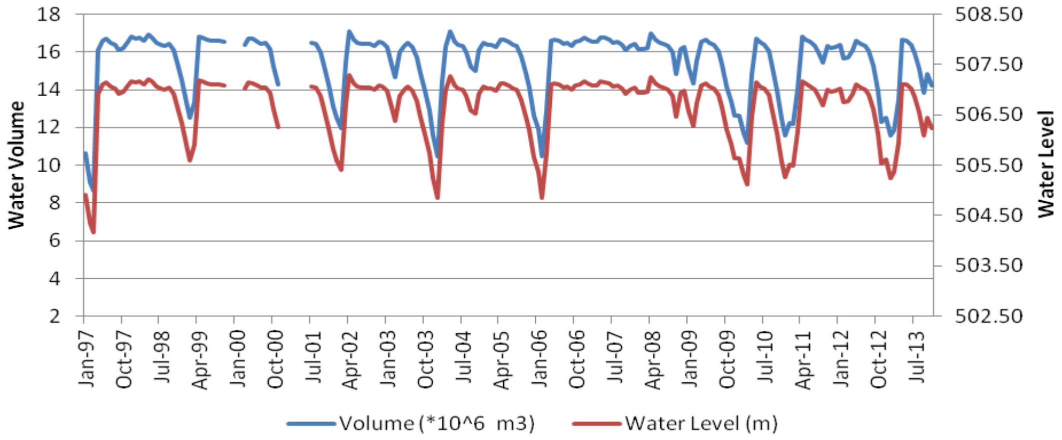


Figure 2.6 Variations of water levels (m) and volume (m^3) in Mindu Dam for a period of 1997-2013 (data from Wami/Ruvu, 2013)

It is widely accepted that evapotranspiration can assist in forecasting hydrology and climate systems hence ecological dynamics (Yang, Zhang, & Hao, 2016). Land use characteristics (residential, agriculture, industrial, forest, and undeveloped area) can also be a factor in determining the severity of bloom formation (Shayo, Lugomela, & Machiwa, 2017). These hydrological variations in the Morogoro Urban suggest optimal conditions for the proliferation of CyanoHABs. A study by Yanda and Munishi (2007) on hydrological and land use/cover change analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) watersheds both in Morogoro which looked at the historical flow data confirmed sedimentation in the catchment due to land use. The same study found a match between the flows and rainfall variations, but also predominance declining flows in both the dry and wet seasons. These seasonal variations in flow are a very important predictor for the formation of cyanobacteria in the catchment.

4.2.3 Water quality studies in Morogoro Urban areas

Morogoro Urban is prone to pollution due to anthropogenic activities (Msigala, Mabiki, Styrishave, & Mdegela, 2017). Numerous studies (Ngoye & Machiwa 2003; Ngonyani & Nkotagu, 2007; Mero, 2011; GLOWS-FIU, 2014) suggest significant levels of water pollution when compared with other studies (Merel et al., 2013; Hazen & Sawyer, 2015 & Glibert, 2017) show optimal conditions for the algal bloom proliferation. Overall, the findings challenge water authorities on how HABs are perceived in the study area. This is also heightened by the fact that HABs can adapt to a changing environment (Anderson, 2012). A recent study by Mushi

(2015) found the occurrence of *Cyanobacteria* species in Morogoro (pristine, agriculture, and urban). According to Mushi (2015), there was no significant variation of the microbial community (Cyanobacteria inclusive) during the entire period of the study. The claim leaves many questions, for example, predicting blooms in the study area. One would argue that the author's claim was based on limited data (short time period) and, therefore, this needs to be re-examined and evaluated.

5.0 Social-Economic Impacts of harmful algae

Several studies (Sanseverino, António, Loos, & Lettieri, 2017; Suzane, 2016) have indicated how CyanoHABs are associated with a wide range of economic impacts on human health, fishery, tourism, and recreational use, and monitoring and management costs. Cyanobacteria exert toxic effects on humans, animals, fish, birds, and other phytoplankton that are associated with (WHO 1999 and Chen, Chen, Zhang, & Xie, 2016). Human health, for example, several studies (Elliott 2012; EPA 2014; Chen et al., 2016; Wolf & Klaiber 2017) have indicated acute effects such as neurotoxicity, hyper-toxicity, diarrhea and amnesia, abdominal pain, headache, altered pulse, respiratory failure, cardiac arrests, and even death. The principle behind this is that cyanobacteria release toxins as their defense mechanism when grazed, disturbed, and or in competition with phytoplankton (Reichwaldt & Ghadouani 2012). This is still debatable.

Tanzania has favorable environmental conditions (ecological, hydro-geological, and physical), and social-economic activities (for example, agriculture, and industries) that support the occurrence, and proliferation of CyanoHABs. A good example is the availability of several small to large standing and non-standing surface freshwater bodies (FAO, 2016). On the other hand, research activities and awareness of harmful algal blooms are lagging (Ndlela, Oberholster, Van Wyk, et al., 2016). Because of its heavy use of nutrients in food supplies, aquaculture can also trigger HABs proliferation. According to the Ministry of Livestock and Fisheries Development (The United Republic of Tanzania, 2013), Tanzanian aquaculture fish farmers increased from 3347 to 17511 in between the year 2000 and 2013 with a corresponding increase in ponds from 4000 to 19930 and landed fish production from 200 tons to 2989.5 tons (The United Republic of Tanzania, 2013).

Several researchers (Grover, 2006; Bushaw-Newton & Sellner, 2012; Merel et al., 2013; Rastogi, Madamwar, & Incharoensakdi, 2015; Sanseverino et al., 2016) have directly linked diarrhea among symptoms of exposure to cyanotoxins. This is important because diarrhea is among the leading waterborne diseases in Tanzania (IHME, n.d.). The current study does not intend to confirm that diarrhea in the study area is caused by cyanotoxins, but it is a hypothesis that needs to be tested. In summary, social-economic activities in Tanzania can be one of the routes of exposure to CyanoHABs.

5.1 Management of algal blooms

A review by Ndlela et al. (2016) that focused on Africa noted that regarding research on CyanoHABs, little had been done. However, efforts have been made to at least formulate a global network to discuss and deliberate on matters related to CyanoHABs and their toxin risk management (Codd, Azevedo, et al., 2005). Further, to mitigate CyanoHABs, some solutions (technical and policies) are in place (in a global perspective); for example, land and water management, water treatment and blooms control (Berger & Gobler, 2008; Shayo, Lugomela, & Machiwa, 2011; Hazen and Sawyer, 2015). Monitoring of CyanoHABs, treatment of algal toxins in drinking, recreational, fish farms, and irrigation waters can significantly minimize health impacts associated with their formation and dominance. Algal bloom management should be proactive because HABs are capable of adapting to a variety of climatic and other environmental conditions (Wolf & Klaiber 2017) that promote their ability to outcompete other phytoplankton (O'Neil, Davis, Burford, & Gobler 2012). According to Anderson (2012), case studies (e.g., heavy rainfall or drought) that mimic climate change scenarios should be used to understand HABs responses. Suzane (2016) also suggests the use of case studies to quantify the social-economic impact of HABs.

Managing CyanoHABs in the context of climate and hydrological variations is challenging (Paerl et al., 2016). Future studies should thus, focus on how climate and hydrological variations affect nutrients dynamics. If nutrient reduction can significantly reduce HABs events (Paerl et al., 2018), then understanding the linkage between climate, hydrological variation, and other environmental factors are essential. There is a global and regional initiative for studying and management of HABs, for example, a global network for cyanobacteria blooms and toxin risk management (CYANONET) in which the United Republic of Tanzania is a member (Codd, Azevedo, et al., 2005). The project is intended for awareness, prevention, and mitigating algal blooms. However, Tanzania, like many other countries' policies, regulations, and guidelines on HABs management, is yet to be established (Miraji et al., 2016). Since there have been reports of HABs species and cyanotoxins in the study area, the opportunity for nation-wide monitoring, prevention, prediction, minimizing, and suppression of HABs should be undertaken.

6.0 Summary and concise conclusions

CyanoHABs species are widely distributed in the study area, and anecdotal observations suggest that they vary with seasons (dry and wet). There is no sufficient limnological data that exist to perform time series analysis for getting a clear understanding of CyanoHABs dynamics in the region. In Tanzania, the fields of CyanoHAB ecology, monitoring, and management are in their nascent stage. There are, however, documentable cases that link seasonal variations of CyanoHABs, especially in Lakes Victoria and Tanganyika. Most of the studies are event-driven, for example, post-mortem studies, although climate, hydrological variations (especially drought years and temperatures), and environmental conditions support their occurrence. Therefore, research and or academic institutions working on CyanoHABs in the country should be assessed and developed/empowered. Likewise, regular monitoring and documenting, and prediction of CyanoHABs dynamics in the regions should be considered. Future studies should focus on awareness and occurrence of CyanoHABs, epidemiological studies, toxicity occurrence, and levels in the food web and timing. Due to the distribution of water bodies in varying localities (dams, rivers, lakes, ponds, and ocean) in Tanzania, it would be wise to conduct a spatiotemporal survey of CyanoHABs and their link with environmental stressors. It is also encouraged to revisit the current management options, for example, water treatment plants for assessing CyanoHABs control efficiencies. Adapting to the risks associated with CyanoHABs occurrences, case studies that mimic future climate change scenarios (e.g., drought and heavy rains) will be more informative. Technological improvement, such as the application of remote sensing for monitoring CyanoHABs, should also be utilized. Policy and guidelines for dealing with algal blooms are yet to be formulated that also consider the effects of climate, hydrological, and environmental (e.g., nutrients, and metals) conditions on HABs proliferations.

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Chapter 3

Harmful algal blooms in aquaculture systems in Ngerengere Catchment, Morogoro, Tanzania: Stakeholder's experiences and perception

This chapter addresses objective (i)

Abstract

The aquaculture sector in Tanzania has experienced a fast-growing trend in the recent years as a result of the livelihood diversification initiative among small-scale farmers in Tanzania. The aquaculture industry and other water reservoirs are hotspots for the proliferation of harmful algae. Regrettably, the dynamics harmful algal blooms (HABs) have been overlooked despite noticeable forcing of climate variability, the interaction between social-economic activities, and a threat to a domestic water supply reservoirs. The study aimed at surveying the occurrence, and stakeholders' experiences of HABs in aquaculture systems in the Ngerengere catchment, Morogoro, Tanzania. A cross-sectional survey and mixed methods approach (focus group discussion-FDG, key informant interviews, and anecdotal observation) was adopted. Moreover, a convenient and purposive sample population was drawn from ponds owners and registered water users in the catchment. A cross-tabulation, descriptive statistics, and content analysis were performed. The results suggest that 95% of respondents were able to recognize the image of blooms displayed to them. Seventy (70) percent of the respondents agreed that water quality has been deteriorating over time, and blooms occur during the dry season. Moreover, 60% of the respondents agreed that water pollution is a serious problem attributed to other sources other than industrial discharge. There was also no consensus regarding the health impacts associated with HABs. Raising awareness on HABs is paramount importance as it will provide the basis for the development of the HABs management framework and health risk assessment.

Keywords: cyanobacteria; harmful algal blooms; water pollutions; aquaculture systems; Ngerengere Catchment; Morogoro

1. Introduction

Harmful algae are photosynthetic and microscopic bacteria that are naturally occurring in marine and freshwater ecosystems (Glibert, Berdalet, Burford, Pitcher, & Zhou, 2018). Harmful algal bloom (HABs) and Cyanobacterial harmful algal bloom (CyanoHABs) have been used interchangeably to describe cyanobacteria species that tend to produce toxins, alter food web, and or those that produce hypoxia (Testai, Buratti, Funari, Manganelli, & Vichi, 2016). A current global discussion indicate that the dynamics of cyanobacteria (HABs) in freshwaters is attributed to a changing environment and or climate change (Anderson, 2014; FAO, 2016). A study by Brooks et al. (2016), suggests that magnitude, frequency, and duration of HABs are poorly understood but also HABs have received inadequate attention.

On a global scale, small-scale fish farmers are the most vulnerable to HABs besides challenges on startup capital, operating resources, and poor farming practices (Pomeroy, 2016). In East Africa, for instance, is an economical water scarcity area (WorldFish, 2007), but also financing aquaculture projects has been lagging behind (Kaliba, Osewe, Senkondo, Mnembuka, & Quagrainie, 2006). In addition, environmental factors such as land degradation, pollution (point and non-point sources), climate and hydrological variability, habitat loss (conversion of wetlands into fishponds) are also adding pressure on small-scale fisheries and the whole ecosystem. Information on harmful algal blooms dynamics and effects in the Ngerengere catchment situated in Morogoro, The United Republic of Tanzania are yet to be researched. However, a survey on environmental flow found water pollution to be a significant problem and recommended efforts should focus on awareness-raising, and ecotoxicological studies (GLOWSFIU, 2014a). The overall implications can be evidenced in a social-economic profile of the Morogoro region, which itemized ten most common causes of morbidity, including diarrhea and skin diseases, which are also symptoms of some cyanotoxins exposure (Sanseverino, Conduto, Pozzoli, Dobricic, & Lettieri, 2016). A comparative study on the microbial community in three clusters (pristine, urban, and agriculture) found, for example, cyanobacterial species of *Cylindrospermopsis,* which is among the harmful algae (Mushi, 2015).

Social-economic factors are thus critical for the intensification of fish farming in the region, if emphasis on extension education of farming practices and technological improvements to the practicing farmers (Wetengere, 2011; Kaliba et al., 2006). According to the Ministry of

Livestock and Fisheries Development (The United Republic of Tanzania, 2016), Tanzania mainland aquaculture fish farmers increased from 3347 to 17511 between the years 2000 and 2013. There was a corresponding increase in fish ponds from 4000 to 19930 and landed production from 200 to 2989.5 tons (The United Republic of Tanzania, 2013a). On the other hand, in a survey of the Morogoro region, despite the efforts made in aquaculture, still the industry is in a nascent stage and intensively operated by small-scale fish farmers (Breuil & Grima, 2014).

The unfortunate role of environmental changes, climate change and weather variability on HABs dynamics and attendant effect on food security has received less attention, especially in the pursuit of sustainable development goals and the 2030 Agenda (Brooks et al., 2016). To our knowledge, no study has yielded findings on the awareness of HABs from water users in the catchment on HABs occurrences and experiences. Only a few cases have shown their concern about water quality standards for fishing and environment, which are also yet to be established (Hawkins, 2010; Miraji, Othman, Ngassapa, & Mureithi, 2016). It is unfortunate that small-scale farmers are unable to access water quality information to inform their decisions rather, they rely on qualitative measures such as source of water, color changes, effects on fish, and being unable to locate markets (Withanachchi et al., 2018). Health effects, for example, are also perceived to be connected to low water quality by farmers (Mayilla, Keraita, Ngowi, Konradsen, & Magayane, 2017). With algal blooms, there are already reported cases (Aziza et al., 2018), for example, a study by Mchau et al. (2019) in Ukerewe (an island in Lake Victoria), evidenced health impacts associated with cyanobacteria-contaminated drinking water. One way to overcome the problem is to assess the occurrence, timing, and awareness of HABs and their health effects in the catchment but also interdisciplinary collaboration (Van Dolah, Paolisso, Sellner, & Place, 2016). The aim of the current study was to investigate the stakeholders' perceptions on occurrence, extent, and timing of harmful algae in aquaculture systems in the Ngerengere Catchment, a sub-catchment of the main Wami-Ruvu basin located in Morogoro region, the United Republic of Tanzania.

2.0 Materials and Methods

2.1. Study area description

The Ngerengere catchment is the sub-catchment of the main Wami Ruvu basin, located in Morogoro region, Tanzania within longitudes and latitudes of 37°32’E 6°51’S, 38°09’E 6°69’S, 37°38’E 7°09’S and 38°38’E 7°05’S respectively (Figure 3.1). The catchment covers approximately an area of 2780 km^2 and characterized by a tropical climate (Gomani et al., 2010). Mindu Dam is the primary source of water and freshwater fishery supplies in the urban and peri-urban of Morogoro (Mdegela et al., 2009). However, erosion and sedimentations due to human activities are more prominent challenges (Natkhin, Dietrich, Schäfer, & Lischeid, 2015) and that it has continuously reduced the depth of the Dam and Ngerengere River (Yanda & Munishi, 2007). Water quality status and trends in the catchment have also been studied with an indication that there is significant pollution contributed by agriculture, domestic, and or industrial activities (GLOWSFIU, 2014b; Mero, 2011; Mushi, 2015; Ngonyani & Nkotagu, 2007; Ngoye & Machiwa, 2003). Furthermore, recent work on chlorophyll-a with climate and hydrological variation also highlights the possible causes of HABs in the catchment (Kimambo, Chikoore, Gumbo, & Msagati, 2019).

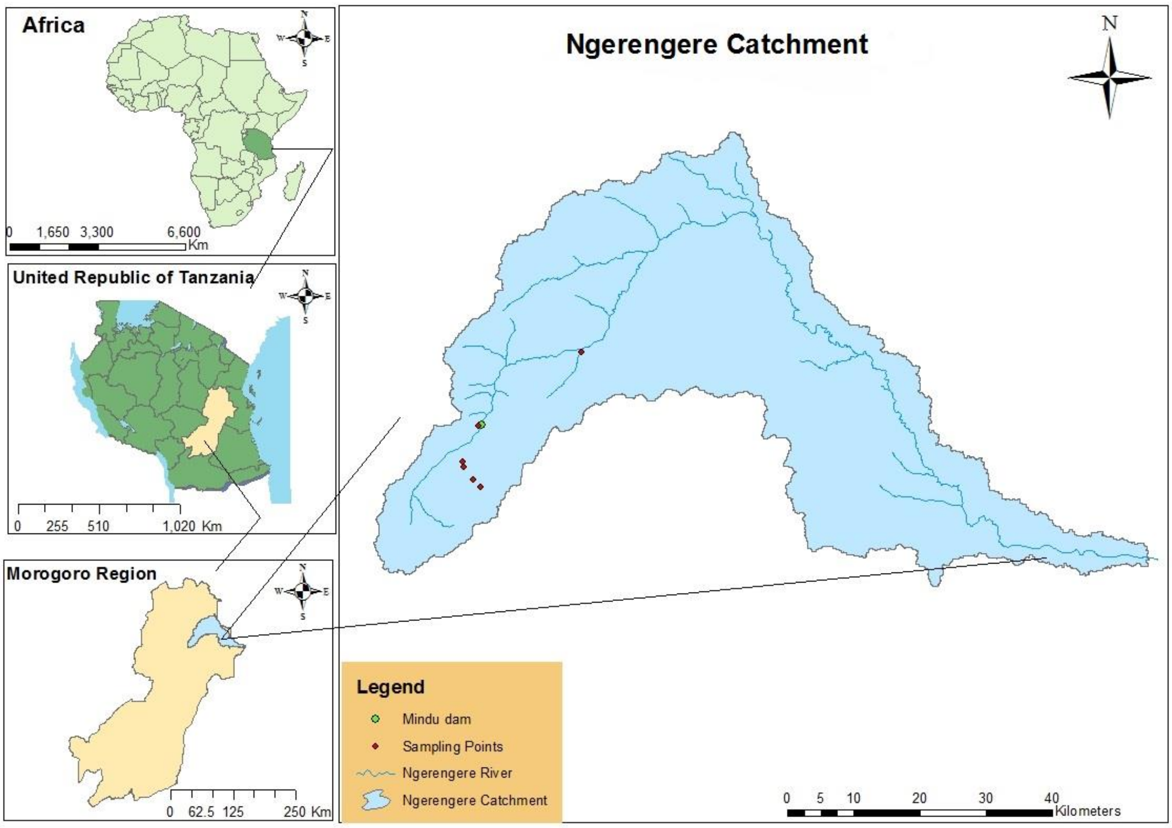


Figure 3.1 Ngerengere catchment, in Morogoro (adopted with permission from Kimambo, Chikoore, & Gumbo, (2019))

2.2.Study design

The study consisted of mixed methods (observation, focus group discussion, questionnaires, and key informant interviews), and this has been found to be helpful, especially in research that lacks a body of research. A questionnaire coded both in English and Kiswahili languages was uploaded into SurveyCTO, which is an open data kit (ODK)-based (available at https://www.surveycto.com/index.html accessed on 28th October 2017), and android-assisted application to gather the required information. The questionnaire (Table S1) had three sections designed to collect social-demographic information, knowledge of HABs (i.e., how HABs appear, causes, threats, and experiences of the respondents in the study area on pollution and water quality) and their management or control measures. General comments were collected in the comments section of the questionnaire.

The sample size conveniently and purposively consisted thirty-one (31) respondents from small-scale fish farmers and registered water users, and experts in the Ngerengere catchment. The power of experience led to the selection and inclusion of the respondents. The study further considered number of reasons including the resources available including time and financial, and a need to get experience from experts about harmful algae in the catchment before the sampling. However, the sample size is theoretically acceptable as emphasized in the previous studies (Gholami, Mortazavi, and Karbassi, 2019; Marshall et al., 2013; Dworkin, 2012;).

Moreover, five key informants from Morogoro districts, and the deputy director of Tanzania Fishery Research Institute were contacted during the 2018 Nane Nane farmers exhibitions in Morogoro. Along with that, two focus group discussions with five participants (as in Carlsen & Glenton, 2011) each were conducted, and held a meeting with ten MORUWASSA officials. During field campaigns, several reservoirs were visited for the visual identification/observation of blooms. Since pond sizes have a significant impact on production and management (Kaliba et al., 2006), the study focused on fish farmers whose ponds had at least 100 m^2 in size and active as in the study by Wetengere, (2011). Since livelihood activities (agriculture and fishing), settlements in the upstream, and erosion have been observed in the catchment (The United Republic of Tanzania, 2013b), Mindu Dam, a reservoir for domestic water supply was included in an attempt to capture such interactions and their possible impacts.

2.3. Socioeconomic status

The Ngerengere catchment has an estimated population of over 1 million people (The United Republic of Tanzania, 2013b). A recent survey (IUCN Eastern and Southern Africa Programme, 2010) on the Wami Ruvu basin noted industries, agriculture, mining, and settlement as the critical socio-economic and livelihood activities. The survey further elucidated that pollution (point and non-point sources), increased demand for water uses in agriculture, and increased urban population triggers water-scarce conditions at times in the catchment. A project jointly led by Global Water for Sustainability, Florida International University (GLOWSFIU), and Wami Ruvu basin office on water quality (GLOWS-FIU, 2014b) noted conflicts between downstream and upstream water users on water quality in the basin. In Morogoro, Fish farms have recently increased mainly due to diversification of livelihoods and or local markets (Chenyambuga, Mwandya, Lamtane, & Madalla, 2014; Mwega et al., 2019; Nunoa et al., 2010).

2.4. Data analysis

The survey data were downloaded from the computer server provided by the SurveyCTO in Microsoft excel format and transferred for further analysis. Images of blooms, mat, and foam-like from field observations were presented for recognition. The study adopted a content analysis (Gill, Rowe, & Joshi, 2018) approach for analyzing the qualitative information and the general comments from the respondents. Jeffreys's Amazing Statistics Program (JASP) computer software (version 0.9.0 of 2018) was used to produce descriptive plots and Chi-Square tests statistics for drawing inferential statements. The description of the significance and interpretation of the results in all the tables (VS-MPR) was adopted from (Sellke, Bayarri, & Berger, 2001). The choice of JASP was due to its potentials over other tools, such as it is a simple, attractive graphical user interface, open-source software, but also as demonstrated in the previous studies (Marsman & Wagenmakers, 2017; Nuzzo, 2017; Quintana & Williams, 2018).

2.5. Ethical consideration

An ethical clearance certificate with reference number SES/17/ERM/09/2006 was issued by the Research Ethics Committee (REC) in the Directorate of Research and Innovation of the University of Venda, Limpopo, South Africa. Moreover, participant were willing to or not to participate in the study.

3.0 Results

3.1. Respondents general attributes and experiences

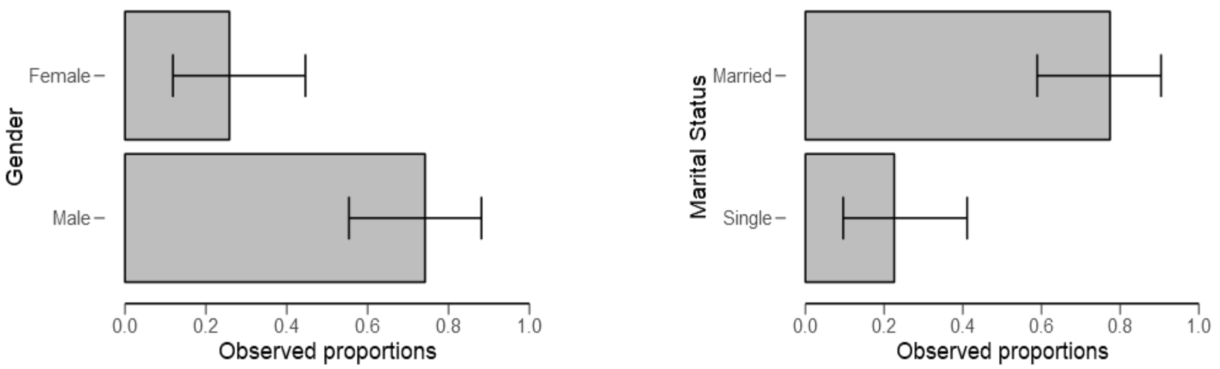
In this subsection, we present information about gender, marital status, education, number of years the respondents stayed in the study area.

Table 3.1 details gender and marital status of the respondents from Ngerengere catchment. The same have been pictured in figure 3.2.

Table 3.1 Gender and marital status multinomial test

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPR[a])
Gender	7.258	1	0.007	10.522
Marital Status	9.323	1	0.002	26.684

[a] Vovk-Sellke Maximum p -Ratio: Based on the p-value, the maximum possible odds in favor of alternative hypothesis (H_1) over null hypothesis (H_0) (Sellke et al., 2001). The p-values of 0.007 and 0.002 are only 10.522 and 26.984 times more likely in favor of an alternative hypothesis than the null hypothesis respectively (more information are available at http://www.shinyapps.org/apps/vs-mpr accessed on 28th October 2018).



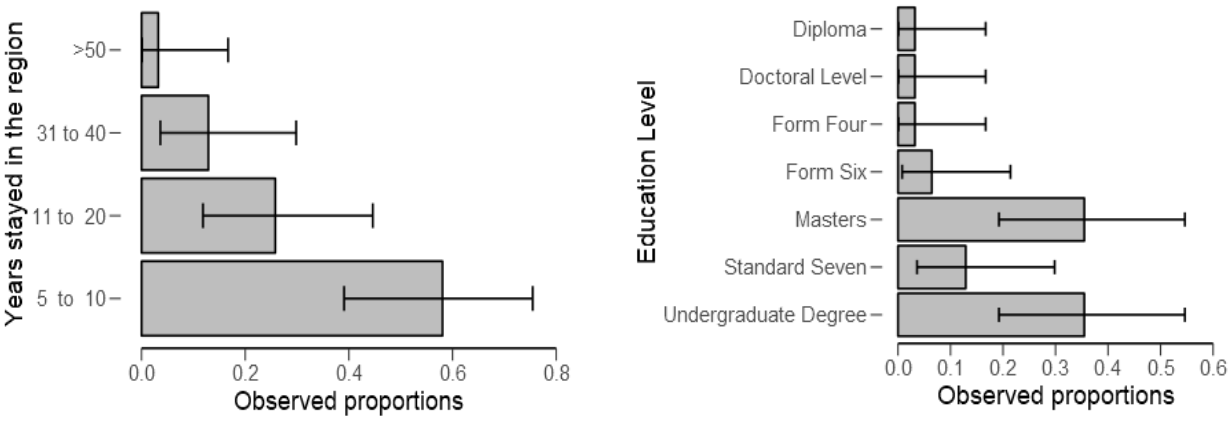
A B

Figure 3.2 Gender (A) and marital status (B) descriptive plots for all the respondents

In the current study, significantly, the larger proportions of respondents were males and married (respectively, p=0.007; p= 0.002, Table 3.1, Figures 3.2A & 3.2B).

Table 3.2 Years stayed in the region and education level multinomial test

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPRa)
How many years have you stayed in the region?	21.258	3	< .001	425.916
Education level (H_0 (a))	28.839	6	< .001	584.901



A B

Figure 3.3 A descriptive plots for a number of years respondents stayed in the study area (A) and education level (B).

From Table 3.2, of the examined categories significantly (P<0.01), respondents (59%) stayed in the study area for about 5 to 10 years (Figure 3.3A) and that 37% had high levels (P<0.05) of education (Figure 3.3B & Table 3.2). Furthermore, a higher number of respondents (59%) were employed (Figure 3.4A & Table 3.3) (p<0.05) and that they were "very well" informed about water problems in the study area (Figure 3.4B) (p = 0.002, Table 3.3).

Table 3.3 Occupation and how the object is informed about the water problem multinomial test

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPRa)
Occupation	28.839	4	<0.001	3735.115
How well are you informed about the problems facing water sources in the region?	12.452	2	0.002	29.877

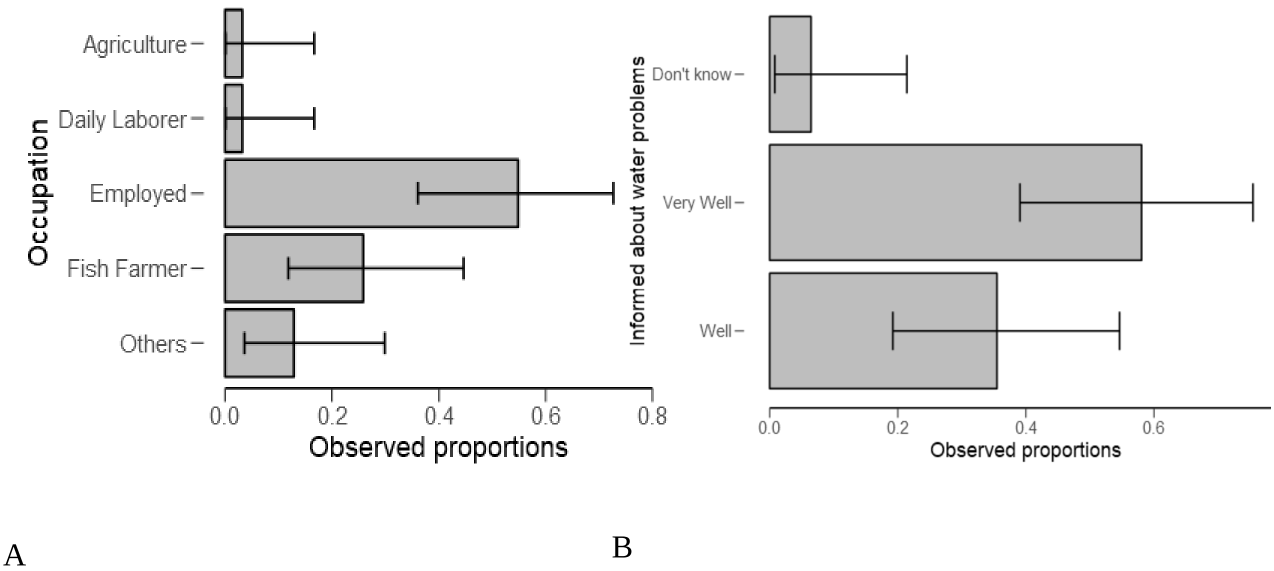
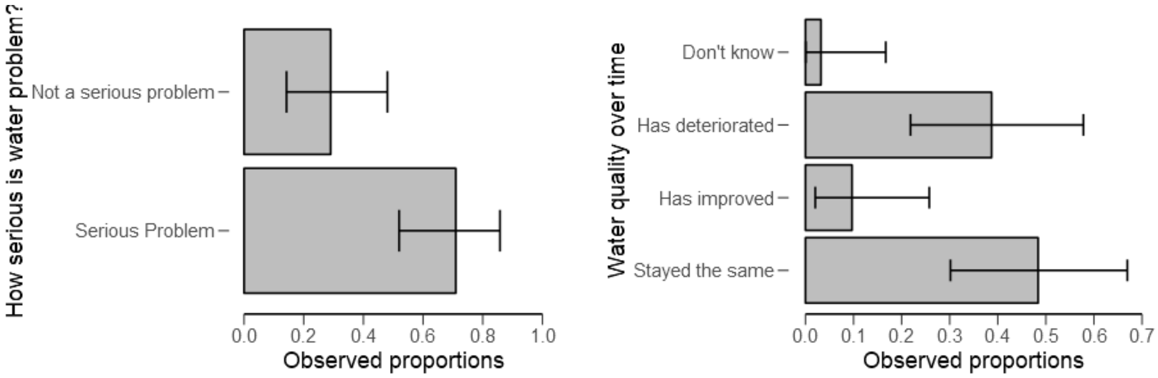


Figure 3.4 Descriptive plots for occupation (A) and how the subjects are informed about water problems in the study area (B)

3.2. Water quality and algal bloom formation

Asked about whether water problems in the region are serious or not serious, respondents (70%) collectively agreed that water problems in the catchment area "serious" (Figure 3.5A). Findings further suggest that 49% of the respondents noted no change in water quality, with 40% who affirmed that water quality has deteriorated over time (Figure 3.5B & Table 3.4).



A B

Figure 3.5 Descriptive plots of water problems (A) and quality over time (B)

Table 3.4 Water problem and quality over time multinomial test

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPRa)
How serious about the water-related problem?	5.452	1	0.020	4.782
How are the changes in water quality for the time you have been in the region?	17.903	3	< .001	103.970

In figure 3.6, results from multiple response options on "what could be the reasons for poor water quality" indicates that overuse of water for agriculture in the Ngerengere catchment ranked high (60%) than other responses.

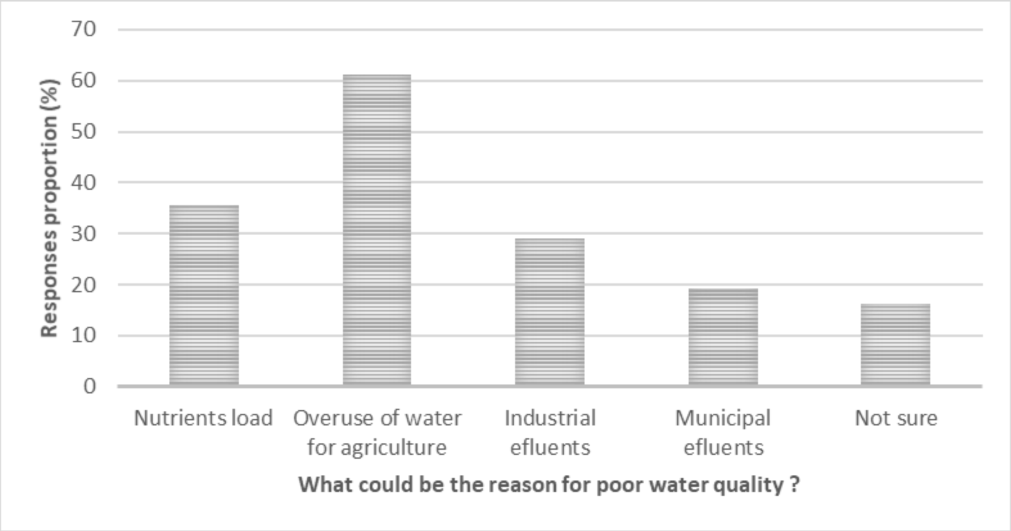


Figure 3.6 Response in % for the reasons of poor water quality in the Ngerengere Catchment.

When asked to respond about any of the listed major threats, pollution ranked high (60%) followed by water shortage and climate change respondents (Figure 3.7).

Table 3.5 Respondents understanding of HABs multinomial test

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPRa)
Have you ever seen blooms (image of bloom displayed for recognition) before?	23.516	1	< .001	21834.894
How regularly do you see blooms?	45.935	4	< .001	7.318e +6
Do you have any idea on HABs in river/ponds/dam/reservoir?	0.806	1	0.369	1.000
Any idea about health effects associated with algal blooms?	0.290	1	0.590	1.000

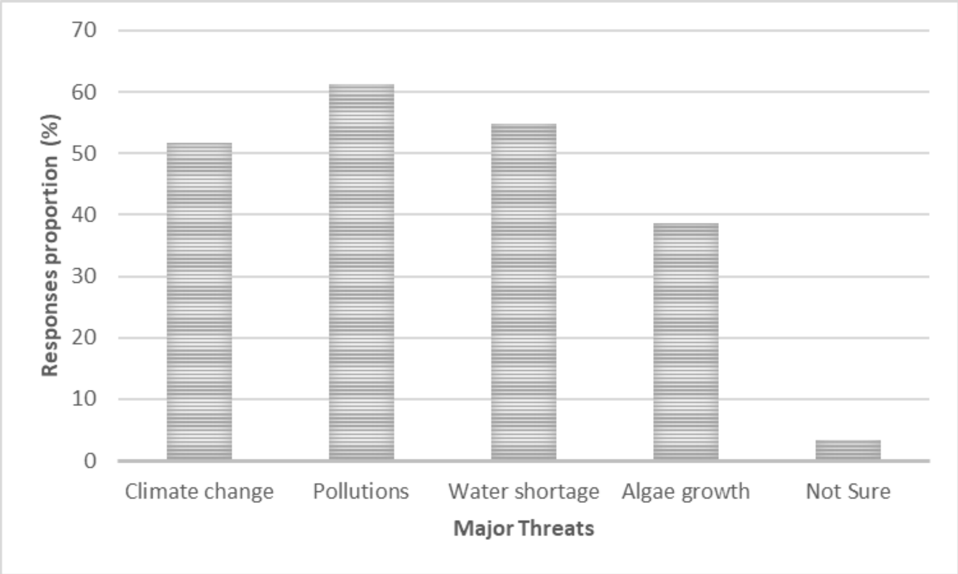
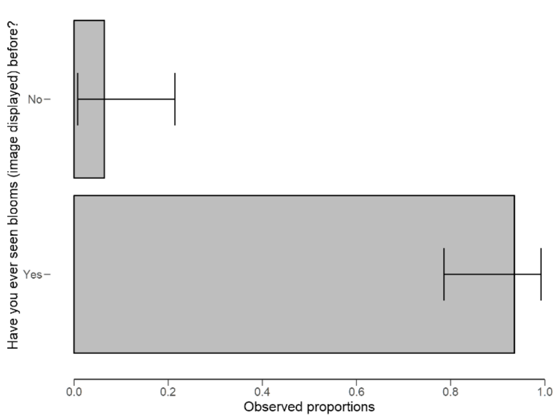


Figure 3.7 Ranks for the major threats as perceived by the respondents

The test statistics revealed that respondents were highly aware (> 95%) of algal blooms features (Figure 3.8A). Herein an image of the algal bloom was displayed to the respondent for recognition during the survey (P< 0.001, Table 3.5). It was further observed that respondents collectively agreed that blooms usually occur once in a season and during the dry season (Figure 3.8B).

When asked about any idea on HABs in the ponds/dam or river (Figure 3.8C) and any idea about health effects associated with algal blooms (Figure 3.8D), there was no significant difference between the groups (p= 0.369 and p = 0.590 respectively) even number of odds in favor of alternative hypothesis that the null hypothesis was one (1) each.



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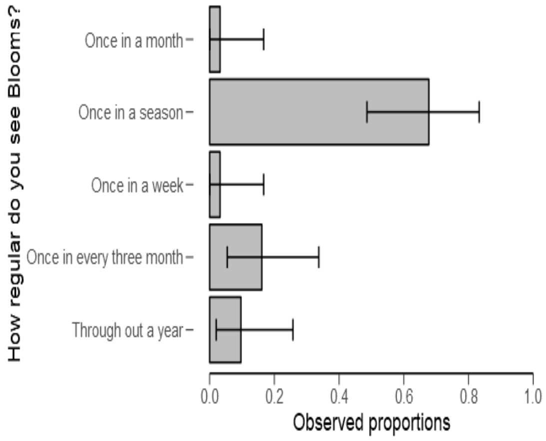

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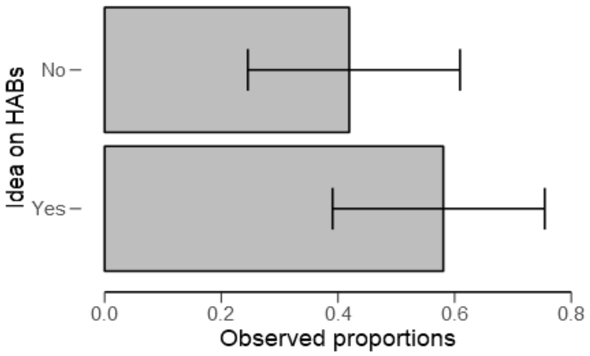

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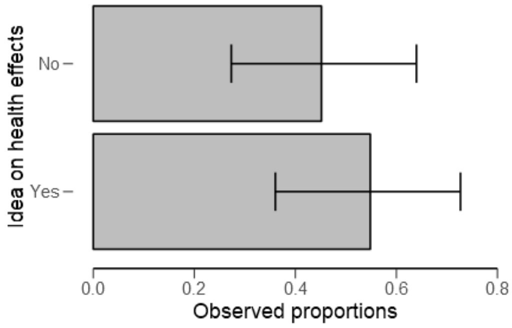

D

Figure 3.8 Descriptive plots for HABs recognition (A), how regular blooms do occur (B), Idea on HABs (C) and the idea of HABs health effects (D)

From figure 3.9A, respondents collectively agreed that sometimes there is a noticeable discharge from the industries (p = 0.044), and sometimes they see crystal-clear water (Figure 3.9B). It was further found that collectively, respondents agreed sometimes they see algal blooms limited with clarity odour apparently (Figure 3.9C). Otherwise, there was no significant difference between the groups (Figure 3.9D) when asked about documenting the history of discharge (p = 0.295, Table 3.6). Moreover, and most respondents (52%) agreed to have seen the severity of algal blooms (Figure 3.10) and dead fish (p = 0.002, Table 3.6).

Table 3.6 Multinomial test for several aspects tested for recognition of blooms

Parameter (n = 31)	Chi Squire (χ^2)	Degree of Freedom (df)	(P-Value) p	Vovk-Sellke Maximum p Ration (VS-MPRa)
Sometimes I see a noticeable discharge from industries.	8.097	3	0.044	2.675
Sometimes we document a history of discharge	3.710	3	0.295	1.022
Sometimes I see crystal-clear water.	20.484	3	< .001	306.378
Sometimes I see algal blooms with limited clarity and odour apparent.	28.226	3	< .001	8941.006
Sometimes I see the severity of algal blooms with one or more of the following, massive floating scum, strong foul odour and or dead fish.	14.806	3	0.002	29.726

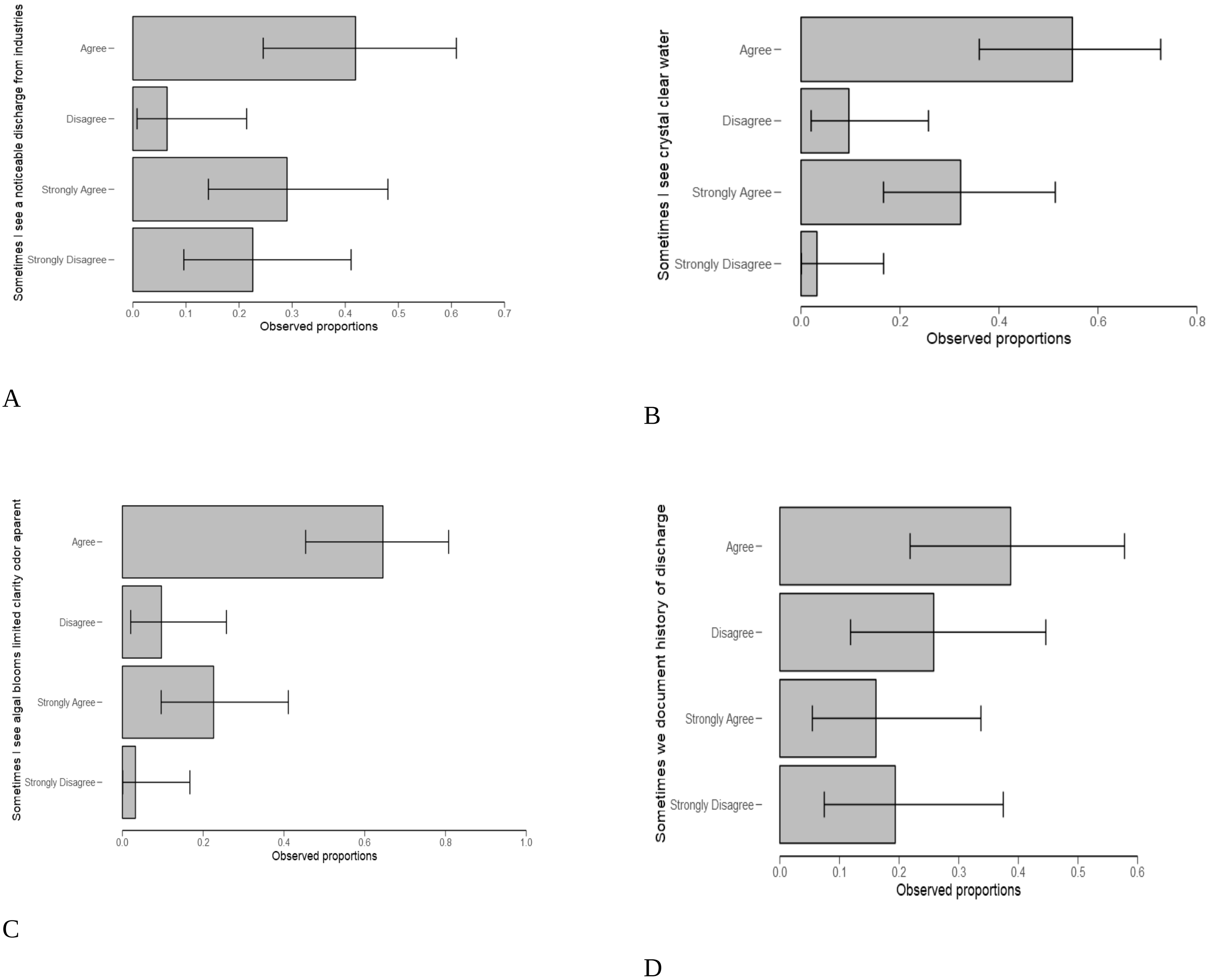

Figure 3.9 Aspects tested in recognition of HABs formation and their course in water

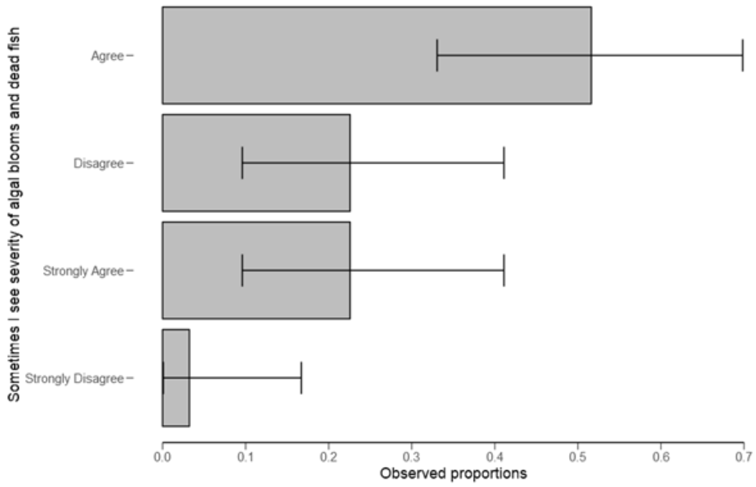

Figure 3.10 Ranks on whether sometimes respondents sees the severity of algal blooms and dead fish

Asked about the conventional control measures of HABS, 35% of respondents pointed that no treatment method is applied (Figure 3.11), followed by filtering and chemical treatment, which scored the same proportion of 30% as methods used in the control of the algae problem.

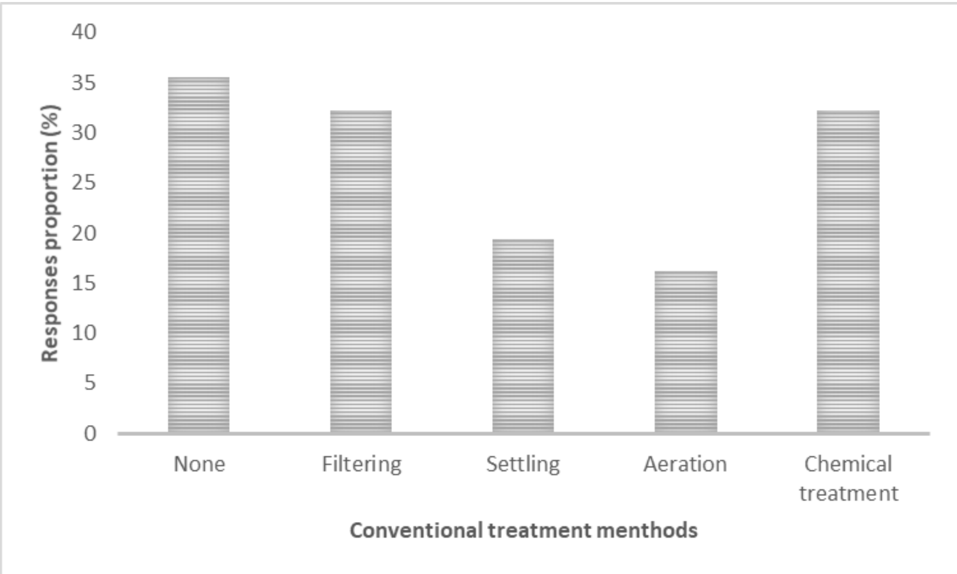

Figure 3.11 The conventional methods for HABs control in the Ngerengere catchment

3.3 Field Observation

Along with the survey, several images (figure 3.12) were taken from different reservoirs, which are also an indicator of the extent of the problem of blooms. This best triangulate the perception from fish farmers on the occurrences of blooms.

Figure 3.12 Plates describing bloom type and specific location, i.e., latitude and longitudes in the brackets (photos by the author during the survey). (A) Visible foam-like algae observed at Konga, Kidangawa (6.9035585S, 37.5925432E); (B&C) Both green coloration and red algae observed at Kingolwira fishponds (6.755683S, 377543226E); (D); mat-like algae observed at Konga Kidangawa (6.9035585S, 37.5925432E).

From the verbatim comments, most respondents commended the study and indicated issues that could have directly asked, such as sources of water pollutions. Some others were concerned with the management of water sources and treatments, for example, "*Pollution of water sources culminating from cultivation and settlement along water bodies should also be aggressive, addressed*" featured in the comments sections. Issues of monitoring from water sources to the downstream was also mentioned. The study further noted management option available or current in practice in the catchment, including use of chalk lime, fencing of the ponds to prevent predators, and use of both underground and surface water to cope with the changing weather/climate.

3.4 Key informant interviews and focus group discussions

During the key informant interviews, and focus group discussions we found that, most ponds in the catchment are earthen. The sources of algal blooms are attributed to nutrients load (during ponds fertilization) and that algal blooms occurs during the dry season. Unlike the group discussions, key informants had knowledge that algal blooms could be associated with health effects in human and in birds. Regarding the control of algae, it was noted there exist a local way of monitoring of water quality by dipping hands palm into a water (indirect way of measuring water quality) and if fish farmers cannot see the hand palm it is an indicator that the water in the ponds need to be changed. The use of rake and or nets to remove algae also featured during the interview. On the other hand, water scarcity remains the major challenge in the catchment.

4. Discussion

4.1 Demographic features

Most respondents in the study were men and married (Table 3.1 and Figure 3.2). The results agrees with the prevailing point of view that gender inequalities are common in the fishery sector and (Bradford & Katikiro, 2019; Fröcklin, de la Torre-Castro, Lindström, & Jiddawi, 2013). Regarding experience, most respondents stayed in the study area for a period ranging from 5 to 10 years (Table 3.2). This may not have affected study findings because the study design targeted people who regularly intermingle within the study area, such as water users, authorities, small-scale fish farmers, and experts. The findings are in line with the previous study wherein the same was also observed in Kilombero by Kangalawe & Liwenga, (2005), which is a district neighboring the study area, and in the same fish farming livelihood activity.

4.2. Perceived knowledge of harmful algae

The study revealed that respondents were very well informed about water problems (Table 3.3) but also out of the tested groups (serious or not serious) 70% collectively agreed that water problems in the catchment area are "serious" (Figure 3.5A), this dovetails nicely with the previous surveys, (e.g., Ngana et al., (2010)). Regarding the water quality and algal bloom formation, for example, the National Water Sector Development Strategy of 2006-2015 stresses the links between water quality and impacts on fisheries (The United Republic of Tanzania, 2006). A similar pattern of results was obtained in the current study, for example, during the experts' interview that water quality was eyed as an issue of concern (Moshi, M, personal communication, 7/8/2018). Moreover, 49% of the respondents noted no change in water quality over the years (Figure 3.5 B), with 40% who affirmed that water quality has deteriorated over time ($p< 0.05$) (Table 3.4). These results demonstrate the high degree of uncertainty over water quality changes. The triangulation show a need for interventions in the catchment and or to refine study by getting more audience.

From Figure 3.6, overuse of water for agriculture mainly for paddy and maize as per observation and the national survey (The United Republic of Tanzania, 2012) scored high, followed by nutrients loads and industrial effluents. This was also confirmed during the key informant interviews, which revealed that controlling agricultural activities upstream Mindu dam is lacking (Angumbwike, N. personal communication, 29/08/2018). Regarding the possible threats (from figure 3.7), increase in pollution ranked the highest (60%) followed by water shortage and climate change, which altogether accounted for 50% of the respondents. The findings are broadly in line with the observation by World Bank-Tanzania (2006). Other respondents also cited algal growth as a problem, the rating was lower than other options, but this could be attributed to low and lack of awareness on HABs dynamics.

The results further demonstrate two things. First, respondents were highly aware (Figure 3.8A and Table 3.5, $P<0.005$) on how algal blooms appear after a photo of algal bloom was displayed to them for recognition. Secondly, respondents collectively agreed that blooms usually occur once in a season, and most of them referring during the dry season (Figure 3.8B), likewise the same were gauged in focus group discussions (FGD), and the key informant interviews. Nonetheless, we believe that it is well justified to indicates the best timing for studying HABs occurrence and mobility, although HABs can form any time of the year (Van der Merwe, 2014).

The results corroborate the findings of Mowe, Mitrovic, Lim, Furey, & Yeo, (2014) on tropical cyanobacteria blooms and the verbatim comments from the respondents in clarifying the season as a factor in algae blooming "green algae blooms in Mindu Dam proliferate mostly during the dry season." The implication is that the responses inform the best timing for the planning of pre and post-management/control of HABs.

4.3. Perceptions of health risk associated with harmful algae

It is widely accepted that some species of harmful algal blooms can cause skin irritations (Rastogi, Madamwar, & Incharoensakdi, 2015; Bellém, Nunes, & Morais, 2013). During a focus group discussion with the fish farmers, it was revealed sometimes that they (farmers) had experienced the same. For example, the interviewee pointed out that they must have soap with them and change clothes because they normally feel skin irritation just after fishing (Raphael, I., personal communication, 10/08/2018).

From the interviews, we speculate that the irritation of skin might be associated with algal bloom effects. The implication is that there is a need to implement measures, one being public health awareness rising on the effects of HABs. It is with regret that guidelines are yet to be developed in Tanzania as noted in the in the previous studies (Hawkins, 2010; Miraji et al., 2016). During key informant interviews, there was also a claim that current guidelines and standards for the management of algal blooms are yet to be in place (Maly, R., personal communication, 7/8/2018). The findings are consistent with the previous study, which shows that the issue of HABs is not well addressed in policies and guidelines (Miraji et al., 2016). Similarly, a recent review noted that there are still questions that need to be answered, especially on policies and ecosystem changes with climate change and population increase (Bradford & Katikiro, 2019).

During the key informant interviews, some noted the policy gap and agreed that conservation training and awareness-raising are considered as an immediate solution for managing harmful algal blooms. Verbatim comments commended the current study in the catchment; for example, "this project will help us identify problems of water quality in the catchment" (Angumbwike, N., personal communication, 29/08/2018). These observations are in line with the study by van der Heijden, van der Shoko, Duijn, Rurangwa, and Bolman, (2018). It was also agreed with most respondents' verbatim comments that there is a need to raise awareness but also proposing an intervention strategy. The findings pose concerns on policy and practices in the fishery sector and the environment. When respondents asked about any idea on HABs in the ponds/dam or river (Figure 3.8C) and any idea about health effects associated with algal blooms (Figure 3.8D), there was no significant difference among groups ($p= 0.369$ and $p=0.590$ respectively). The results also highlight that little is known about HABs and as well as health effects associated with algal blooms. Furthermore, during the interviews and the FGD, the same uncertainty featured, for example, a statement made by one of the interviewees that "some species of algae could be toxic, but not sure." (Dunia Mlanzi, Personal Communication 06/08/2018).

These findings gauge similar observations, which were also reported in the previous surveys and most important in a developed world, whereby 60% of fishers in Southern Louisiana did not know what does HABs mean (Lopez, Jewett, Dortch, Walton, & Hundell, 2008). Extension services seem to be a key constraint to farmers in Tanzania as the issue features in many reports (Rothuis et al., 2014; van der Heijden et al., 2018). These findings stress concerns about awareness that rising programs need to be addressed either through training and or more from extensions services.

In order to verify the respondent's concerns on the link between water quality problem and any observed ecological responses, we administered six Likert scale questions and from the results (Figure 3.9A, Table 3.6) respondents collectively agreed that sometimes there is a noticeable discharge from the industries ($p = 0.044$). Respondents agreed that they sometimes see crystal-clear water (Figure 3.9B). They also agreed sometimes they see algal blooms limited with clarity odour apparently (Figure 3.9C). On the other hand, there was no significant difference among groups (Figure 3.9D) when asked about documenting the history of discharge ($p = 0.295$; Table 3.6). Moreover, and most respondents (52%) agreed to have seen the severity of algal blooms (Figure 3.10) and dead fish ($p< 0.002$; Table 3.6). When comparing our results to those of earlier studies, a similar conclusion, for example, fish are dying because of polluted water, which was reported by Niang (IUCN Eastern and Southern Africa Programme, 2010).

4.4 Harmful algal blooms management and control

Regarding the conventional control measures of HABs, 35% of respondents said no treatment method is applied (Figure 3.11), followed by filtering and chemical treatment (both scoring

30%). Herein the design (i.e., asking multiple-choice questions) utilized meant to probe more reactions from the respondents. As a part of management, during the focus group discussion and interviews, farmers use hand palms mimicking the Secchi disk depth technique for monitoring the turbidity in their fishponds. Water is added into the pond if they cannot see the palm of their hand, baseline being the Elbow. Some other fishponds management techniques, for example, the use of lime, have been tested for sterilization, nutrient enrichment, and or for regulating pH changes (Lazur, Cichra, & Watson, 2013). The same was also revealed, as quoted during the focus group discussion with fish farmers.

“chalked lime is applied (Chokaa in Kiswahili) to the fishpond before introducing Fingerlings and just after harvesting” (Mlegu, D., personal communication, 10/08/2018)

In the present study, the field images/observations agree with respondents' comments and key informant interview findings that blooming occurs mostly during the dry season (July, August, September, October, and November) (Angumbwike, N, personal communication, 29/08/2018). The difference in blooming (i.e., mat, bloom, and foam-like) and colors in (Figures 3.12A to 12D) probes more studies in the catchment.

5. Conclusions

The study investigated stakeholder’s experiences and perception on harmful algal blooms in the Ngerengere catchment in Morogoro, Tanzania. The findings show that respondents are very well informed about the problems of water quality and the reasons for the cause, such as overuse of water for agriculture, and nutrients. Respondents were able to identify algal blooms when an image of bloom displayed to them and that they collectively agreed that algal bloom proliferates more during the dry seasons (June to September and January to February). That tallied with the anecdotal observations, which showed the occurrences of algal blooms of all forms (bloom, mat, and foam-like) and that some had a red hue. On the other hand, there was no consensus regarding the health effects associated with HABs. Respondents collectively agreed that they sometimes see the severity of algal blooms and dead fish. While the paper provides useful insight about HABs in Ngerengere catchment, in the United Republic of Tanzania, the implication may be specific to the study area. Since the sample size was small and specific to stakeholders around the Ngerengere Catchment, the results may reflect only the people of Urban Morogoro. Future researches should consider repeating the same study, monitoring of environmental conditions, toxic strains identification, and their mobility into the higher energy level and for a broader scale.

Data Availability: Data used (as guided by the ethical clearance) to support the findings of this study are available from the corresponding author upon request.

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Chapter 4

Harmful Algae in Aquaculture Systems in Ngerengere Catchment, Morogoro, Tanzania: Descriptive community structure and environmental concerns

This chapter addresses objective (ii) and (iii)

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 aim of the study was 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 physicochemical parameters in situ and the laboratory. A benchtop Flow Camera (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 physicochemical variables and meteorological patterns. The study found common CyanoHABs such as *Microcystis*, *Cylindrospermopsis*, *Anabaena* (now designated *Dolichospermum*), *Lyngbya* as well as other species such as Diatoms and Euglenophytes which are also considered a nuisance. Virtually, a colonial cyanobacteria species dominated the fishponds, while Mindu Dam was more of filamentous species. The study suggests that the Mindu dam, based on Carlson's Trophic State Index (TSI), falls under eutrophic while the fishponds were hypereutrophic. Associated physicochemical parameters, heavy rainfall, and prolonged dry conditions influenced cyanobacterial blooming. 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.

Keywords: aquaculture systems; harmful algae; community structure; environmental concerns; Morogoro

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 conditions, but also alters the food web, which is problematic for humans, domestic animals, fish, and wildlife (Nyakairu, Nagawa, & Mbabazi, 2010). Impacts of CyanoHABs into the environment, humans, and pets have been previously studied (Barange et al., 2018; Brooks et al., 2016; Busch, Zielinski, & Cembella, 2013; Flores, Miller, & Stockwell, 2018; Griffith & Gobler, 2019; Hazen & Sawyer, 2015; Ho & Michalak, 2015; Lopez, Jewett, Dortch, Walton, & Hudnell, 2008; Paerl, Otten, & Kudela, 2018; Sanseverino, Conduto, Pozzoli, Dobricic, & Lettieri, 2016; Suzane, 2016; Wells et al., 2015). About 40 to 70 % of cyanobacteria blooms reported worldwide are toxic (Turner et al., 2018). Majority of toxin-producing species are planktonic (e.g., *Anabaena, Aphanizomenon, Planktothrix, and Cylindrospermopsis*) and benthic (e.g., *Lyngbya*), but also there are others (for instance *Gloeotrichia*) which have both planktonic and benthic properties (Watson, Whitton, Higgins, Paerl, & Brooks, 2015). The tendency of CyanoHABs in freshwater ecosystems is to increase due to environmental and climatic changes (Graham et al., 2018); however, there is still a knowledge gap in understanding their interaction and or dynamics (Chen, Chen, Zhang, & Xie, 2016). 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 metrics (Ho & Michalak, 2015).

Till now, there are about 2000 species in 150 genera of cyanobacteria (Vincent, 2009), and more than 55 species in 30 genera have been confirmed to be toxin-producers (Table 4.1) (UNESCO, 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).

Table 4.1 Different orders, characteristics, and genera for cyanobacteria (UNESCO, 2004; Vincent, 2009; 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*

Harmful algal blooms may survive and exploit a wide range of environmental conditions. Some of includes, uptake of phosphorus, fix atmospheric nitrogen, acquisition of inorganic carbon, dissipating excess light energy, and photo-adaptive mechanism (Westermark & Steuer, 2016; Berg & Sutula, 1969, 2015; Watson et al., 2015). Although there have been several studies in the recent decade, understanding cyanobacteria dynamics is of paramount importance. 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, & 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, Lai, Hsu, & Shiah, 2017; Patiño, Dawson, & VanLandeghem, 2014; Wells et al., 2015).

Traditional methods for quantification of planktons community in the environment are somewhat slow, tedious, and laborious, although they have contributed to the research. In Morogoro, Tanzania, previous studies have demonstrated the use of molecular research approaches in quantifying the 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, Omary, Mathew, & Nonga, 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 (GLOWSFIU, 2014b, 2014a; Mero, 2011), which might influence algal proliferation. Coupled effects of land-use change, climate, and hydrological variation on water resources have also been reported in the previous studies (Natkhin, Dietrich, Schäfer, & Lischeid, 2015). The hydrological connectivity of the catchment raises concern and that there is a need to validate or contribute to the previous studies to assist in the management decision of the Ngerengere catchment.

Chlorophyll-a has been widely accepted as a proxy for the estimation of Cyanobacteria (Merel et al., 2013). However, as stated earlier, 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, & 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 at providing 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 (Figure 4.1). Mindu Dam is the main reservoir supplying water for domestic uses to a larger population in Morogoro Urban and fishery (Ngoye & Machiwa, 2004). Regarding the climate, daily maximum temperatures range between 18-33 °C and annual precipitation between 800-1500 mm (Kimambo, Chikoore, & Gumbo, 2019). There is a noticeable hydrological connection between river tributaries in the upper Ngerengere catchment with active fishponds and the Mindu Dam.

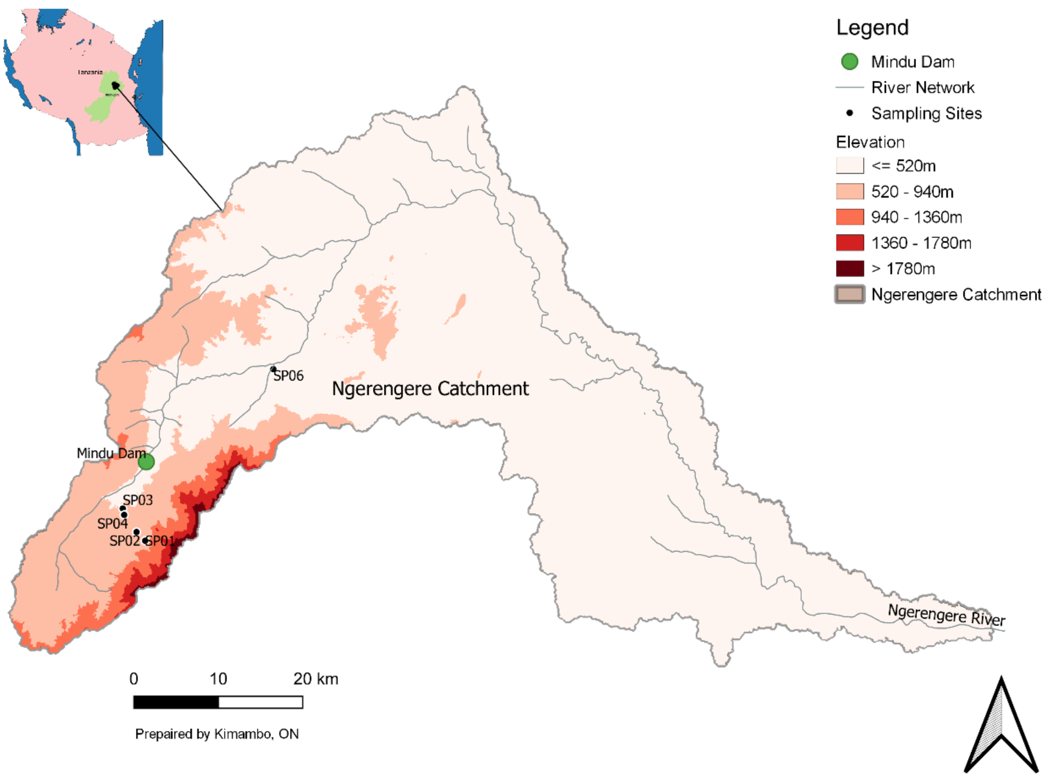

Figure 4.1 A map showing sampling points, namely SP01, SP02, SP03, SP04, SP05, and SP06, in the Ngerengere catchment.

Land-use changes and climate variability and change in the Ngerengere catchment has also been 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. A study by Mbungu (2016) found that a contribution of both climate variability and human activities to the changes in streamflow is 46% and 54%, respectively.

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 4.2 and the supplementary information in figure S1). 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 polyethylene bottles and transported to the laboratory in a cooler box until the 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 color determination while for the total alkalinity, a titrimetric method, and thereafter estimated using equation 1 (American Public Health Association, 1999).

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

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

The total phosphorus concentration (mg/L) was determined by the ascorbic acid colorimetric method using a spectrophotometer 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 minutes. The supernatant was then measured at 665 nm, and 750 nm and the Chlorophyll-a concentrations were calculated according to equation 2 (Holm-Hansen & Riemann, 1978).

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

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/100mL) 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 10X objective, flow cell of 100 µm (Descy & Sarmento, 2008; IOC-UNESCO, 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 previously suggested (Rosen, Davis, Gobler, Kramer, & Loftin, 2017; Komárek & Hauer, 2013). 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, López-Urrutia, & Nogueira, 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 physicochemical and biological parameters. Bootstrap enables a two-dimensional map to identify trends and uniqueness of observations, especially when the data re standardized (Forkman, Josse, & Piepho, 2019). The correlation analysis was done to confirm the PCA results. For meteorological data, a pattern 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 minutes observation) mainly to gauge any perturbation in weather. The descriptive statistics, Pearson's 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 (Sulis, Buscarinu, Soru, & Sechi, 2014).

Table 4.2 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 figure 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 meters 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	The sampling point is a 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	The sampling point is a Public owned reservoir that supplies freshwater and freshwater fishery to a larger population in the 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	The sampling point is a government-owned fish farming Centre with several fishponds in series, with 2 m depth. The center is known to produce fingerlings. 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).

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 a low variation of 11% and 9%, respectively (Table 4.3).

3.2 Morphological identification

Cyanobacterial species of Coccoid, filamentous, colonial (*Microcystis*) were found in nearly all sampling points (supplementary information Figures S2 to S7). In all the sampling points and phases, cyanobacteria occurred together with other green algae species, such as diatoms, and *Euglenophytes*. Sampling point SP01 species identified were *Microcystis* (Figure S2 A, B & C); *Lepocincilis acus* which resamples single-cell Euglena species) (Figure S2 D); *Oscillatoria* (Figure S2 E & G) which resembles (Huynh & Serediak, 2006)) and *Scenedesmus* (Figure S2 F) (compares well with (Van Vuuren, 2006) and (Bellinger & Sigee, 2010)). Species observed at sampling point SP02 (Figure 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, 2004)) (Figure S3 B); Merismopedia (Figure S3 C); *Scenedesmus opoliensis* (Figure S3 D) (Prescott, 1954), Collonial *Microsistis* (Figure S3 E & S3 H)*; Lepocincilis acus* (Figure 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, & Meyer, 2008)) (A); *Chroococcus* (B), *Microcystis* (Figure S4 C); *Merismopedia* (Figure S4 D), *A. cicrinalis* (Figure S4 E), *Scenedesmus* (Figure S4 F) (elongated cylindrical cells joined side by side with rectangular plate-like colonies of 2, 4, 8, 16 cells as in (Bellinger & Sigee, 2010) & (Huynh & Serediak, 2006)); *Anabaena* (Figures S4 H, J, and P), *Pediastrum* species in different views (Figures S4 G, I, and L). Regarding sampling point, SP04 species identified were *Anabaena* (Figure S5 A); *Microcystis* (Figures S5 B, C & D); *Merismopedia* (Figure S5 F); *Euglena* spp. (Figure 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 & Codd, 2014)). *Oscillatoria (*Figure S6 *A); Lingbya* species *(*false branched*)*, (Figures S6 B and C), *Microcystis aeruginosa* (Figure S6 F), *Cylindrospermopsis* (curved) (Figure S6 D), and *Cylindrospermopsis* (Straights) *(*Figure S6 E*) (*resembles those reported in (Newcombe, House, Ho, Baker, & Burch, 2010) and (UNESCO, 2004)); *Nodularia (*Figure S6 *G).* Species observed at sampling point SP06 were *Anabaena (*as those available at https://planktonnet.awi.de/) (Figures S7 A & M), *Leponcinclis* (Figure S7 B), *Nostoc* (Figure S7 C), *Microcystis aeruginosa* (Figures S7 D & K); *Microcystis warbegii* (Figure S7 E), *Aphanizomenon* (Figure S7 F), *Nodularia* (Figure S7 G); *Oscillatoria* (Figure S7 I), *Closterium Nitzsch* (Figure S7 H elongated and crescent, sickle-brown shaped) and *Pediastrum* (Figure S7 L disc-shaped and oval to circular colonies).

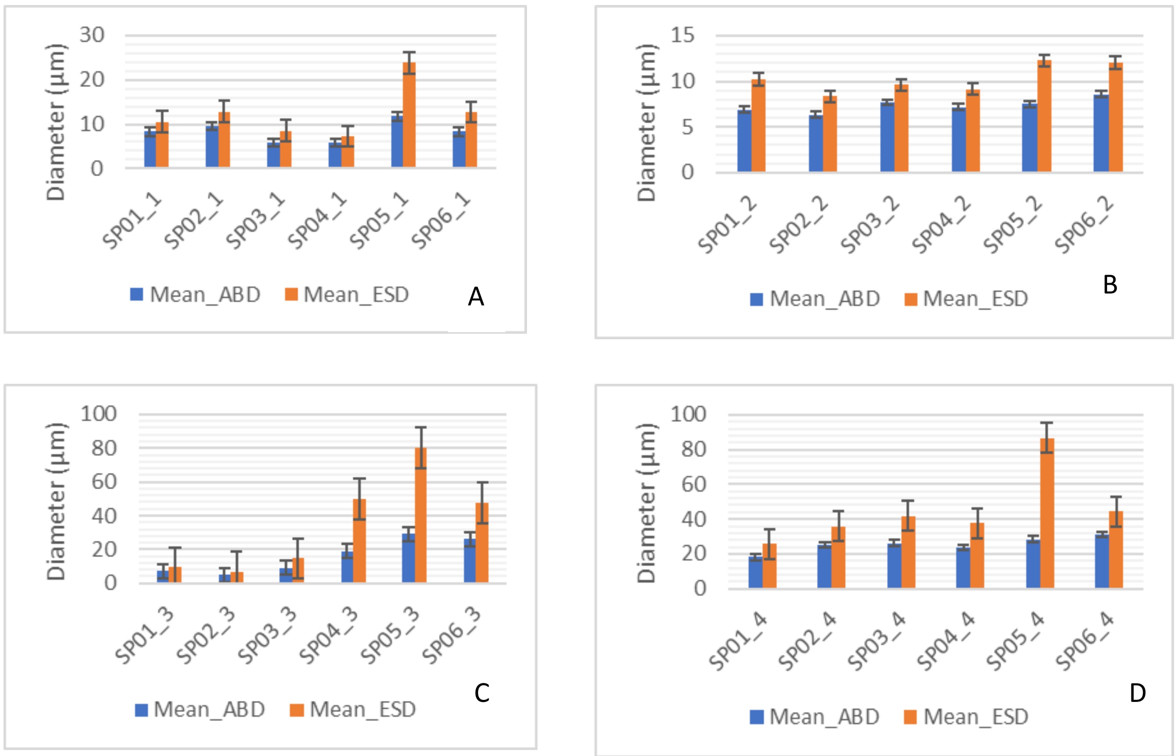

Figure 4.2 Area-based diameter (ABD) and equivalent spherical diameter (ESD) for all the sampling points and sampling phases (**A**; represent phase one (October 2017), **B**; phase two (January 2018), **C**; phase three (May 2018) and **D**; phase four (September 2018)).

Regarding the biovolume, unlike other sampling phases (Figure 4.2A, 4.2C, and 4.2D), sampling phase two (Figure 4.2B) 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 (Figure 4.2) 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 the Pearson's correlation matrix (table 4.4) 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 the Secchi disc depth is following 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 concentration, 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 principle component analysis ordination plot (figure 4.3) demonstrate the associations in the aforesaid variables.

Table 4.3 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).

Table 4.4 Correlation matrix (Pearson's) 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 (◦c)**	**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 (◦c)	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

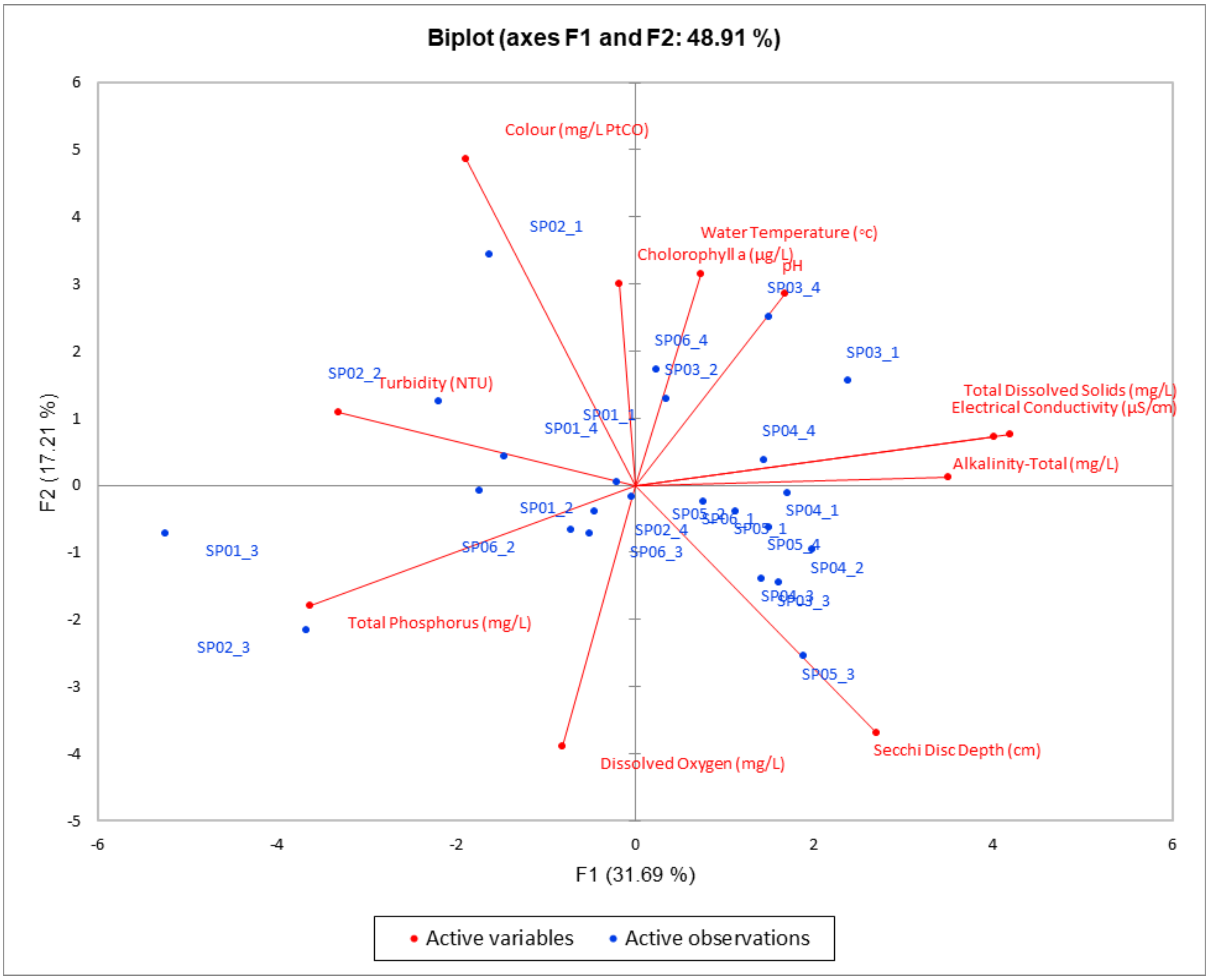

Figure 4.3 Principal component analysis (PCA) ordination plot of active variables and the for sampling point and schedules combined within the main components (F1 and F2). The variables investigated overlaid with the sampling point and phases includes Chlorophyll-a (Chl-a)(µg/L), Color (mg/L Pt.Co), 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).

The bootstrap biplot (Figure 4.4), summarizes the relationships between physicochemical parameters and active observations (sampling points). From the raw data, for instance, sampling point five and phase three (SP05_3) showed high values of Secchi disk depth, SP02_1 showed high values on color, SP03_1, and SP02_3 had a unique value of total phosphorous concentrations and alkalinity, which could also be observed in the PCA results (Figure 4.3).

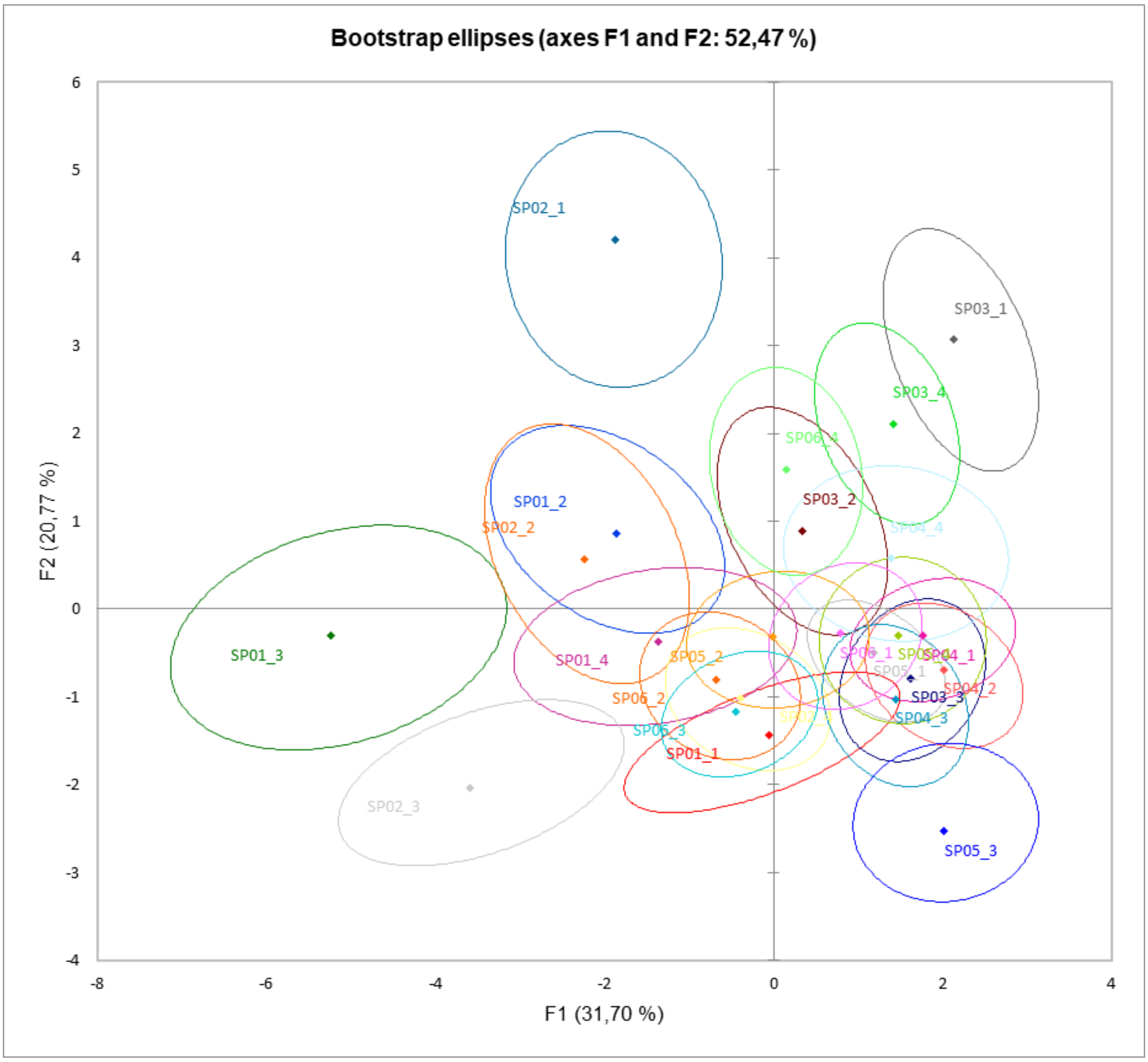

Figure 4.4 A representation of bootstrap ellipses for active sampling points and schedules or phases. Herein, the sampling points are grouped based on their characteristics and or uniqueness at 95% confidence intervals.

3.4. Trophic State Index (TSI)

Trophic state index results (supplementary information Table S1) 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

A patterns for meteorological (observations taken after every 30 minutes for the whole of the period of study (October 2017 to September 2018) was also examined. The meteorological parameters examined include air temperature (°C), relative humidity (%), atmospheric pressure (mmHg), rainfall (mm), and wind directions (Supplementary information figure S8A to S8E). Air temperatures varied between 15-35°C, and relative humidity (%) ranged between 0-80 % with low humidity values occurring during the dry season (June, July, September). The atmospheric pressure was in the range of 951-968 mmHg with relatively high values during the dry season. Regarding wind patterns, a notable phenomenon was a shift in wind direction, i.e., from northeasterly (NE) to southeasterly (SE) during January backing to Southwesterly during MAM season. In addition a case of high rainfall event which ammounted to flash flood also featured in the rainfall pattern.

4. Discussion

Generally, in the present study, total phosphorous concentration, turbidity, chlorophyll-a, and color registered a huge variation of 149%, 108, %, 80%, and 89%, respectively. These variations are attributed to the characteristics of individual sampling points and timing or sampling phases. On the other hand, temperature and pH showed a low variation of 11% and 9%, respectively (Table 4.3). 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 as previously noted by 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 figures 4.2A to 4.2D). The results of this study support the view of Havens *et al.* (2016), that heavy rainfall in the first place tends to suppress occurrences of cyanobacteria bloom through the transport of nutrients to the downstream, mixing of water, and increased turbidity. A similar study conducted in the subtropical area in Brazil (Moura, Aragao_Tavares, Nisia K, & Amorim, Cihelio, 2017), for example, suggests that extreme climatic events increase water temperatures and total phosphorous and promote harmful cyanobacteria.

Water turbidity ranged between 4-233.3 NTU, and Secchi disk depth values ranged between 4.7-107.7 cm. The two parameters showed a significant negative correlation (-0.509), which is principally correct. The study further found pH ranging between 6.5-9.7, while alkalinity ranged between 20.9-198.3 mg/L with the sampling sites SP03 and SP04 registering relatively high values of alkalinity. The reason for the higher values of alkalinity could be associated with their location because the two sampling sites are close to a rice paddy. However, pH and alkalinity values were within the ranges reported by Boyd, (1998) and Sallenave, (2012). Similar findings were also reported in Brazil (Figueredo & Giani, 2009). Total dissolved solids and electrical conductivity registered a significant positive association with alkalinity, and this triangulates well with the existence of a rice paddy near the fishponds.

From Table 4.3, total phosphorus concentration levels ranged between 0.1-5.8 mg/L. The higher values were observed from sampling sites SP01 and SP02. The high values can be attributed to the application of animal manures to enrich nutrients in the fishponds (anecdotal observation). 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), a 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 favor cyanobacteria growth. Total phosphorous concentration 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 et al., (2016) had argued that phosphorus control is the central core issue

In the current study, species of *Microcystis*, *Anabaena*, *Lingbya*, and *Cylindrospermopsis* species were identified. The study findings confirm that cyanobacteria occur together with other green algae species such as Diatoms and *Euglenophytes* (Supplementary Figures S2 to S7). The findings corroborate with reports from 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, which is the tropical characteristics (blooming might occurs at any time of the year). The findings are not far from the observation by Mowe, Mitrovic, Lim, Furey, and Yeo, (2015) that other tropical characteristics are species-specific; for example, *Microcystis* blooms occur during the wet season due to elevated nutrient levels, but also, it may not restrict other dominant species such as Anabaena and

Cylindrospermopsis. It is with these reasons the findings raise a need for further studies, especially on dynamics and interactions of both toxic and non-toxic species. There is also 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. Mindu dam also showed a dominance of species of larger equivalent spherical diameter (Figure 4.2), which is attributed or linked to the filamentous species than the other sampling sites. The difference between this dominance of species in the fishponds and the Mindu Dam can be associated with a constant withdrawal of water from the Dam while in fishponds, the water is relatively stagnant. The dominance of filamentous species in Mindu Dam is consistent with the findings in Ethiopia by Tilahun & Kifle, (2019), whereas the authors suggest that, limited nitrogen could have triggered the unusual dominance of filamentous species of cyanobacteria genus *Cylindrospermopsis* over the dominant persistence genus *Microcystis*. Dominance still raises concerns and research questions about catchment management.

Chlorophyll-a, on the other hand, registered values ranging between 9.4-103.9 µg/L for all the sampling points, implying that they can be categorized as a eutrophic reservoir as per Istvánovics, (2009). Since chlorophyll-a is widely accepted as an indicator for algal bloom, long term monitoring and prediction of HABs is necessary for preventive and control measures. Algae and suspended particles make the water cloudy, which in turn reduces Secchi disk depths (see the correlations in Table 4.3). The derived or calculated Trophic State Index (Table S2) showed that most of the sampling points had 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 & Gin, 2011). Literature suggests that Carlson's Trophic State Index (TSI) values <30 are common among lakes and reservoirs with oligotrophy, and between 50-70 correspond to eutrophic while hypereutrophic are common at TSI values >70 (Pavluk & Vaate, 2017). The STI status and the chlorophyll-a support incidences of algal bloom proliferation in the sampled reservoirs, which links well with the morphological findings.

5. Conclusion

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. The study contributes to the morphological identification of potential CyanoHABs in the region with knowledge and data gaps. Species of *Microcystis*, *Anabaena*, *Cylindrospermopsis*, *Aphanizomenon*, and *Lyngbya*, but also other algal species such as diatoms, and *Euglenophytes* were identified and that they occurred throughout the study duration (i.e., October 2017 to September 2018). Mindu Dam showed to be dominated by filamentous species of cyanobacteria than other sampling points. On the other hand, with the exception of the 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 as it is for domestic water supply. The findings suggest a need for proactive measures due to the existing interconnectivity nature between the fishponds, river tributaries, and the Mindu Dam. Moreover, the Morogoro population is at risk of consuming CyanoHABs through drinking water and or fishery. Further research efforts might particularly directed in epidemiological, ecotoxicological, and their mobility to the higher energy levels for more informed management strategies.

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Chapter 5

The unusual reddish-bloom appearance in a freshwater fishpond at Kingolwira National Fish Farming Center, Morogoro, Tanzania

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This chapter addresses objective (iii)

Abstract

The study aimed at examining a case of what constituted the uncommonly reddish-bloom appearance in the fishponds during the dry season (September 2018) at Kingolwira National Fish Farming Center located in Morogoro, Tanzania. A benchtop FlowCAM® was used to investigate species' morphology. One-time assessment of physicochemical characteristics during the event was performed from the reddish and non-reddish fishponds. Images were compared with the available literature, but also t-test statistics were performed to examine the difference between the two fishponds. The results show that the fishponds were significantly ($p<0.05$) different from each other in terms of physicochemical parameters except for water temperatures. Furthermore, the non-reddish fishpond was dominated by *Microcystis* species and the reddish fishpond by *Euglenophytes* species. Both the identified species have the potential to produce secondary metabolites (toxins) or producing a hypoxia condition that is harmful to the fishery, aquatic ecology, and human. Future studies should consider extensive and regular diurnal and long-term monitoring to confirm toxicity nature and dynamics further.

Keywords: Harmful algae; *Microcystis*; reddish-bloom; *Euglenophytes*; FlowCAM; Morogoro

1.0 Introduction

Harmful algal blooms (HABs) are now a concern to the global community, and that is predicted to compromise climate change adaptation as well as mitigation across sectors (GEOHAB, 2015). In the aquatic environment, three main things are considered regarding HABs, namely, toxin production, food web altering, and hypoxia generation (Paerl et al., 2011). In Tanzania, about 1119 species of phytoplankton have been reported, which includes diatoms (54.7%), green macroalgae (25.5%), blue-green algae (14.5%), and euglenoids (5.5%) (The United Republic of Tanzania, 2001). It is further estimated that there are close to 14,000 freshwater fishponds in the country, and their distribution depends on water availability, suitable land for farming, and awareness and motivation (Mushi, 2006). The dwindling of the available surface water resources and the need for diversification of livelihoods (Paavola, 2008) has stirred the movement into fish farming for both small and large scale farmers even with limited resources (Kaliba, 2006). A recent report also noted that the fish farming industry as a fast-growing social-economic activity in Tanzania (Rukanda & Sigurgeirsson, 2018). Besides, small-scale fish farmers lack extension services to support the sector (Kangalawe & Liwenga, 2005; Mdegela et al., 2011; Niang et al., 2014). A study by Chenyambuga et al. (2014) assessed the productivity and marketing of Nile Tilapia in Mbarali and Mvomero districts in Mbeya and Morogoro regions, respectively noted several constraints including irregular water supply, drought cases, and poor management practices. Furthermore, the occurrence of harmful algal blooms in the chosen area is scant in the literature (Kimambo et al., 2019). Some other observation, for example, Miraji et al. (2016), noted that standards and guidelines for nuisance algal blooms (example, cyanotoxins) are yet to be developed.

Due to impacts associated with nuisance algal blooms on the fishery, water quality, and human, rapid assessment is inevitable. Red algae are a widespread group of uni-to-multicellular aquatic photoautotrophs, of which about 98% are marine, and 2% are freshwater (Deluquei & Lopez-Bailtista, 2007). As noted earlier, red algae as harmful algal blooms have the potential to deplete oxygen hence effect to fish (Stone & Daniels, 2006). Red algae have been reported in fishponds, and their implication on water quality and fish are also vivid (Zuccarello et al., 1999; Stone & Daniels, 2006; Kim & Kim, 2014; Mandal et al., 2017; Mandal et al., 2018).

In Tanzania, studies on red algae have been reported interchangeably (seaweeds and algae) in marine or coastal ecology (Msuya & Neori, 2002; Buriyo et al., 2004; Msuya, Kyewalyanga, & Salum, 2006; Troell et al., 2011). The social-economic potentials of the industry have led Tanzania to be among the group of leading carrageenan-producing (food derived from red algae or seaweeds) in the tropical area along with the Philippines and Indonesia (Deluquei & Lopez-Bailtista, 2007).

Impacts of red algae on aquaculture, ecology, and human health are trace in Tanzania, and the only available work is that of Hahn (2009). The author isolated algal strains from freshwater ponds located at the University of Dar es Salaam and Lake Victoria and developed candidate species (due to lack of pure culture) with the phylum Actinobacteria species to represents planktonic freshwater bacteria (cyanobacteria inclusive). Respectively, Hahn (2009) placed the strains under "Candidatus Aquiluna rubra" [Aqua water; Luna the moon and rubra the red] and "Candidature Rhodoluna planktonica" both referred as aerobic red-pigmentation strains. This overview demonstrates the need for investigation on algal blooms species and their dynamics in freshwaters in the region.

In studying algal blooms, several techniques are available, including conventional techniques such as manual microscopes, molecular, analytical techniques, and the use of remote sensing. The conventional techniques are laborious and time-consuming but are still useful. Advanced technologies such as flow imaging camera (FlowCAM) have been reported to be efficient in screening, determination, and or assessing the morphological characteristics of individual species in a variety of liquid samples. The techniques have been used before for algal species identification and enumeration in both field and laboratory. The present study aimed to identify species responsible for the reddish blooming which happened at Kingolwira National Fish Farm Centre, Morogoro, during the dry season (July-September 2018) and consequently, to provide feedback to farmers during the site visit.

2.0 Materials and Methods

Kingolwira National Fish Farming Center is located at 6° 45' 20.46" S latitude and 37° 45' 15.56" E longitude, Morogoro, Tanzania (Figure 5.1). The center is government-owned, mainly for farmers' demonstrations, hatching, and production of fingerlings to the nearby fish farmers. The infrastructures are well maintained, and the source of raw non-treated water for the center is from the Bigwa River, which is a tributary of the Ngerengere River.

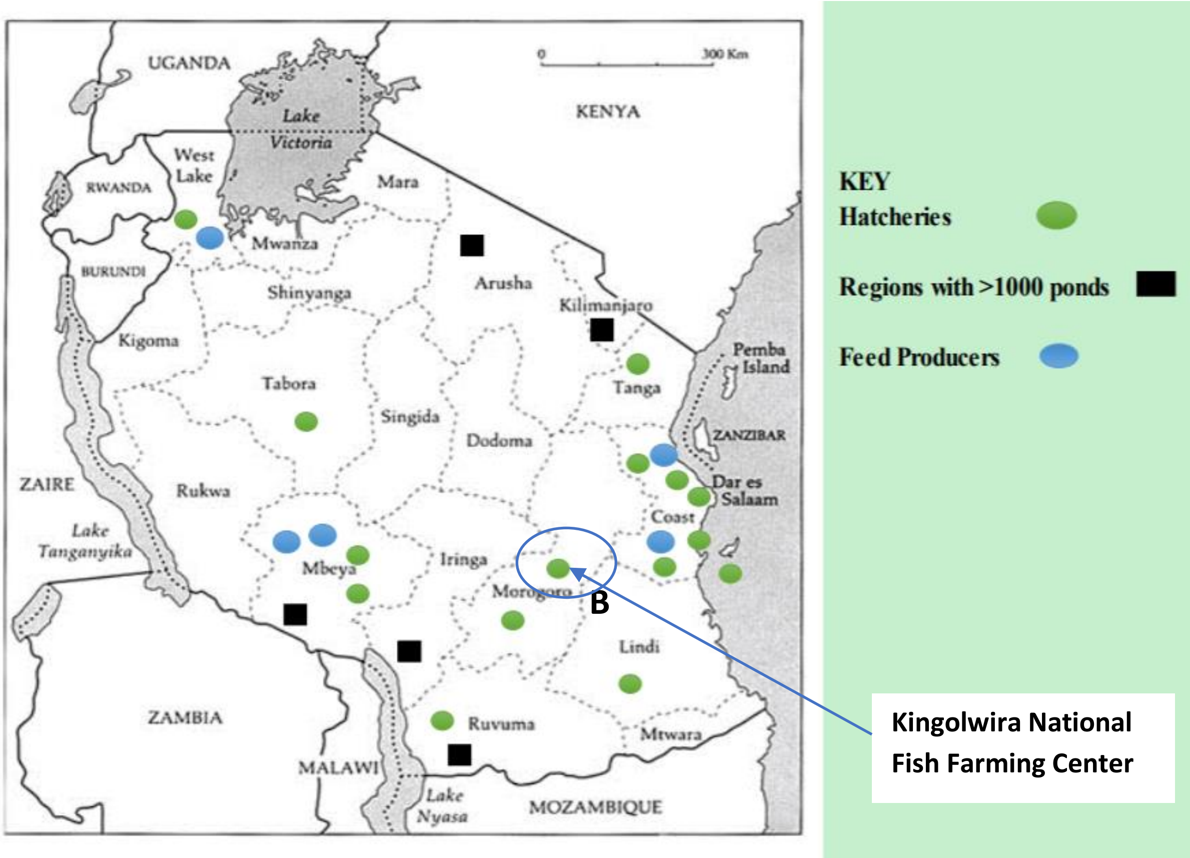

Figure 5.1 Map of Tanzania with the distribution of areas including >1000 fishponds, hatcheries, and feed-produce centers (adopted with permission from Rukanda & Sigurgeirsson, 2018).

A composite sample (1 L) was collected from the two fishponds (i.e., reddish-green and the other with greenish coloration) at the time of observation for the main project and during the dry season (September 6, 2018). Polypropylene bottles were used for collecting water samples for the algal identification and nutrients analysis. Subsamples of 50 mL in an amber glass bottle preserved with 1% Lugol's solution as in Shan et al. (2019) were transported in a cooler box to the University of Venda, South Africa for analysis.

A benchtop FlowCAM® (Model VS4 serial Number 5049 copyright 2003-2012 Fluid Imaging Technologies, Inc., 65 Forest Falls Drive, Yarmouth, Maine 04096, USA) particle analyzer was used in the identification of individual cells in the specimens. The FlowCAM® was configured at 10X objective, flow cell (FC) 100 µm, and under auto image mode. Parallel to sampling observations field photos/images (Figure 5.2) and physicochemical parameters (Table 5.1) (i.e., pH, Oxygen-Redox Potential, dissolved oxygen, total dissolved solids, electrical conductivity, and water temperature) were measured in triplicate using the calibrated

HANNA HI98194 multiparameter meter. The total phosphorus was determined in the laboratory using a Spectrophotometric analysis (phopshomolybdenum test), analogous to a method of EPA 365.2+3 as per the manufacturer's directives (Merk KGaA, Darmstadt, Germany). The images from the FlowCAM® were compared (mainly the morphometric features) with the field guidelines (Kannan & Lenca, 2012). Descriptive statistics and distribution of the particles were handled with the Visual Spreadsheet® 3.0, which comes with the FlowCAM. Anecdotal observation (photos from the field) were also taken for recognition. A descriptive and t-test statistics for the physicochemical characteristics between the two fishponds were performed using XlSTAT 2019.1.3 (Addinsoft, 2019).

3.0 Results and Discussion

Table 5.1 shows a comparison between the physicochemical characteristics of the water in both reddish bloom and non-reddish bloom fishponds, as measured in situ at the time of sampling.

Table 5.1 Selected water quality parameters for both non-reddish bloom and reddish bloom fishponds at Kingolwira National Fish Farming Center, Morogoro Tanzania

	Non-reddish fishpond			**Reddish fishpond**			
Parameter	**Mean**	**Standard Deviation**	**CV (%)**	**Mean**	**Standard deviation**	**CV (%)**	**T-test statistics (P value at α = 0.05)**
pH	9.07	0.02	0.25	7.68	0.15	1.90	0.003*
Oxygen Redox Potential (mV)	100.37	1.63	1.62	132.80	8.71	6.56	0.032*
Dissolved Oxygen (mg L^{-1})	4.34	0.05	1.06	3.11	0.22	6.92	0.006*
Electrical Conductivity (µS cm^{-1})	103.33	2.31	2.23	65.67	2.08	3.17	<0.0001*
Total Dissolved Solids (mg L^{-1})	51.67	1.15	2.23	32.67	1.15	3.53	<0.0001*
Temperature (℃)	27.27	0.23	0.85	27.85	0.35	1.27	0.441 (NS)
Total Phosphorous (mg L^{-1})	BDL			1.13	0.057	5.04	NA

CV: Coefficient of variation; N: Not Applicable; *Statistically Significant; BDL: below the detection limit (<0.5 mg L^{-1}); NS: Statistically Not Significant

Water temperature showed no significant differences ($p>0.05$), while other investigated parameters (pH, ORP, DO, EC, and TDS) showed a significant difference between the two fishponds. The pond with reddish coloration gauged relatively lower pH, with higher oxygen redox potential and lower electrical conductivity but also relatively lower dissolved oxygen. Total phosphorus (TP) for the non-reddish bloom pond was below the detection limit (<0.5 mg L^{-1}), while the reddish bloom pond recorded a mean TP of 1.13 mg L^{-1}. Despite the differences, all the measured parameters were within the desirable ranges compares well with the ranges in fishponds reported by Bhatnagar and Devi (2013). The dissolved oxygen values were on the threshold for the fish to survive. Field images of both non-reddish and reddish blooming are presented in Figures 5.2A and 5.2B for recognition.

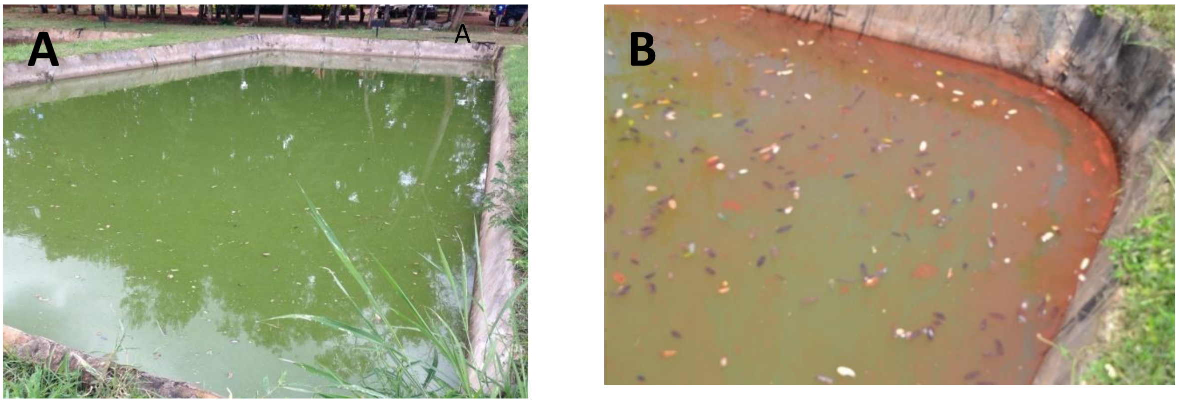

Figure 5.2 Plates for the non-reddish fishpond (A) and reddish fishpond blooming (B) as observed during the dry season (September 6, 2018) at Kingolwira National Fish Farming Center, Morogoro, Tanzania (Kimambo et al., 2018).

Cyanobacteria vary in colour from blue-green, grey-green, violet, brown, purplish to red when examined under the microscope. The colours depend on the relative proportion of their photosynthetic pigment, for example, chlorophyll (green), phycocyanin (blue), and phycoerythrin (red) (van Vuuren et al., 2006). The field images, for example, Figure 5.2B, show a visible mixture of both green and reddish blooming. The red algae in the photo look like the one reported by Stone and Daniels (2006). According to Stone and Daniels (2006), euglenoids (e.g., *Euglena Sanguinea* and *E. granulata*) are associated with the red coloration of water but also can produce toxins. During sampling (anecdotal observation and or filed experiences), the bloom was smelling earthy/musty, which is sometimes associated with nuisance algal blooms, as noted by Watson et al. (2015).

3.2 Morphological identification

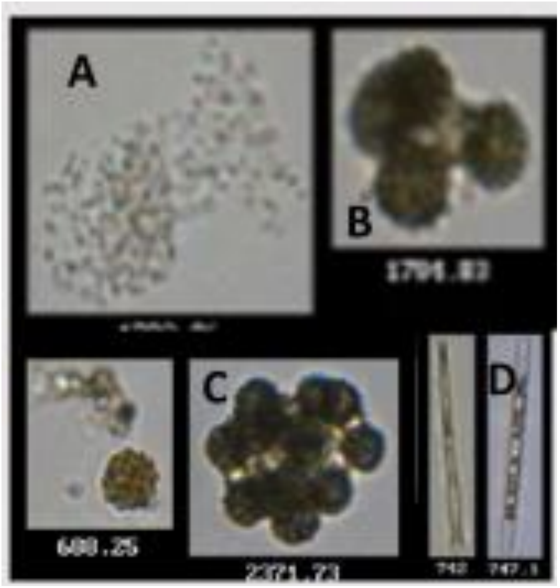

Figure 5.3 Species identified at the non-reddish blooming pond are *Microcystis* (A, B & C) and filamentous species of *Nodularia* (D).

Unlike the reddish fishpond, the non-reddish (Figure 5.3) fishpond was dominated by defined *Microcystis* cells than the reddish pond (Figure 5.4), that is, there are distinct features (by virtualization) between the species from the two ponds.

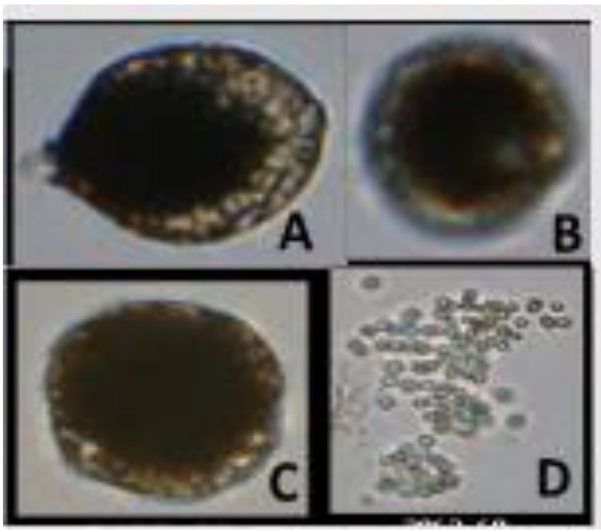

Figure 5.4 Species identified at the reddish-blooming ponds were *Phacus limnophilus (A)*

(resembles species under *Euglena*), *Haematococcus* (B & C), and *Microcystis* (D).

Species identified at the reddish-blooming ponds, for example, *Phacus limnophilus* (A), resembles species under *Euglena*, which is described by is movement during growth stages (http://algaevision.myspecies.info/taxonomy/term/1798). Other species were *Microcystis* (D) and *Haematococcus* (B), as previously reported by Bellinger and Sigee (2010). FlowCAM® uses equivalent spherical diameter (ESD) and area-based diameter (ABD) algorithm to estimate particle/image bio-volume (Buskey & Hyatt, 2006; Edler & Elbrächter, 2010; Davis, 2015; Ma et al., 2014; Wang et al., 2015). Summary results from the FlowCAM of both non-reddish and reddish blooming fishponds are well depicted in Table 5.2 by their area-based diameter (ABD) and equivalent spherical diameter (ESD).

Table 5.2 Summary statistics as per the FlowCAM® results for non-reddish and reddish ponds.

	Non-reddish pond		Reddish-fishpond	
Summary statistics	Area-Based Diameter (ABD) µm	Equivalent Spherical Diameter (ESD) µm	Area-Based Diameter (ABD) µm	Equivalent Spherical Diameter (ESD) µm
Mean	31.08	44.34	26.18	41.16
Minimum	18	18.91	18	18.75
Maximum	89.72	209.11	72.17	89.94
Standard Deviation	13	22.49	10.25	14.84
Coefficient of variation (%)	41.84	50.73	39.13	36.05

The results suggest that ESD for non-reddish fishpond registered significant high values (209.49 µm) while the reddish fishpond registered a maximum value of 89.94 µm. This implies that the non-reddish fishpond had high biovolume than that of the reddish blooming fishpond. During the FlowCAM® runs, particles with less than 18 um Area-based diameter were filtered out, therefore similar minimum values for both fishponds. Form the descriptive results (Figure 5.4) show a dominance of two species, namely *Microcystis* and *Euglena* species. The anecdotal observation as well shows the differences in the color of the water, which is the interest of the study and worrisome to farmers.

According to Stone and Daniels (2006), most of the red algae in freshwaters are *Euglena* species, such as *Euglena sanguinea*, *E. granulate*, and *Planktothrix* species (mostly "*Haematococcus*"). The study findings compare well with that in algaebase (http://www.algaebase.org/search/species/detail/?species_id=aace9d12a12d42e45) and the algaevision (http://algaevision.myspecies.info/taxonomy/term/1840 which is closely related to *Haematococcus* species. Other species, for example, Figure 5.4A, resembles *Phacus limnophilus* (http://algaevision.myspecies.info/taxonomy/term/1798), which falls under *Euglena* species (Guiry in Guiry & Guiry, 2019), and that may change in shapes (sometimes appearing oval/round) as they develop (Kannan & Lenca, 2012). *E. sanguinea*, as well, has been reported to be able to form reddish bloom and toxins (Kannan & Lenca, 2012). According to Zimba et al. (2010), *E. sanguinea* has been associated with many fish kills which were difficult to believe, which means that a considerable gap in the literature that need quick excursion. Greenish-reddish (from euglenophytes) blooming might be challenging because "euglenophytes do not have unique pigment biomarkers which can be used to locate using remote sensing and or other analytical procedures" Zimba et al. (2010).

During an interview with an officer in charge of the Kingolwira National Fish Farming Center regarding the performance of the pond, he replied that; "the fishpond which showed a reddish coloration is not so productive as compared to other ponds and fish kept in sometimes their skins look like fungal-infected" (Kajitanus O.O, personal communication, September 06, 2018).

With that concern, one might speculate and link it with the levels of dissolved oxygen (lower values) and total phosphorus (high values), which differed significantly between the two fishponds (Table 5.1). This uncommon observation of green-reddish bloom and which happened during the dry season in one of the freshwater fishpond at Kingolwira National Fish Farming Center provokes more scientific questions. Some other studies elsewhere right away consider them as invasive species (Zohdi & Abbaspour, 2019). Since climate change has been linked with blooms proliferation, future studies should assess the linkage between cases of extreme algal blooms and extreme weather events and or climate variability. There are still schools of thought that can be depicted from the case study, such as a competition between red-pigmented, green-pigmented species in freshwater resources, and small-scale farmers might be exposed to harmful algal blooms. The use of palm hand, as reported by Rukanda and Sigurgeirsson (2018), which is commonly for assessing water quality, is unhealthy if exposed to HABs events. The study acknowledges that several limitations are thought to impact the quality of our findings, for example, according to Manoylov, (2014), common preservatives such as formaldehyde and Lugol's solution can discolor cells which alter the morphology of colonial and filamentous forms. The use of Lugol's solution in the present study could have distorted the cells, although previous studies have used the same with the positive results. In future studies of the same can be repeatedly and compared with a standard microscope but also comparing the stained versus destained samples.

4.0 Conclusion

The study employed a case study approach to morphologically identify algae species responsible for reddish-green bloom in freshwater fishponds at Kingolwira National Fish Farming Center, Morogoro, Tanzania during the 2018 dry season. The present study adds to the body of knowledge about potential harmful algal blooms in the region with a paucity of data. The study found that the non-reddish fishpond was dominated by *Microcystis* species while the reddish post registered more of *Euglena* species, which could be the one responsible for the reddish coloration. *Microcystis* is popularly known for its ability to produce secondary metabolites (cyanotoxins) while *Euglena* is in rare cases but have the potential to harm fish, ecology, and human if they are exposed. The anecdotal observation noted that blooms were from noon hours towards the evening but also could smell an earthy/musty smell, which is also associated with HABs. Moreover, the fishponds attest to a significant difference between the two fishponds for almost all the water quality parameters between the reddish and non-reddish blooming fishponds, except for the water temperature. The present study is the first or among the very few reports on reddish blooming in freshwater fishponds in Tanzania, although it has been reported in some other parts of the world. The study serves as the basis for future studies on reddish bloom in freshwater reservoirs/aquaculture systems in Tanzania. Future studies could fruitfully explore this issue further by considering a potential health risk assessment and toxicological effects of nuisance blooms on the fishery industry and humans health in Tanzania. It is also a question of future research to conduct monitoring, especially the diurnal variation of blooms and molecular-level analysis. This can be more informative than working on the individual factor effect.

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Conflict of interest: Authors declare that there is no known conflict of interest.

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Chapter 6

Retrospective analysis of Chlorophyll-a and its correlation with climate and hydrological variations in Mindu Dam, Morogoro, Tanzania

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This chapter addresses objective (iii) and (iv)

Abstract

The measurement of Chlorophyll-a in aquatic systems has usually correlated to harmful algae in water bodies. Harmful algal blooms (HABs) are a result of the massive proliferation of blue-green algae (Cyanobacteria). Harmful algal blooms pose threats to both the environment as well as human health, and despite this well-known fact, their monitoring and management are still challenging. Climate change, extreme weather events, and hydrological changes are the main drivers and predicted to benefits HABs dynamics in most parts of the world. In Tanzania, studies of HABs proliferation and their possible correlation with variability in climate and hydrology still lag despite high demand for developing predicting tools and prevention of HABs proliferation. The present study reports on the retrospective analysis of HABs variation in Mindu Dam located in Morogoro, Tanzania using remote sensing techniques. In the present study comparison between in situ measurement and ocean color (OC2) Chlorophyll-a with the surface reflectance's (band and band combinations) of Landsat 7 and Landsat 8 Operational Land Imager (OLI), was performed. Another approach involved searching for patterns and trends, and teleconnection between Chlorophyll-a index (best band ration) and the climate and hydrological variations in the catchment. The findings demonstrated that minimum and maximum temperatures, solar radiation, Chlorophyll-a concentration registered significant increasing trends. Wind speed and directions, and water levels for Mindu Dam showed a significant decreasing trend. On the other hand, rainfall showed no trend. The patterns suggest that there are links and causality between the HABs variations and meteorological parameters

such as temperatures, solar radiations, and water levels. The study, therefore, contributes to the application of recent advances in remote sensing and retrospectively analysis of bloom dynamics and search for their link with climate and hydrological changes.

Keywords: Cyanobacteria; Harmful algal blooms; Chlorophyll-a; remote sensing; climate engine tool.

1.0 Introduction

Harmful algal blooms (HABs) are among the many environmental issues of concern in freshwater systems (Ho & Michalak, 2015). Climate and hydrological variations are associated with HABs proliferation (Paerl, 2014). However, programs and schemes for monitoring HABs dynamics are not well developed and practiced, especially in developing countries (Ndlela et al., 2016). According to Kumar and Mutanga (2018), the reasons for the lagging behind in the developing world include data accessibility, technological skills to process data, and opportunities for research.

Remote sensing has been widely used to measure water quality parameters, including Chlorophyll-a measure which is related to HABs proliferation (Watanabe *et al.*, 2015; Gholizadeh et al., 2016) and the data obtained using this approach has shown high reliability (Dörnhöfer & Oppelt, 2016). Chlorophyll-a is used as the proxy for the quantification of total cyanobacteria (Pereira-Sandoval *et al.*, 2019). Other metrics used for quantifying blooms are species-specific (morphological identification), toxic metrics, and remote sense-based metrics, which can estimate chlorophyll- concentration data in areas where are out of reach (Ho & Michalak, 2015). Regarding remote sensing, several studies have developed different algorithms for Chlorophyll-a estimation for use as an indicator for HABs (Shen et al., 2012a; Palmer et al., 2015; Wang et al., 2016; Chen *et al.*, 2017; Ogashawara *et al.*, 2017; Yang & Anderson, 2016; Yang et al., 2017; Bohn et al., 2018).

Gholizadeh *et al.* (2016) and Ho and Michalak, (2015), narrated the significances of using remote sensing over other methods, for example, traditional methods for the monitoring of water quality, are time-consuming, labor intensive and costly, unlike remote sensing methods. Other advantages of remote sensing methods include the coverage of the larger area and, in some cases, high resolutions (Zamyadi *et al.*, 2016). Moreover, the use of remote sensing techniques comprises factors such as spatial-temporal coverage, forecasting, the accuracy of collected information, although no single method can give an accurate understanding of HABs

(Shen *et al.*, 2012b). Despite all the advantages, remote sensing suffers from limitations such as the need for atmospheric corrections if working with raw images, as well as requirements for calibrations and validation (Gholizadeh *et al.*, 2016). Another disadvantage attributed to the use of remote sensing is that some analyses are limited to specific conditions not applicable to images taken under different conditions (Zamyadi *et al.*, 2016).

The present study aimed to examine the algorithms for estimation of Chlorophyll-a in Mindu Dam using google engine (GE) and climate engine tools. It also sought to investigate Chlorophyll-a variation (retrospectively) overtime in the catchment and a comparison of Chlorophyll-a with climate and hydrological status in the catchment. The hypothesis tested is that climate and hydrological dynamics have played a significant role in cyanobacteria bloom in the catchment. The assumption set forward is that the estimated values of Chlorophyll-a and or band ratios are a true representative of the time in which the capture occurred. The premise is due to lack of monitoring data and the difference between Landsat 7 and 8 in capturing images (i.e., days that they revisit the same place).

2.0 Materials and Methods

2.1 Study site description

Mindu Dam (Figure 6.1A) is in Wami Ruvu Basin, with an estimated area of 3.8 km^2 (Ngoye & Machiwa, 2004). Mindu Dam is the primary source of water and freshwater fishery supplies in urban and peri-urban communities of Morogoro (Mdegela et al., 2009). Land use characteristics, soil erosion, and sedimentation are more prominent challenges (Natkhin et al., 2015) that continuously reduce the depth of the Dam and Ngerengere River (Yanda & Munishi, 2007).

2.2 Climate and Hydrological data

Data used in the current study include meteorological parameters (i.e., monthly rainfall, monthly maximum and minimum temperatures, solar radiations, wind speed, and directions), collected in the span of 30 years (1988 to 2017) courtesy of the Tanzania Meteorological Agency. Hydrological data (Mindu Dam's water levels for a period of 1997 to 2017) in the catchment courtesy of Wami Ruvu basin office, and Nino-3.4 index (*NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/* 0).

2.3 Generation of remote sensing data

Surface reflectance's for different bands for both Landsat 7 and Landsat 8/ OLI from 1999 to 2017 and 2013 to 2017, respectively (depending on their launch date) for the estimation of Chlorophyll-a concentration for the Mindu Dam were obtained from the climate engine (https://clim-engine.appspot.com/#). The climate engine is powered by google earth engine, the University of Idaho, and Desert Research Institute (http://climateengine.org/app). This facility has not been used effectively for studies in developing countries (Kumar & Mutanga, 2018). In remote sensing, most surface features are derived based on surface reflectance measurements (Vermote et al., 2016). In the present study climate engine web-interface (Figure 6.1B) was used to extract Landsat 7 Collection 1 Tier 1 and Real-Time data Surface reflectance (LANDSAT/LE07/C01/T1_SR) and Landsat 8/OLI surface reflectance. Data, according to the source, can be at a point or polygon (average). The location (region of interest) over the Mindu Dam on the map was drawn in order of polygon vertices, as illustrated in Figure 6.1B. The dataset, according to the source (https://explorer.earthengine.google.com/#detail/LANDSAT%2FLE07%2FC01%2FT1_SR) are atmospherically corrected (i.e., cloud, shadow, and water were filtered) as well as per-pixel saturation mask and that they are ready for use. Studies trials and system development are underway (Zlinszky et al., 2017).

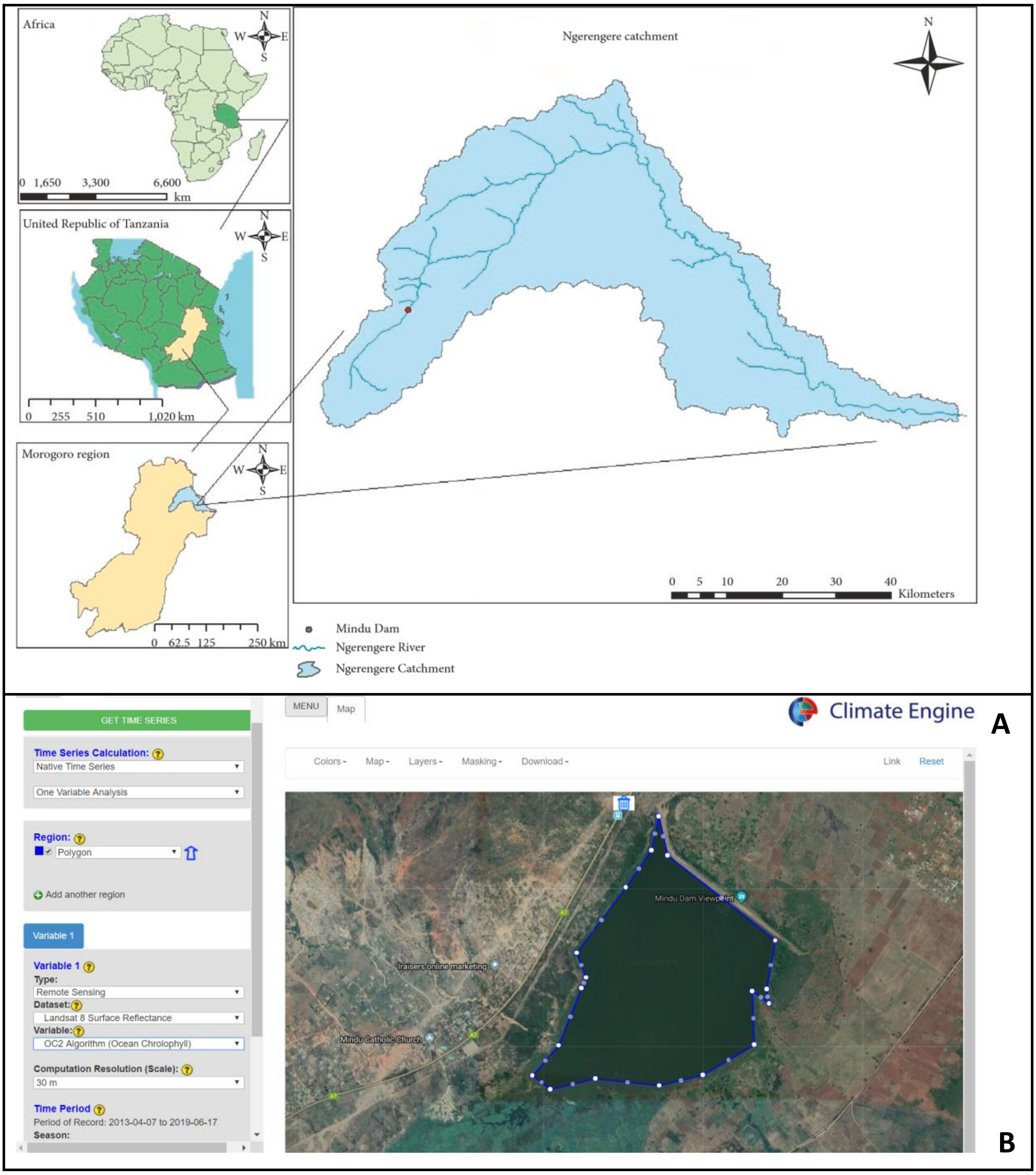


Figure 6.1 Study area map depicting the location of Mindu Dam in the Ngerengere catchment (Kimambo et al., 2019) (**A**) and an interactive web-interface for the Climate Engine (https://clim-engine.appspot.com/#) (**B**) the region of interest (ROI).

Other approaches employed in this study involved the use of OC2 Chlorophyll-a concentration, as in Keith et al. (2016) in near-surface water. This work further followed the time series analysis approach as in Malahlela et al. (2018), a study which was conducted in Vaal Dam in South Africa. A similar approach was also used in Lake Victoria by comparing OC2

Chlorophyll-a and climate parameters to assess the teleconnection between climate phenomena and algal blooms proliferations (Cózar et al., 2012). The study used the OC2 Chlorophyll-a algorithm (retrieved from climate engine web tool) for both Landsat 7 and 8 surface reflectance for comparison. The time frame from their launch date (Landsat 7 will have a larger dataset than Landsat 8 for that purpose) was also considered to have a considerable number of observations. In the present study, we found four mostly studied bands (Band 2, Band 3, Band 4, and Band 5) and their combinations as suggested in the previous reports (Gholizadeh et al., 2016 and Ho et al., 2017).

2.4 Spectral characteristics and their justifications

Previous assessments for spectral type and features were explicitly reviewed in terms of their advantages and disadvantages (Gholizadeh et al., 2016). These Authors indicated that Band 2, Band 3, Band 4, and band ration (Band 5/Band 3) at a significant level $p < 0.01$ (the single and or combinations) showed good correlation with Chlorophyll-a concentration (see their properties in table 6.1). Other researchers have reported Band 2, Band 5, and Band 2/Band 4 as a useful measure for Chlorophyll-a.

Table 6.1 Properties of Landsat 8 (adopted from Fu et al. 2018)

Channel Name	Spectral range (µm)	Central wavelength (µm)	Spatial resolution (m)
B1 Coastal	0.433-0.453	0.443	30
B2 Blue	0.450-0.515	0.4825	30
B3 Green	0.525-0.680	0.5625	30
B4 Red	0.630-0.680	0.655	30
B5 NIR	0.845-0.885	0.865	30
B6 SWIR 1	1.560-1.61	1.61	30
B7 SWIR 2	2.100-2.300	2.2	30
B8 Panchromatic	0.500-0.680	0.59	15
B9 Cirrus	1.360-1.390	1.375	30

2.5 Field Campaign and sample analysis

Samples collected for *in situ* Chlorophyll-a data were in four (4) phases (5th October 2017, 2nd

February 2018, 31st May 2018, and 9th September 2018) and as per the design of the parallel experiment.

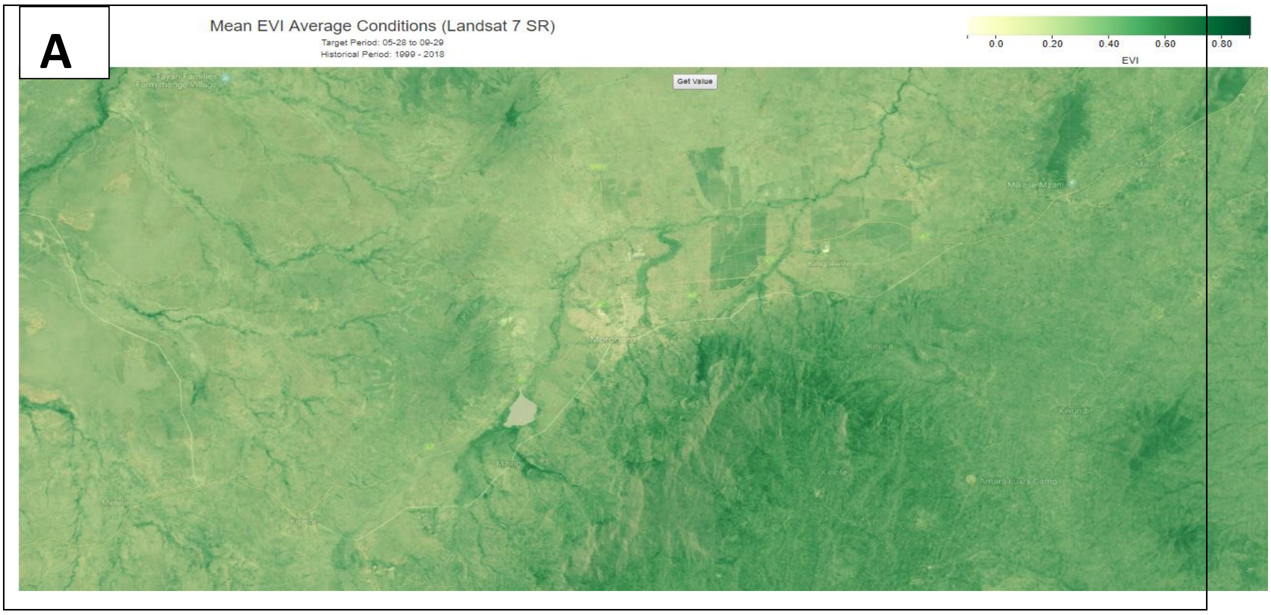
2.6 Data analysis and test statistics

Individual patterns and Mann-Kendall trend tests for all the meteorological (rainfall, temperatures, solar radiations, and winds), hydrological (water levels), and blooms (OC2 Chlorophyll-a) were performed using XLSTAT (Addinsoft, 2019). We compared Nino-3.4 Index anomalies by tracking the negative anomalies with cases the high concentration of blooms (due to lack of monitoring data, OC2 Chlorophyll-a values meant as an indicative measure for the occurrences of Chlorophyll-a in the reservoir) as in Cózar et al. (2012).

3.0 Results and Discussion

3.1 Vegetation changes in the catchment

The trend of vegetation in the catchment depicted in Figures 6.2A and 6.2B. Figure 6.2A shows the land presentation of an enhanced vegetation index (EVI) (historical period 1999 to 2018), while Figure 6.2B shows the percentage of change of vegetation (target period 2017 to 2018). The results show up to about 30% decrease in vegetation is registered when using Landsat 7 surface reflectance. The change in vegetation could be attributed to anthropogenic activities coupled with climate and hydrological variations are the main factors that directly influence the proliferation of algae. Farming practices and deforestation are issues of concern and are believed to have contributed to the siltation of the Mindu Dam (Paavola, 2008).



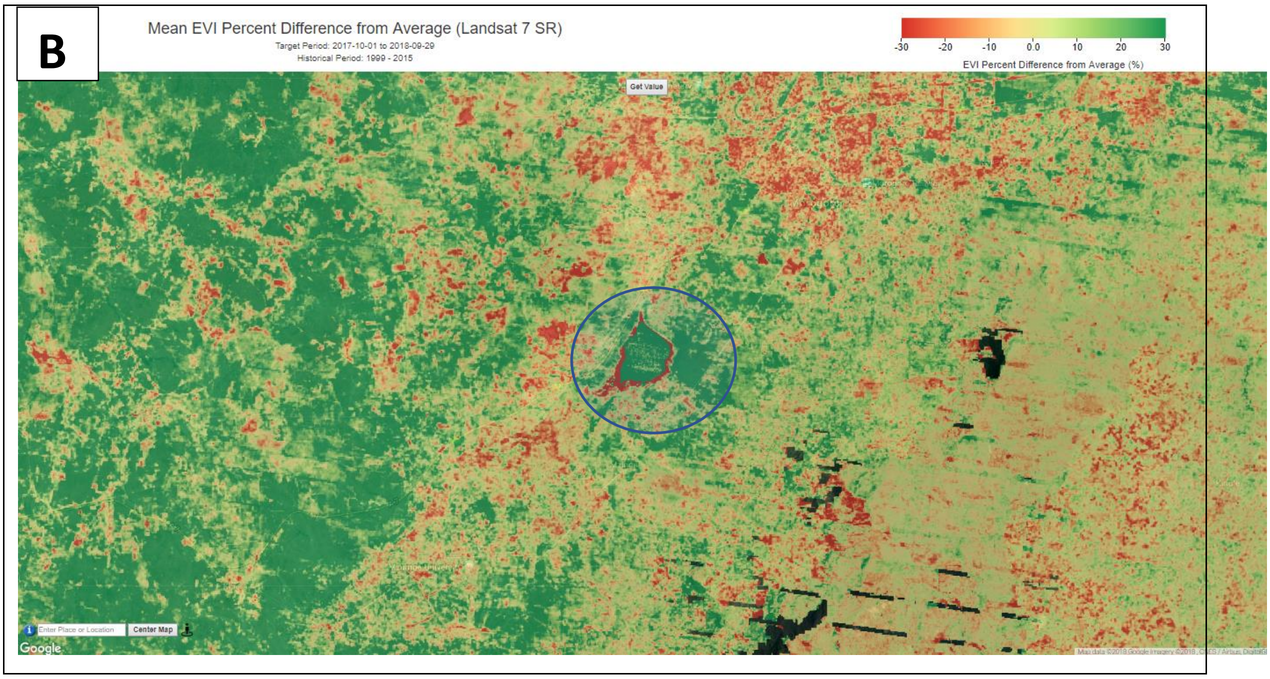


Figure 6.2 Enhanced Vegetation Index (historical period 1999 to 2018) (**A**) and Enhanced Vegetation Index showing the percentage of change of vegetation (target period 2017-2018) (**B**) (images retrieved from climate engine web tool available on https://clim-engine.appspot.com/climateEngine#). The circled area on the map shows the location of Mindu Dam.

A similar study conducted by Cózar et al. (2012) compared OC2 Chlorophyll-a with meteorological conditions (for example, ENSO) and found a teleconnection between the phenomenon's over Lake Victoria. In this study, the authors highlighted the potential role of cultural-eutrophication (human-induced) in moderating the dynamics of phytoplankton in Lake Victoria. Changes in vegetation in the study area, also imply levels of human-induced activities. The vegetation changes corroborate with the observations in the previous reports (Yanda & Munishi, 2007). Intensive human activities directly affect or plays a role in water quality and hence, the proliferation of algal blooms. For example, a study by Michalak et al. (2013) noted a link between agricultural activities and an increasing phosphorus loading coupled meteorological conditions (not specific) in controlling HABs formation. Furthermore, Michalak et al. (2013) suggested that the factors are inconsistent with the predicted future conditions.

3.2 Comparison between *in situ* and ocean color Chlorophyll-a (Landsat 8 surface reflectance) concentrations

Figure 6.3 indicates a graphical relationship for OC2 Chlorophyll-a for Landsat 7 and Landsat 8 for a period of 2013 to 2017 as well as the in-situ observation (all field campaigns). In situ Chlorophyll-a concentration (doted) seems to be varying in the same way satellite retrieved Chlorophyll-a were varying. In situ Chlorophyll-a ranged from 9.43 to 34.52 µg/L, which falls within the range of OC2 for Landsat 8. On the other hand, most Landsat 7 OC2 values are <10 µg/L, which were inferior to Landsat 8 OC2. The observed high pick for Landsat 8 OC2 Chlorophyll-a are 57.50 and 66.67 µg/L corresponding to January 11, 2014, and January 17, 2016, respectively. [Note: in the first place, we omitted the two extreme values for OC2 Chlorophyll-a (Landsat 8) as they seemed to be an outlier, but for this study, they were extracted and then mapped for future discussions].

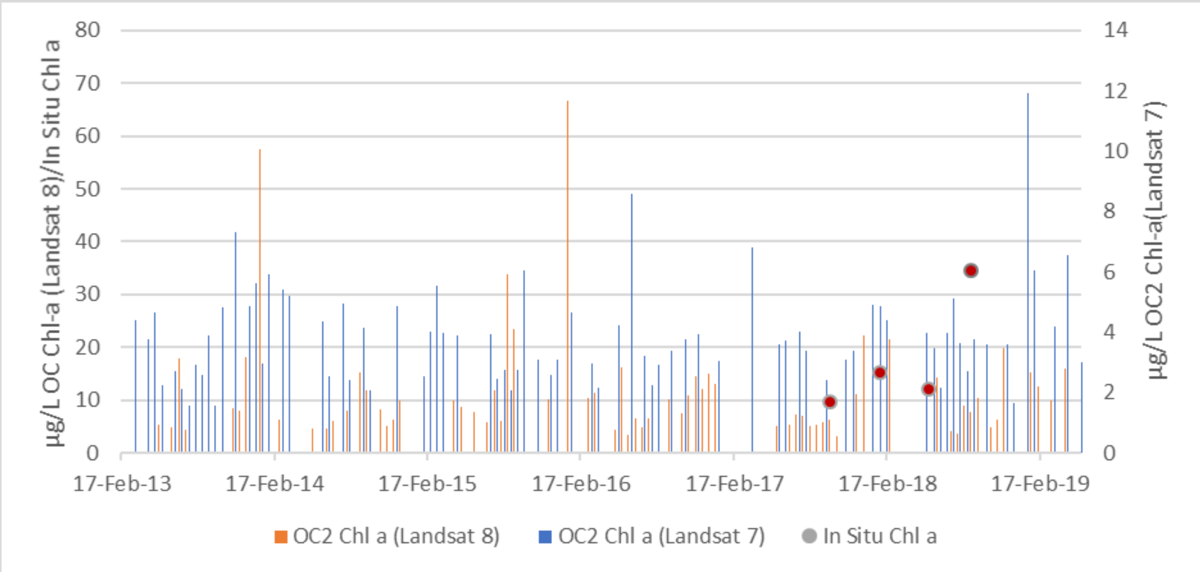
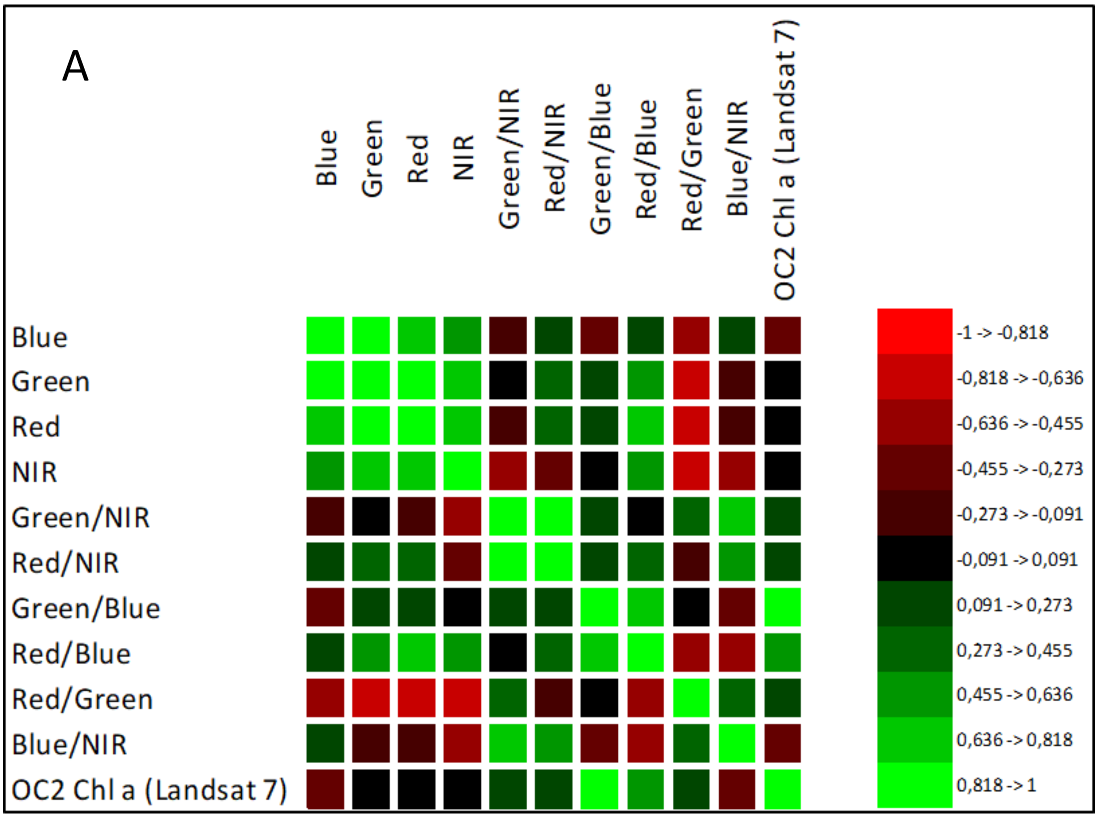


Figure 6.3 Typical OC2 Chlorophyll-a for both Landsat 7 and Landsat 8 surface reflectances (from 2013 to 2019), and in situ (selected phases in the year 2017/2018) Chlorophyll-a variation.

Previous studies, for example, Malahlela et al. (2018), used Landsat 8 Operational Land Imager (OLI) for estimating Chlorophyll-a concentrations. Contrary to the present study, these authors developed an algorithm that worked better with Red and NIR bands. As stated earlier, our study used OC2, which is based on the Blue and Green bands (https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/) algorithm. From Figure 6.3, in situ values patterns (doted) are in accordance with both Landsat 7 and 8 OC2 Chlorophyll-a. The correlation between OC2 and individual band and band combination is studied to assist in selecting the best combination.

3.2.1 Correlation tests

Biplot, correlational analysis for band and band combination for both Landsat 7, Landsat 8 surface reflectance, and OC2, are shown in Figures 6.4A and 6.4B, and these were used to provide the criterion to estimate Chlorophyll-a (i.e., considered as Chlorophyll-a index).



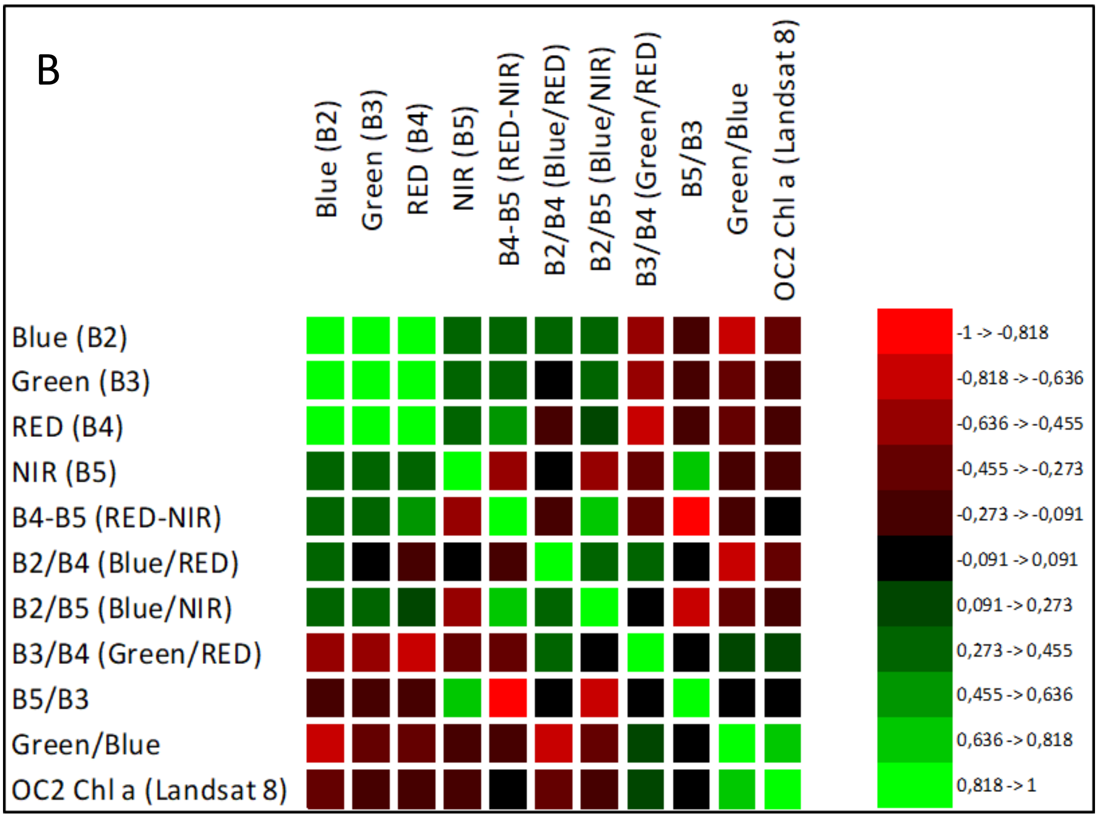


Figure 6.4 Correlation coefficient for individual bands, bands-combination, and OC2 for both Landsat 7 surface reflectance (A) and Landsat 8 surface reflectance (B).

Over the tropics, in situ monitoring data for cyanobacteria blooms are lacking, therefore developing a time series pattern for comparison with other environmental variables is challenging. A review by Mowe et al. (2015), for example, failed to do a detailed analysis of the light intensity, stratification of lakes, flushing of water bodies because of data scarcity. As discussed earlier, that band and bands combination has been previously used to estimate Chlorophyll-a concentration. In the current study, the Green-Blue ratio showed a strong correlation with OC2 for both Landsat 7 and 8 (see Figure 6.4A and 6.4B). Specifically, of all band ration tested, the ratio between green and blue (Green/Blue) for all the sensors registered a strong correlation of 0.942 and 0.729 for Landsat 7 and Landsat 8, respectively. On the other hand, the coefficient of determination was 0.888 and 0.532 for Landsat 7 and Landsat 8, respectively. The results corroborate with those reported by Haet al. (2017), which used Landsat 8 OLI that obtained the best estimation by a ratio of two reflectances at 562 and 483 nm (corresponding to the OLI Band 3 and Band 2, respectively). The band ratio (as in Figure 6.5) differs in terms of time scale since both Landsat 7 and Landsat 8 were launched in 1999 and 2013, respectively, and both satellites continue to acquire data.

When the Mann-Kendall trend test for OC2 Chlorophyll-a using Landsat 7 surface reflectance, the results showed an increasing trend, which is in line with the raw OC2 Chlorophyll-a (Figure 6.7). Figure 6.5 shows the graphical representation for band ratios (Chlorophyll-a index) for both Landsat 7 and 8.

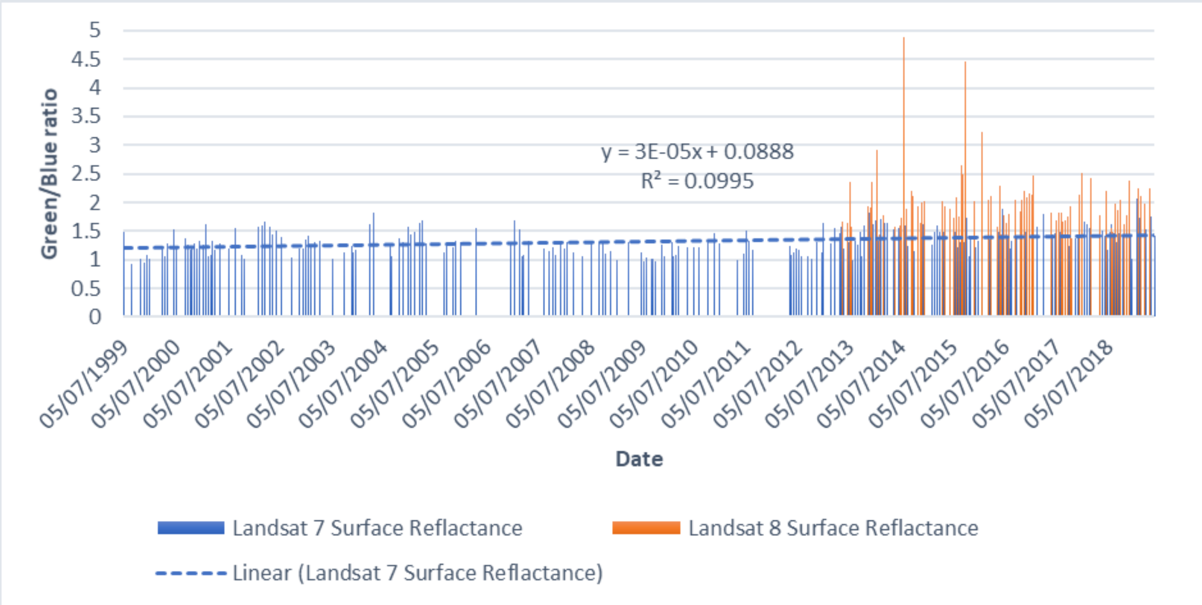


Figure 6.5 Plot for the Band ratio (Green/Blue) for both Landsat 7 and Landsat 8/OLI surface reflectance. Landsat 8 registered a slightly superior ration than that of Landsat 7.

From Figure 6.5, the observed highest band ratio values (4.7 and 4.8) in Landsat 8 values correspond to the extreme values of OC2 Chlorophyll-a (Figure 6.6) which occurred on July 22, 2014 (4913.51 mg/m^3 of Chlorophyll-a) and September 27, 2015 (1233.91 mg/m^3 of Chlorophyll-a). The two values were omitted in figure 6.3 because they were suppressing other values if presented as raw OC2. The band ratio (Green/Blue) depicted the magnitude of both the observations (Figure 6.5) mentioned above. An interesting finding is that extreme values occurred during the dry months/seasons from June to September as well as January, which is also relatively dry. With regards to images extracted using the climate engine web interface (Figure 6.6A and 6B), observed more concentration at the center towards the north-eastern side of the Mindu Dam.

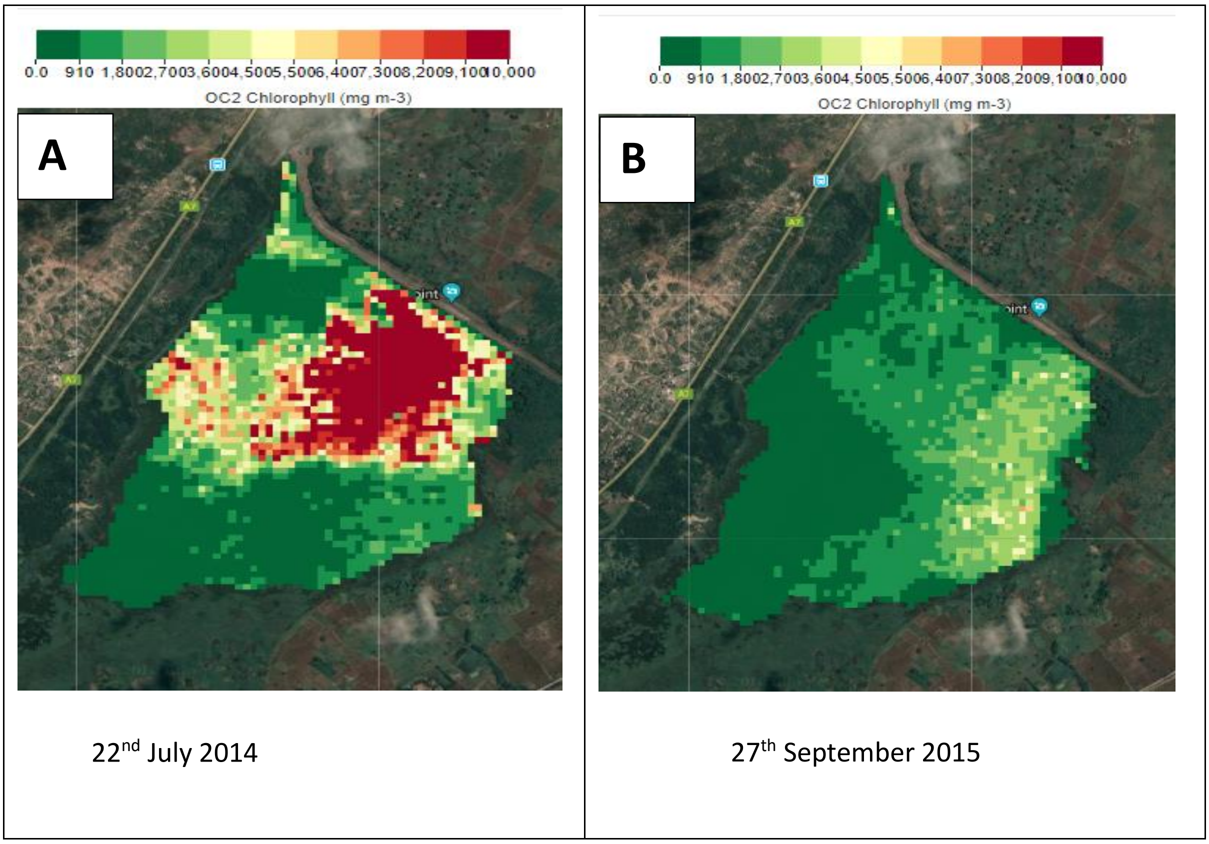


Figure 6.6 Maximum values for OC2 Chlorophyll-a concentration as extracted from the two dates that registered or signalled high strength.

Threshold values of Chlorophyll-a in recreation and ponds for example, in New England Lakes, based on world health organization (WHO) are set to be low (Chlorophyll-a <10 µg/L), moderate (10-50 µg/L) and high (50-5000 µg/L) (Keith et al., 2012). According to the same Authors, health effects associated with contaminated water, if consumed or exposed, are in three categories.

i. Low: skin irritation and gastrointestinal illness
ii. Moderate: all the symptoms of the group (i) with long term illness
iii. High: all the signs of the group (ii) and potential for acute poisoning

The extreme values of OC2 Chlorophyll-a as well as in situ Chlorophyll-a in the current study fall under the moderate to high and low categories when using Landsat 8 Landsat 7 OC2 algorithm surface reflectance, respectively. The observation suggests further investigation on refining monitoring techniques for assessing possible health effects associated with algal blooms in the catchment.

3.3 Trend for the Ocean color Chlorophyll-a using Landsat 7 surface reflectance

Figure 6.7 shows OC2 Chlorophyll-a using Landsat 7 surface reflectance as obtained from the Climate Engine web interface and which has a duration that is relatively close to the period of the climatological dataset. After performing a Man-Kendal trend test, the results indicated a significant ($p<0.001$) increasing trend for the Chlorophyll-a in Mindu Dam.

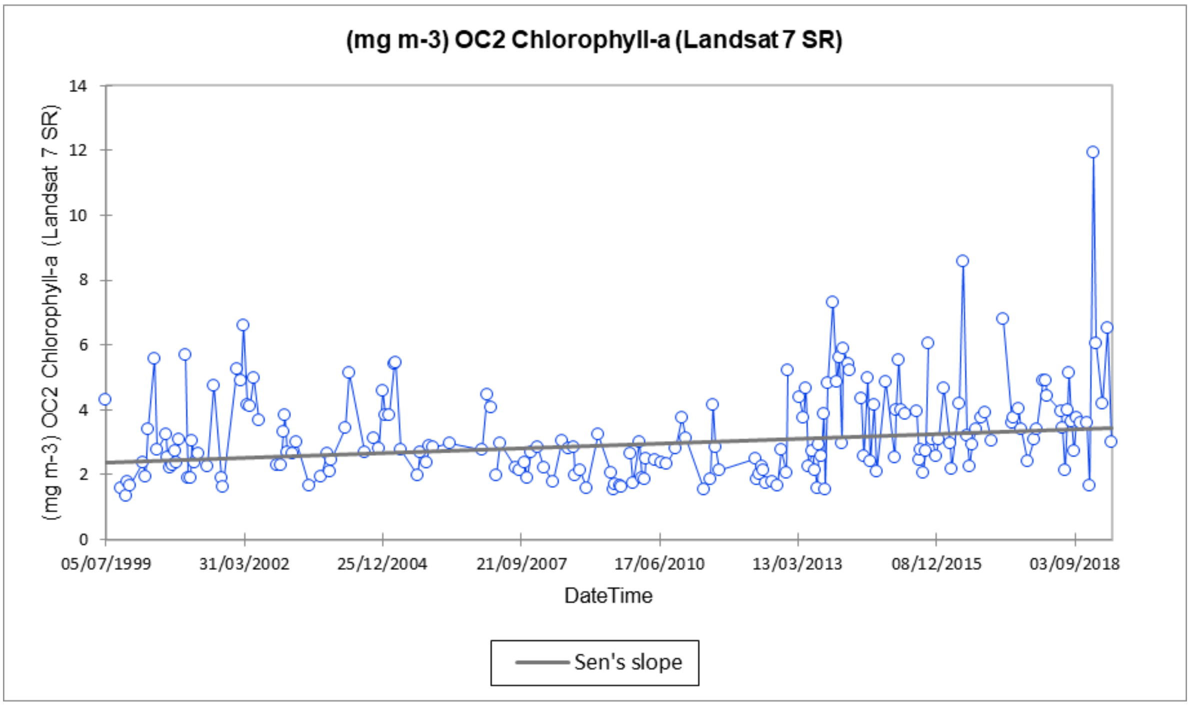


Figure 6.7 Mann-Kendall trend series for the OC2 Chlorophyll-a concentration using Landsat 7 surface reflectance. The plot exhibits a significantly increasing trend with relatively more considerable variation starting from 2013.

3.4 Climate and relief features in the Upper Ngerengere Catchment

Several studies have reported on the hydrological and climate variability in the Ngerengere catchment (Natkhin et al., 2015; Ernest et al., 2017; Kimambo et al., 2019). One factor that miss in the previous studies is the topographical influence. The present research articulates and deduces the implication of the studied variations and changes on HABs (forgotten factor). Figure 6.8 illustrates the relief features that are responsible for local weather variations (for example, orographic effects). The reservoir (Mindu Dam) situated in a valley, surrounded by the Uluguru Mountains (as illustrated in Figure 6.8), is surrounded by which part of eastern arch mountains (Uluguru Mountains), which are influencing the local weather in Morogoro Urban.

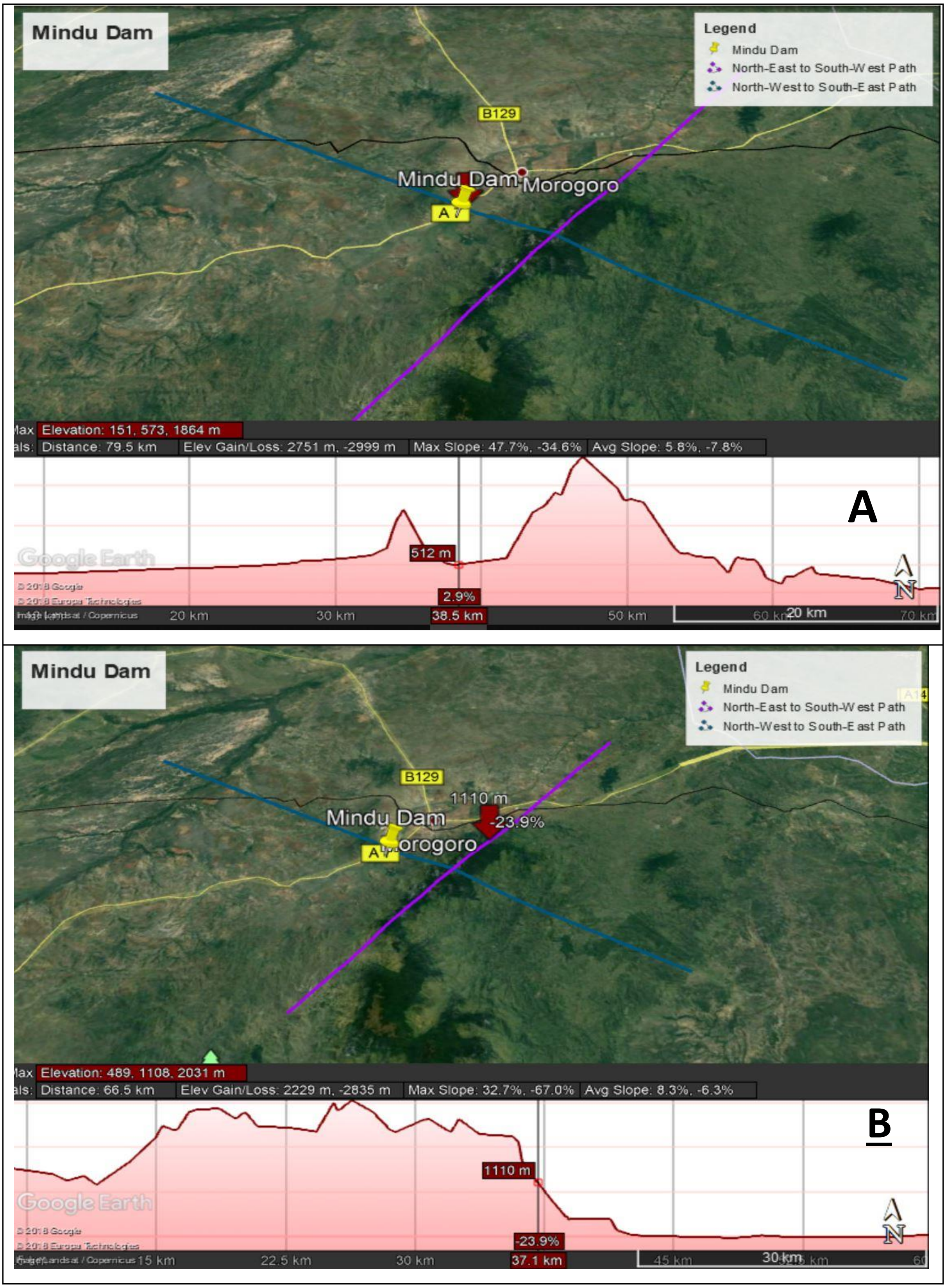


Figure 6.8 A cross-section of relief features near the study area. From North West (NW) to the South East (SE) path (A) and North East (NE) to the South West (SW) path (B) (courtesy of

google earth). The relief demonstrates the escarpment of which is responsible for the local weather influences (orographic effect)

Regarding the importance of relief features on algal blooms dynamics, a widespread discussion is that topography (such as a mountain) controls the temperature say for the leeward side of the hill (Birdwell, 2011). Wind speed and directions variability probe the chance for having higher temperatures in the leeward side of the mountain. The correlation test (Table 6.2) showed a significantly ($p<0.05$) strong correlation between maximum temperature, solar radiation, and wind speed but a weak relationship with wind direction at 1200Z.

Table 6.2 Correlation Matrix (Pearson) between the variables

Variables	Monthly Total Rainfall (mm)	TMX (°C)	TMN (°C)	SLR (MJ/M2)	WD0900Z (Degree)	WD1200Z (Degree)	Wind Speed (Knots)	Water Level (cm)	Nino-3.4
Monthly Total Rainfall (mm)	**1**								
TMX (°C)	**0.153**	**1**							
TMN (°C)	**0.583**	**0.756**	**1**						
SLR (MJ/M2)	0.025	**0.736**	**0.491**	**1**					
WD0900Z (Degree)	-0.021	0.060	0.060	0.100	**1**				
WD1200Z (Degree)	-0.047	**0.148**	0.064	**0.130**	**0.825**	**1**			
Wind Speed (Knots)	**-0.146**	**0.674**	**0.389**	**0.554**	**0.534**	**0.587**	**1**		
Water Level (cm)	0.018	**-0.551**	**-0.396**	**-0.394**	0.039	0.048	**-0.423**	**1**	
Nino-3.4	**0.144**	-0.043	0.043	0.031	-0.045	-0.063	-0.099	**0.146**	**1**

Note: Bolded figures are significant at $\alpha = 0.05$

3.5 Rainfall, temperature and solar radiations for the Morogoro Synoptic station

Figure 6.9 depicts the trends for monthly precipitation, maximum and minimum temperatures as well as solar radiation for Morogoro synoptic weather station. In the study area, Mann-Kendall trend analysis (1988 to 2017) demonstrated a significant increasing trend for both maximum and minimum temperatures, solar radiations, while rainfall showed no significant trend (see Figure 6.9). Observed temperatures have been considered as the central organizing factor in determining the potential for HABs to occur (Gobler et al., 2017), although synergistic functions with other parameters such as phosphorus might be more informative. Several studies have indicated a link between climate variability and bloom changes in different geographical regions, for example, Zhang et al. (2012) investigated a link between climate variables and bloom phenology using multiple regression models. Zhang et al. (2012) found that the phenological changes for Lake Taihu in China are strongly linked to climate. The study further demonstrated that blooms occur earlier and last longer with the increase in temperature, sunshine hours, and global radiations and decrease of wind speed.

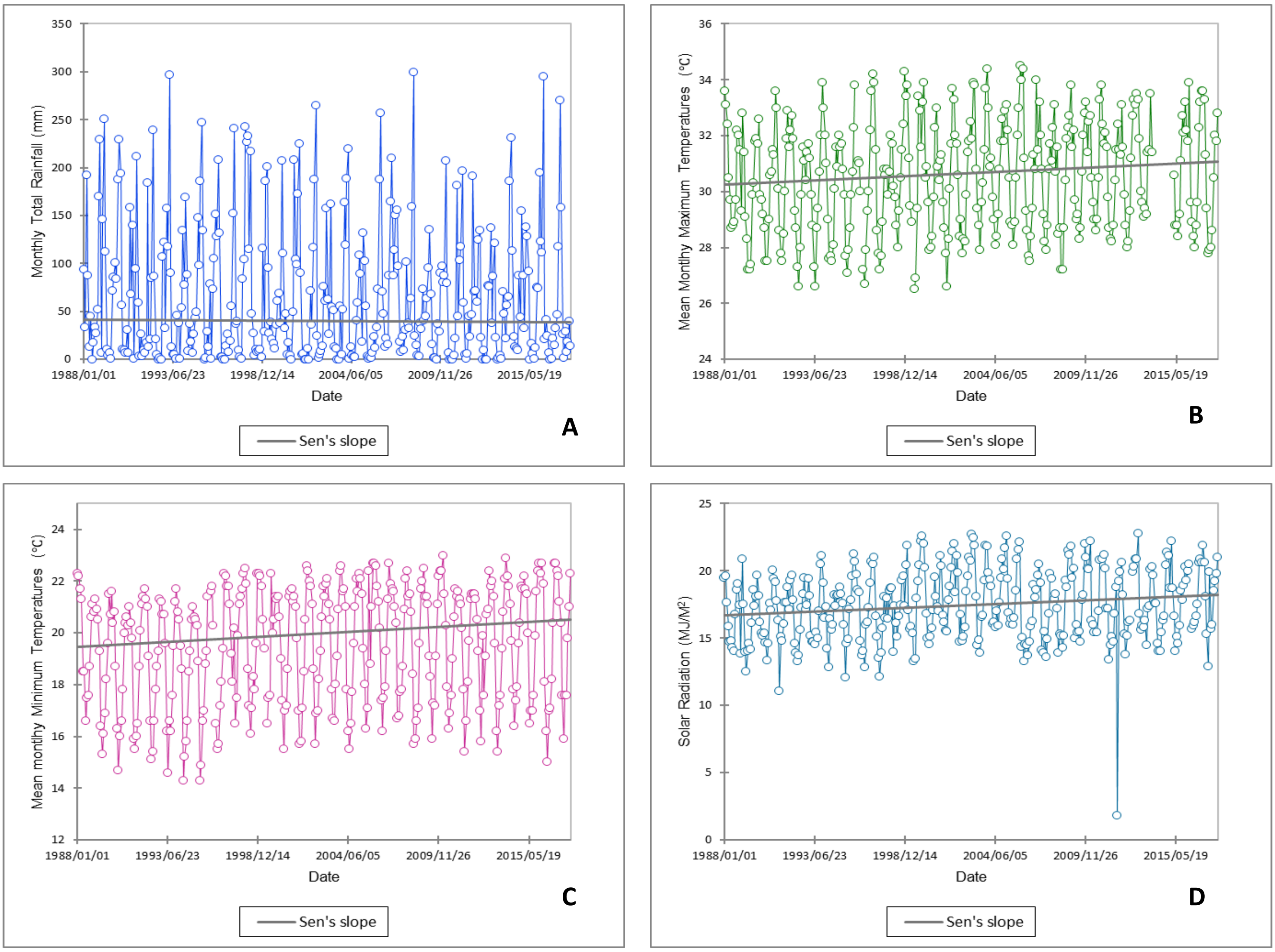


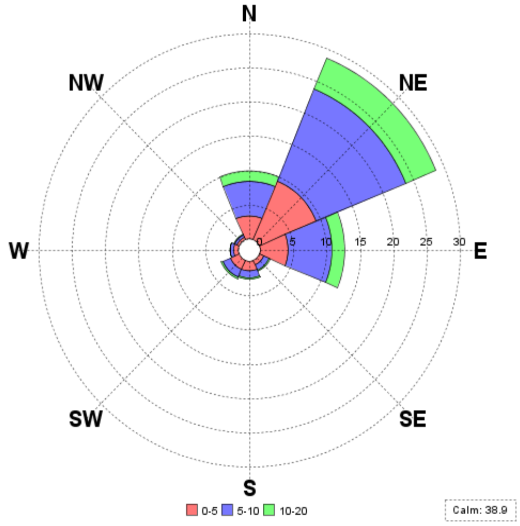
Figure 6.9 Monthly total rainfall (mm) (A), monthly maximum (B) and minimum temperatures (°C) (C), and Solar radiation (MJ/M^2) (D) for a period of 1988 to 2017 for Morogoro Synoptic Weather stations. Mann-Kendall trend test indicated that with exception total monthly rainfall Mean maximum and minimum monthly temperatures and solar radiations registered a significant increasing trend ($p < 0.05$).

A recent study which was conducted in the Morogoro region (Ernest et al., 2017) performed a Mann-Kendal trend test to assess the influence of urbanization on an urban heat island (UHI) using normalized difference vegetation index (NDVI) and climate data. The study found a significant increase in the impervious surface of 9, 48, and 82 km^2 in 1999, 2000, and 2015, respectively. The same authors further noted that UHI was not apparent in 1999 but 2000 and 2015 with a temperature increase of 1.8 and 1.22℃, respectively. Another phenomenon that Ernest et al. (2017) could have investigated is the contribution of relief features (as in Figure 6.8) because the windward side of the mountain is usually cold and moist while the leeward side of the hills is warmer and drier (orographic effect- Birdwell, 2011). This information could have assisted in quantifying the contribution from natural climate variations and impervious surfaces, as claimed by the authors. However, an observation made by Ernest et al. (2017) is enough to hypothesize that temperature increase might have influenced the proliferation of algal blooms in the Catchment. The popular concept mentioned above regarding the variation of temperature both in the windward and leeward side of the mountains is also associated with seasonal wind shifts and the relief features that support the argument.

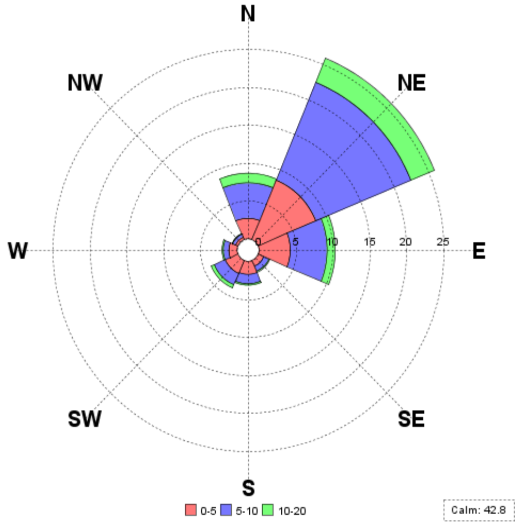
3.6 Wind patterns in the catchment

Figure 6.10 narrates the results from mean monthly wind roses charts with wind speed (km/hr) for the Morogoro synoptic weather station, Morogoro, The United Republic of Tanzania. The sketch demonstrates that for November to February, the winds have north-easterly dominance while backing to South Westerly to Southerly towards August (unlike other months which usually are 5-10 km/hr and sometimes 20 km/hr, wind speed for these months are ranging from 0-5 km/hr). The considerable variation observed for September and October ranging from southerly to north-easterly but with a dominance of easterly component (Note: wind speed is in km/hr).

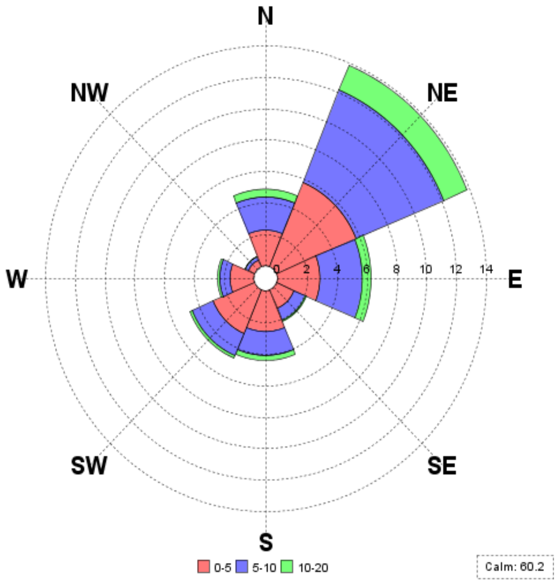
Morogoro January wind rose (%) 1988 - 2017



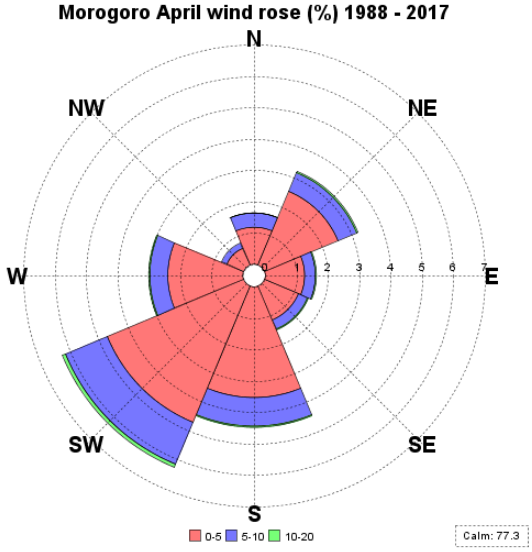
Morogoro February Windrose (%) 1988 - 2017



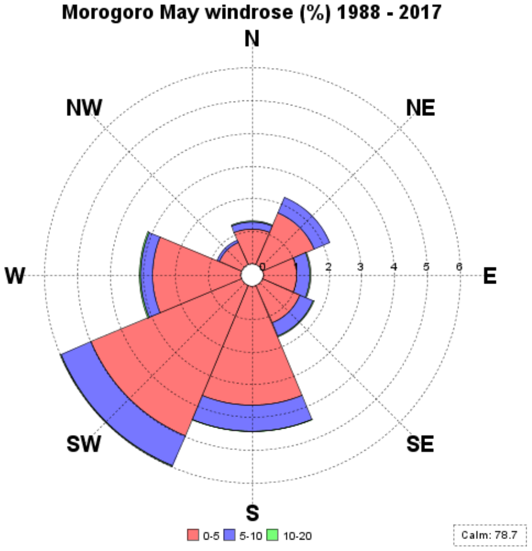
Morogoro March windrose (%) 1988 - 2017



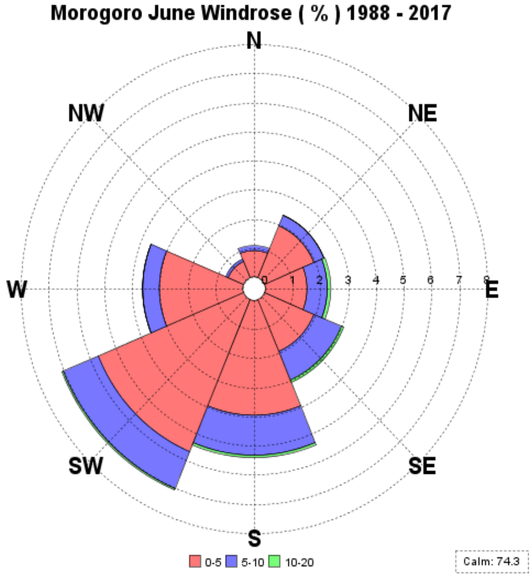
Morogoro April wind rose (%) 1988 - 2017



Morogoro May windrose (%) 1988 - 2017



Morogoro June Windrose (%) 1988 - 2017



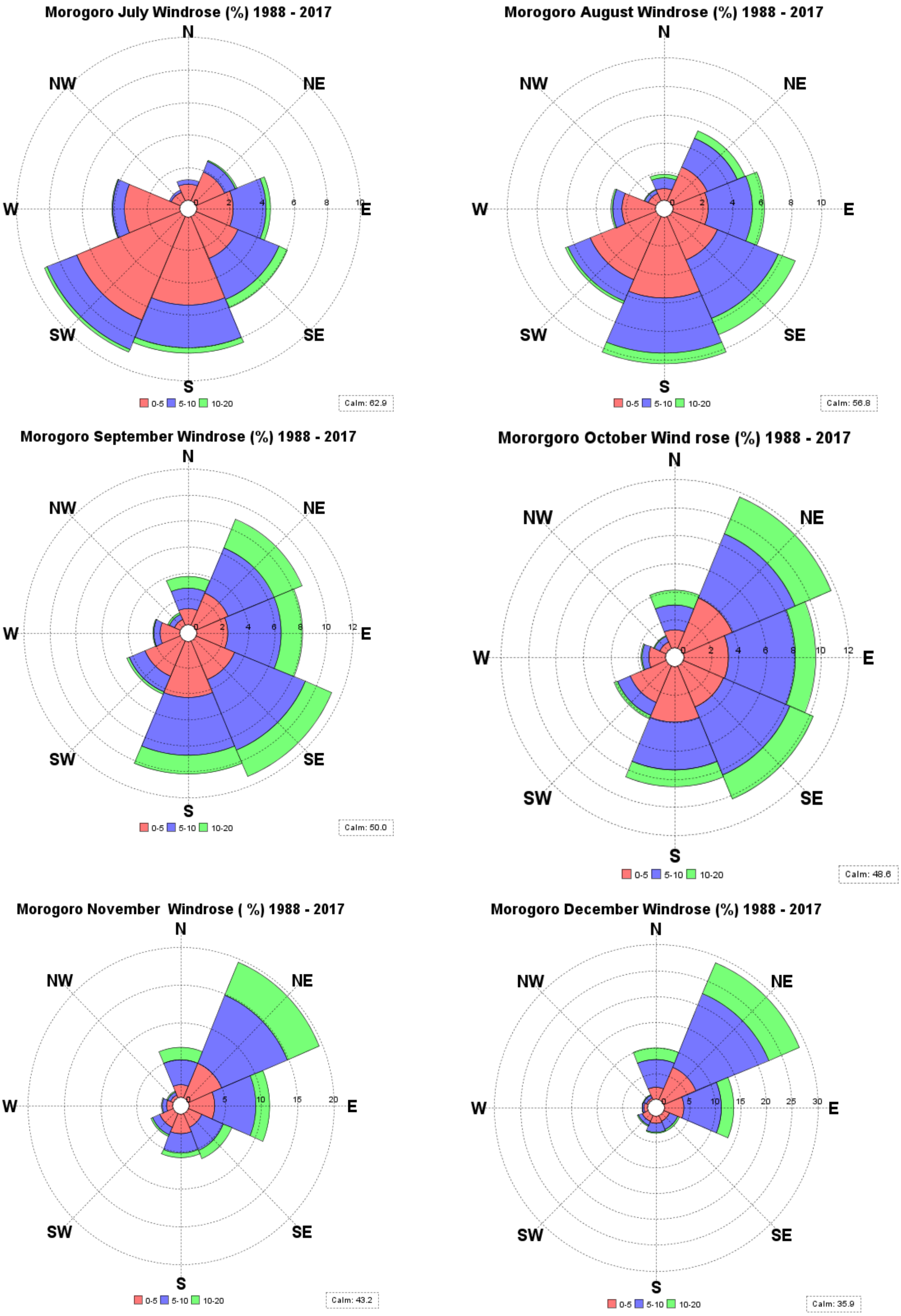
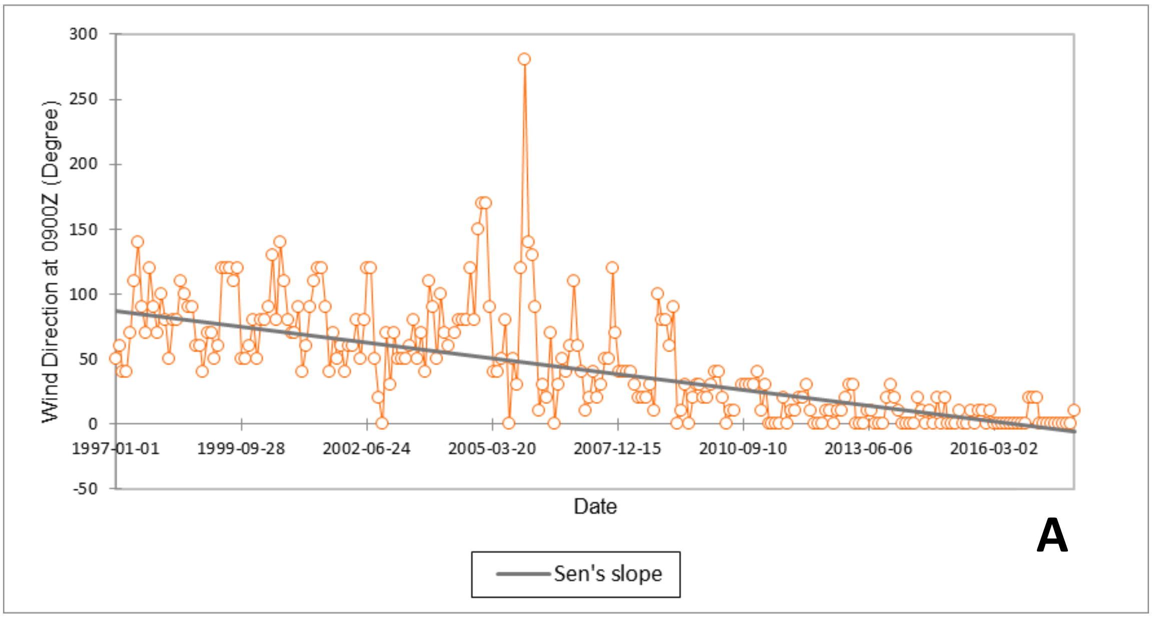
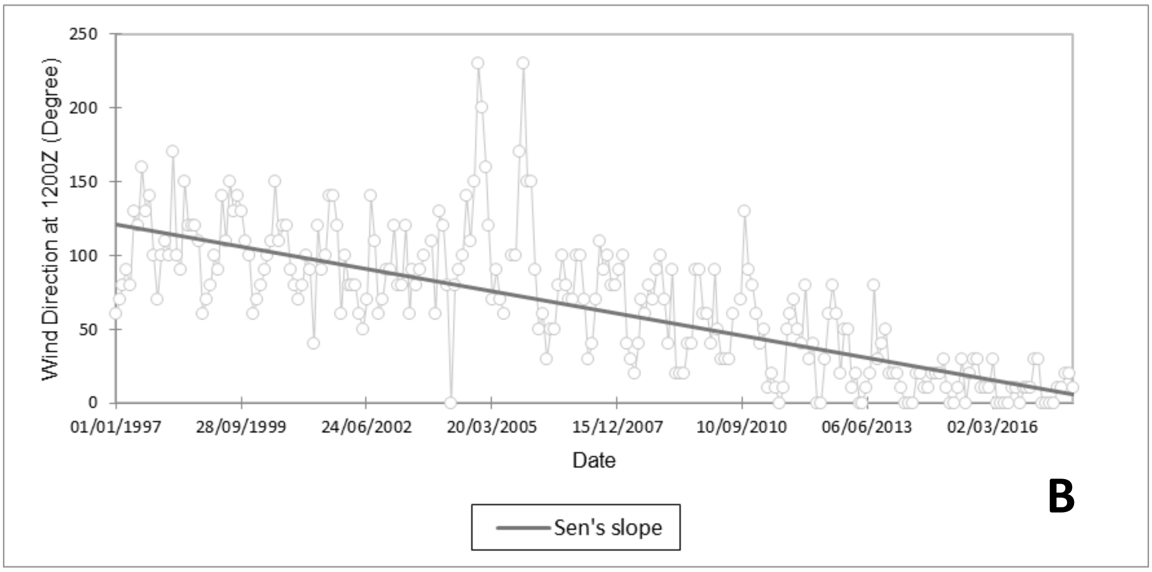


Figure 6.10 Mean monthly winds roses charts with wind speed (km/hr) at Morogoro synoptic

weather stations from 1988-2017.

Apart from mean wind analysis for different months in the study area, Mann-Kendall trend analysis for both wind direction at 0900Z and 1200Z (degrees) and wind speed (knots) still indicates a shift in both parameters and that wind direction are becoming more north-easterly component while speeds are tending to calm conditions. The Mann-Kendall trend test was significant ($p < 0.05$) for both wind speed and directions (Figures 6.11A, 6.11B, and 6.11C, respectively). The decreasing trend in wind speed was not surprising as this has been earlier reported (Cózar et al., 2012) over the East Africa Region as well as for the global scale (Karnauskas et al., 2017). The implication for the decreasing trend in both wind speed and directions directly implies a reduced vertical mixing of water. In combination with increasing temperature, it might escalate or intensify the proliferation of harmful algal blooms.





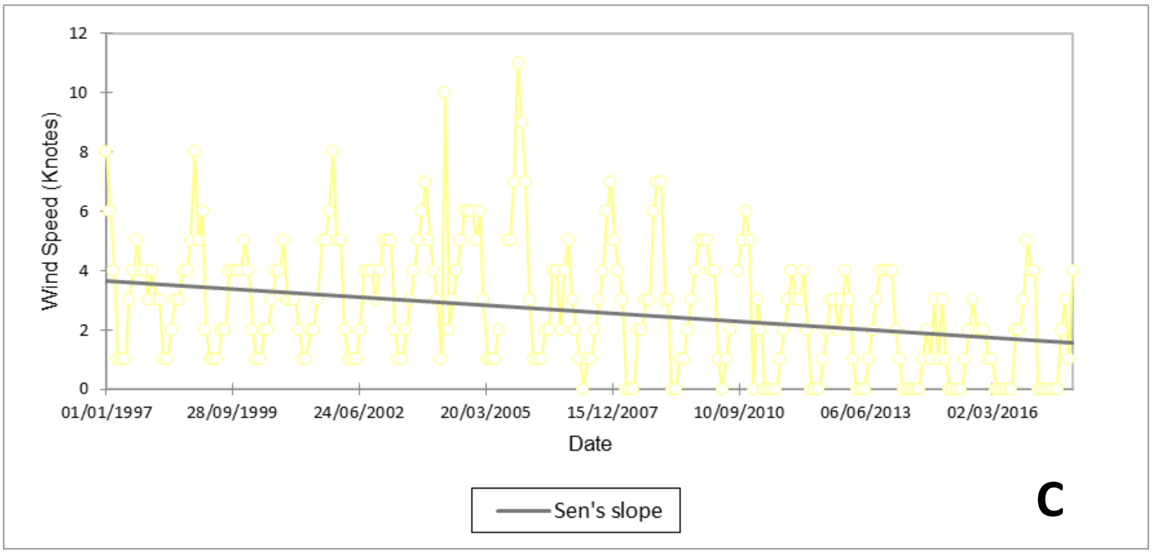


Figure 6.11 Mann-Kendall trend test for mean monthly wind direction (1997-2017) at both 0900 (A) and 1200Z (B) and Wind speed in knots (C) at Morogoro synoptic weather station.

3.7 Water level for Mindu Dam

Mindu waters levels (Figure 6.12) depicted a significant variation in the catchment from 1997-2017. The significant decreasing trend (Kendal tau = -0.163, p=0.05) in water levels observed at Mindu Dam insinuates to two factors, one is either increase in domestic water demand hence water abstraction or the increased evapotranspiration due to warming and or both. Previous studies have reported a decreased inflow in the catchment that is linked to both natural and human factors such as water abstraction cum demand and climate changes (Natkhin et al., 2015).

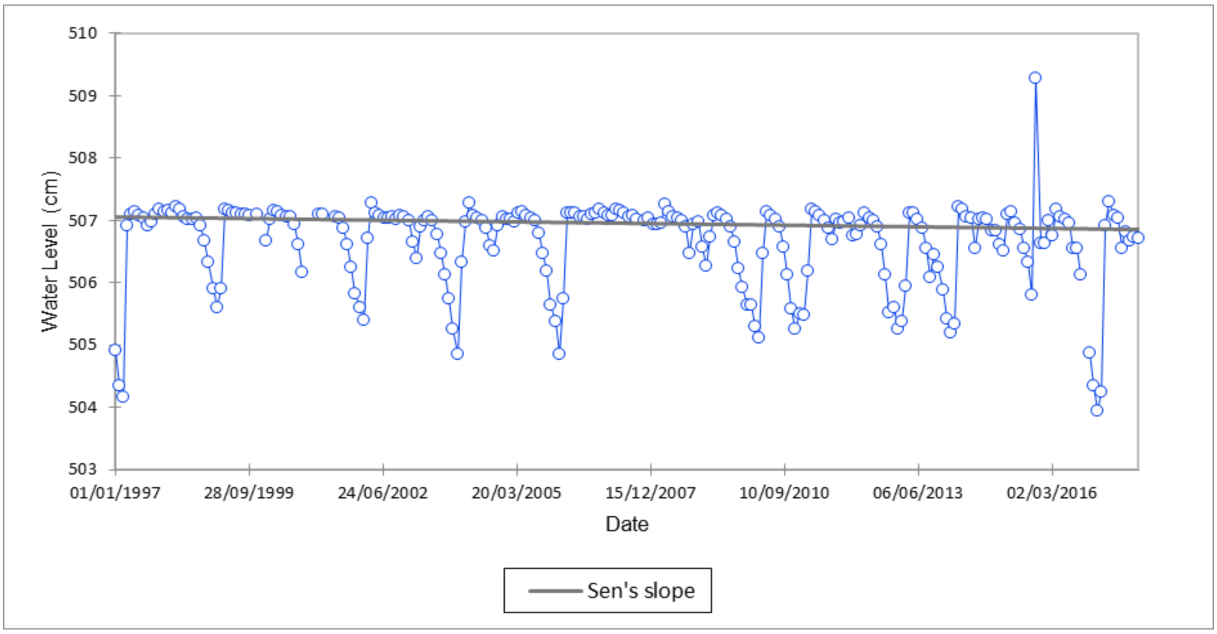


Figure 6.12 Trend of monthly water variation for Mindu Dam. The Mann-Kendall trend test indicates a decreasing trend (Kendal tau = -0.163, $p<0.05$).

3.8 Nino-3.4 Index

The variation of monthly rainfall and Nino-3.4 Index indicates a significant variability of both dry and wet fluctuations, i.e., positive anomalies for a high amount of monthly total precipitation and negative anomalies for a lower amount of monthly total rainfall (Figure 6.13). The Nino-3.4 index is used for monitoring and ranking the relative strength of the El Niño-Southern Oscillation (ENSO), i.e., the rolling 3-month average sea surface temperature in the east-central tropical Pacific (Dahlman, 2009). When an index is 0.5°C or higher, El Niño condition exists and when the index is -0.5°C or lower La Niña conditions exist (Dahlman, 2009). Eastern Africa is usually associated with wet weather conditions during El Nino and dry conditions during La Niña (Anyamba & Glennie, 2018). El Niño-Southern Oscillation, on the other hand, provides insight on drought in the East Africa region, which links to HABs proliferation.

It is the expectation that El Niño and La Niña alteration directly or indirectly influences blooms dynamics in the catchment through droughts/dry and wet/heavy rainfall conditions. In the search (visually) for the patterns, for example, cases for an extremely high concentration of blooms were noted corresponding to the highest peaks of green/blue ratio. Extracting the documented ENSO events and tracing their link with algal blooms events in the study area is the best approach for the understanding of HABs dynamics in the catchment.

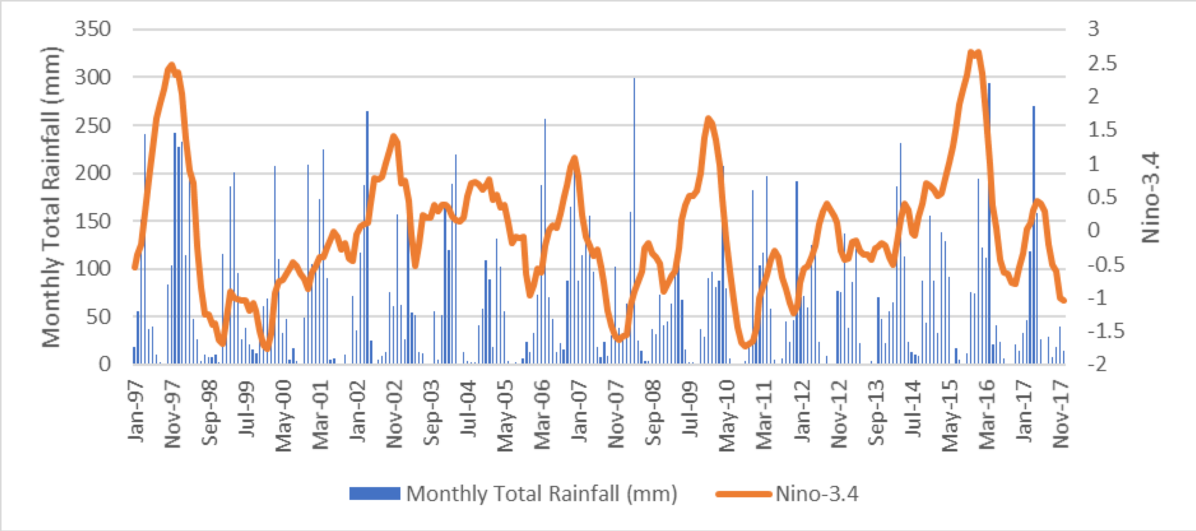


Figure 6.13 Nino-3.4 Index for the period of January 1997 to May 2017 overlaid with total monthly rainfall (mm).

By visual inspection, El Niño/La Niña phases seem to agree or match with total monthly rainfall variations in the catchment (Figure 6.13). The underlying assumption is that during the drought/dry condition, there are chances for the proliferation of blooms and that Chlorophyll-a values are high. Cases of extreme values (i.e., OC2 Chlorophyll-a for 4913.5184 and 1233.9116 mg/m^3) of Chlorophyll-a concentration (Landsat 8 surface reflectance) for Mindu Dam at that time Nino-3.4 (monthly) corresponded to a negative value which indicated dry conditions and positive value which meant a wet status (-0.3 and 2.12 Nino-3.4 indices respectively). Other cases (when the first two cases omitted) observed high pick for Landsat 8 OC2 Chlorophyll-a of 57 and 66.7 µg/L corresponding to January 11, 2014, and January 17, 2016, respectively. The corresponding Nino-3.4 index for the same period was -0.34 and 2.66, respectively. The expectation was that all the high values of OC2 Chlorophyll-a goes hand in hand with negative values (La Niña phase), but that was always.

As part of health risk assessment, associated impacts such as cholera symptoms can also be issues to consider. Similar scenario features in the previous studies on El Niño and cholera (though it is not an intention for the present study) where cholera cases were found in El Niño years (Moore et al., 2017). However, the findings of the present study corroborate with the research of de Souza et al. (2018), which investigated signs of climate change effects on cyanobacterial bloom in a subtropical coastal lagoon. The same authors found an association of blooming with negative anomalies in precipitation that occurs during La Niña periods. A similar approach that assessed the influence of El Niño-induced drought on the cyanobacteria community of Koka Reservoir in Ethiopia noted a shift in the cyanobacterial community (Tilahun & Kifle, 2019). According to these Authors, the drought condition caused nitrogen limitation, which might have triggered unusual dominance of cyanobacteria genus *Cylindrospermopsis* over the persistent dominant genus *Microcystis* in the reservoir. There is a need for monitoring of the dynamics of the algal bloom in the catchment. The study approach has demonstrated the complexities in the dynamics of cyanobacteria in Mindu Dam in Ngerengere Catchment.

Climate change has been noted to influence phytoplankton dynamics in many water bodies in East Africa. A study by Barker et al. (2000) for example, conducted in the south-eastern highlands (Lake Masoko, Songwe region) in Tanzania in one of the Crater Lakes claimed that many Lakes in East Africa have shown to be relatively stable (during the Holocene period) and some resilient to environmental changes except Crater Lakes. The study further noted that the Lake ecosystem was highly sensitive to both climate change and tephra (clastic volcanic materials) deposition. The significant findings, according to Barker et al. (2000), were the reductions in diatoms, an increase in conductivity, and the expansion of cyanobacteria. This evidence justifies the extrapolation of the hypothesis to other areas due to the experiences and predicted changes and or variations in the climate and hydrology in East Africa (World Wide Fund For Nature, 2006).

Generally, there is a consistent pattern for all the variables which agrees with the popular understanding of the mechanism for algal blooms proliferations. The influencing factors for the proliferation of harmful algal blooms include decreased trends in wind speed and shift in wind directions, the decline in the Dam's water levels as well as increased trends in temperatures and solar radiation in the catchment. There are also pieces of evidence of anthropogenic activities reported in the previous studies and watershed destruction, leading to water shortage for domestic use and environmental flow in the basin in recent decades (Yanda & Munishi, 2007). On the other hand, tropical disturbances (episodic climate and hydrological events) such as heavy rains (Kimambo et al., 2019) and the variation in the intertropical convergence zone (ITCZ) may also play a key role on blooms dynamics in the study area (Cózar et al., 2012).

4.0 Conclusion

The results presented in this study suggest a teleconnection between meteorological and hydrological parameters and the Chlorophyll-a in the catchment. In summary, the Mindu Dam water levels registered a significant decreasing trend in recent decades. A substantial shift in both wind speed and directions, i.e., wind direction, is becoming a more north-easterly component while speeds are tending to calm conditions. Minimum and maximum temperatures, solar radiations had rising trends, while rainfall was found to be neutral (based on 1988 to 2017 data). The implication is that the factors and their patterns are in line with the widespread discussion on HABs development. It is exhibited in the increasing trend of OC2 Chlorophyll-a in recent decades when using Landsat 7 surface reflectance, which significantly showed a rising trend. Moreover, there was a link between the Nino-3.4 indices and extreme cases of blooms when using Landsat 8 surface reflectance, although other cases were against the Nino-3.4 index. Generally, the results suggest that the approach (retrospective analysis of algae and its comparison with the climate and hydrological changes) used in the present study is informative. It can be utilized to inform policy and practices (e.g., education, planning, and monitoring) to all the responsible stakeholders. The study contributes to the application of recent advances in remote sensing and retrospectively analysis of bloom dynamics and search for their link with climate and hydrological changes. Since water levels registered a decreasing trend while rainfall was neutral future works should focus on accurately assessing the contribution of evapotranspiration as well as water abstraction for domestic uses. Furthermore, concentration on accurate monitoring of HABs (temporal and spatially) for developing an algorithm and or model for predicting the future proliferation of HABs is inevitable.

The study suffered several limitations. Lack of monitoring data (both *in situ* and remote sensing) for the dam was the main limitation. The study area lies in the deep tropics, characterized by frequent cloudiness, particularly during the rainy, i.e., March April May (MAM) season, which might have affected data capture and coverage. The challenges forced the use of the OC2 Chlorophyll-a algorithm for Landsat 7 surface reflectance to obtain a trend for blooms (band ratio) for comparison and search for a link with meteorological and hydrological patterns in the reservoir. Landsat 7 showed a few inferior values than that of Landsat 8 and *in situ* Chlorophyll-a. However, their long-term datasets could establish a significant trend. Another limitation that might have contributed to our conclusion is the approach of analyzing the trends individually and manual search for the link and or associations.

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Chapter 7

Summary, conclusions and recommendations for future works

7. Summary

CyanoHABs produce a wide range of secondary metabolites (cyanotoxins) and hypoxia conditions that alter the food web. CyanoHABs have registered impacts on food security, tourism, water resources, fishery, and human health. Their growth is not spatially homogenous, and that there is an information gap on their dynamics. Besides the fact that Tanzania is rich in water resources such as the ocean, lakes, rivers, dams, ponds, and shreds of evidence of environmental constraints, climate and hydrological variations (episodic events), on CyanoHABs, much is yet to be done. In Tanzania, for instance, the only recorded incidences are the mass fatalities of Lesser flamingo in Lake Manyara, Arusha. Since the aquaculture farms/fishponds are also hydrologically connected with the domestic water reservoirs in the Ngerengere catchment, there is a need for a thorough analysis. The study aimed to explore the impacts of climate variability and hydrological modification on cyanobacteria potentials in aquaculture systems in the Ngerengere catchment in Morogoro, Tanzania.

The hypothesis being tested is that climate variability and hydrological modification increase the threat of harmful cyanobacteria in aquaculture systems in the Ngerengere Catchment. The study was accomplished through the following specific objectives; (i) to survey the occurrence of cyanobacteria in freshwater ecosystems and their link with hydro-meteorological and environmental variations in Tanzania (ii) to identify and characterize common cyanobacteria species, their community structure, and environmental concerns in aquaculture systems in the Ngerengere catchment, Morogoro (iii) to examine the link between climate variability, hydrologic modification, and cyanobacteria potentials and (iv) to analyze the trend of chlorophyll-a and its correlation with climate and hydrological variations in Mindu Dam, Morogoro, Tanzania.

7.1. The methodology involved in the study

In this study, a review of the literature (i.e., historical reconstruction) on CyanoHABs occurrences in Tanzania and their link with climate and hydrological variation was conducted.

A stakeholders' perception and experience using multistage methods (i.e., questionnaire, focus group discussions, key informant interviews, and anecdotal observations) were also examined. Water samples were collected and analyzed to identify and characterize common species of CyanoHABs and in-situ measurements of physicochemical characteristics. Case studies were also diagnosed to examine how CyanoHABs link with other key environmental observations. The study also involved obtaining online data for chlorophyll-a to analyze their trends and their teleconnection with climate and hydrological variation in Mindu, Dam, situated in the Ngerengere catchment. Detailed methodological approaches are described in individual chapters.

7.2. Significant findings and conclusions

7.2.1. Occurrences of cyanobacteria in aquaculture systems in Tanzania

Herein, the main objective was to reconstruct knowledge from secondary sources on the occurrences of CyanoHABs in Tanzania and their link with meteorological and environmental variables (Chapter 2). The study found that no sufficient limnological data exists in Tanzania to perform time series analysis to capture the dynamics of harmful algal blooms. The field is also in the nascent stage. The scoping review further revealed that guidelines and standards on CyanoHABs are yet to be developed. In an area with data paucity, case studies (e.g., extreme weather events) that mimic climate change and variability could be more informative than one-time laboratory studies to assist decision making in the management of CyanoHABs.

Regarding the survey on stakeholders' perception of CyanoHABs in the Ngerengere catchment (Chapter 3), 95% of the respondents could recognize blooms as displayed to them, with 70% noting that algal blooms proliferate more during the dry season. Sixty per cent (60%) of the respondents attributed the source of pollution to other sources (e.g., overuse of agriculture) other than industrial discharge. Respondents were uncertain about any health effects associated with blooms. Although it could be linked to other factors, during the survey, farmers revealed that they sometimes feel itching during and after fishing, which may be linked to toxic effects from CyanoHABs. This suggests a need for further analysis of the associated health risks and a need to raise awareness on CyanoHABs.

7.2.2. Identification and characterization of common cyanobacteria species, community structure an environmental concerns in aquaculture systems in the Ngerengere catchment

The results provide evidence of occurrences of common species of CyanoHABs in the

Ngerengere catchment, such as *Microcystis*, *Cylindrospermopsis*, *Anabaena*, *Lyngbya* and other species such as *Diatoms* and *Euglena*, which might be a nuisance to the environment. The superior results are that colonies forming cyanobacteria dominated the ponds; on the other hand, filamentous species were the dominant species in Mindu Dam for all the sampling phases. Associated physical-chemical conditions support a simplified explanation of cyanobacteria blooms dynamics to environmental variables. At least one physical-chemical variables significantly correlated with the one another. Carlson's Trophic State Index (TSI) suggests that Mindu Dam (SP05) was more of eutrophic status while other sampling points were hypereutrophic. The findings link well with the observation made in Chapter 3 that fish farmers had experienced skin irritations during fishing, which is also supported by the morphological assessments in Chapter 4, which justifies a need for more studies.

7.2.3. The link between climate variability, hydrologic modification, nutrient flow, and cyanobacteria potentials

This objective is also partly addressed in the previous subsection (7.2.2), which demonstrates the link between Chlorophyll-a (a measure of algal blooms) and environmental drivers in the catchment. During the study period, two events or cases (heavy rain and unusual occurrence of red algae) which mimic the climate and hydrological variations in the Ngerengere catchment were observed and diagnosed. In the first event, a heavy rainfall (episodic hydrological event) caused a flash flood in the Ngerengere catchment had shown to influence the variation of blooms (the equivalent spherical diameters and area-based diameters) between sampling phase one and two (see the description in Chapter 4). The flood event caused the overflow of the Ngerengere River and some of its tributaries, affecting the fishponds since most of them are earthen ponds. The phenomenon was localized (enhanced by the orographic nature of the place) and steered by the presence of the Intertropical Convergence Zone and the tropical cyclone Berguitta. The event mimics the climate variability (extreme events) and is part of hydrological episodes that in the previous, has been observed to influence CyanoHABs proliferation.

The second event was an unusual occurrence of reddish colouration in fishponds at Kingolwira National Fish Farming Centre, Morogoro, during the field campaign (Chapter 5). The occurrence of red algae in the ponds is linked with the dry condition season. This study also mimics environmental changes as it is a unique observation in the study area. The results showed that fishponds (i.e., those with reddish colouration and those which were not) were significantly different from each other in terms of investigated environmental variables) except for water temperatures and that *Euglena* and *Microcystis* were the dominant species, respectively. Both the identified species can produce secondary metabolites (toxins) harmful to the fishery, aquatic ecology, and humans. Also, red algae in fishponds are the first to be reported in the fishponds in Tanzania to the best of our knowledge.

7.2.4. Analysis of the trend of chlorophyll-a and its correlation with climate and hydrological variations in Mindu Dam, Morogoro

Several tools and approaches are used in studying CyanoHABs dynamics. In an area like Ngerengere Catchment, where research is lagging, a retrospective analysis of Chlorophyll-a and their link with environmental conditions might address this research gap. A link between climate and hydrological variations and CyanoHABs can be established with the help of remote sensing and teleconnection techniques. The findings demonstrated that rainfall trends are neutral (global perspectives attribute this to increased extreme events), while minimum and maximum temperatures, solar radiation, chlorophyll-a concentration registered significant and increasing trends. On the other hand, wind speed and directions, water levels for the Mindu Dam showed a significant decreasing trend. The patterns suggest links and causality between the CyanoHABs variations and hydro-meteorological parameters such as temperature, solar radiation, and water level. The methodological approach demonstrates the applications of recent advances in remote sensing and retrospective analysis of bloom dynamics and searches for their link with climate and hydrological changes.

7.3. Contribution of the study to the body of knowledge

This interdisciplinary work relating climate variability and hydrological modifications to blooms of cyanobacteria is groundbreaking, not only in climate science applications but also in Africa. It significantly contributes to the understanding of CyanoHABs dynamics in the face of climate change and hydrological variation. The research on factors that promote their blooming or production of biotoxins and hypoxia has been ongoing globally. This work will be an asset to the search for solutions for problems caused by cyanobacteria in aquatic systems, which are hardly studied. Furthermore, the study is the first to report red tide in inland fish farms in Africa. The results will find application in several regions of Africa.

7.4. Recommendations for professional development and policy makers

It is hoped that the materials presented will find application in several regions of Africa, in particular, Tanzania, where the study was conducted to inform managers, policy reorientations and professional development. It is hoped that the study findings will be an asset to the progress in the search for solutions for problems caused by cyanobacteria in aquatic systems, which are hardly studied.

7.5. Limitations

Regarding the scoping survey, while the paper provides useful insight about HABs in Ngerengere catchment, in the United Republic of Tanzania, the implication may be specific to the study area. Since the sample size was small and specific to stakeholders around the Ngerengere Catchment, the results may reflect only the people of Urban Morogoro. On the morphological assessment, Lugol's solution (a preservative) can discolor cells which at times can alter the morphology of colonial and filamentous forms. The use of Lugol's solution in the present study could have distorted the cells, although previous studies have used the same with the positive results. In future studies of the same can be repeatedly and compared with a standard microscope but also comparing the stained versus destained samples.

On the trend analysis, the study suffered several limitations. Lack of monitoring data (both *in situ* and remote sensing) for the dam was the main limitation. The study area lies in the deep tropics, characterized by frequent cloudiness, particularly during the rainy, i.e., March April May (MAM) season, which might have affected data capture and coverage. The challenges forced the use of the Ocean Colour chlorophyll (OC2) Chlorophyll-a algorithm for Landsat 7 surface reflectance to obtain a trend for blooms (band ratio) for comparison and search for a link with meteorological and hydrological patterns in the reservoir. Landsat 7 showed a few inferior values than that of Landsat 8 and *in situ* Chlorophyll-a. However, their long-term datasets could establish a significant trend. Another limitation that might have contributed to our conclusion is the approach of analyzing the trends individually and manual search for the link and or associations. This could be questions for future studies on the methodological approach.

7.6. Recommendations for future works

The study recommends the following for futures works;

i. Future studies should focus on long-term monitoring of CyanoHABs and epidemiological studies to determine the effects of harmful algal blooms on higher trophic energy levels. The focus should also be on developing local to regional standards and guidelines on the management of CyanoHABs. The development of guidelines and standards on CyanoHABs should consider both the changing climate, hydrology and social-economic activities in the region.

ii. Future researchers should consider repeating the same study by increasing the sample size at a broader geographical scale. The survey findings serve as a basis for the development of the CyanoHABs management framework and health risk assessment.
iii. Future efforts should specifically focus on the cyanotoxins identification and quantification from individual species and the development of a framework for heightening mitigative and adaptive measures in the catchment, especially during pre- and post-occurrence.
iv. Studying the nature and impacts of flash floods in the region, installing automatic weather stations, and integrating them into the systems of national meteorological centres is inevitable.
v. Future studies should consider extensive analyses to confirm the nature of bloom's toxicity and dynamics, specifically the diurnal variations.
vi. Future studies should consider data reconstruction and long term in situ monitoring of chlorophyll-a to develop an algorithm that will cover a wide geographical area.

Supplementary information

Table S1 A questionnaire used for collecting information from respondents

<table>
<tr><td colspan="5">Physical Address:
University of Venda, University Road, Thohoyandou, Limpopo Province, 0950, South Africa</td></tr>
<tr><td colspan="3">Date:</td><td colspan="2">ID:</td></tr>
<tr><td>SNo.</td><td>Variable</td><td>Variable label</td><td>Variable codes and values</td><td>Skip-rules, information etc. (hints)</td></tr>
<tr><td colspan="5">Introduction</td></tr>
<tr><td>1</td><td>Introduction</td><td colspan="2">Hello!

My name is…………………………, a Ph.D. Scholar in the School of Environmental Sciences, University of Venda, South Africa. I am working for a Ph.D. project on “Impacts of climate variability and hydrological modifications on Cyanobacteria potentials in aquaculture systems in the Ngerengere Catchment in Morogoro, United Republic of Tanzania.”

Before the implementation of the project, it is important to collect baseline information as a basis for evaluating the impact of the project in the future.

You have been chosen to participate in this survey. I would like to assure you that the information you provide will be used for the intended purpose, and your identity will never be disclosed when such information is presented.</td><td>Must</td></tr>
<tr><td>2</td><td>Consent</td><td colspan="2">You should have received notification from Ward/Village leaders on our coming and the overview</td><td>Must

(The</td></tr>
</table>

		of questions that I would like to ask you today. Did you receive that? (Yes/No) Do you have any questions before we begin? (Yes/No)		respondent will be asked to sign in the consent form)
Personal details				
3	District	Districts	Morogoro (Urban) Mvomero Kilosa Morogoro (Rural) Ulanga Kilombero	(Select One)
	Ward	Ward name		Option
4	Gender		Male Female	
5	Marital status	Marital status	Single Married Divorced Separated Widowed	
6	Years stayed in the study site	How many years have you stayed in this place?	<5 05 to 10 11 to 20 21 to 30 31 to 40 41 to 50 50+	Numeric< 100

7	Education level	What is your education level?	No formal education Standard seven Form Four Form Six Diploma First Degree Masters PhD	
8	Occupation	What is your main occupation?	Retired Fish Farmer Livestock keeper Businessperson Employee Daily laborer Others specify…..	
Knowledge test				
9	Water Source	What is the source of water you are using?	River Wells surface/undergroun d) Dam Tap water Reservoir Rainwater harvesting	
10	Water uses	Used for what? (What are the ultimate purposes?)	Cooking Washings	

			Bathing Irrigation Recreational/Gardening Livestock Fish farm	
11*	Informed about water problems	How well are you informed about the problem facing water sources in the region	Very well Well I don't know	
12	How serious it is	How serious about water-related problems in the region?	A serious problem Not a serious problem don't know	
13*	Water quality over time	How are the changes in water quality for the time you have been in the region?	has improved stayed the same has deteriorated don't know	
14	Reason for poor quality	What do you think the major reason?	nutrients load overuse of water for agriculture industrial effluents municipal effluents don’t now	
15	Major threat	What do you think are the major threats?	climate change pollutions water shortage algae growth	(elaboration of the major drivers)

			don't know	
16	Recognition	Have you ever seen this before in the dam/pond? (Printed image for the blooms, scum, and mat of algae should be displayed here for recognition)	Yes No	
17*	Occurrence (year time frame)	How regularly do you see blooms?	Once in a week Once in a month Once in every 3 months Once in a season Throughout a year	If (Yes in the above question)
17*	Idea on Toxicity	Any idea (are you aware) about toxic/harmful algal bloom in the ponds	Yes No	
18*	An idea of health effect	Any idea (are you aware) about health effects associated with algal blooms	Yes No	
19		Sometimes there are noticeable discharge from industries to the running water/river/dam	Strongly Disagree Disagree Agree Strongly Agree	Select one
20		Some time we document a history of discharge from industries/wastewater/sewerage	Strongly Disagree Disagree Agree Strongly Agree	Select one
21		Sometimes I see crystal clear water	Strongly Disagree Disagree Agree	Select one

			Strongly Agree	
22		Sometimes I see quite a crystal clear, yellowish or brownish apparent	Strongly Disagree Disagree Agree Strongly Agree	Select one
23		Sometimes I see high algal levels with limited clarity	Strongly Disagree Disagree Agree Strongly Agree	Select one
24		Sometimes I see severity high algae levels with one or more of the following, massive floating scum in the lake/pond or washed up on shore, strong foul odour or dead (fish) remains	Strongly Disagree Disagree Agree Strongly Agree	Select one
Algae control measures				
25*	Government support	What is the government support (if algae are the problem)	text	must
26*	Traditional treatment methods	What is the traditional method of treatment/control measures for algae in both drinking/recreational waters?		must
27	Conventional treatment methods	What are the conventional treatments/control measures applied for the reduction of algae in the dam/pond/reservoir?	None Filtering Settling Aeration Chemical treatment Other, specify text	must
28*	Comments	Any comment for the survey/content/project	text	must

29	For the Enumerator (text)	What are other observations that may be important for the survey?		Observation
30	Photo/image	Take a photo for any observations (e.g., pond, visible blooms)		Option
31	Geo_point	Please record GPS for the position		Must
32	Thanks	Thank for your participation in this survey		Must

**The questions were asked during the key informant interviews and group discussion.*

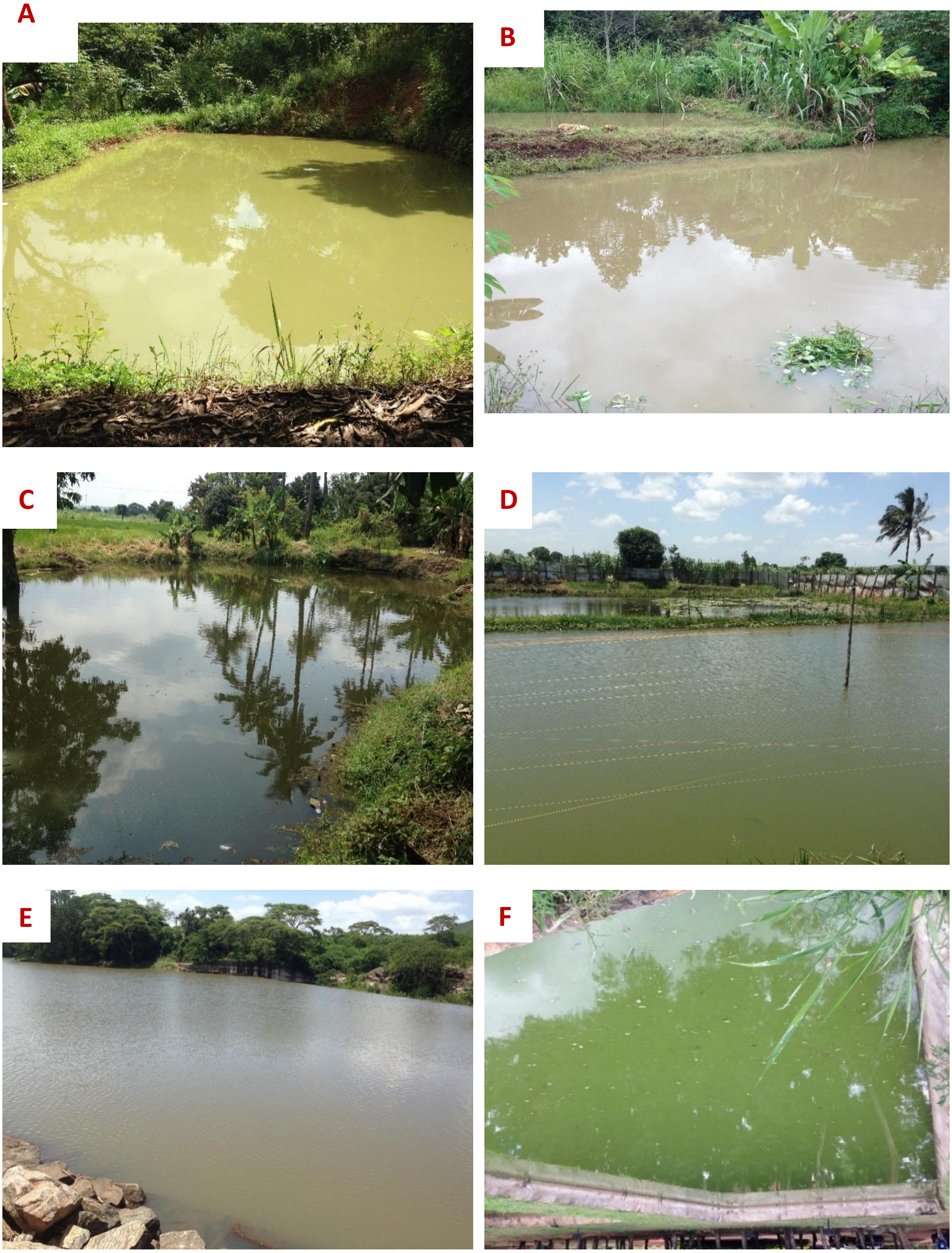

Figure S1 Plates for sampling points (A: SP01, B: SP02; C: SP03, D: SP04, E: SP05 and F: SP06) as captured by the authors.

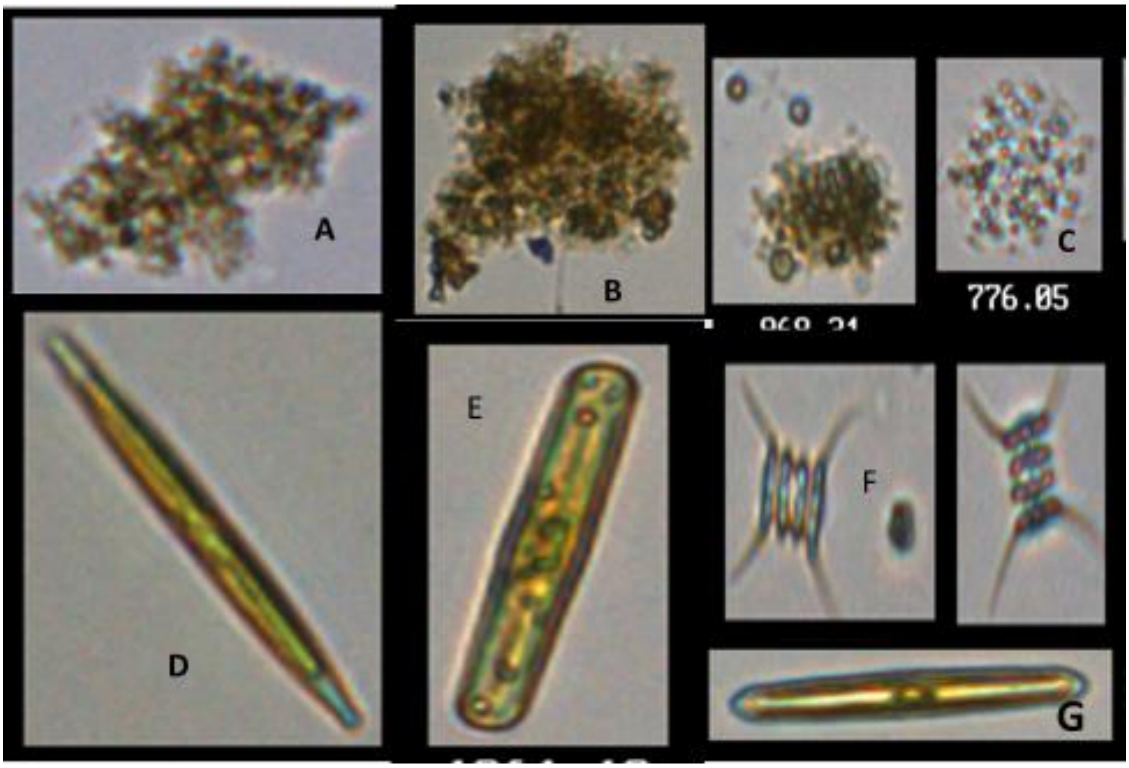

Figure S2 SP01 - *Microcystis* (A, B & C); *Lepocincilis acus* (single cell Euglena species) (D); *Oscillatoria* (E & G), *Scenedesmus* (F).

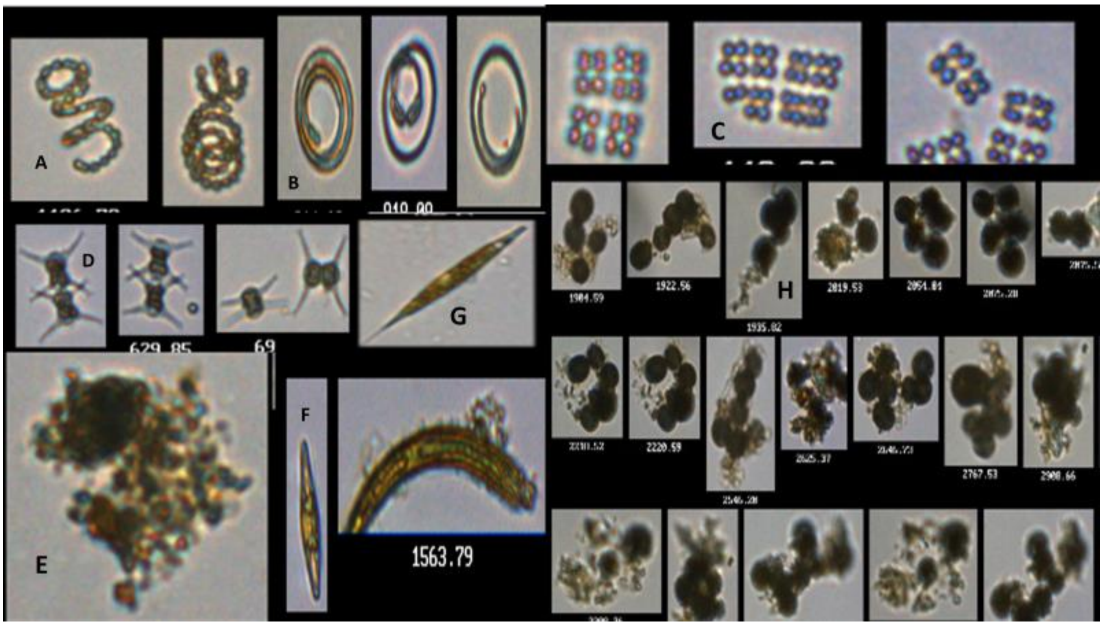

Figure S3 SP02-*Anabaena cicrinalis* (cylindrical with rounded ends) (A); *Cylindrospermopsis* (curved/coiled) (B); *Merismopedia* (C); *Scenedesmus opoliensis* (D); *Collonial M. aeruginosa* (E, H); *Lepocincilis acus* (G) (Order: *Euglenales*, genus: *Leponcinclis)* and *Microcystis* (F & G)

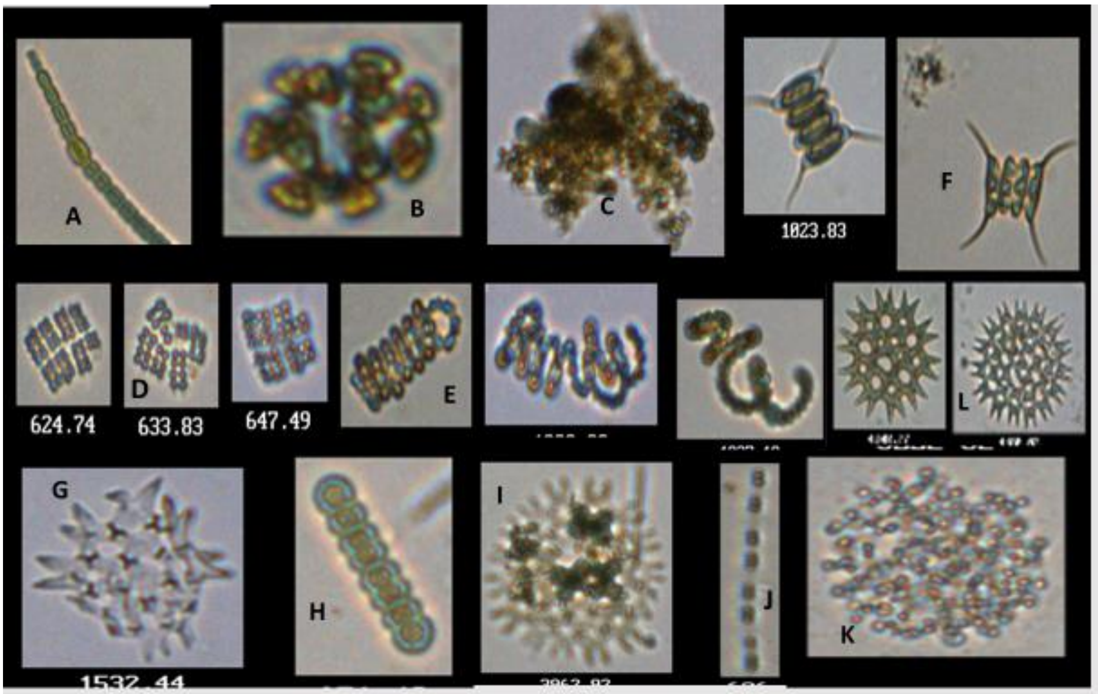

Figure S4 SP03-Filamentous *Anabaena bergii* (A); *Chroococcus* (B); *Microcystis* (C & K); *Merismopedia* (D), *Anabaena cicrinalis* (E), *Scenedesmus* (elongated cylindrical cells joined side by side and form rectangular plate-like colonies of 2, 4, 8, 16 cells); (F) *Anabaena* (H), *Pediastrum* species in different views (G, I, and L).

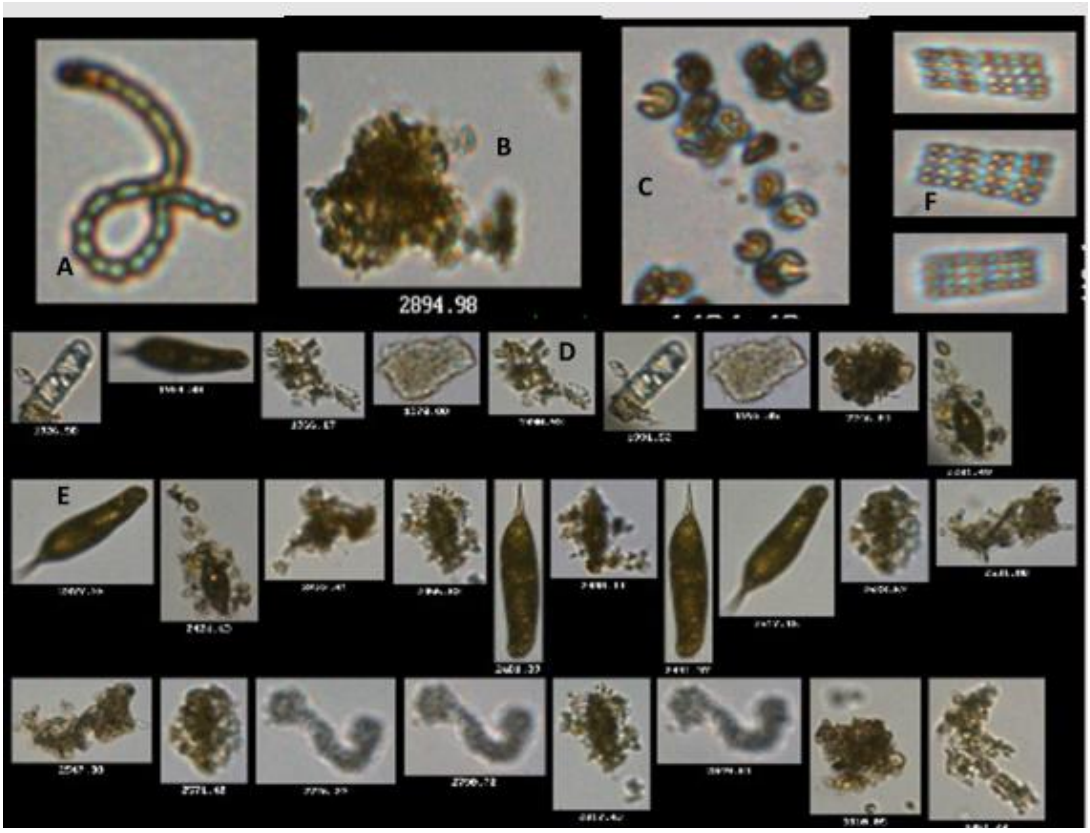

Figure S5 SP04-*Anabaena* (A); *Microcystis* (B, C & D); *Microcystis aeruginosa* (D, E and F); *Euglena* spp. (E), *Merismopedia* (F).

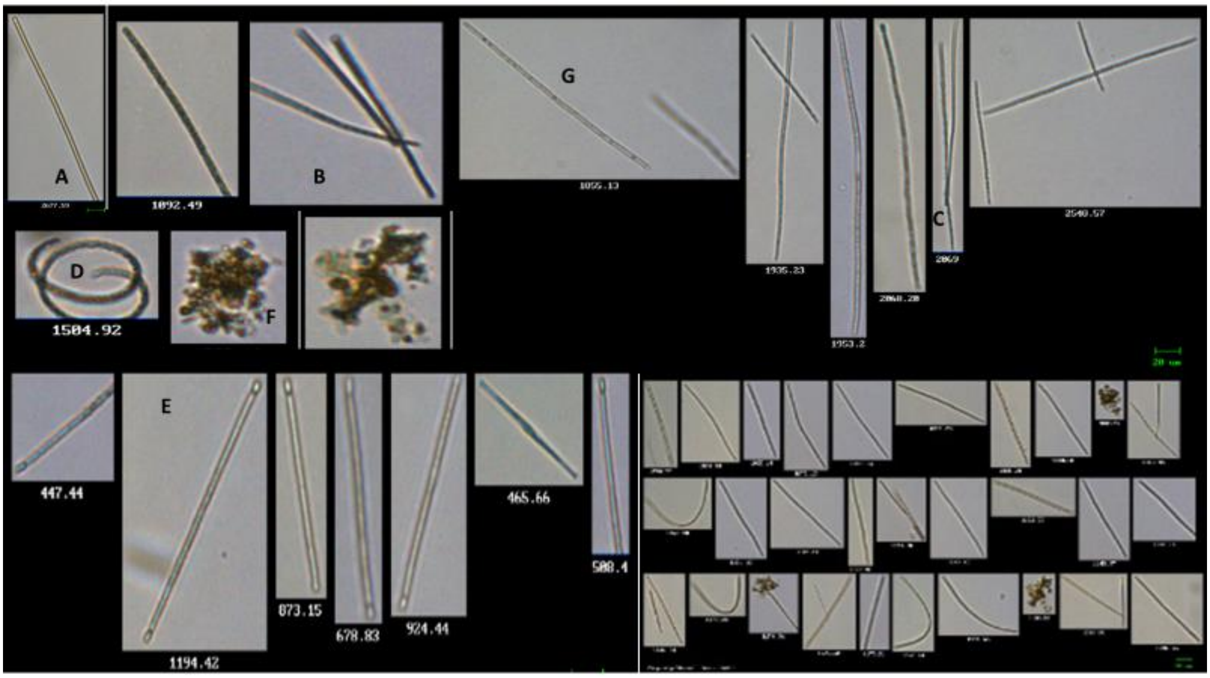

Figure S6 SP05-Filamentous species of *Oscillatoria (A)*; *Lingbya* species *(*false branched (B), *Microcystis aeruginosa* (F), *Cylindrospermopsis* (curved) (D) and *Cylindrospermopsis* (Straights) *(* E*); Nodularia (G)*

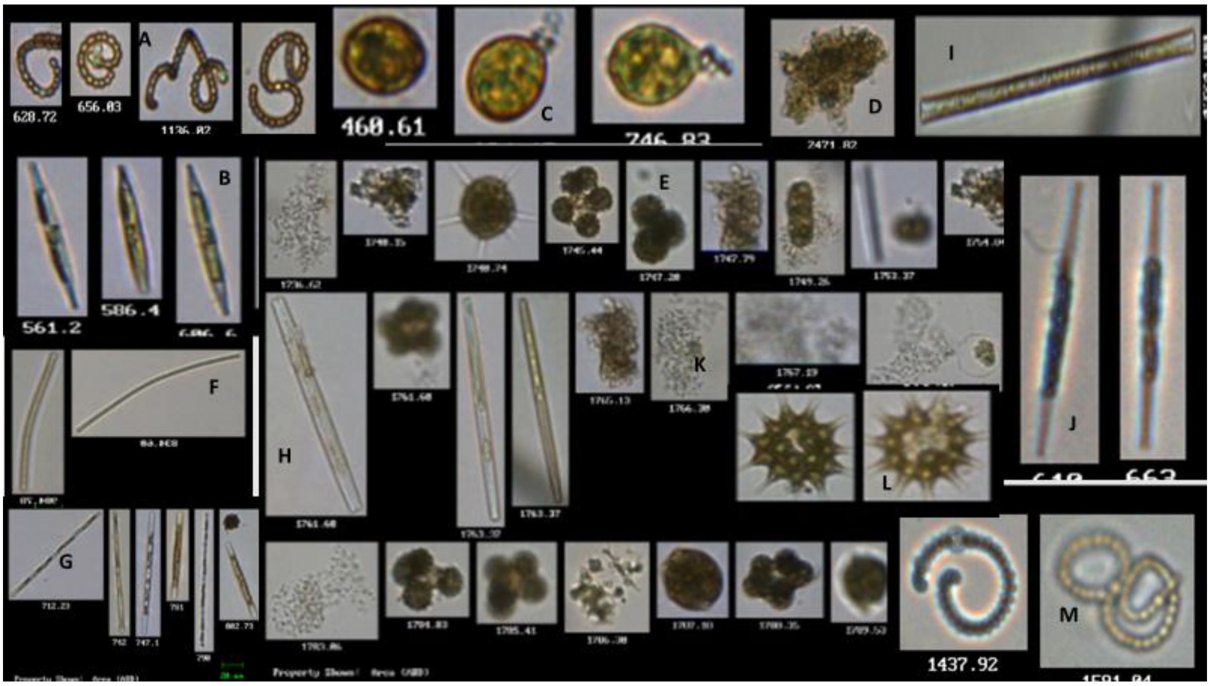

Figure S7 SP06-*Anabaena*[1] (A & M), *Leponcinclis* (B), *Nostoc* (C), *Microcystis aeruginosa* (D & K); *Microcystis warbegii* (E), *Aphanizomenon* (F), *Nodularia* (G); *Oscillatoria* (I), *Closterium Nitzsch* (H) (which are elongated and crescent, sickle-brown shaped with varying degree of curvature), and *Pediastrum* (L) (which are disc-shaped, oval to circular colonies, consisting of 4 to 64 cell).

[1] https://planktonnet.awi.de/

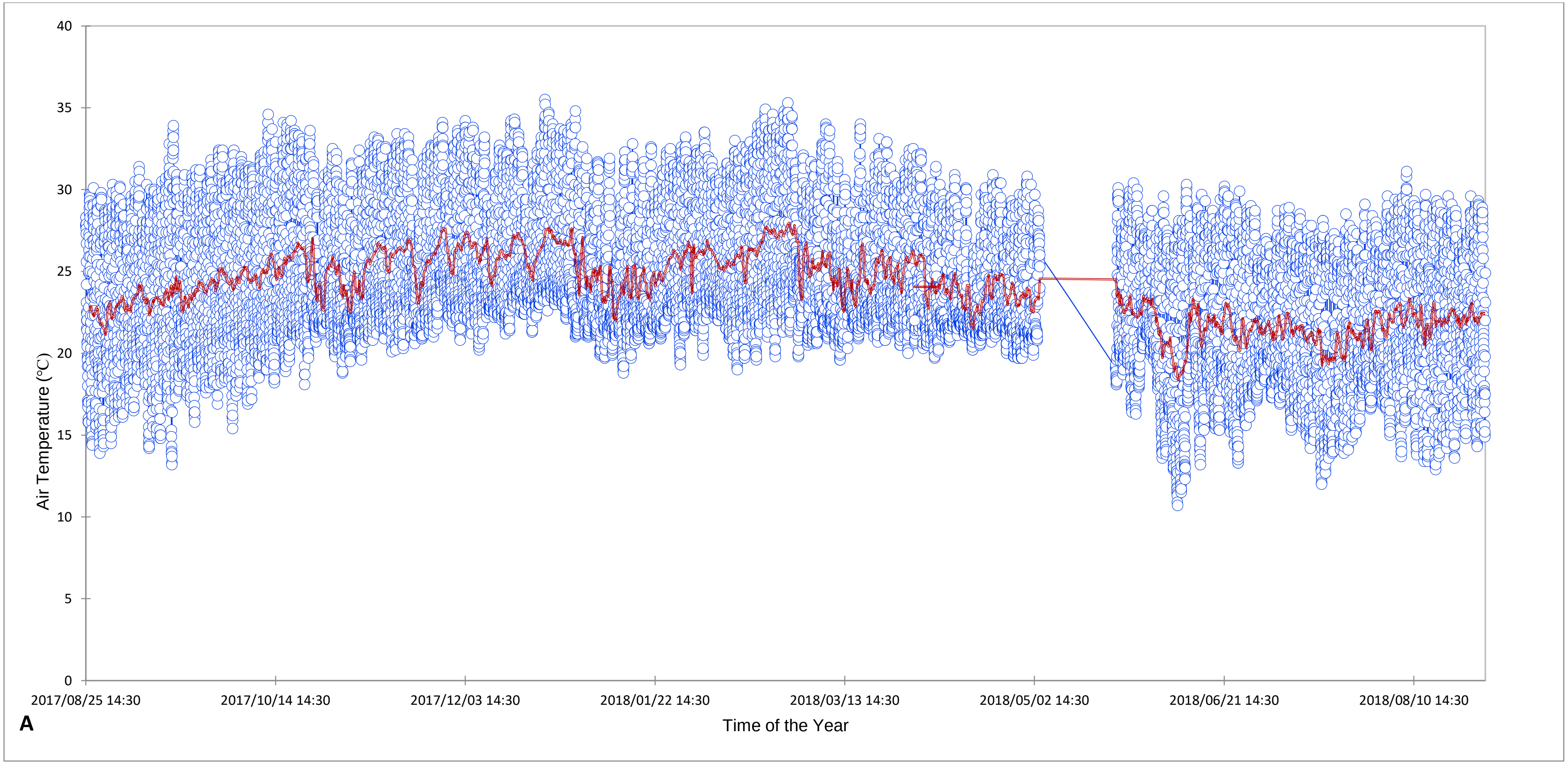

Figure S8 A Air temperature (°C) for a period of October 2017 to September 2018 from an automated weather station situated at Solomon Mahlangu College of Science and Education, Sokoine University of Agriculture Morogoro Tanzania.

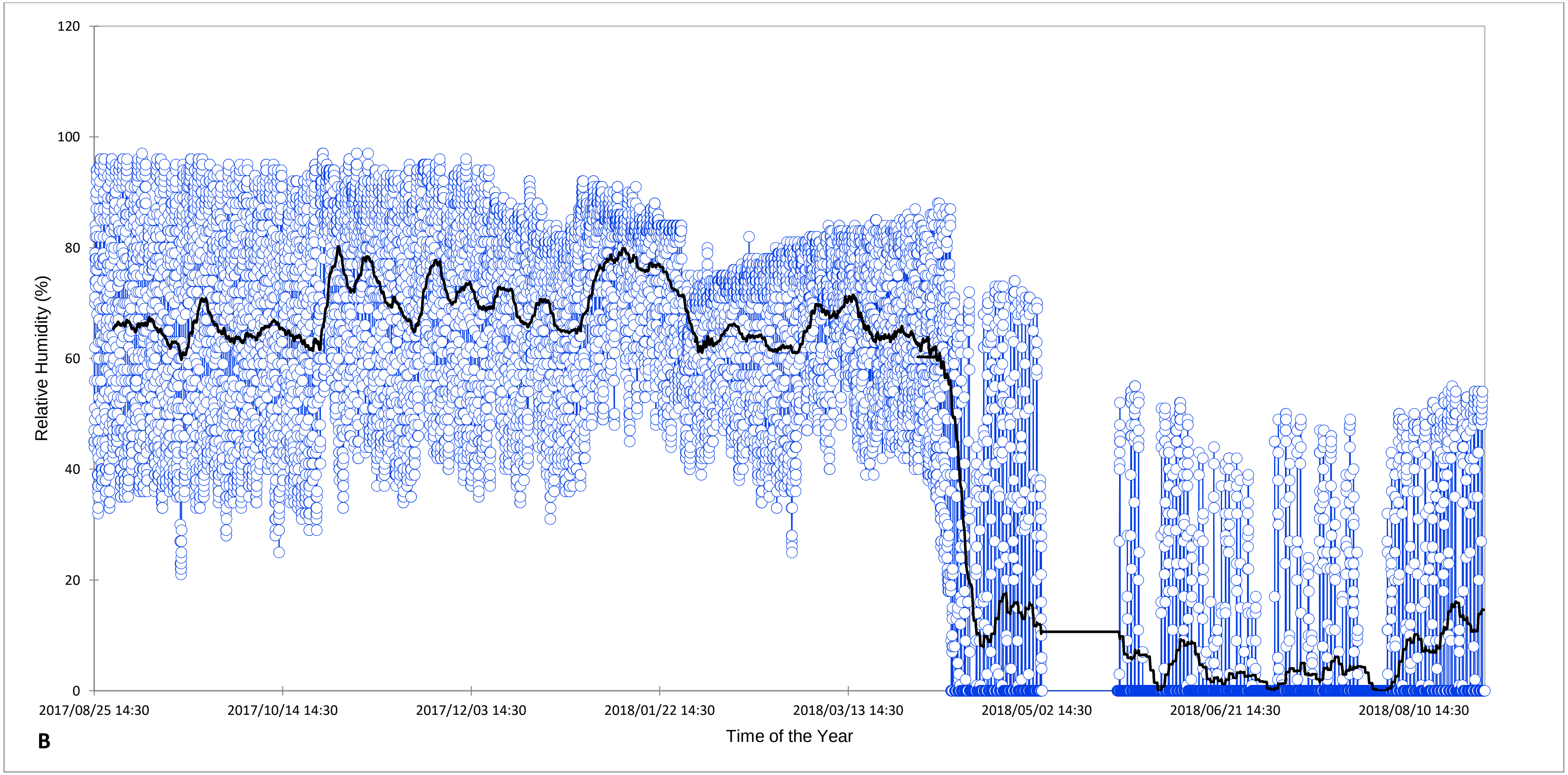

Figure S8 B Relative humidity (%) for a period of October 2017 to September 2018 from an automated weather station situated at Solomon Mahlangu College of Science and Education, Sokoine University of Agriculture Morogoro Tanzania.

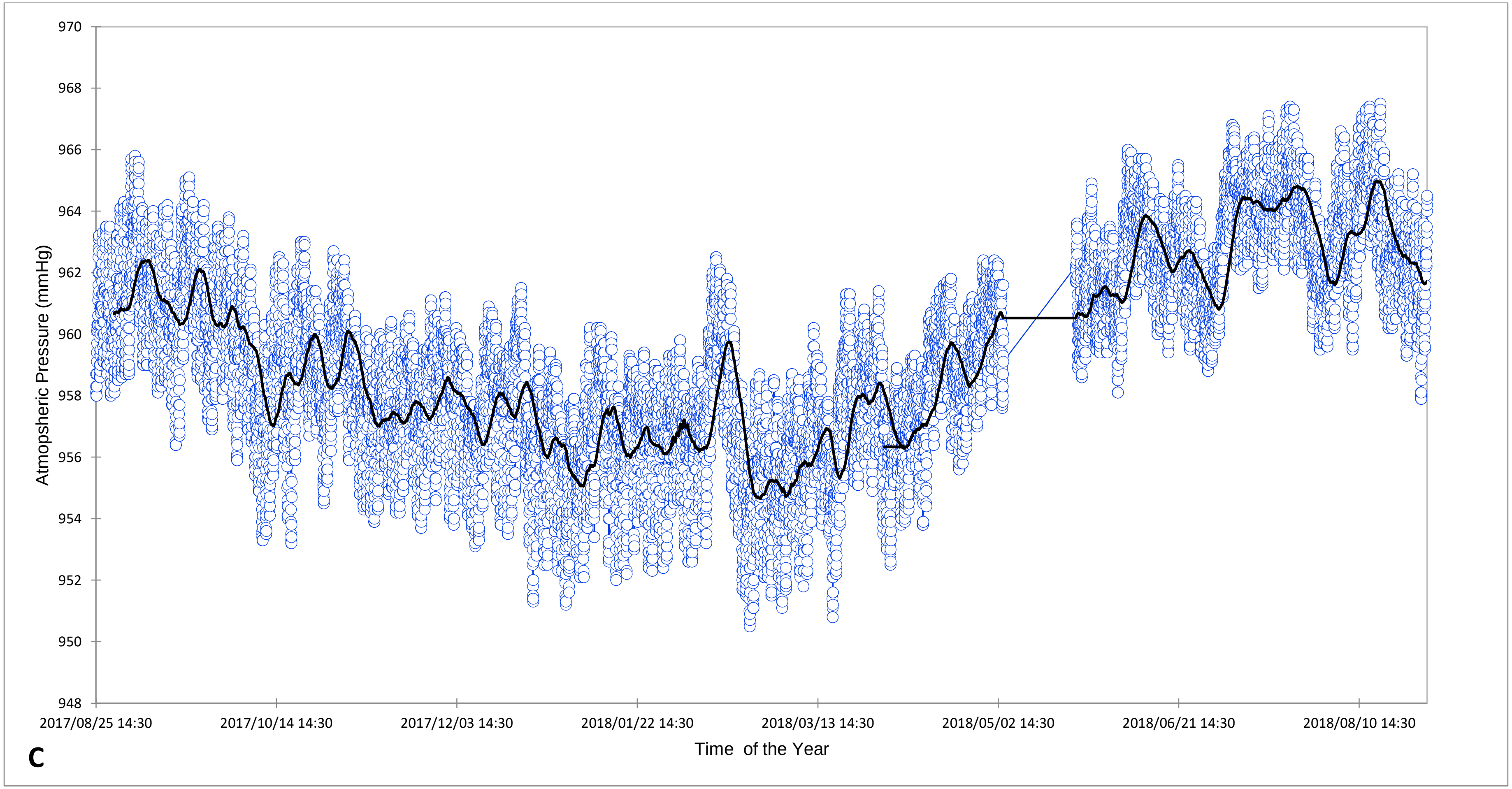

Figure S8 C Atmospheric pressure for a period of October 2017 to September 2018 from an automated weather station situated at Solomon Mahlangu College of Science and Education, Sokoine University of Agriculture Morogoro Tanzania.

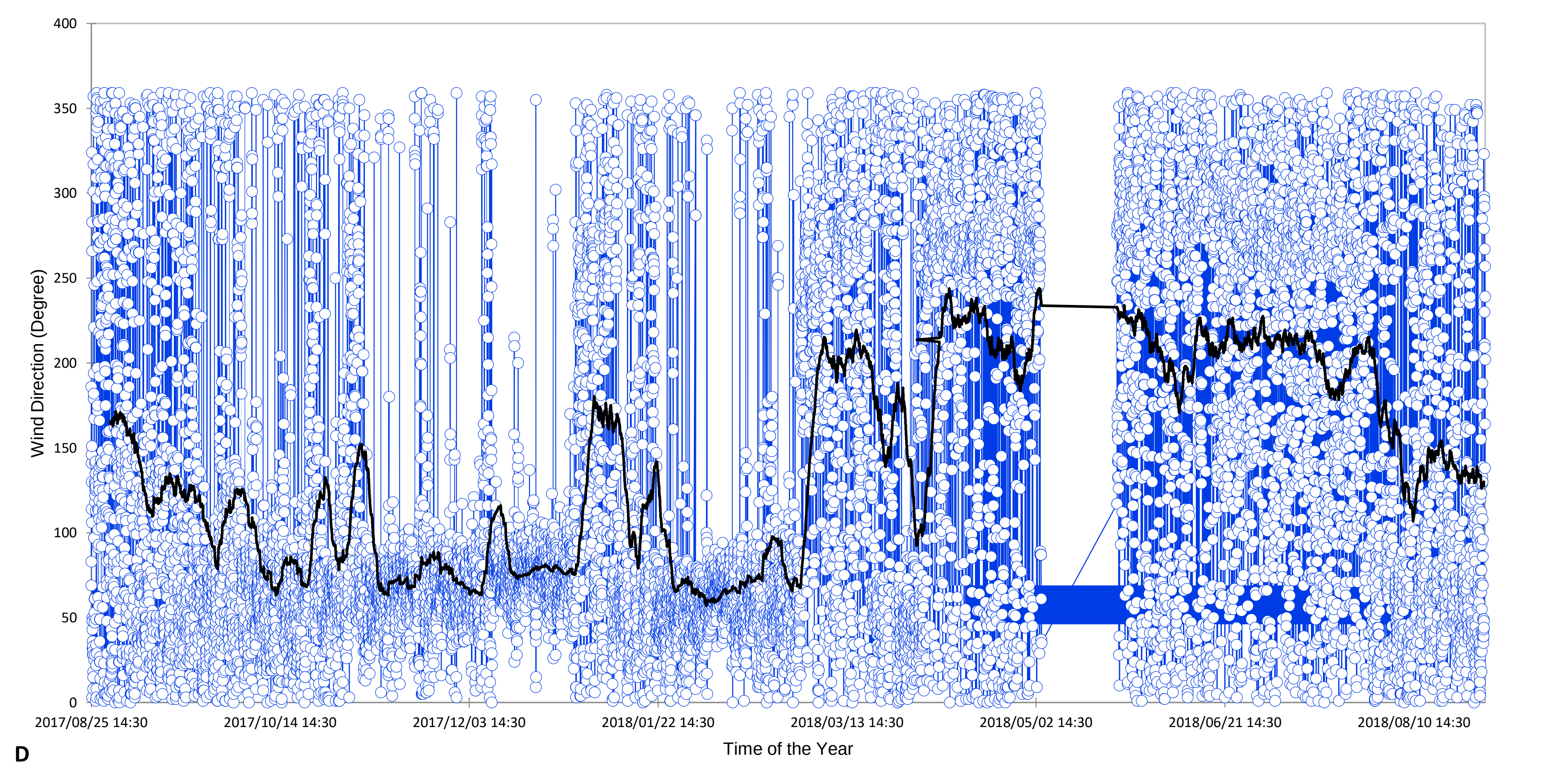

Figure S8 D Wind direction (in degrees) for a period of October 2017 to September 2018 from an automated weather station situated at Solomon Mahlangu College of Science and Education, Sokoine University of Agriculture Morogoro Tanzania.

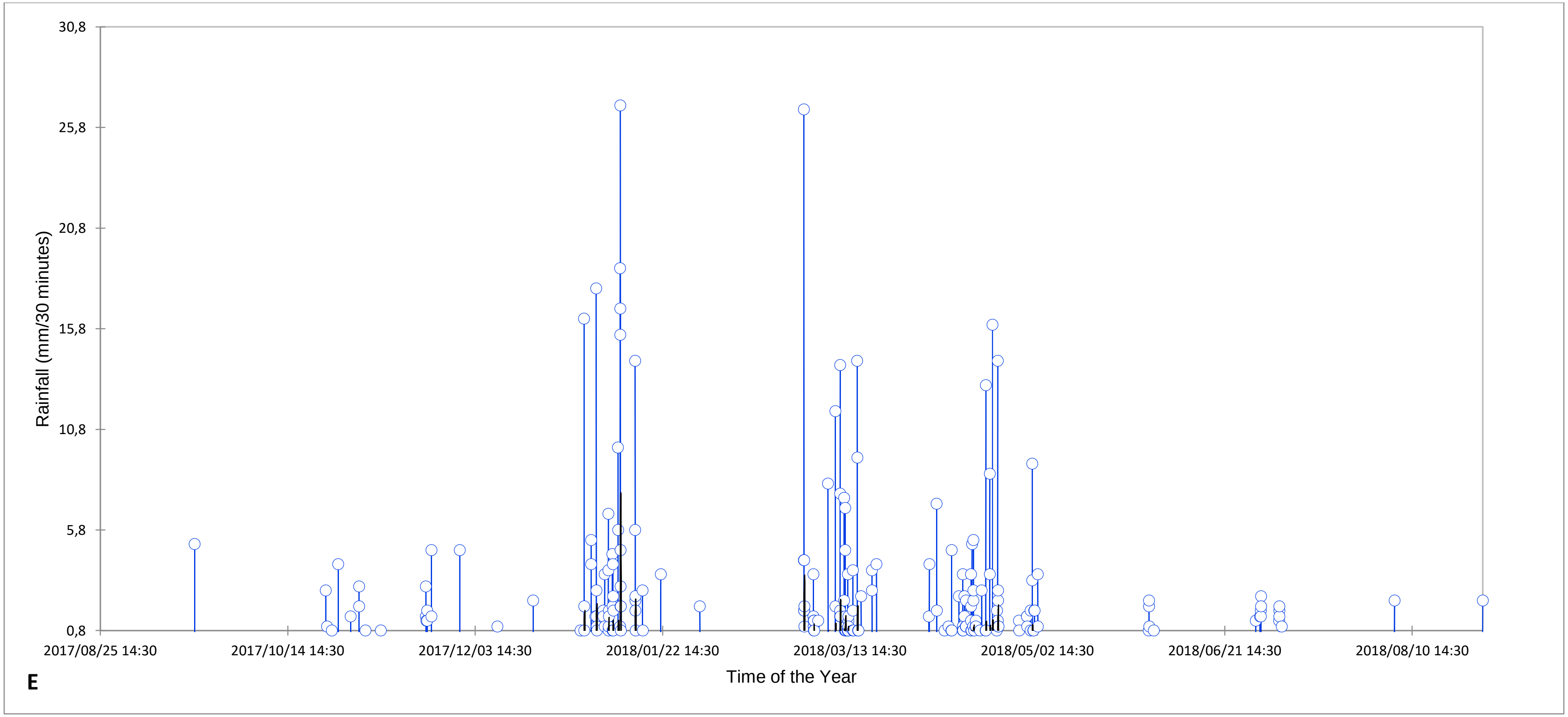

Figure S8 E Rainfall (mm) for a period of October 2017 to September 2018 from an automated weather station situated at Solomon Mahlangu College of Science and Education, Sokoine University of Agriculture Morogoro Tanzania.

Table S2 Carlson Trophic State Index for all the sampling ID and Schedules

Date	Sample_ID	Chlorophyll-a (µg/L)	Secchi Disk Depth (cm)	Secchi Disk Depth (m)	Total Phosphorus (mg/L)	Total Phosphorus (µg/L)	TSI (Chlorophyll-a)	TSI (Secchi Disk Depth)	TSI (Total Phosphorus)	Mean TSI
05 October 2017	SP01	74.3	38	0.38	1.8	1767	73	74	112	86
05 October 2017	SP02	58.9	5	0.05	0.6	633	71	102	97	90
05 October 2017	SP03	47.4	28	0.28	0.4	433	68	78	92	80
05 October 2017	SP04	21.9	58	0.58	0.3	333	61	68	88	72
05 October 2017	SP05	15.2	55	0.55	0.1	133	57	69	75	67
05 October 2017	SP06	22.7	19	0.19	0.3	267	61	84	85	77
02 February 2018	SP01	9.9	28	0.28	0.6	567	53	79	96	76
02 February 2018	SP02	103.9	32	0.32	0.3	267	76	76	85	79
02 February 2018	SP03	99.9	34	0.34	0.7	733	76	75	99	83
02 February 2018	SP04	11.5	76	0.76	0.4	433	55	64	92	70
02 February 2018	SP05	9.4	42	0.42	0.3	300	53	72	86	70
02 February 2018	SP06	14.5	50	0.50	0.2	167	57	70	78	68
29 May 2018	SP01	14.0	5	0.05	4.8	4767	56	104	126	96
29 May 2018	SP02	10.9	23	0.23	5.6	5633	54	81	129	88
29 May 2018	SP03	23.4	32	0.32	0.6	567	62	77	96	78
29 May 2018	SP04	35.0	51	0.51	0.4	400	65	70	91	75
29 May 2018	SP05	34.5	108	1.08	0.1	133	65	59	75	66
29 May 2018	SP06	37.2	35	0.35	0.4	367	66	75	89	77
06 September 2018	SP01	34.2	25	0.25	2.0	1967	65	80	114	86
06 September 2018	SP02	15.7	62	0.62	0.5	533	58	67	95	73
06 September 2018	SP03	28.3	18	0.18	0.5	500	63	85	94	81
06 September 2018	SP04	38.6	50	0.50	0.3	300	66	70	86	74
06 September 2018	SP05	12.0	50	0.50	0.6	633	55	70	97	74
06 September 2018	SP06	17.9	27	0.27	0.3	267	59	79	85	74

Trophic State Index (TSI)
(http://www.wwwalker.net/bathtub/help/Carlson_Trophic_State_Indices.htm)