Exploring Impact of Temperature and Precipitation on Cyanobacteria in Lake Naivasha

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August 2022

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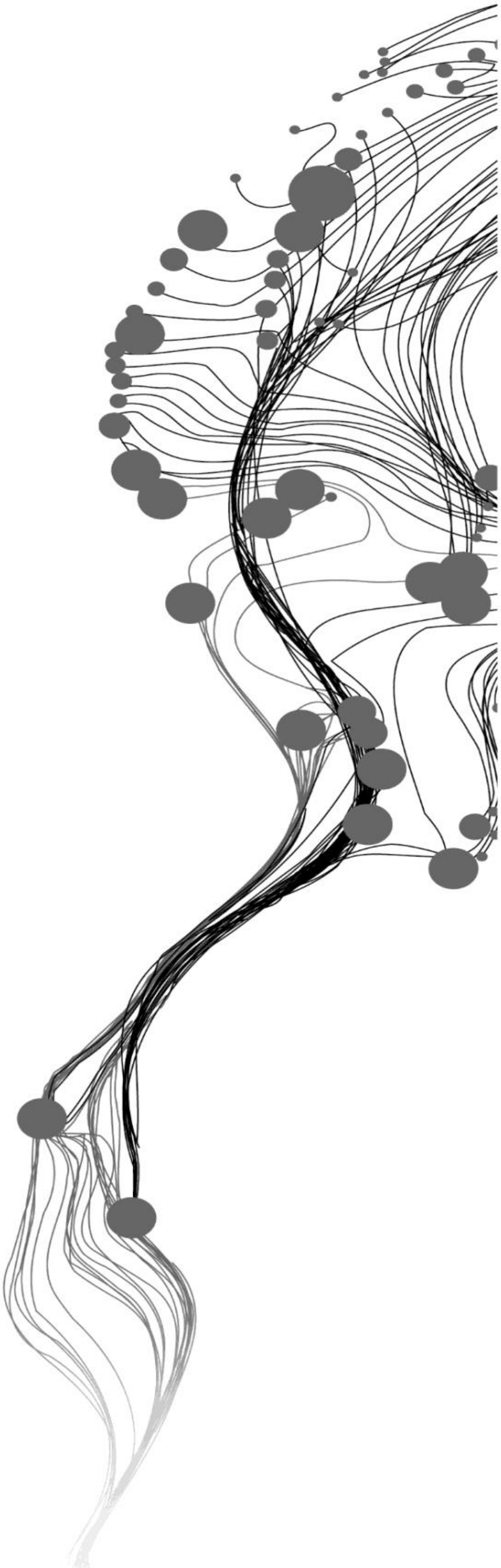

Exploring Impact of Temperature and Precipitation on Cyanobacteria in Lake Naivasha

SHRUTI PANDE
Enschede, The Netherlands, August 2022

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Water Resource and Environmental Management

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ABSTRACT

Fresh water lakes are an important for society. They a major source of drinking water in many regions. Farmers use lake water for irrigation. Many local communities are dependent on the lake for the fish stock for livelihood as well as for food. Lake water is used by industries for their functioning. In some regions the lake water contributes towards the electricity generation. Lakes enhance the natural beauty which leads development of tourism and water sports activities such as water skiing, adventure boating, fishing. In current scenario, due to increase in these activities the water quality of lake is deteriorating due to eutrophication or addition of nutrients in the lake water. The eutrophication in lake is causing uncontrolled growth of cyanobacteria leading to blooms. Certain species cyanobacteria produce toxins that harm the lake water ecosystems as well as the human welfare by contaminating the drinking water supplies. Therefore, it is important to monitor them. In addition to eutrophication, increase in lake surface water temperature and changes in precipitation pattern due climate change are enhancing the bloom intensity as well as the frequency of cyanobacterial blooms events. Cyanobacteria thrive in warm water temperature with high concentration of nutrients especially nitrogen and phosphorous. To understand the weather increase in lake surface water temperature or changes in precipitation patterns are the cause for cyanobacterial bloom in freshwater lakes, Lake Naivasha was selected as study area. To understand the relationship, first trends in surface water temperature and precipitation derived from satellite data were investigated. Next presence of photosynthetic pigment phycocyanin and chlorophyll-a present in cyanobacteria was detected by using remote sensing reflectance and analyzed. Later the growth window for cyanobacteria bloom was determined and bloom indices such as bloom intensity, bloom extend, and bloom severity were estimated during the growth windows. The study concluded that the lake surface water temperature is stable and not increasing. The lake surface water temperature does not have any effect on cyanobacterial growth, but it is at ideal temperature for certain species of cyanobacteria to thrive on. The Precipitation patterns have not changed drastically but it seems to have a stronger influence than lake surface water temperature on the bloom indices, but the results may be inconclusive probably due to over estimation of precipitation, shorter time series, issues retrieval of chlorophyll-a and phycocyanin by using lake water leaving reflectance. For future estimation of cyanobacterial bloom over lake Naivasha, satellite data providing longer time series is recommended. The algorithm used by this study to detect cyanobacteria could not determine its presence in some years therefore using a different algorithm might help in better understanding of blooms. Understand the nutrient inputs in lake Naivasha will further strengthen the results.

Key words- Fresh water lakes, Lake surface water temperature, Precipitation, Cyanobacterial blooms, Chlorophyll-a, Phycocyanin.

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1. INTRODUCTION

BACKGROUND AND JUSTIFICATION

A phytoplankton bloom or algal bloom is a phenomenon occurring in water bodies where the balance between phytoplankton production or primary production due to the availability of nutrients and sunlight (bottom-up) and consumption or grazing of these phytoplankton (top-down) is disrupted. The production rate is faster than the consumption rate, accumulating the excess phytoplankton in the water bodies.(Paerl et al., 2001; Sharma et al., 2011). The release of organic and inorganic waste into the waterbodies due to rapid industrialization is the root cause of phytoplankton bloom as the nutrient status, pH, turbidity, and temperature changes. The availability of excess nutrients i.e., eutrophication accelerates the primary production of phytoplankton and thus causing massive blooms(Sharma et al., 2011). These massive blooms grow out of control and not only damage the water ecosystem but also the living organism depending on it. Therefore, these phytoplankton blooms are also referred as harmful algal blooms(NOAA, 2017). The composition of phytoplankton species in a bloom is not constant all the time. The phytoplankton species such as diatoms dominate in winter, green algae are seen in winter, spring and summer and cyanobacteria are dominant in late Summer and fall.(Sharma et al., 2011).

Of all the harmful algal blooms, cyanobacteria are the most notorious phytoplankton species. Freshwater ecosystem such as lakes especially whose water is being used for societal benefits are under a great threat due to cyanobacterial bloom. It affects the aquatic habitats and contributes to anoxia and fish kills.(Carmichael and Boyer, 2016).Blooms of cyanobacteria forms a foul-smelling mucilaginous scum over the lakes which affects the recreational use of the lakes and makes lake water unfit as a drinking water resource(Chirico et al., 2020). Moreover, Cyanobacteria is one of the species which produce cytotoxins. The release of cytotoxins in the drinking water or in recreational water supplies can create serious effect on human health and environment. (Sanseverino et al., 2016). The cytotoxins produced by the cyanobacteria causes acute effects on digestive, endocrine, nervous, hepatopancreatic systems of mammals (including humans)(Paerl and Huisman, 2009; Paerl and Otten, 2013; Smucker et al., 2021).Due to the negative impact of cyanobacterial blooms on ecology, economy, and human heath, their monitoring has become imperative for the management of the lakes(Chirico et al., 2020).

Monitoring of Cyanobacterial bloom using remote sensing.

Although the monitoring of cyanobacteria in the lakes can be done by in-situ methods such as field sampling, laboratory analysis, microscopic visual identification and enumeration, these methods do not provide concentration of cyanobacteria over a larger area of lake. Moreover, these methods are highly laborious, time consuming and expensive. The accuracy of in-situ methodologies is questionable due to field sampling error and laboratory error. To overcome the problems arising due to these methods, remote sensing provides an opportunity to understand the spatiotemporal variations of different variables for entire lake because of its synoptic and frequent coverage. It also offers historical records for different variables taken under consideration to study its trends over time(Gholizadeh et al., 2016).

There are different remote sensing algorithms which use the photosynthetic pigment chlorophyll-a(Matthews et al., 2012) and phycocyanin(Ruiz-Verdú et al., 2008) in cyanobacteria as a surrogate to estimate cyanobacterial blooms and scums in lakes. These algorithms essentially depend on the spectral reflectance and absorption of a cyanobacterial bloom. The spectral characteristics of a typical cyanobacterial bloom are shown in the fig 1. **a** and **b** show low reflectance at 440 and 500nm due to absorption by chlorophyll-a and carotenoid respectively, **c** shows maximum reflectance is seen between 560 and 570 due to lack of absorption by algae thus giving green color to algae for human eyes, **d** is the strong absorption at 620nm by the phycocyanin pigment which is unique to cyanobacteria, **e** indicates weak reflection at 640nm due to backscattering from dissolved organic matter or florescence of accessory pigment, a dip at **f** is the strong absorption by chlorophyll-a at 675nm, strong reflectance peak at **g**, around 690-700nm is caused due to combined effect of pigment and water absorption, the weak peak at h around 810nm might be due to backscattering from algal cells combined with absorption of near infrared by clear water.(Li, 2020)

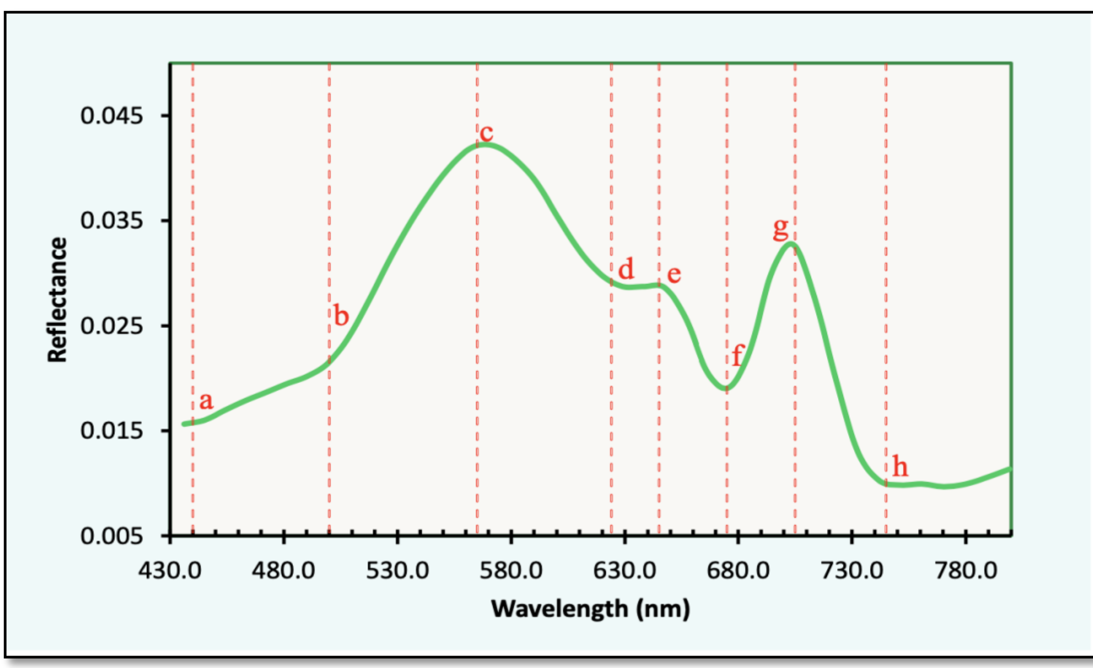

Figure 1 Remote Sensing reflectance of Cyanobacteria bloom in Inland Waters source-(Li, 2020)

Based on these spectral characteristics' various Spectral shape-based indices are developed to determine presence of cyanobacterial scums in lakes. For example, fluorescent line height (Gower et al., 1999), maximum chlorophyll index (author et al., 2005),cyanobacterial index (Stumpf et al., 2012), maximum peak height algae index (Matthews et al., 2012), floating algae index (Hu, 2009). (Alikas et al., 2010)used maximum chlorophyll index to investigate the seasonal dynamics, spatial distribution, and coverage of cyanobacterial bloom over Lake Peipsi (Estonia/Russia) and Lake Võrtsjärv (Estonia). Spectral shape index has been used for long term monitoring of cyanobacteria in Lake Erie USA (Wynne et al., 2013).
Before starting to monitor the harmful algal bloom, it is important to know what primary reasons for cyanobacteria are to grow and proliferate to blooms and scums.

Factors controlling the cyanobacteria bloom

As established earlier that increase in organic nutrients input in the water ecosystem is a main reason for occurrence of phytoplankton blooms. The main nutrients that contribute for the growth of cyanobacteria are nitrogen and phosphorus.(Chirico et al., 2020; Sharma et al., 2011) Cyanobacteria have certain distinctive adaptation which support their domination during the event of bloom. They can use the atmospheric di nitrogen as a source by fixing it therefore evading conditions where nitrogen is limited. In addition to this, cyanobacteria can take up and store excess phosphorus which they can utilize under phosphorus limiting conditions. This adaptation to changing nutrient conditions allow them to thrive in nutrient deficient as well as nutrient enriched condition(Paerl, 1988; Paerl et al., 2001)
If eutrophication triggers of cyanobacterial bloom, then climate change is the catalyst for the recent upsurge and amplification of these blooms. Global warming and changing precipitation patterns motivate the cyanobacteria blooms to grow. Lake ecosystems are susceptible to increase in temperature(Sharma et al., 2015).(Woolway et al., 2020) has listed warming lake surface water as a response to climate change. The water temperature is the influencing factor for the various chemical and physical properties of water ecosystems such as pH, salinity, solubility, and diffusion rates. It also influences the water eutrophication potential (Mooij et al., 2007; Su et al., 2012). Increasing temperature in water enhances the microbial activities in sediments releasing the internal phosphorous and increasing the nutrient load(Valdemarsen et al., 2015). Investigations show that cyanobacterial growth rate is optimal in warmer lake water temperature than other phytoplankton groups such as diatoms and algae. At raised water temperature, other phytoplankton groups cannot survive thus making less competitive environment for the Cyanobacteria to dominate over the lakes. (De Senerpont Domis et al., 2007; Elliott et al., 2006). The maximum lake surface temperature needed for cyanobacterial replication varies between 20 degrees to 41 degrees(Carey et al., 2012). Due to their adaption to grow at different water temperatures, various cyanobacteria species can dominate the lake water surface even when the nutrient concentration is low(Smucker et al., 2021).
The lakes are vulnerable to intense vertical stratification due increased lake surface water temperature. Vertical stratification is the formation of warm layer at the surface of the lake (epilimnion) over the cold deep layer of the lake(hypolimnion). The warm layer has lower density as compared to colder layer because increased temperature lowers the density. As the lake surface water temperature increase due to climate change, the stratification process begins

earlier in the spring and continue for into the autumn.(De Stasio Jr. et al., 1996; PEETERS et al., 2007). Vertical stratification benefits various Cyanobacterial species as they have gas vacuoles which give them buoyancy to maintain their position on the water surface(WALSBY et al., 1997). Due their ability to be buoyant over water, during their growth window, cyanobacteria accumulate and proliferate as surface scums(Paerl et al., 1985). The dense scums on the surface of the lake have high photosynthetic rate and often blocks the light from reaching the non-buoyant phytoplankton and macrophytes hindering their growth(Paerl and Otten, 2013). The cyanobacterial scums and the extension of vertical stratification contributes to longer duration of hypoxic conditions caused due to microbial decomposition of dying blooms and nighttime utilization by cyanobacteria which may lead to fish death(Paerl and Huisman, 2009; Paerl and Otten, 2013; Smucker et al., 2021)

Global warming has also altered the precipitation patterns. Variability in spatial and temporal precipitation distribution is evidence for changing of hydrological cycle patterns (IPCC, 2021; Reichwaldt and Ghadouani, 2012).The variability in the precipitation patterns exerts influence on the water quality by mobilizing or diluting the rate of nutrients and changing the physical conditions of the freshwater bodies(Codd, 2000). During and after the course of a precipitation event, the concentration of nutrients such as phosphorus, nitrogen increases significantly in a water body leading to eutrophication (T. Huang et al., 2014; Kebede and Belay, 1994; Zaw and Chiswell, 1999).The length of dry and wet period of the precipitation controls the availability of nutrients in the freshwater bodies. In course of longer dry periods, there is a surge in availability of nutrients as they concentrate as there is no water to dilute it(Kleinman et al., 2006; Reichwaldt et al., 2015).The extended dry periods and high temperatures slowly increases the turbidity or the amount of suspended solids in the lakes(Reichwaldt et al., 2015).In the event of high precipitation, there is reduction in the cyanobacterial biomass due to enhanced flushing and it may take few days for blooms to appear again. However high intensity precipitation combined with storm amplifies the nutrient load in the freshwater bodies(Budai and Clement, 2007; Kleinman et al., 2006). Extreme precipitation events initiate massive soil erosion leading to high nutrient input in freshwater bodies(Chorus, I, 2021; T.-L. Huang et al., 2014).The dilution of the concentrated nutrients due to addition precipitation is almost negligible as the incoming nutrients from the surface runoffs and subsurface flows over suppresses the dilution effect. Due to the sediment transport during high precipitation, the turbidity increases and there is decrease in penetration of radiation in the water column(Reichwaldt et al., 2015). The buoyant cyanobacteria are highly adapted to different light intensities and the higher turbidity levels favors their growth.

To understand the effects of lake surface water temperature and precipitation on occurrence of cyanobacterial bloom in lakes**,** lake Naivasha was chosen as a study area. After Lake Victoria, lake Naivasha is the only freshwater lake of the twenty-three major chain of lakes, almost all of which are highly alkaline(Harper and Mavuti, 2004; Ruhakana, 2017; Worthington and Worthington, 1933). In expedition to Eastern African lakes in 1930, (Beadle, 2008) noticed that lake Naivasha is full of floating lilies and submerged macrophytes which is an indicator of clear state of water. However, due to increased human activities in the lake’s catchment area, the water quality of lake water is deteriorating. The increase in human influence resulted in accumulation of sediments (Stoof-Leichsenring et al., 2011). This had led to increase in turbidity of lake water due to which there has been fluctuations in the occurrence of submerged macrophytes and the water lilies have disappeared(Britton et al., 2007).The human interventions such urban runoff, agricultural runoffs, reduction in water levels due water abstraction are responsible for the increasing nutrient concentration acceleration the process of eutrophication, making the lake susceptible to cyanobacterial blooms(Harper et al., 2011; Kitaka et al., 2002). (Harper et al., 2012) reported that the concentrations of chlorophyll-a have increased from 30 μg/l in 1982 to 142μg/l by 2011. The chlorophyll-a concentration prior to human induced changes, was observed to be below 50 μg/l but since 1980s the chlorophyll-a values have observed an increasing trend over lake Naivasha due to eutrophication. It is evident from historical community composition, even though there was the presence of cyanobacteria since 1970s, the cyanobacterial blooms appeared over lake Naivasha since 2005 (Raffoul, 2012)

1.1 RESEARCH PROBLEM

Studies indicate that cyanobacterial bloom is causing the deterioration of water quality of lake Naivasha, increasing temperature and changes in precipitation might be the reasons for it(Krienitz et al., 2013; Murakaru, 2010; Otiang’a-Owiti and Oswe, 2007; Raffoul et al., 2020). This study investigates relationships between occurrence of cyanobacterial blooms with lake surface water temperature and precipitation over Lake Naivasha from the year 2002-2011 using remote sensing techniques. The Lake surface water temperature is considered because we expect that it has influence on occurrence of cyanobacterial bloom. Precipitation is considered because it is the major driver for the surface runoffs. The detection of harmful cyanobacteria bloom of cyanobacteria will be done by analyzing the chlorophyll-a concentration and phycocyanin using remote sensing algorithms as these are photosynthetic pigments present cyanobacteria.

1.2 RESEARCH OBJECTIVES

General objective

The main objective of this study is to determine the relationship of harmful algal blooms/scums of cyanobacteria with lake surface temperature and precipitation for the years 2002-2011 using remote sensing techniques.

Specific objectives

1. Investigation of existence of trends in lake surface water temperature and precipitation patterns
- RQ1- Is there increase in lake surface water temperature and changes in precipitation patterns in the years from 2002 to 2011?
2. Detection of harmful algal blooms by estimating chlorophyll-a and Phycocyanin using remote sensing algorithm.
- RQ2- Are the harmful agal blooms present on Lake Naivasha in the years 2002 to 2011?
3. Analysis of harmful algal blooms of cyanobacteria growth period and determining effects of precipitation and lake surface water temperature during the growth period
- RQ3- What is the growth period of Cyanobacterial bloom and is Lake surface water temperature and precipitation affecting the growth of harmful algal blooms in lake Naivasha?

2. METHODOLOGY

2.1 STUDY AREA

Lake Naivasha is situated between 0°45'S, 36°20'E. It is approximately 1890 m.a.s.l., 100 km^2 to 150 km^2 in area, and in the main basin it 3 to 6 meters deep(Harper et al., 2011). It is a RAMSAR site (Ramsar Convention Secretariat, 2016) which is located 80 km northwest of Nairobi, Kenya. Lake Naivasha is the second largest freshwater resource after Lake Victoria in the semi-arid country-Kenya. (Harper et al., 2011; Krienitz et al., 2013). Malewa river is responsible for contributing to the majority of inflow, and seasonal rivers Gilgil and Karati contributing ten percent. The complete catchment area of lake is approximately 3376 km^2 (Ase et al., 1986; Otiang'a-Owiti and Oswe, 2007).The warmest months are February, March, and April with average day time temperature up to 26°C. The average rainfall is in between 80mm to 100mm in the months of April and May. The average daily sunshine depends in February is 7 hours and 4 hours in July and August(Hinds, 2015).

In last 70 years, due to increased human activities in the lake's catchment area, the water quality of is deteriorating. The escalation in human influence is resulting in increasing accumulation of sediments (Stoof-Leichsenring et al., 2011). The agricultural activities such as clearance of papyrus clearance for horticulture development(Boar et al., 1999),use of fertilizers and species introduction has changed the limnology and productivity of the lake(Harper, 1991).Water pollution of lake Naivasha, originating due changes in agricultural patterns is causing increased nutrient availability and the discharge of organic matter from the settlement area is the major threat to the lake especially when the natural filters i.e. papyrus trees are not present around the lake. The concentration of Nitrogen and Phosphorus is increasing at alarming rate in the freshwater lake due the increase in nutrient and organic matter availability. The pollutants are entering the lake water from point and non-point sources such as semi-treated municipal sewage, agricultural runoffs from the Naivasha town and horticulture farm in the catchment areas.(Kitaka et al., 2002).The major repercussion of these changes has intensified the eutrophication phenomenon. (Harper et al., 2011) have summarized different factors which has accelerated the process of eutrophication in lake Naivasha: the introduction of invasive species of plants and animals changing the food web dynamics because of it, reduction in volume of the water due to water abstraction and thus increasing the nutrient concentration. The increase in cyanobacteria is the response to the eutrophication occurring in the Lake Naivasha (Harper et al., 2011; Kitaka et al., 2002; Krienitz et al., 2013).In a study done by(Ballot et al., 2009), it was indicated that there has been decrease in the diatoms and increase in the cyanobacteria in lake Naivasha. The risk of production of cytotoxins has increased in the lake due to the formation of dense algal blooms of the colonial coccoid cyanobacteria. Cytotoxins possess a serious threat to the wildlife dependent on the lake as well as humans via consumption of contamited water and poisoned fish(Krienitz et al., 2013).

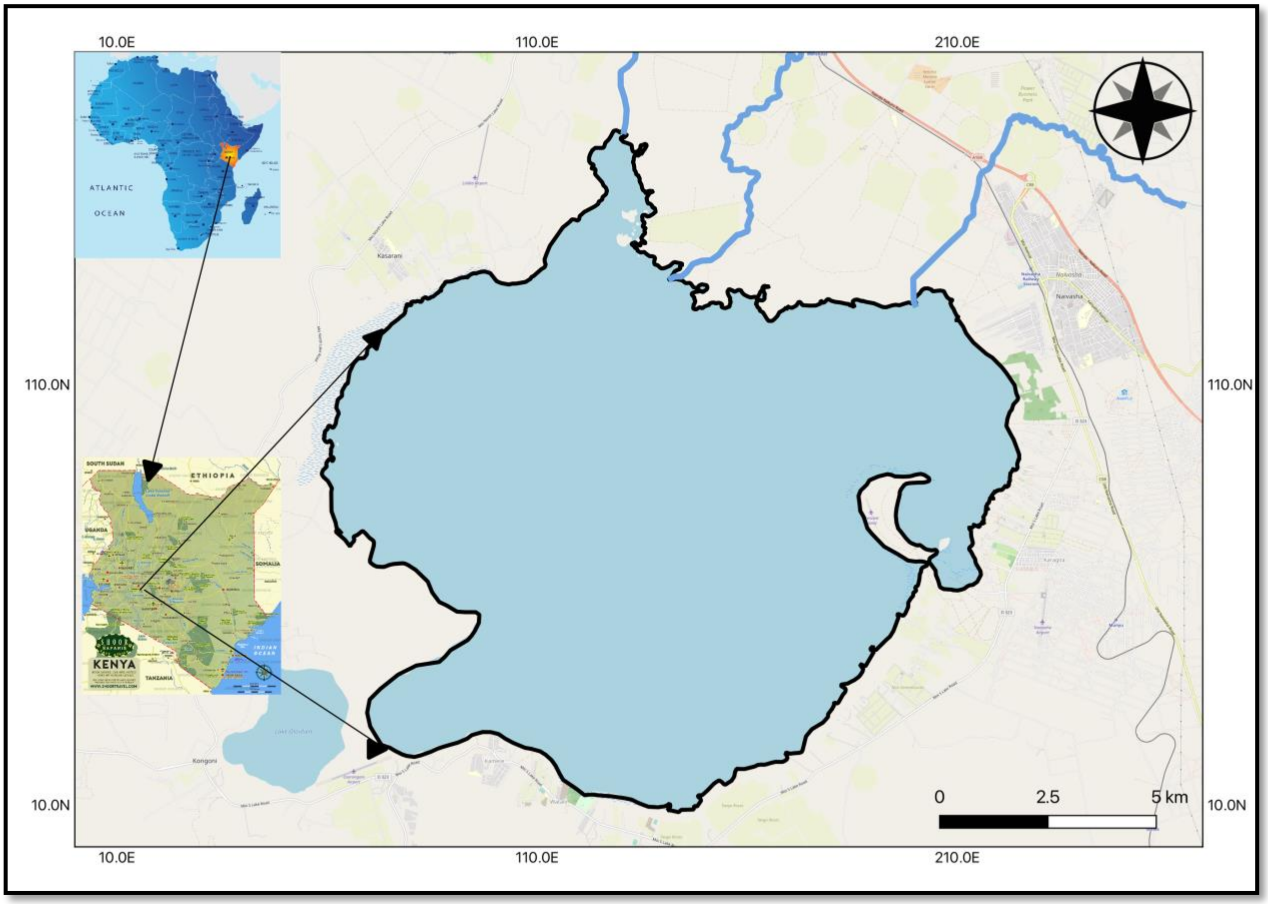

Figure 2 Study area

2.2 OVERALL METHODOLOGY

To investigate the research questions of this study, pre-processed data og lake surface water temperature, lake water leaving reflectance (Rw) at 620nm,665nm, 681 nm, and chlorophyll-a for lake Naivasha was downloaded from Lake CCI website. The pre-processed precipitation data was downloaded from GPM-IMERG. The lake CCI data was further processed to get the valid observations by filtering them with quality levels provided Lake CCI. These valid observations were further filtered to get the values for same location point on the lake. In case of precipitation data, unit conversion was done. Once the dataset for all the variables was ready, timeseries with standard deviation as an error bar was plotted for lake surface water temperature, lake water leaving reflectance at 620nm,665nm, 681nm, chlorophyll-a and precipitation. In case of chlorophyll-a in-situ absorptions were available, therefore verification of lake CCI derived chlorophyll-a was carried out. To understand the changes in lake surface water temperature and precipitation, the time series decomposition method was applied to separate the trend and seasonality. Lake water leaving reflectance at 620nm,665nm, 681nm were used to detect phycocyanin by cyanobacteria index. Furthermore, seasonal growth for cyanobacterial bloom was estimated by analysing the chlorophyll-a in the years which detected phycocyanin and bloom indices such as bloom intensity, bloom extend, and bloom severity were estimated. In the end the effects of lake surface water temperature and precipitation were investigate during the growth windows.

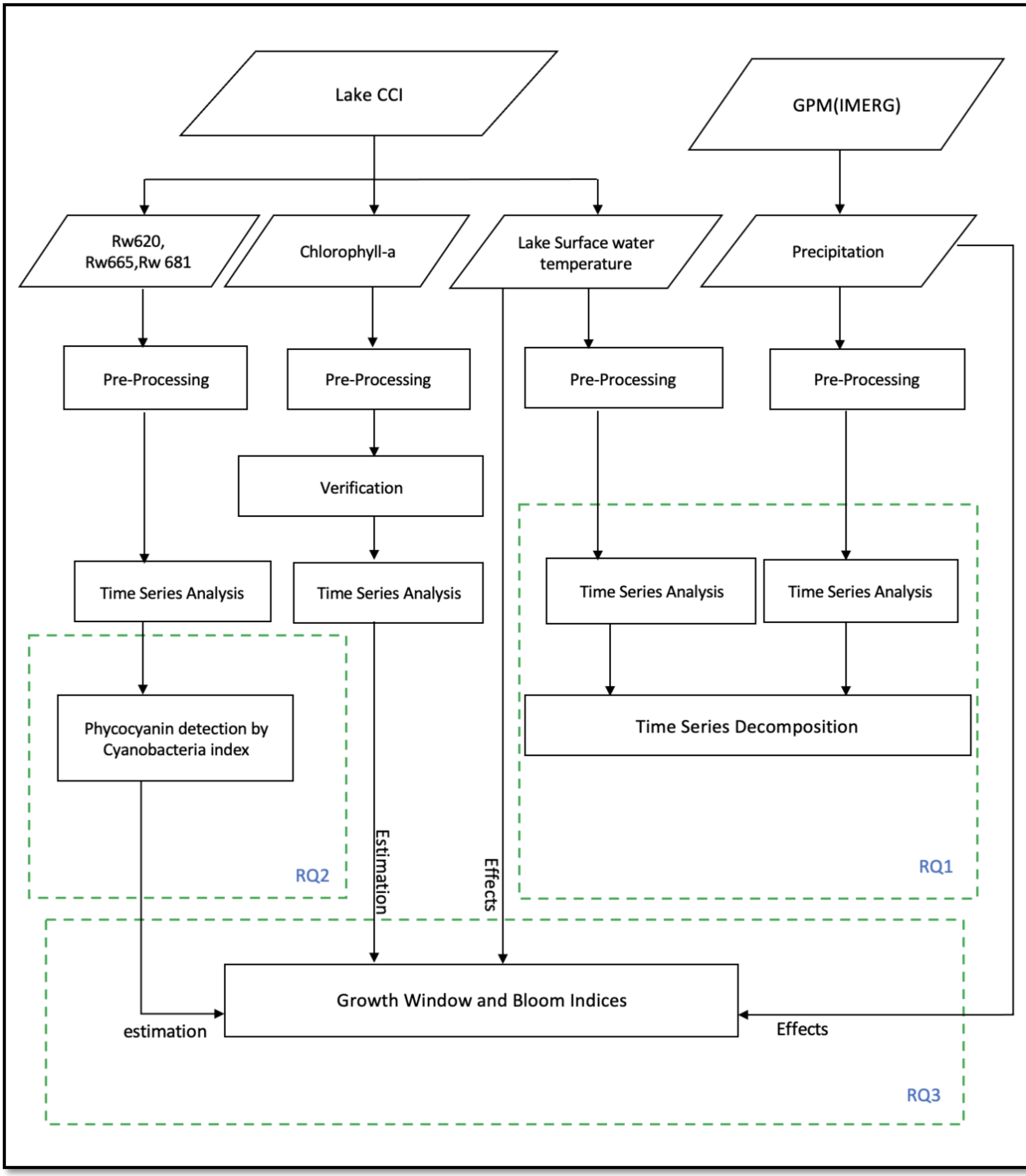

Figure 3 Methodology Flowchart

2.3 SATELLITE DATA DESCRIPTION

The data for Lake Naivasha's lake surface water temperature, lake water leaving reflectance, chlorophyll-a concentration and precipitation was downloaded for the year 2002-2012. Year 2012 was excluded for this because it did not cover the whole year but 2002 was included to understand when cyanobacterial growth started. The data for lake surface water temperature, lake water leaving reflectance and chlorophyll-a was downloaded from the climate data records developed by the lake Climate Change Initiative, abbreviated as lake CCI. Lake CCI aims to provide longest period of combined satellite observations. They asses the requirement of the climate researchers then develops, test, existing algorithms and choose the best algorithm and standard to produce high quality lake Essential Climatic Variables(ECV) products across the sensors to get the longest period of observations for the lake ECV. They validate the derived products data by involving independent climate research groups.(Crétaux et al., 2020).The precipitation data was downloaded from Integrated Multi-Satellite Retrievals for Global Precipitation measurement abbreviated as IMERG (GPM)(Huffman et al., 2019).The algorithm for integrated Multi-Satellite Retrievals for Global Precipitation measurement integrates information from the GPM satellite constellation to determine the precipitation over the majority surface of the Earth. The precipitation is estimated by using the different passive microwave sensors available in the GPM satellite constellation. The Lake CCI and IMERG datasets are stored in netCDF 4 format having three dimensions-latitude, longitude, time. Table 1 gives the general specification of the data set in this study. The brief description of lake CCI variables and precipitation data downloaded from IMERG(GPM) is given below.

→ **The lake Climate change Initiative (Lake CCI) variables**

- **Lake surface water temperature**

To understand trends in the lake surface water temperature, the daily records for lake surface water temperature were downloaded for Lake Naivasha. Lake CCI gives the water temperature of the lake's uppermost layer which is lest that 0.1mm thick. The temperature values obtained for the uppermost layer of the lake is called lake's skin temperature which may differ from the temperature measured by the thermometers. This is so because the lake temperature measured by the thermometers is a few centimeters below the air-water interface. The unit of lake surface water temperature data was in Kelvin. Lake CCI provides the quality level for per datum of lake surface water temperature. Here the quality levels signify the degree of confidence in lake surface water temperature values and its estimated uncertainty's validity. The Quality level zero is no data and quality level 1 is bad data. These two quality levels are never valid. The quality level two and three are worst quality and low quality respectively. Quality level four is acceptable quality and quality level five is best quality. For this study the minimum quality level chosen was more than three, which is acceptable quality. After applying the quality filter, the daily lake surface water temperature values were average to monthly average for further analysis.

- **Lake Water leaving reflectance**

The daily Lake water leaving reflectance values for wavelengths 620nm,665nm and 681nm were obtained from the lake CCI records for lake Naivasha. These three wavelengths were used in spectral shape index based on (Wynne et al., 2008) to detect the presence of phycocyanin over the lake surface as is an accessory pigment present in cyanobacteria with a characteristic absorption peak at 620nm. To derive the lake water leaving reflectance as the final product, Lake CCI first inputs the level 1 B data of MERIS sensors for the target regions and entered in a geospatial database. Then radiometric corrections are also done. Then water pixels are identified, and later atmospheric correction is done over water pixel to obtain Lake water leaving reflectance values. The daily lake water leaving reflectance was averaged to monthly mean for further analysis.

- **Chlorophyll-a**

Lake CCI estimates the chlorophyll-a concentration based on the lake water leaving reflectance derived. All harmful algae have photosynthetic pigment called chlorophyll-a therefore chlorophyll-a concentrations was used as an indicator for algal photosynthetic activity. Lake CCI uses globally validated algorithms to retrieve the chlorophyll-a concentration (Gilerson et al., 2010; Mishra et al., 2013; O'Reilly, 2000; Simis et al., 2005). The unit for estimated chlorophyll-a is mg/m^3. The lake CCI variables were downloaded from https://data.ceda.ac.uk/neodc/esacci/lakes/data/lake_products/L3S/v1.0/

→ **IMERG(GPM) Precipitation**

The monthly precipitation records for precipitation were downloaded from the GPM data directory(https://gpm.nasa.gov/data/directory). The Monthly final run product is the total of the half hourly product, and it includes the rain gauge data. The monthly final run precipitation product downloaded was in mm/hour(Huffman et al., 2019). The mm/hr precipitation data was converted to mm/month for further monthly analysis.

Srno	Variables	Satellite sensor	Spatial resolution	temporal resolution and coverage
1.	Lake Surface Water Temperature.	Metop-AVHRR and ERS-ATSR	Remapped to 0.008. (Near to 1 km at the equator)	Daily from 1995-present
2.	Lake Water leaving Reflectance (Rw_620, Rw_665, Rw_681)	ESA-MERIS	Remapped to 0.008. (Near to 1 km at the equator)	Daily from 2002-Present
3.	Chlorophyll-a	ESA-MERIS	Remapped to 0.008. (Near to 1 km at the equator)	Daily from 2002-Present
4.	Precipitation	different passive microwave sensors available in the GPM satellite constellation https://gpm.nasa.gov/missions/GPM/constellation	0.1° x 0.1°	Monthly 2000 June-Sep 2021

Table 1- Satellite data summary for variables used in the study

2.4 DATA PRE-PROCESSING

→ Lake CCI Variables

The first step for the data processing was to filter the lake surface water temperature values with the given quality levels mention in 2.3(lake surface water temperature). As mentioned earlier the quality level chosen for this study was above three. Fig 4 shows the data before and after quality filter for lake surface water temperature. The quality filter gave the valid observations for lake surface water temperature.

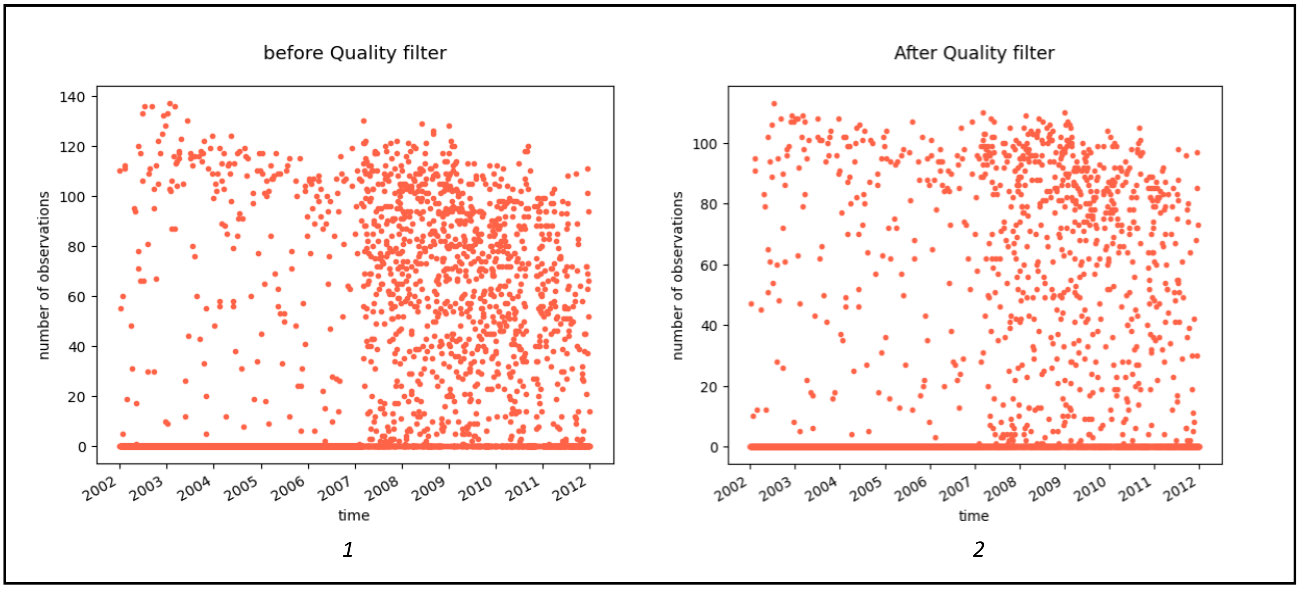

Figure 4 1- Original observations 2- valid observations after quality level filtering

Next, number of valid observations for the lake CCI variables were investigated. The investigation revealed that the count of valid observations for the lake CCI variables was not the same, which indicated that the values of the lake CCI variables were not the same spatially. In other words, the pixel count was different for different lake CCI variables. This issue might be due to use of different remote sensing sensor for data retrieval. Fig 5 shows the difference in valid observations for lake CCI variables. To achieve the objectives of this study, all the valid observations lake CCI variables must be same spatially therefore, the lake surface water temperature, lake water leaving reflectance data were filtered using a mask based on valid Chlorophyll-a data points. Chlorophyll-a was chosen because it had the lowest number of pixel count in the lake CCI variables. fig 6 shows the same number of valid observations spatially for lake CCI variables after the chlorophyll-a mask was used.

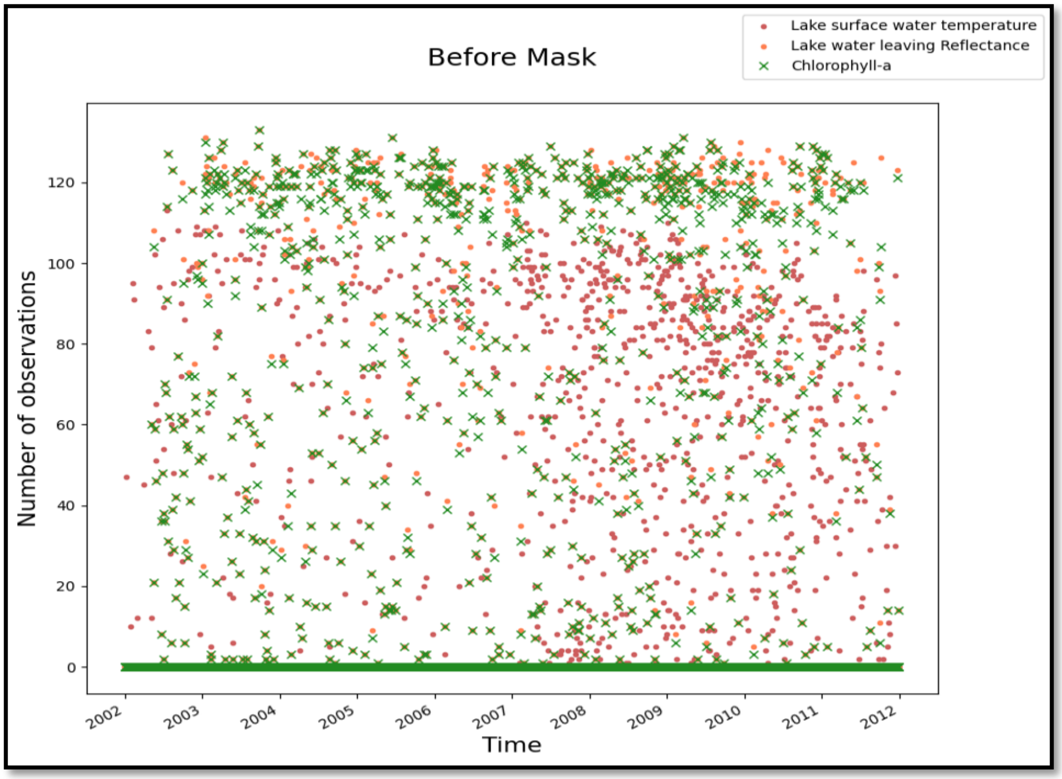

Figure 5- Valid Lake CCI observations of different location points

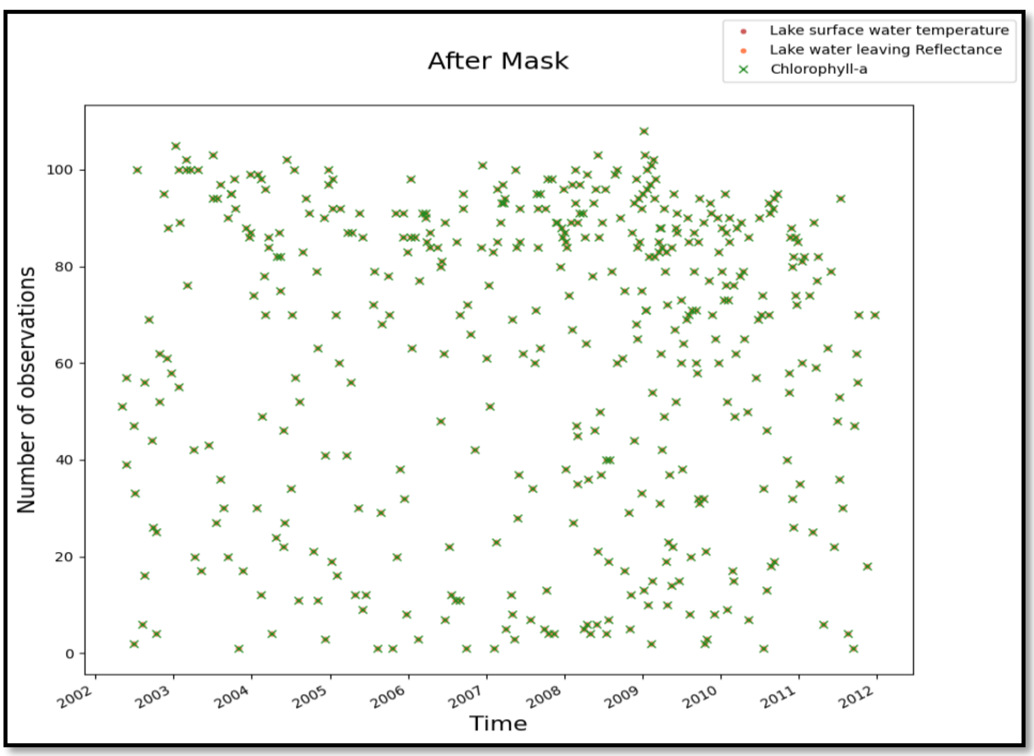

Figure 6- Valid Lake CCI observations of same location point

Once the valid observations of same location points were retrieved for all the lake CCI variables, the average daily values were resampled to monthly average to plot the time series of the lake CCI variables for the year 2002-2011. The frequency was changed from daily average to monthly average for better spatial coverage as the daily valid observations were not available for all days. This was due to losing the data in the previous steps. There is a possibility that the data was not recorded by the remote sensing satellite for some days due to cloud cover.

→ **IMERG(GPM) Precipitation**

As mentioned in section 2.3(IMERG-GPM precipitation) the monthly precipitation data is provided in mm/hr. Therefore, precipitation data was converted to mm/month to plot the precipitation time series for the years 2002-2011. To get the accurate data for all the months, the precipitation values in the months with 31 days (January, March, May, July, August, October, December) were multiplied by 744(24*31). In the months with 30 days (April, June, September, November) the precipitation values were multiplied by 720(24*30). In the leap years (2004,2008), for the month of February the precipitation values were multiplied by 696(24*29) and for the non-leap years, the precipitation values for the month of February were multiplied by 672(24*28).

2.5 CHLOROPHYLL-A VERIFICATION

Cyanobacteria have chlorophyll-a which absorbs light for photosynthesis. According to Beer Lambert's law, absorption is directly proportional to concentration which means higher the concentration of chlorophyll-a higher the absorption for photosynthesis (Jon H. Hardesty and Bassam Attili, 2010; Salama, 2021-personal communication).Therefore, to verify the lake CCI chlorophyll-a concentration, it was compared to in-situ chlorophyll-a absorption. The in-situ absorption was available only for 23-sepetember 2010. Fig 7 shows the location of the in-situ absorption measured for chlorophyll-a at 490 nm mapped over the lake CCI chlorophyll-a concentration. There are 11 in-situ location for the absorption in the central and northern region of the Lake. The lake cci chlorophyll-a concentration appears to be between 10 to 60 mg/m^3.

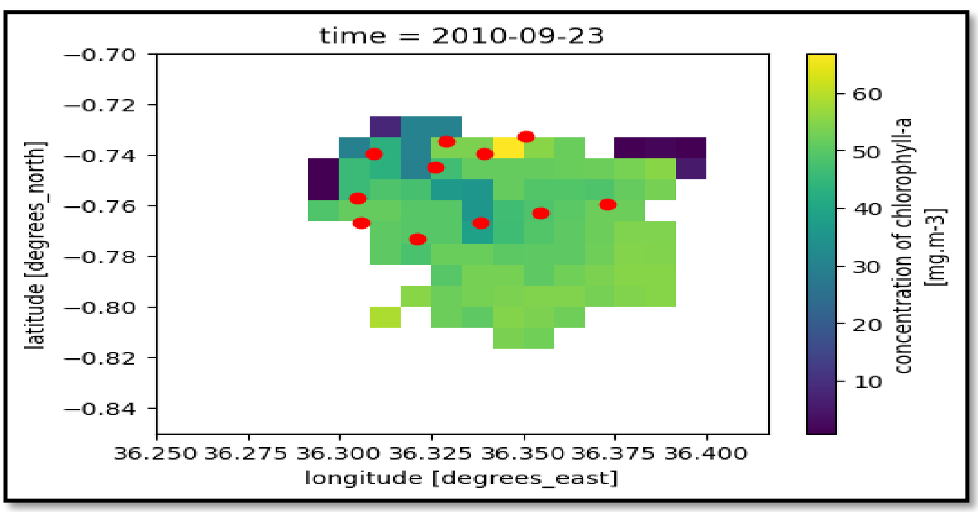

Figure 7-Location of in-situ absorption over the Lake CCI chlorophyll-a concentration map

2.6 TIME SERIES AND ERROR BARS

Before beginning with analysis of the objectives, all the variables were assessed for variability also known as spread, scatter, or dispersion of the values in the timeseries(Bhandari, 2022). To understand this variability in the time series plots constructed for the Lake CCI variables and Precipitation values, error bar plots were created. In any plot, an error bar represents the variability of the point as a line passing through it parallel to one of the axes. The error bars either represented by range or standard deviation(Bargen, 2022; Cumming et al., 2007).Fig 8 show how an error bar plot looks like. In case of this study, the point is the monthly averages of the variables considered and the error bars are parallel to the y axis represented by standard deviation. Standard deviation as the error bar of the data tells us the how much data is spread out especially around the mean or average(Stephanie Glen, 2022). A lower standard deviation error bar suggests that the values are closer to mean indicating that the mean values accurately represent the data whereas higher standard deviation suggests that the data is spread over a large range and mean is not reliable(Bargen, 2022).

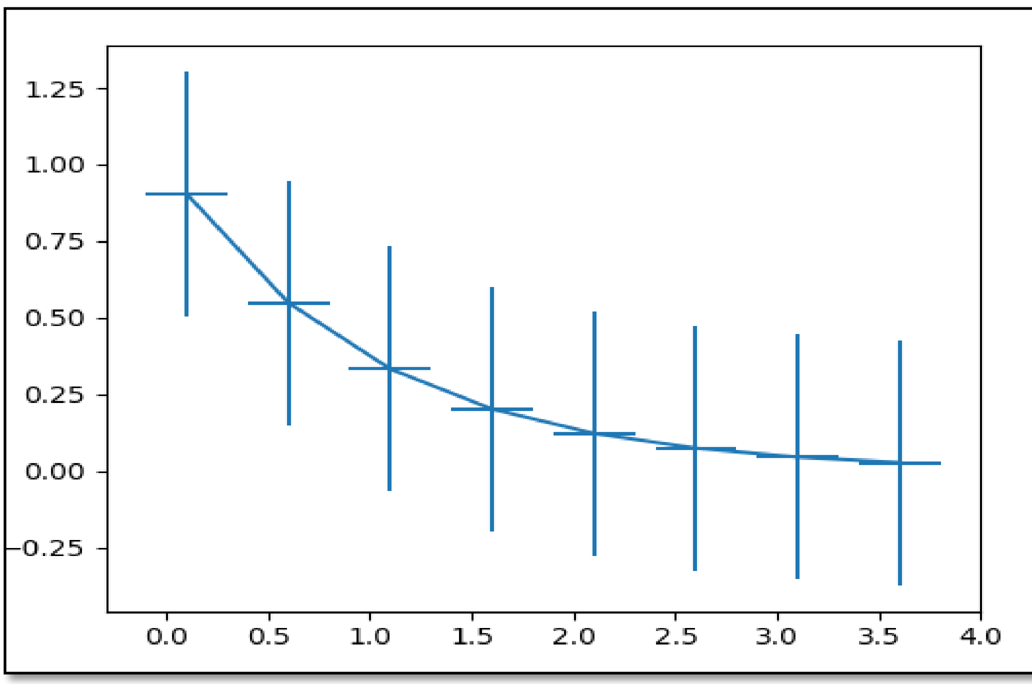

Figure 8-Example of an error bar plot source-(John Hunter et al., 2017)

2.7 INVESTIGATION OF EXISTENCE OF TRENDS IN LAKE SURFACE WATER TEMPERATURE AND PRECIPITATION PATTERNS

RQ1- Is there increase in lake surface water temperature and changes in precipitation patterns in the years from 2002 to 2011?

For the research question one, the study investigated the time series of lake surface water temperature and precipitation. The time series generated for lake surface water temperature and precipitation show variety of patterns. A time series is composed of four types of fluctuations(Dagum, 2013): -

a. A long-term tendency or secular trend.
b. Cyclic changes overlaying on the long-term trend.
c. A seasonal variation within each year depending on the nature of time series
d. Residual variations due to changes affecting the variables such as climate change.

To understand these fluctuation, Seasonal-Trend decomposition using LOESS, (STL) method of decomposition was used. The seasonal component shows the repeating patterns occurring in the time series and trend shows the level low frequency variations in the data with nonstationary, long-term changes. In this method seasonality is allowed to change over time and smoothness of trend can be controlled.(Cleveland, R. B. et al., 1990; Hyndman and Athanasopoulos, 2018).In this study for both the time series the length of the seasonal smoothening was 9 and the length of trend smoother was 13. For further to understand the effect of seasonality on the time series, monthly climatology for the lakes surface water temperature and precipitation was analyzed.

2.8 DETECTION OF HARMFUL ALGAL BLOOMS BY ESTIMATING CHLOROPHYLL-A AND PHYCOCYANIN USING REMOTE SENSING ALGORITHM.

RQ2- Are the cyanobacterial bloom present on Lake Naivasha in the years 2002 to 2011?

For the second research question, the photosynthetic pigments,chlorophyll-a and phycocyanin were investigated. Since chlorophyll-a pigment is used for photosynthesis in green algae, it is an indication for photosynthetic activity in the lake hence its concentration is often corelated with presence of green algae(Tress et al., 2021). Cyanobacteria also contain chlorophyll-a but in addition, they have one more photosynthetic pigment called phycocyanin which enhances the chlorophyll-a's oxygen production efficiency under low light conditions (Zeece, 2020). Phycocyanin pigment is a functional protein complex having absorption feature at 620 nm (Mishra and Mishra, 2014) The absorption is in red-orange wavelength range giving the pigment a blue color and therefore cyanobacteria are also called blue green algae (Zeece, 2020). Since phycocyanin is present in cyanobacteria, the cyanobacterial bloom reflects light differently than other species containing chlorophyll-a and therefore can detected separately from the other photosynthetic species present. In this study, to separate and detect the presence of cyanobacteria between the years 2002-2011, Cyanobacteria Index was calculated using spectral shape index developed by(Wynne et al., 2008)

- **Cyanobacterial Index using Spectral Shape Algorithm**

As seen in the fig 9 the spectral curve has a distinct trough indicated by red arrow at 620nm which corresponds to maximum absorption by the phycocyanin and therefore by using this trough, spectral shape algorithm was determined. For specific identification of cyanobacteria, the lake water leaving reflectance 620nm, 665nm and 681nm were used to identify the presence phycocyanin.

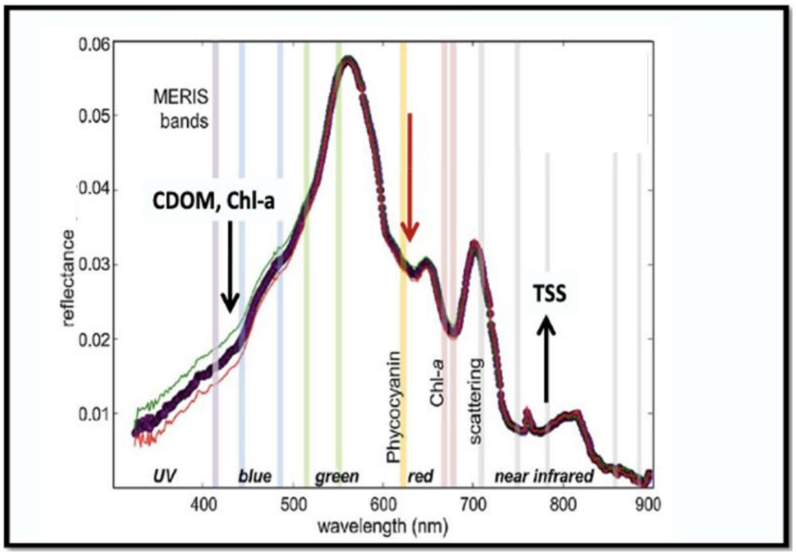

Figure 9- Spectral curve showing absorption by phycocyanin at 620nm(red arrow) for MERIS sensor. source-(Stumpf et al., 2016)

The cyanobacteria index was calculated using spectral shapes algorithm as follows(Lunetta et al., 2015; Mishra et al., 2019; Urquhart et al., 2017; Wynne et al., 2013)

$$CI = -SS(\lambda) \text{ .... eq 1}$$

$$SS(\lambda) = \rho_s(\lambda) - \rho_s(\lambda_-) + \{\rho_s(\lambda_-) - \rho_s(\lambda_+)\}\frac{(\lambda - \lambda_-)}{(\lambda_+ - \lambda_-)} \quad \text{............eq 2}$$

Where

ρ_s = Rayleigh corrected top of the atmosphere reflectance

λ = 665nm

λ_- = 620nm

λ_+ = 681nm

The elevated phycocyanin absorption is presumed to depress the reflectance at 620nm causing SS (665) to change from negative to positive. Therefore when the CI values of SS(665)<0 cyanobacteria are presumed to be absent and when SS(665)>0, they are present(Lunetta et al., 2015). In other words, the Cyanobacteria index values greater that zero means the cyanobacteria is present and less than zero means it is absent. This index has been used by (Matthews et al., 2012) to separate cyanobacteria from other blooms in African lakes.

For each grid box of the Lake Naivasha, the resampled lake CCI monthly mean water leaving reflectance at 620nm,665nm,681nm were used to get the cyanobacteria index using equation 1 and 2. The number of grid boxes with cyanobacteria index higher than zero were determined within the lake for each month and plotted as a time series. Instead of calculating mean values for cyanobacteria index, the study counted the number of grid boxes which had cyanobacteria index higher than zero thereby determining which fraction of the lake was covered with cyanobacteria. The time series of Cyanobacteria index revealed years having cyanobacteria over lake surface. The cyanobacteria index is not a quantitative measure of phycocyanin occurrence as opposed to mean chlorophyll-a concentration hence the mean of cyanobacteria index has no quantitative meaning therefore it was used to determine the point on lake surface having phycocyanin. Since cyanobacteria is not a quantitative measurement, it was used to separate the pixels with phycocyanin, and chlorophyll-a was used to determine the quantitative analysis.

2.9 ANALYSIS OF HARMFUL ALGAL BLOOMS OF CYANOBACTERIA GROWTH PERIOD AND DETERMINING EFFECTS OF PRECIPITATION AND LAKE SURFACE WATER TEMPERATURE DURING THE GROWTH PERIOD

RQ3- What is the growth period of Cyanobacterial bloom and is Lake surface water temperature and precipitation affecting the growth of harmful algal blooms in lake Naivasha?

The methodology for research question three was divided in two parts. The first step was to determine the seasonal window for the cyanobacterial bloom. In addition to this bloom indices mention in table 2 were derived and then the effect of lake surface water temperature and precipitation was analyzed during the cyanobacterial growth window.

As the valid observations are spatially same for chlorophyll-a and the lake water leaving reflectance wavelengths, the grid box which detected phycocyanin also has chlorophyll-a concentration value therefore to determine the growth window of cyanobacterial bloom, rate of change of chlorophyll-a concentration was analyzed for the years in which cyanobacteria index detected phycocyanin. Growth window for cyanobacterial bloom was detected by using the seasonal growth window method used by (Adams et al., 2021) in their study for chlorophyll-a.

To identify the start and end of the growth window, first the time series data of chlorophyll-a was smoothened to reduce the effect of noise in the data and then optima peaks were flagged in chlorophyll-a concentration plot by finding peaks in the smoothened data. The growth window ended at the first peak. For each year the growth window was investigated for the dry season and wet season.

The quantitative algal bloom indices (Binding et al., 2018) described in table 2 were calculated for the seasonal window and compared with lake surface water temperature and precipitation

Srno	Bloom Index	Definition
1.	Bloom intensity	Mean chlorophyll-a concentration
2.	Bloom Extent	Total area of pixel flagged as phycocyanin by cyanobacteria index
3.	Bloom Severity index	Bloom intensity × Bloom Extent

Table 2-Bloom indices with definition.

To calculate bloom extent, the total cyanobacteria index count was multiplied with the resolution which in this case it was 1000m or 1km as seen in (table 1).

Next to understand the effects of lake surface water temperature and precipitation on occurrence of cyanobacteria over lake Naivasha, the monthly lake surface water temperature and precipitation trends leading up to the growth window were investigated to understand their effect on cyanobacterial bloom intensity, extent, and severity. This was done by plotting the peak identified chlorophyll-a concentration and cyanobacteria index plots with the lake surface water temperature and precipitation plot. Later the average lake surface water temperature and precipitation for the observed growth window was estimated.

3 RESULTS

3.1 SPATIOTEMPORAL VARIATION IN CHLOROPHYLL-A CONCENTRATION AND CYANOBACTERIA INDEX

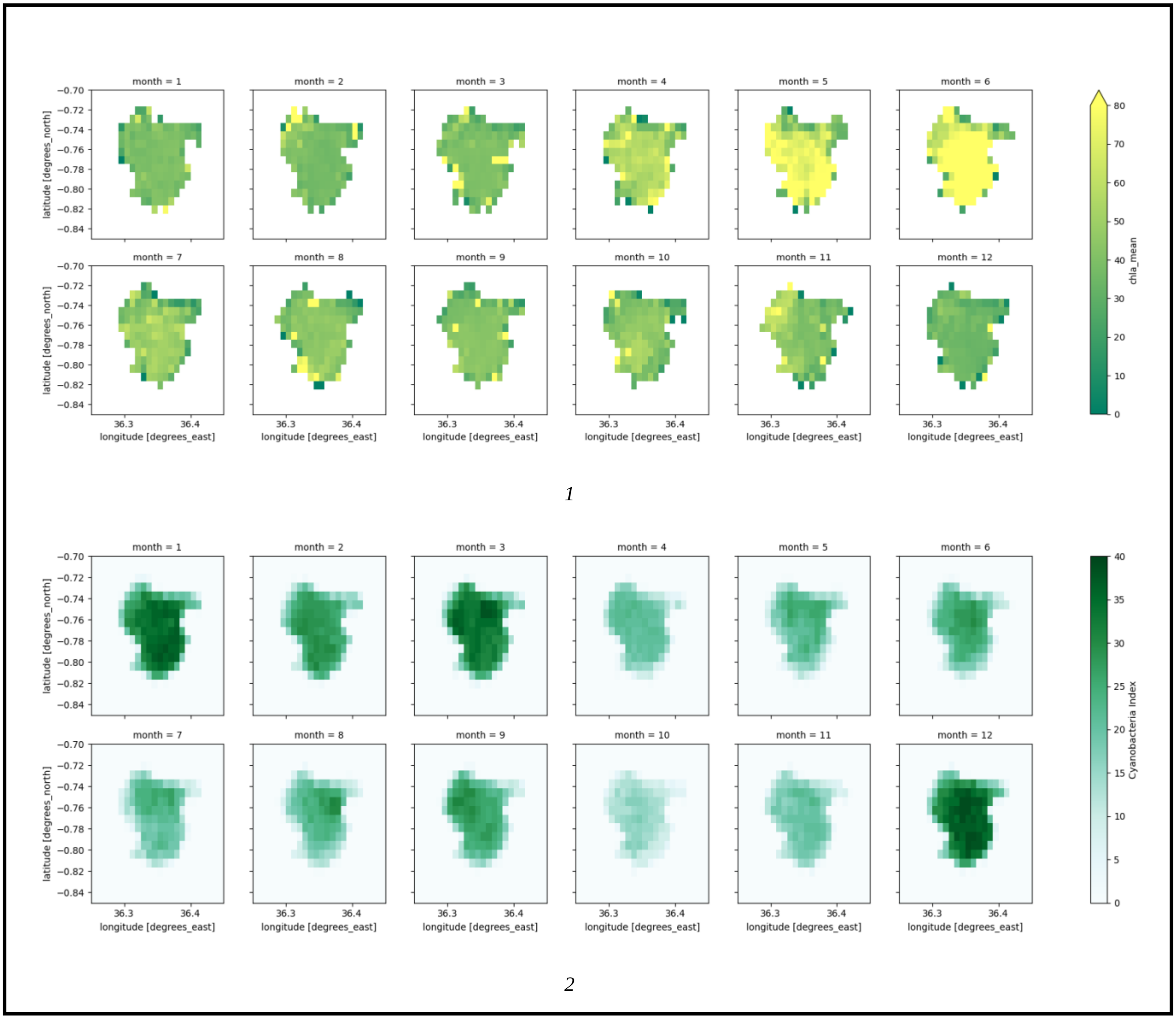

Figure 10 Monthly spatial distribution of 1. chlorophyll-a and 2. Cyanobacteria index between 2002-2011

Fig 10 shows the monthly climatology of chlorophyll-a concentration derived by lake CCI and phycocyanin count derived from cyanobacteria index between the years 2002-2011. The monthly climatology of chlorophyll-a shows highest concentration of 80 mg/m^3 to 100 mg/m^3 only in the months of May and June. This could be due over estimation of chlorophyll-a data in few years or interference of turbidity with the measurements. In rest of the months the concentration varies between 50 mg/m^3 to 70 mg/m^3. High levels of chlorophyll-a indicates that lake Naivasha is eutrophic as concentrations exceed 25 mg/m^3.(Caspers, 1984; Murakaru, 2010).The monthly climatology of cyanobacteria index suggests that the phycocyanin count was highest in December-March. The chlorophyll-a concentration during this period was observed in the range 40 mg/m^3 to 60 mg/m^3. TCompared to these three months the phycocyanin count was lowers in other months, but almost diminishes count was observed month of October, but chlorophyll-a concentration remained in the same range. his could because chlorophyll-a is present green algae as well as water plants. It is to be noted that, the climatology of chlorophyll-a concentration and cyanobacteria index for the months of January, February, March, and April is between the year 2003-2011 as the 2002 data for these months was not available because ESA-MERIS was launched in March 2002.

3.2 CHLOROPHYLL-A VERIFICATION

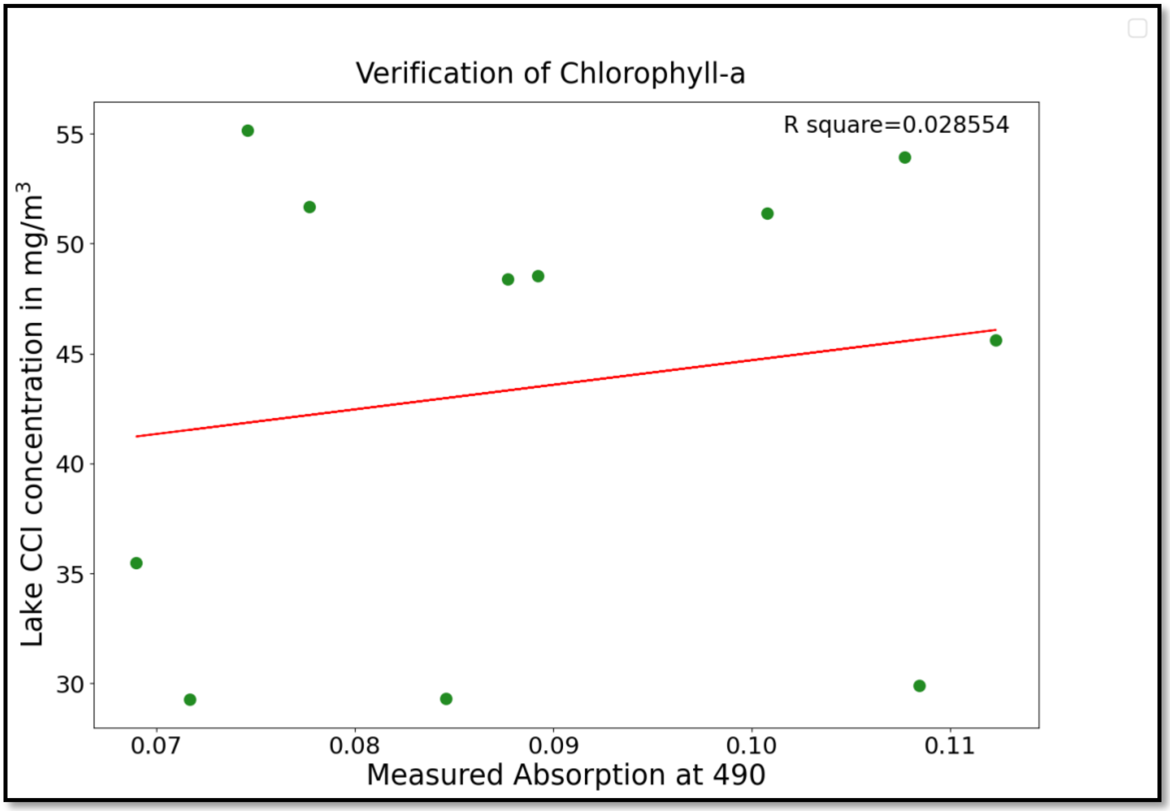

Figure 11 in-situ absorption vs Lake CCI concentration graph

The fig 11 shows the plot of in-situ absorbance at 490nm against lake CCI chlorophyll-a concentration in mg/m^3. The absorption of chlorophyll-a is between 0.07 to 0.11 and the Lake CCI concentration for the in-situ location is between 25 mg/m^3 to 55 mg/m^3. The r square value of the plot is 0.03. The r square value is low suggesting that the correlation between in-situ chlorophyll-a and the lake CCI retrieved chlorophyll-a is very low indicating no linear correlation.

3.3 TIME SERIES AND ERROR BAR ANALYSIS

In the time series plot (fig, no 12-15) for lake surface water temperature, water leaving reflectance, and precipitation, chlorophyll-a, the X-axis represents the months in each year and Y-axis represents the mean monthly values of the lake CCI and IMERG datasets with an error-bar. The capped tipped line over the data point is an error bar of standard deviation. In the year 2010, the data for month of October is missing from the Lake CCI data variables.

The fig 12 shows the time series mean monthly lake surface water temperature in kelvin. Overall, the lake surface temperature varies between 291 to 297 k i.e., 18°C to 24 °C. There is no significant upward or downward movement seen in the plot. This implies that the mean lake surface water temperature was stable in the years 2002 to 2011 but the monthly mean lake surface water temperature shows a similar pattern at regular interval in all the years revealing a strong seasonality. Visual inspection of error bars show that they have lower height suggesting that the mean values accurately represented the lake surface water temperature values.

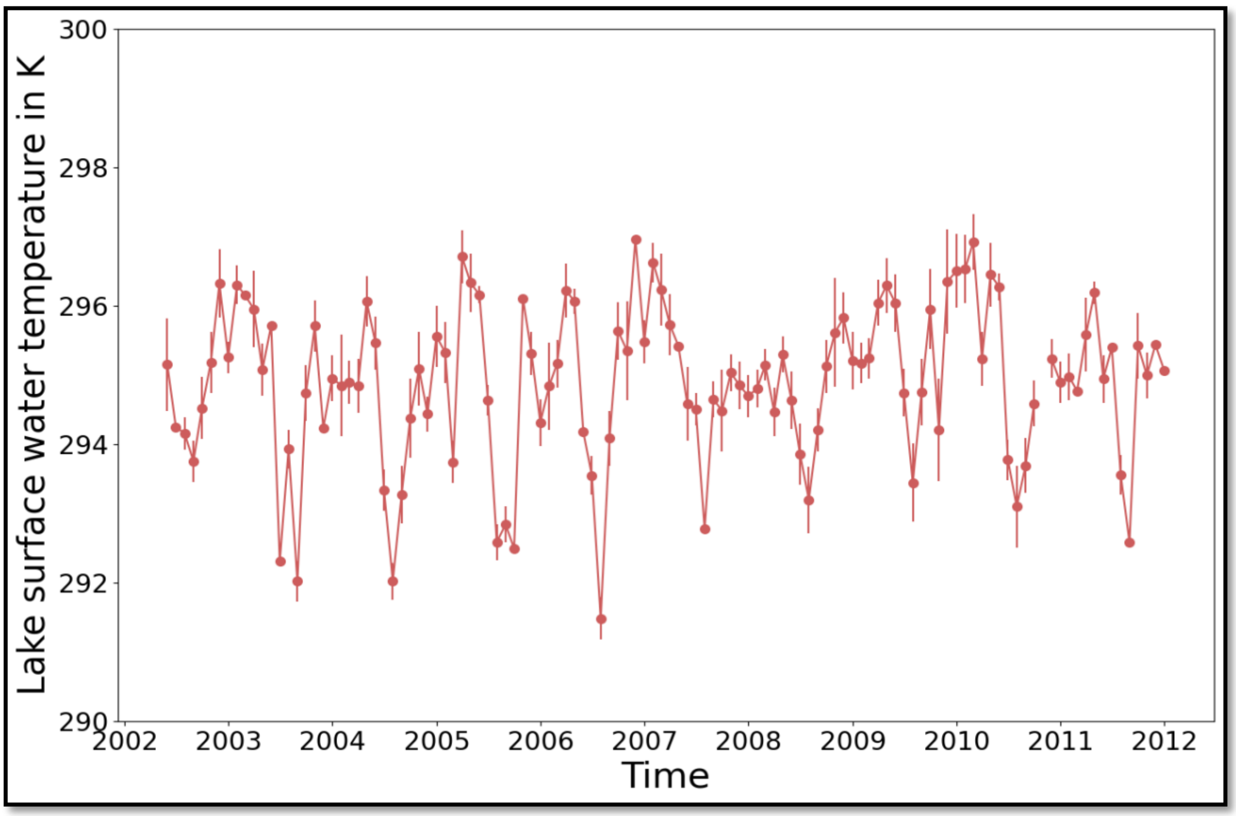

Figure 12 Time Series of lake surface water temperature

The fig 13 plot shows the mean monthly precipitation in mm/month. The amount of precipitation varies between 10 to 270 mm/month. There is not upward or downward slope indicating the amount of precipitation is not increasing or decreasing in the timeseries, however a similar rise and fall was observed in the timeseries indicating a strong seasonality. The average precipitation levels decreased from 250mm/month to 150mm/month from the year 2007.Overall in the month of April of all year high amount of precipitation was recorded. The error bars informs that the data has less variability as the error bar heights are closer to the mean. There is a possibility that IMERG overestimated the precipitation because according to (Ayugi et al., 2016) the mean monthly precipitation in entire Kenya does not exceed 150mm/month.

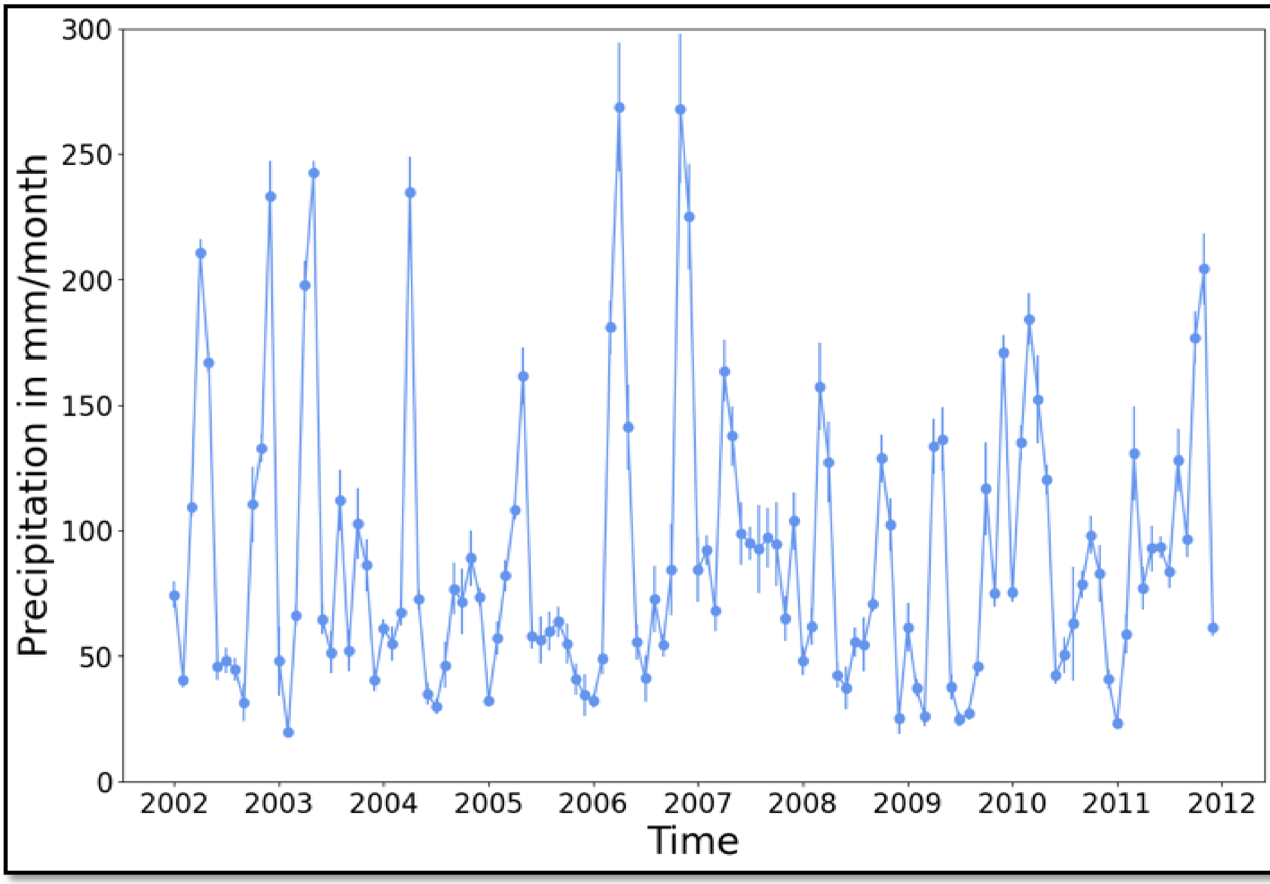

Figure 13 Time Series of precipitation

The fig 14 illustrates the plots of lake water leaving reflectance at 620nm,665 nmand 681nm. The intensity of the reflectance was between 0 to 0.12. The reflectance data for all three wavelength appears to be similar. The lake water leaving reflectance peaked December of 2002 to 0.10 and then quickly dropped in the next months. The time series remained stable between 0 to 0.06 without any high peaks from the year 2003 till 2008. In the year 2009-2010, the reflectance was high probably due to increased turbidity from the constituents such as suspended solids. In their study (Ndungu et al., 2013) had problem retrieving chlorophyll-a during same period due to high turbidity. The water leaving reflectance dropped to 0.03 in the month of September of 2010 and remained stable between 0.02 to 0.03 in the year 2011. Looking at the error bars all three wavelength, all of them show same variability around mean and the bar heights was same too. The variability was steady as error bar don't show extreme height, but the heights in 2009-2010 are not very closer to mean. The reflectance data of 2009-2010 suggest a moderate variability in the data but the data of rest of the year is less variable.

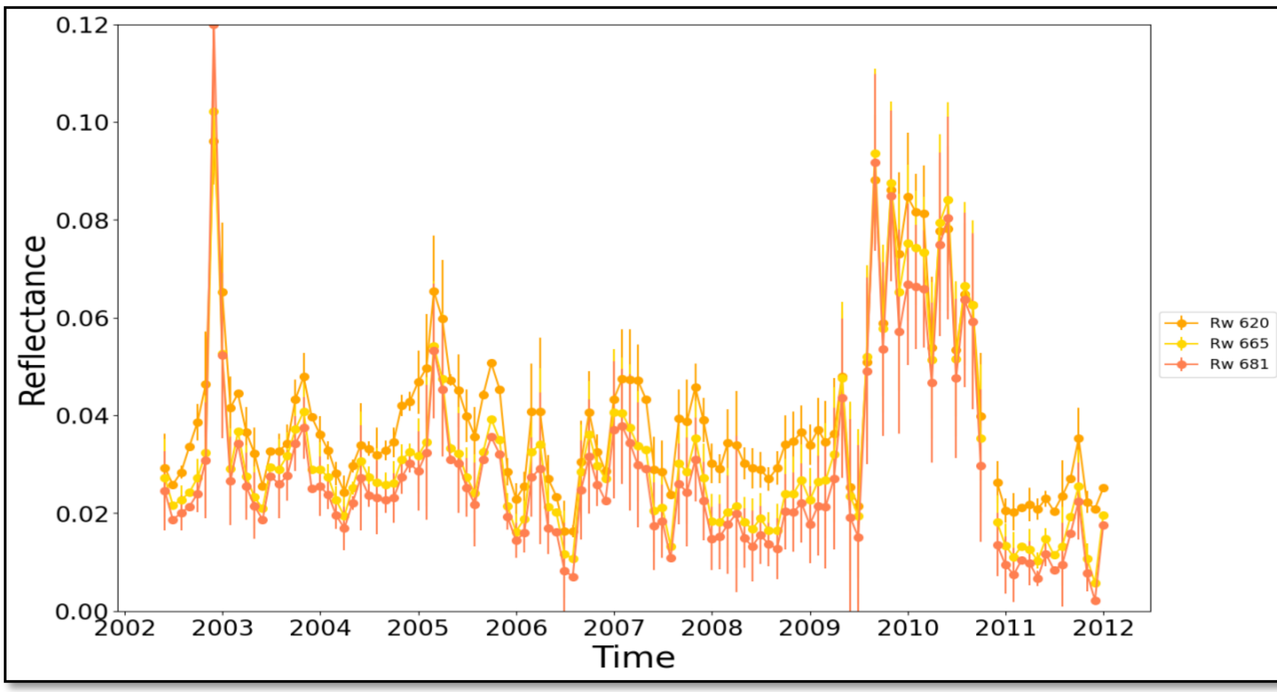

Figure 14 Time Series of Lake water leaving reflectance at 620nm,665nm,681nm

The fig 15 demonstrates the mean monthly chlorophyll-a concentration in mg/m^3. The chlorophyll-a concentration does not show any seasonality in the timeseries. Overall chlorophyll-a concentration is stable between 0 to 100 mg/m^3 in all the years except the months of May and June of 2009 where it rockets to 250 mg/m^3 and 240 mg/m^3. The error bar inspection reveals that there was less variability in of chlorophyll-a concentration up to the year 2006. In 2007, in the months of April and November the bar height is high compared to the previous error bars. In 2007 the variability is again low. the months of March 2009, October 2009, May 2010, September 2010 show high variability due to high reflectance recoded by the sensors.

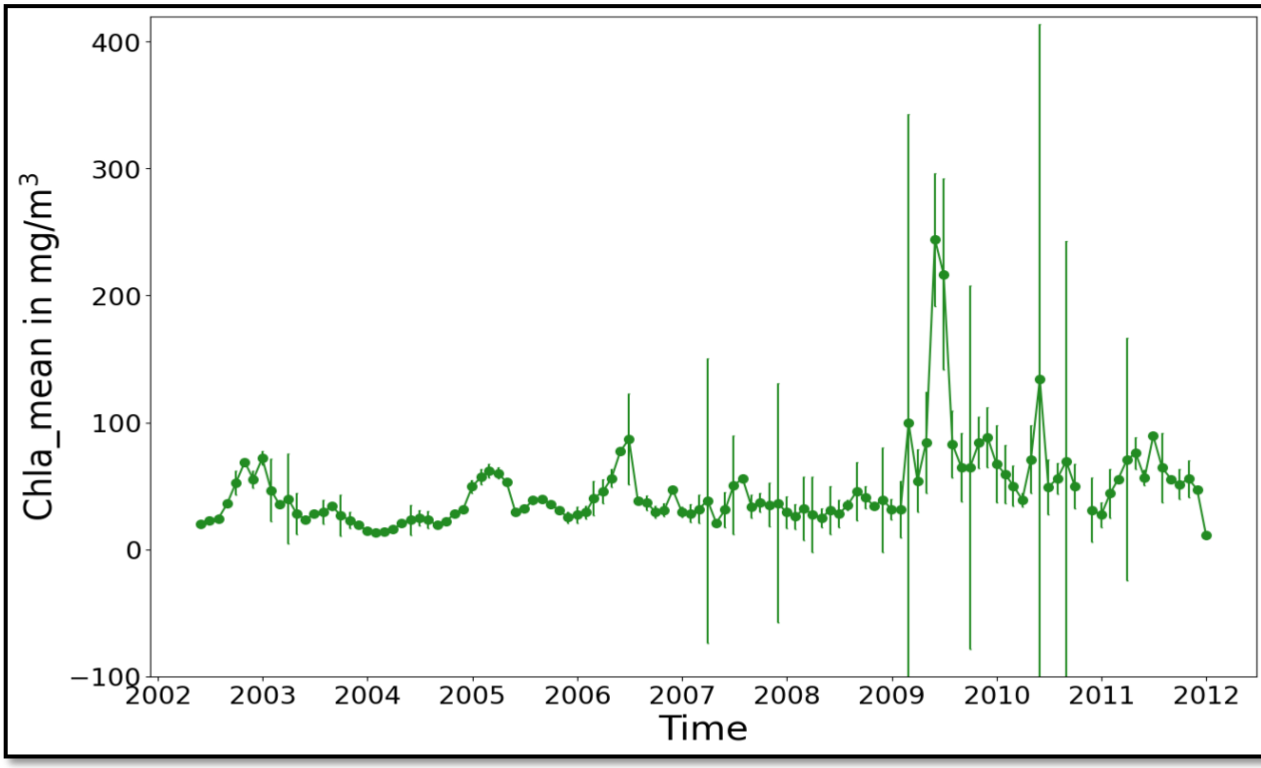

Figure 15 Time Series of Chlorophyll-a

3.4 INVESTIGATION OF EXISTENCE OF TRENDS IN LAKE SURFACE WATER TEMPERATURE AND PRECIPITATION PATTERNS

RQ1- Is there increase in lake surface water temperature and changes in precipitation patterns in the years from 2002 to 2011?

3.4.1 TIME SERIES DECOMPOSITION OF LAKE SURFACE WATER TEMPERATURE

The seasonal decomposition of temporal trends of lake surface water temperature are displayed in fig 16. The upper panel shows time series data observed. The second panel and third shows decomposition of time series into trend and seasonality respectively. The fourth panel show the residuals.

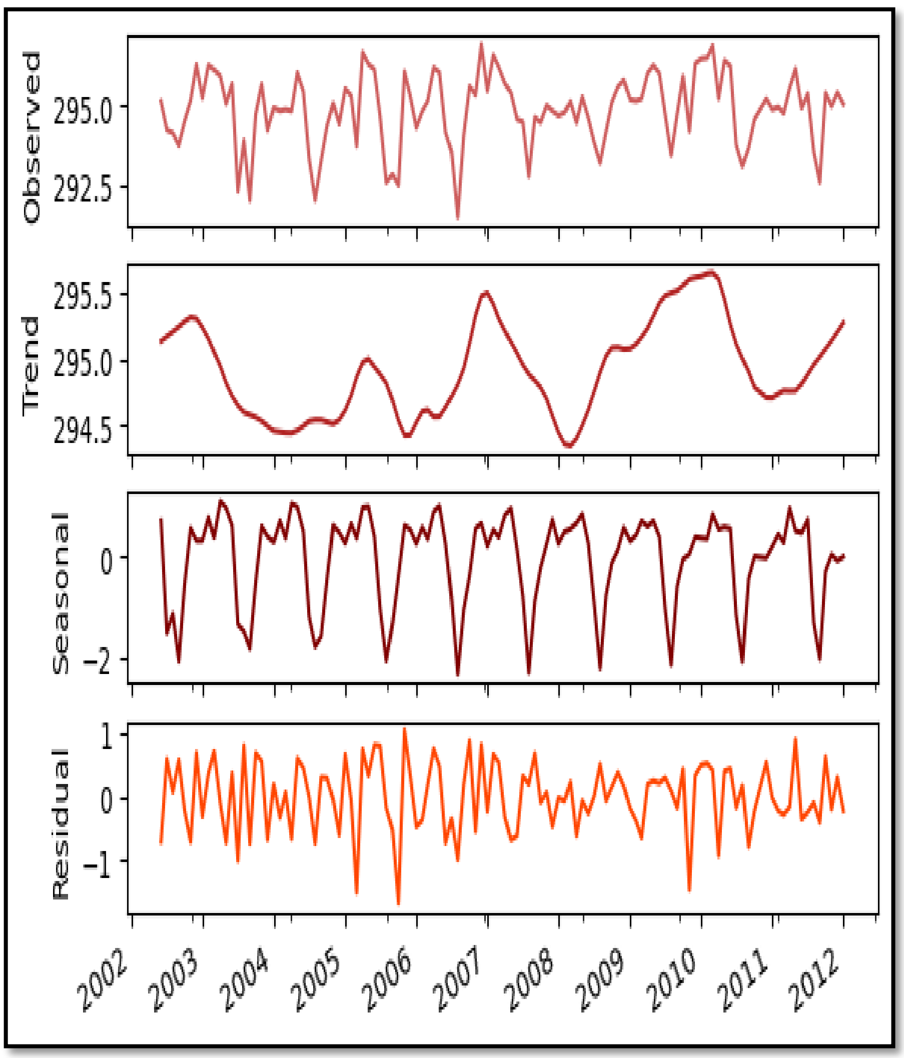

Figure 16 Time series decomposition of lake surface water temperature

The mean monthly lake surface water temperature does not show an exponential rise or fall in duration of the time series. The trend fluctuated between 294.5 K to 295.5 K (21.5 degree to 22.5 degrees). The trend decreased from 295.3 to 294.5 between the years 2002-2004 and remained stable between 294.5 k to 295k up to 2009.A slight upward shift in trend was observed since 2009 as the fluctuation were between 295 to 295.5. Overall, the seasonal plot shows a strong seasonality displays some similarity with the observed values. The underlying seasonal trend was clearer from the monthly climatology of lake surface water temperature between 2002 and 2011 which presented in the fig 17.

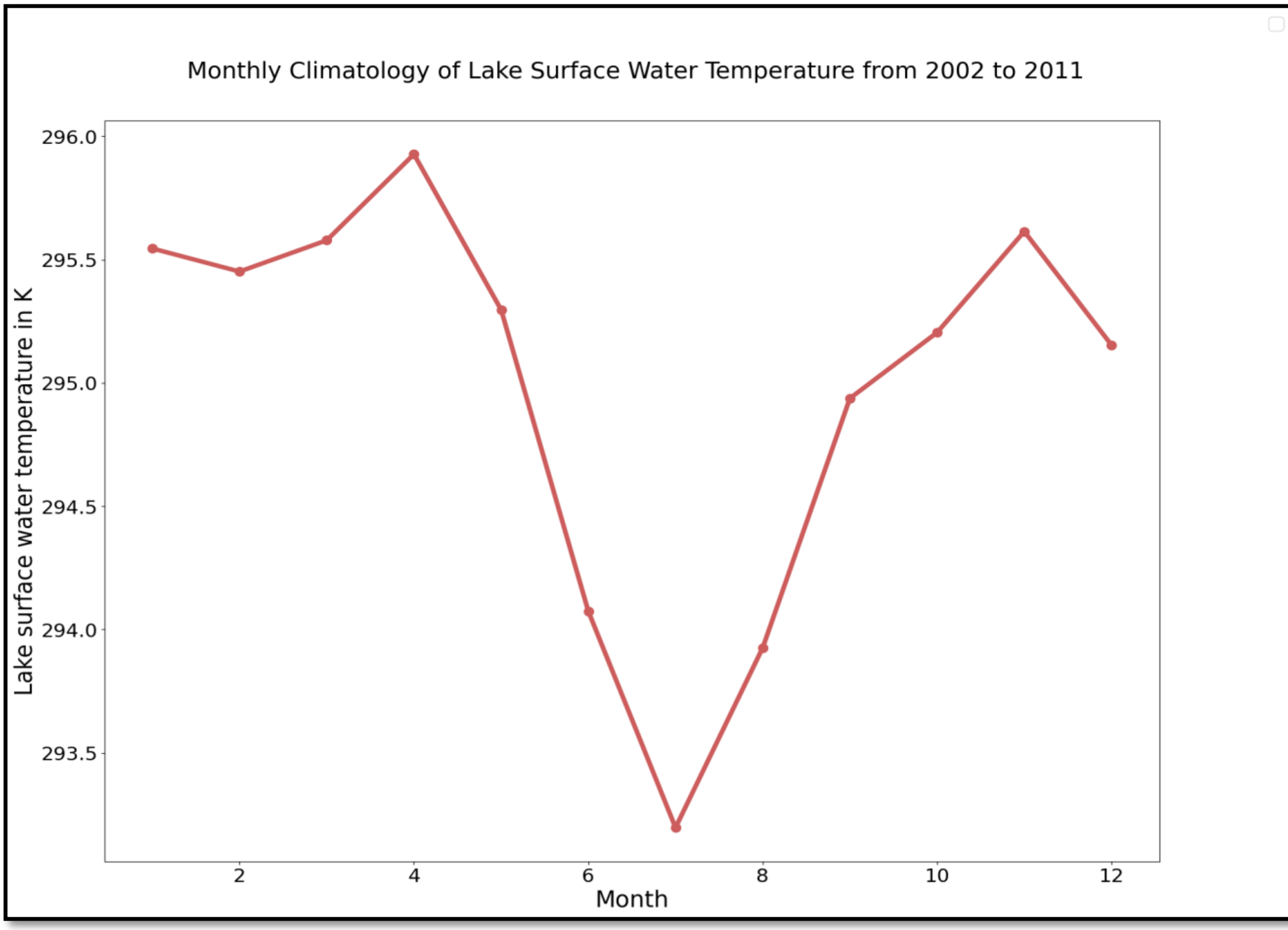

Figure 17 Monthly Climatology of lake surface water temperature

Overall, in all the years a specific seasonal pattern was observed. The maximum and minimum lake surface water temperature did not exceed 295.6 K (22.6°C) and 293.2K(20.6°C) respectively. In the months of December, January, February the approximate temperature was observed between 295 to 295.5 kelvin which is 22°C to 22.5°C. A slight elevation approximately by 0.6 K was observed in the months of March, April. The temperature values decreased by 2.4 K between the months of April (295.6K) and July (293.2). From August the temperature quickly rose by 2.3 K from 293K to 295.5K (20 °C to 22.5 °C Celsius) up to November. Fig 18 shows the spatial distributions monthly climatology of lake surface water temperature of lake Naivasha.

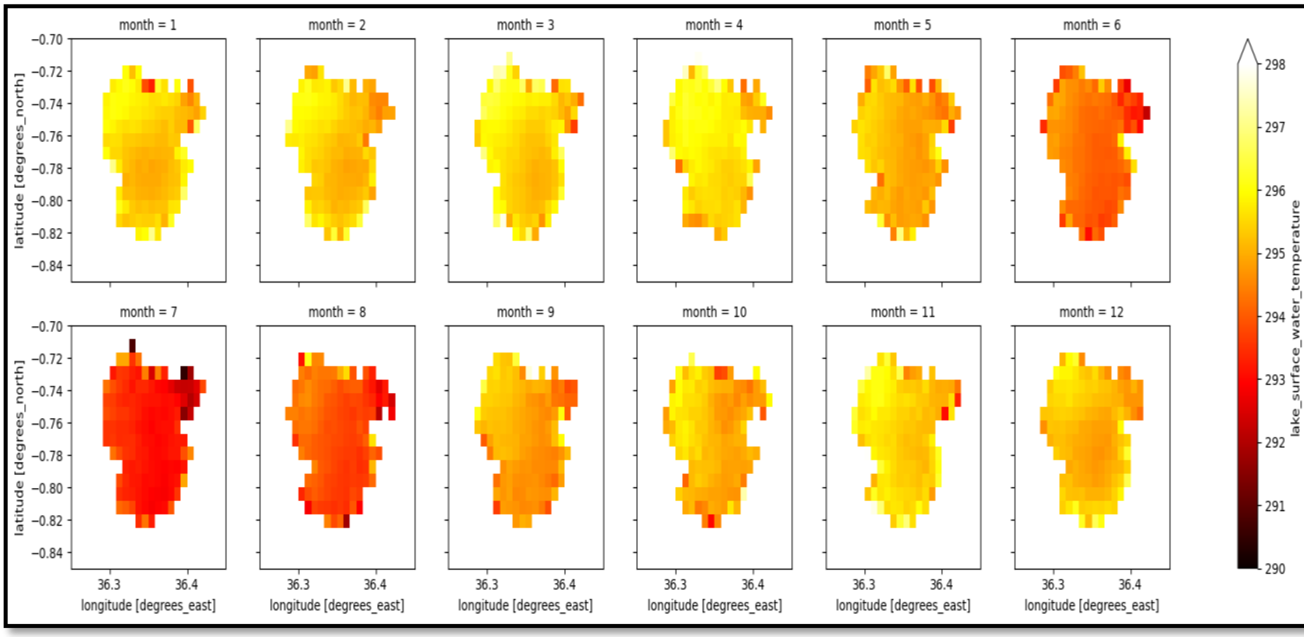

Figure 18 Monthly spatial distribution of lake surface water temperature

In the fig 18, it is observed that in months of December, January, February the lake surface water temperature was slightly lower in the center region than at the edges. In the month of April, the temperature was slightly higher in the northern region. The spatial pattern indicates rest of the months show uniform distribution water temperature.

3.4.2 TIME SERIES DECOMPOSITION OF PRECIPITATION

The fig 19 illustrates seasonal decomposition of temporal trends for precipitation. The upper panel shows time series data observed. The second panel and third shows decomposition of time series into trend and seasonality respectively. The fourth panel show the residuals.

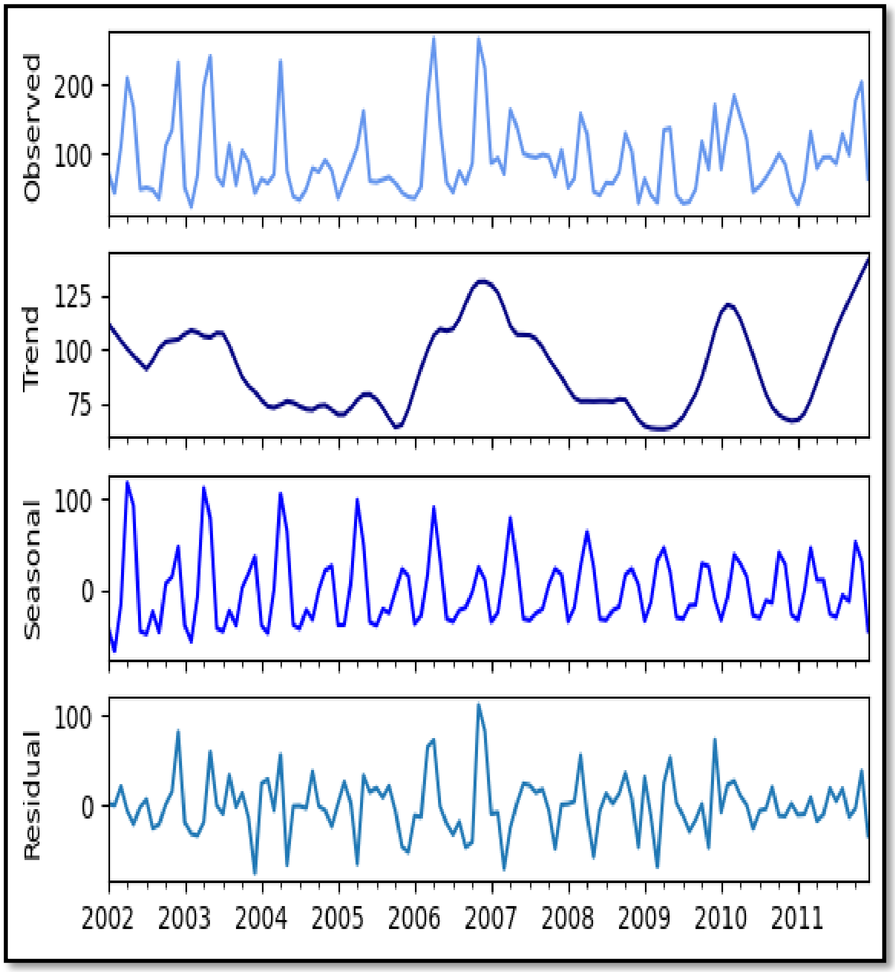

Figure 19 Time series decomposition of Precipitation

In the fig 19 the trend of the monthly mean precipitation showed fluctuation between 75 to 125 mm/month. The trend displayed no clear positive or negative slope indicating that the precipitation was neither increasing nor decreasing in the timeseries. The precipitation levels first decreased from 100 mm/month to 75 mm/month between the year 2002-2005, then increased briefly between 2006-2008 mm/month 75 to 125 mm/month. From the year 2009, trend decreased between 75 mm/month to 90 mm/month, but later on it showed increase in precipitation values for 2011.The seasonal plot almost matches the observed values plot. From the seasonal pattern it was observed that the seasonal trend is changing from 2008.The seasonality is more understood with monthly climatology displayed in the fig 20.

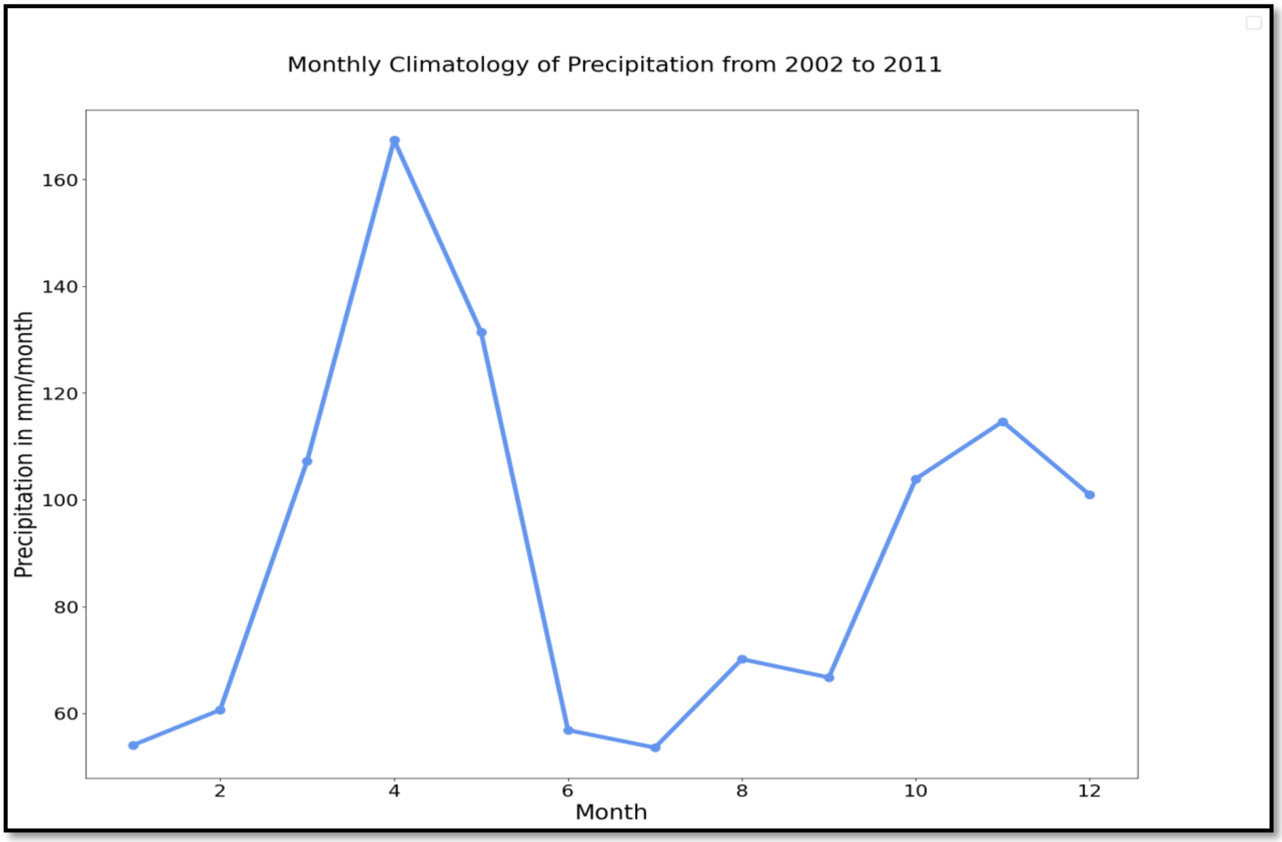

Figure 20 Monthly Climatology of precipitation

According to the monthly climatology(fig 20), the precipitation is not uniformly distributed in all the months. It has a particular pattern between 2002-2011. In the months of March April May, the precipitation was elevated with prominent peak in April with 167.5 mm/month whereas between October-December the precipitation was moderately less with a peak in November(114mm/month). Lowest precipitation was observed in July-September and January-February. Based on the precipitation, the months grouped into wet season and dry season. Months with precipitation higher than 100mm/month were classified as wet season and months below 100mm/month were classified as dry season. Table 3 shows the months in dry season and wet season.

srno	months	seasons
1.	January, February, June, July, August, September	Dry Season
2.	March, April, May, October, November, December	Wet Season

Table 3 Months with dry and wet season

3.5 DETECTION OF HARMFUL ALGAL BLOOMS BY ESTIMATING CHLOROPHYLL-A AND PHYCOCYANIN USING REMOTE SENSING ALGORITHM.

RQ2- Are the harmful agal blooms of cyanobacteria present on Lake Naivasha in the year 2002 to 2011?

The time series of cyanobacteria index is shown in fig 21. According to the cyanobacteria index, high phycocyanin count was detected in the year 2002,2003,2005,2007,2008 and 2011. The cyanobacteria index was interpreted based on the bloom size calculated using the bloom extend from table 2. The spatial distribution did not show entire lake but only the region where cyanobacteria index detected phycocyanin.

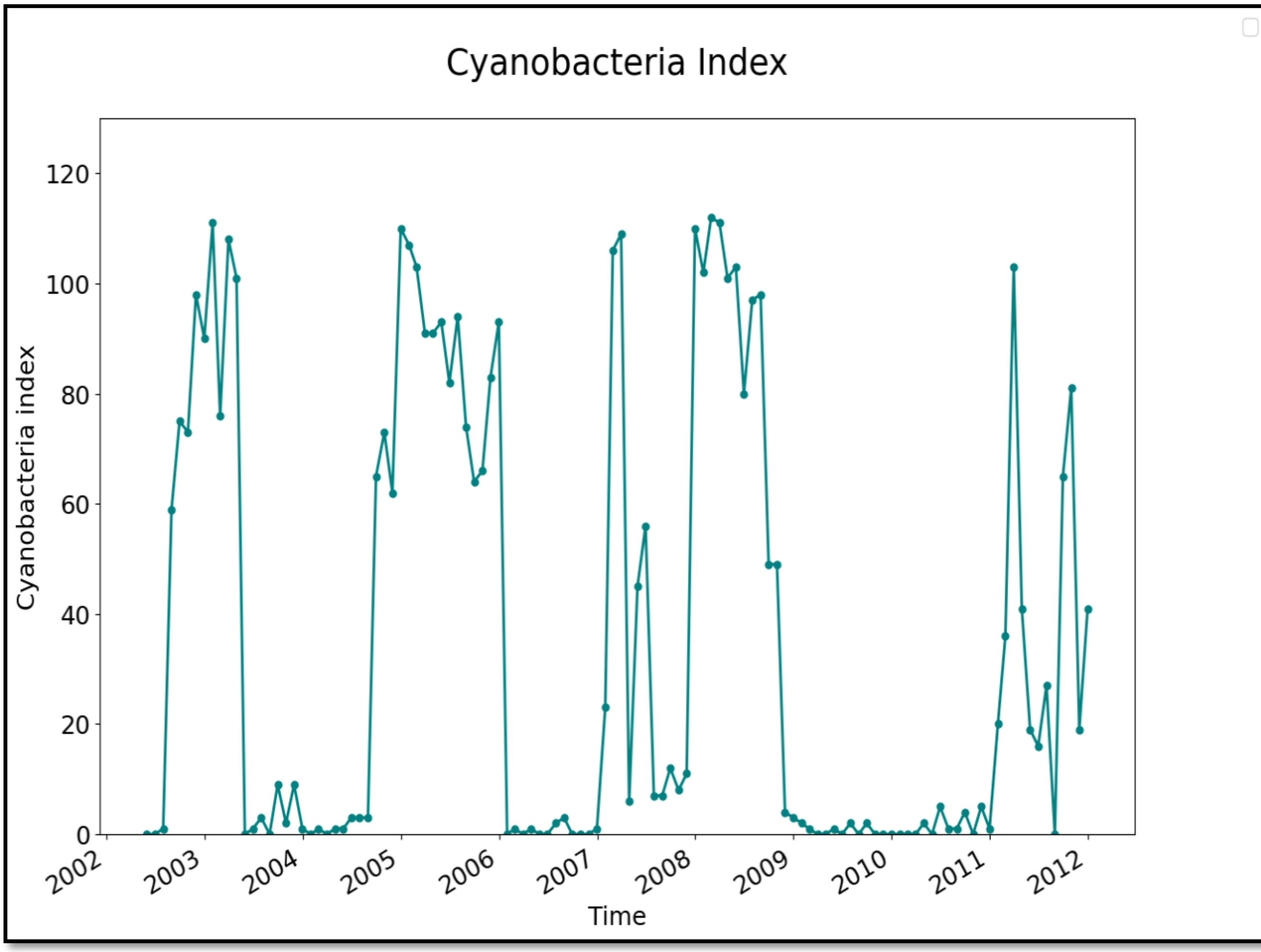

Figure 21 Time series of Cyanobacteria index

Between the year 2002-2003 the bloom size increased steadily and reached almost to 111km^2 in January and reduced slightly in February by 35 km^2 but quickly increased in next month and remained constant up to April 2003. In May 2003 the bloom area reduced to nothing and then cyanobacteria index did not detect phycocyanin rest of the year. Spatial distribution(fig 22, 1) showed bloom extend predominantly in the central part of the lake with some high count central northern region. Compared to previous year, lesser bloom size of average 66 km^2 was observed between the months of September to November 2004 but it quickly increased to 101 km^2 in December and remained between 80 km^2 to 100 km^2 the month of July 2005. Between August to December 2005, on an average the bloom reduced by 26 km^2. Spatial distribution (fig 22, 2) showed that the presence of cyanobacteria in entire region detected as water pixels by the Lake CCI algorithm. In the year 2007, the cyanobacteria index detected high count phycocyanin in January, February, and March and then slightly lower in between May-June. The average bloom extent in January, February, March was 80 km^2 and reduced by 30 km^2 in May-June. The spatial distribution during January-March (fig 23, 1) showed that the cyanobacterial are present all over the lake but slightly higher count was seen in the southern region possibly due a very intense bloom or scum. In May-June (fig 23, 2) there was reduction in bloom area, and it was in the center of the lake. Next, high Cyanobacteria index was next observed in between the December 2007 to August 2008 with average bloom size of 101 km^2 and almost reduced to half in the next months. Spatial distribution (fig 24, 1) show that the area centered in the middle section. In September and October, the bloom size reduced but high phycocyanin count was seen in the northern part of the lake in the spatial distribution maps(fig 24, 2). In the year 2011, the index detected high bloom extent of 103 km^2 was observed in the month of April and the average bloom extent between the January to April was 50 km^2. The areas reduced by 30 km^2 in next three month and blooms appeared to have disappeared in month of August but reappeared back in September and continued to bloom between October to December having same average area as January-April. Over the lake(fig 25, 1) the blooms are concentrated in the center covering almost whole lake between January and April and low in month of July. Between September to December(fig 25, 2), the bloom shifted to the Northeast region of the lake. Table 4 shows the average bloom extend for the years with cyanobacteria index

Sr.no	Year	Average Bloom Extent km^2
1	December2002- April 2003	87.8
2.	September 2004-December 2005	84.4
3	January-March 2007 May-June 2007	79 .3 36
4	December 2007-August2008	92
5	January and April 2011 September to December 2011	50 37

Table 4 Average bloom extent in the years with cyanobacteria

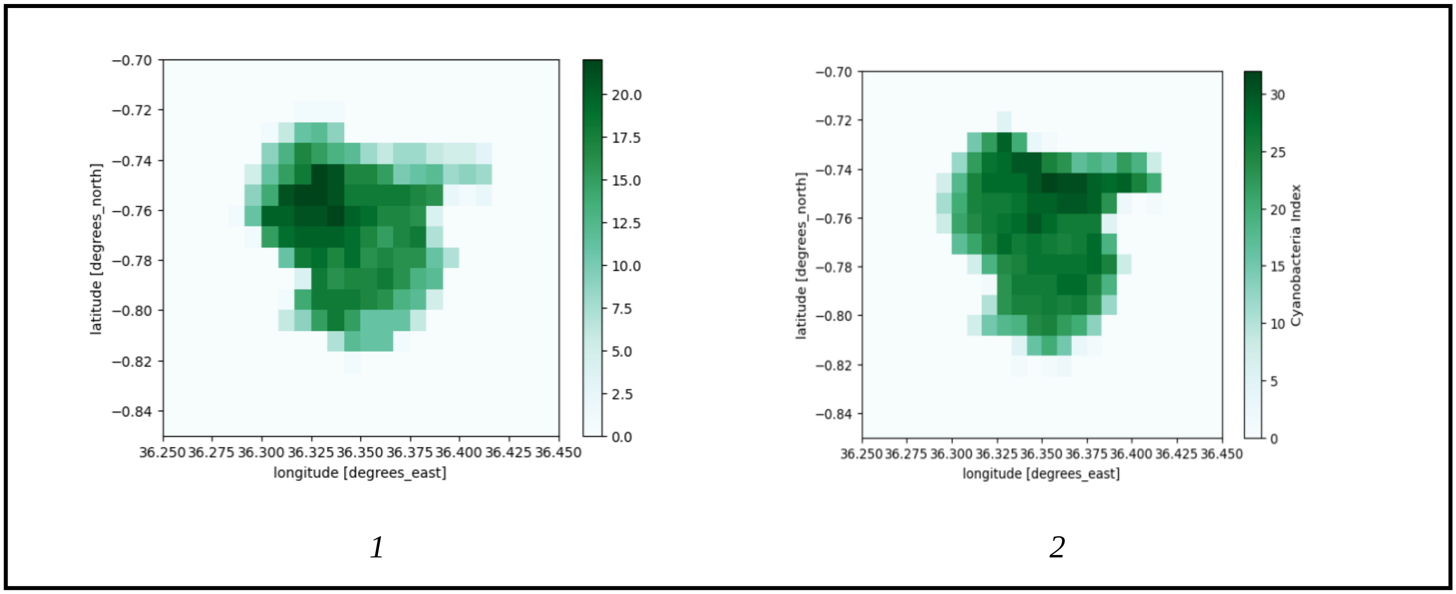

Figure 22 1 -Spatial extent of cyanobacterial bloom in 2002-2003 and 2- Spatial extent of cyanobacterial bloom in 2004-2005

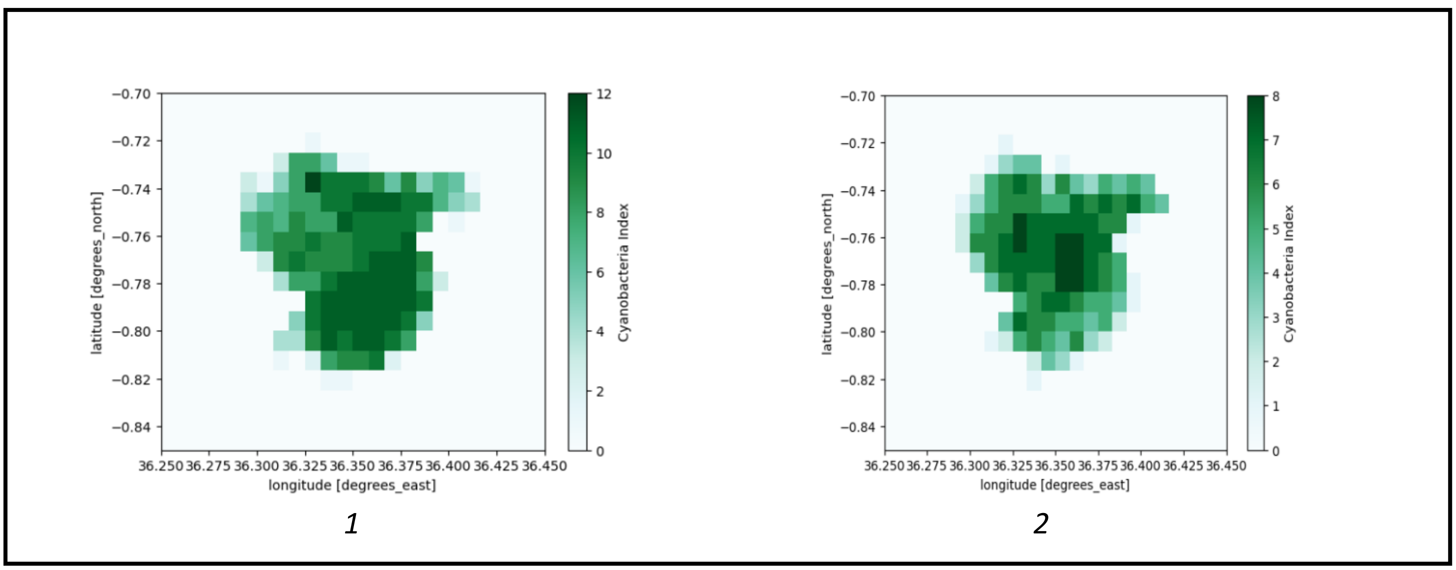

Figure 23 1-Spatial extent of cyanobacterial bloom between January-March 2007. 2-Spatial extent of cyanobacterial bloom in May-June 2007

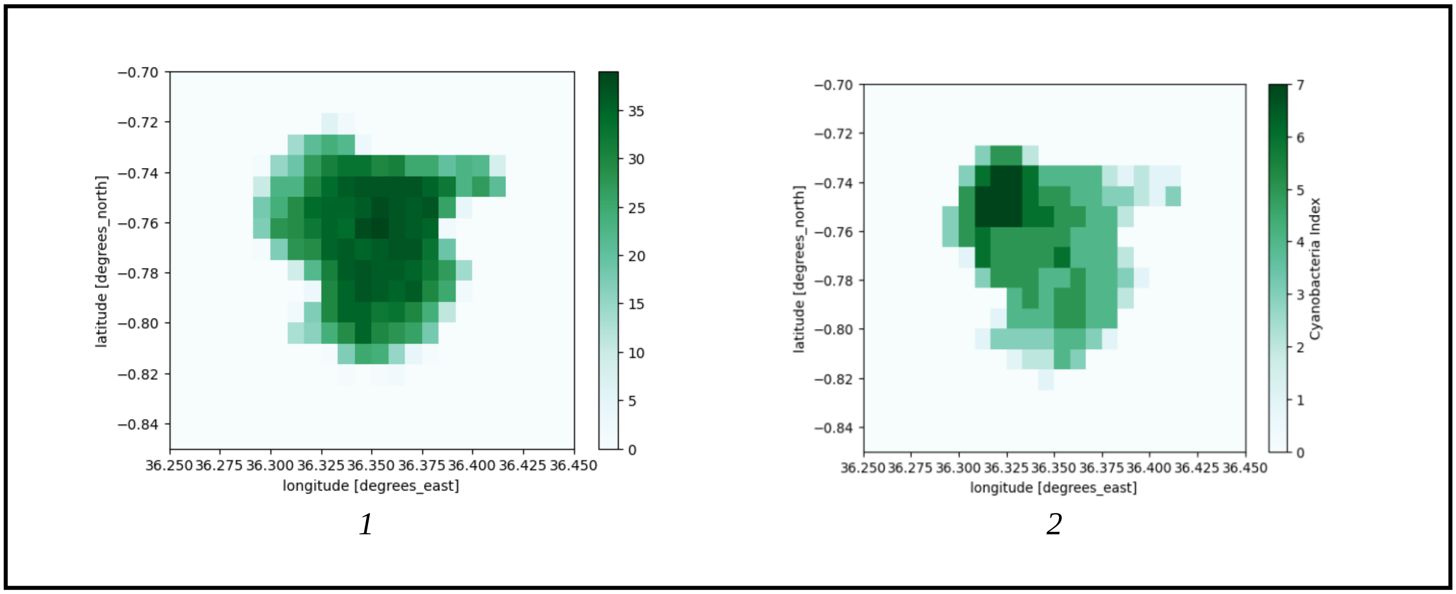

Figure 24 1- Spatial extent of cyanobacterial bloom between Decembe2007-August 2008, 2 Spatial extent of cyanobacterial bloom in September-October 2008

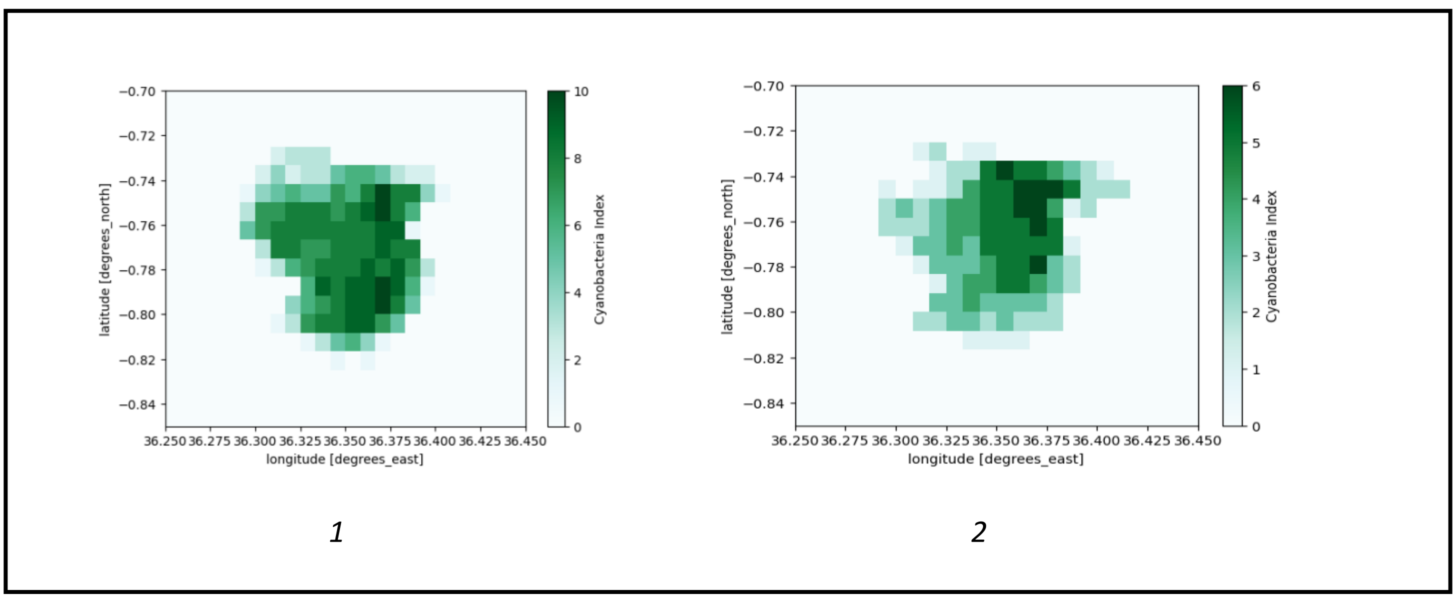

Figure 25 1 Spatial extent of cyanobacterial bloom between January-April 2011, 2-Spatial extent of cyanobacterial bloom in September-October 2011

3.6 ANALYSIS OF HARMFUL ALGAL BLOOMS OF CYANOBACTERIA GROWTH PERIOD AND DETERMINING EFFECTS OF PRECIPITATION AND LAKE SURFACE WATER TEMPERATURE DURING THE GROWTH PERIOD

RQ-3 What is the growth period of Cyanobacterial bloom and is Lake surface water temperature and precipitation affecting the growth of harmful algal blooms in lake Naivasha?

3.6.1 SEASONAL GROWTH WINDOW AND BLOOM INDICES

The fig 26 shows the timeseries of chlorophyll-a concentrations and phycocyanin detected by using cyanobacteria index over lake Naivasha. The data for chlorophyll-a was smoothened, and the peaks are identified to determine the rate of change of chlorophyll-a during the years detected positive for cyanobacteria index. In the months of year 2002-2003 which detected phycocyanin, the first optimum peak of chlorophyll-a concentration was observed in the June 2002, suggesting the end of previous growth window. For the time series considered in this study, the cyanobacteria index was first observed in August 2002 therefore the growth window for year 2002-2003 was considered from August 2002.The next optimum was seen observed in May suggesting the end of growth, therefore the maximum growth was between August-April for the year 2002-2003. The maximum chlorophyll-a concentration during this growth window was 66.55 mg/m^3. In this way, by analyzing the peaks in the chlorophyll-a concentration timeseries coinciding with the months showing phycocyanin, the growth window was determined. Table 5 summarizes the growth window, wet or dry season determined from table 3 during the seasonal window, estimated bloom indices and peak chlorophyll-a concentration in the bloom.

According to table 5, In general the months of January, February, March is common in all the years experiencing cyanobacterial bloom. The start and end of the blooms depends on the season. The average bloom intensity is between 32 mg/m^3 to 65 mg/m^3. with cyanobacterial blooms in June-October 2011 showing the highest intensity. Depending on the season, the bloom extent on an average cover 40% to 80% of the lake surface. The most extensive bloom was observed in 2007-2008 growth period which covered almost 80% of the lake area however the bloom severity was worst in the 2002-2003 and 2004-2005 growth window. Despite having large extent 2007-2003 growth window had the low intensity making it third most sever bloom occurrence over lake Naivasha. The peak chlorophyll-a concentration and intensity had decreased during some growth period but towards the end of time series it was higher than the start of the time series. The least sever blooms were observed between May-July of 2007. In 2011 growth windows, a significant shift is observed in the bloom intensity. Highest chlorophyll-a concentration was observed in January- March 2011 growth window and highest bloom intensity was observed in June-October growth window.

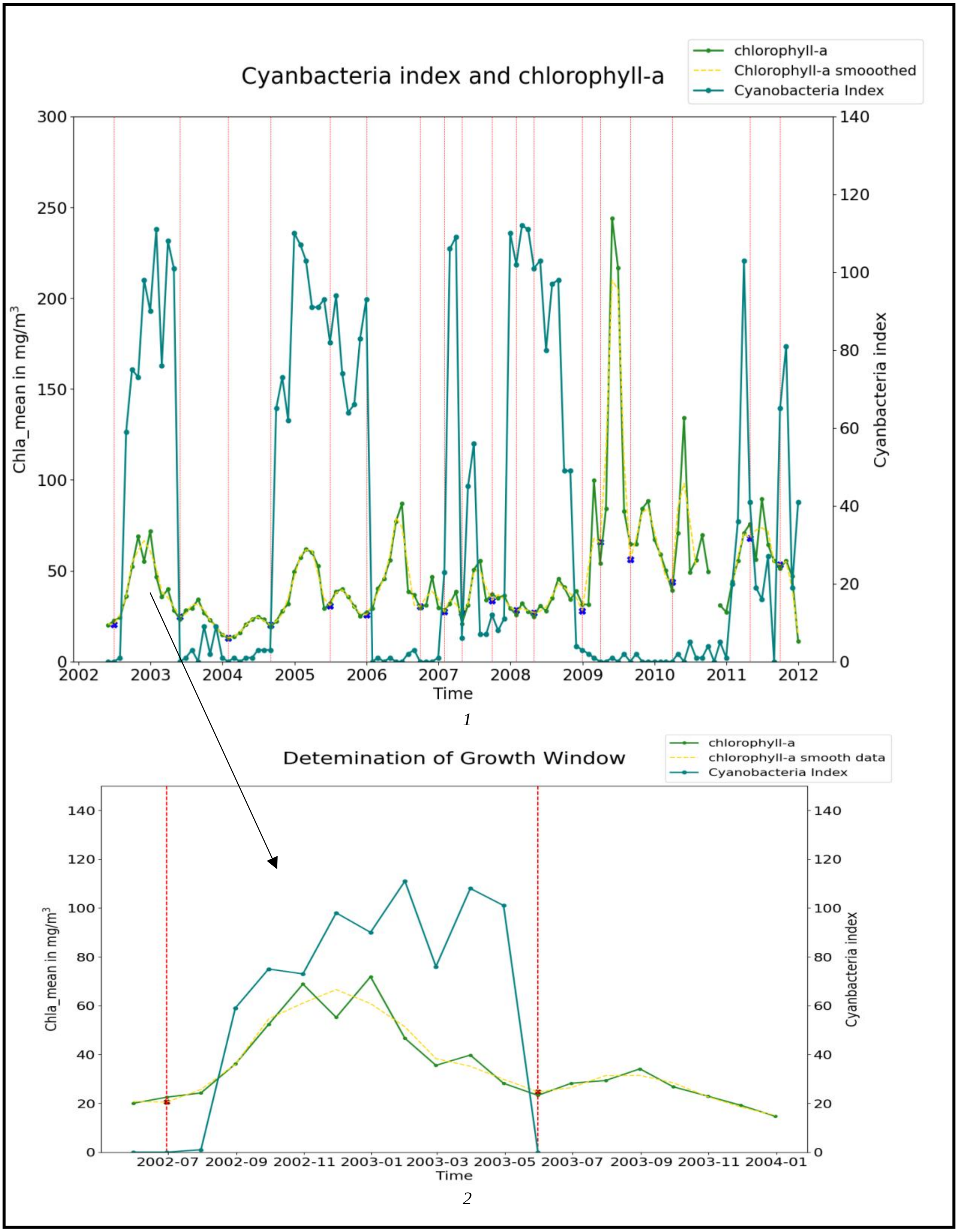

Figure 26 1-time series of cyanobacteria index with chlorophyll-a 2- Determination of growth window between 2002-2003

Sr.no	Year	Growth Window	Seasons	Average Bloom Intensity mg/m^3	Average Bloom Extent km^2	Bloom Severity mg/m^3 km^2	Peak Cha concentration mg/m^3
1	2002-2003	August 2002-April 2003	Start in dry season, end in wet season	48	87.8	4176	66.55
2.	2004-2005	September 2004-December2005	Dominated by wet season	38.8	84.4	3259	61.44
3	2007	January-March May -July	Dry Season Wet Season	32 45	79 36	2528 1620	31.6 50.1
4	2007-2008	December 2007-October 2008	Dominated by wet season	32	92	2944	42.8
5	2011	January-March June -October	dry season dry season	56.7 65	50 37	2835 2405	70.7 55

Table 5 Estimation of Growth window and bloom indices

3.6.2 EFFECTS OF LAKE SURFACE WATER TEMPERATURE AND PRECIPITATION CYANOBACTERIAL GROWTH

The fig 27 and fig 28 shows a plot of chlorophyll-a concentration and cyanobacteria index with respect to lake surface water temperature and precipitation. Based on the growth window, the average lake water temperature and precipitation during that growth window was calculated.

Table 6 show the results derived for average lake surface water temperature and average precipitation, with the bloom indices.

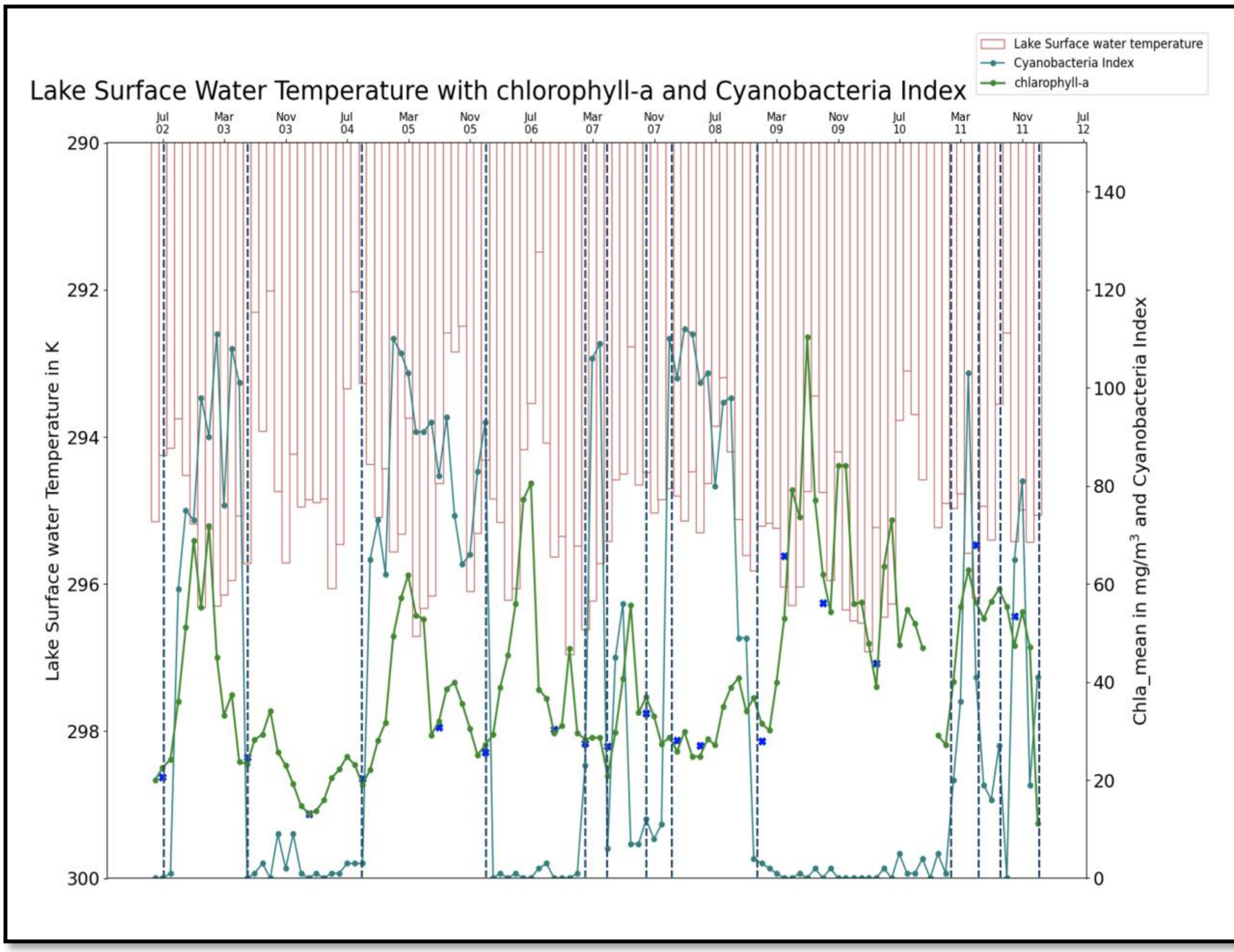

Figure 27 Chlorophyll-a and Cyanobacteria index with lake surface water temperature

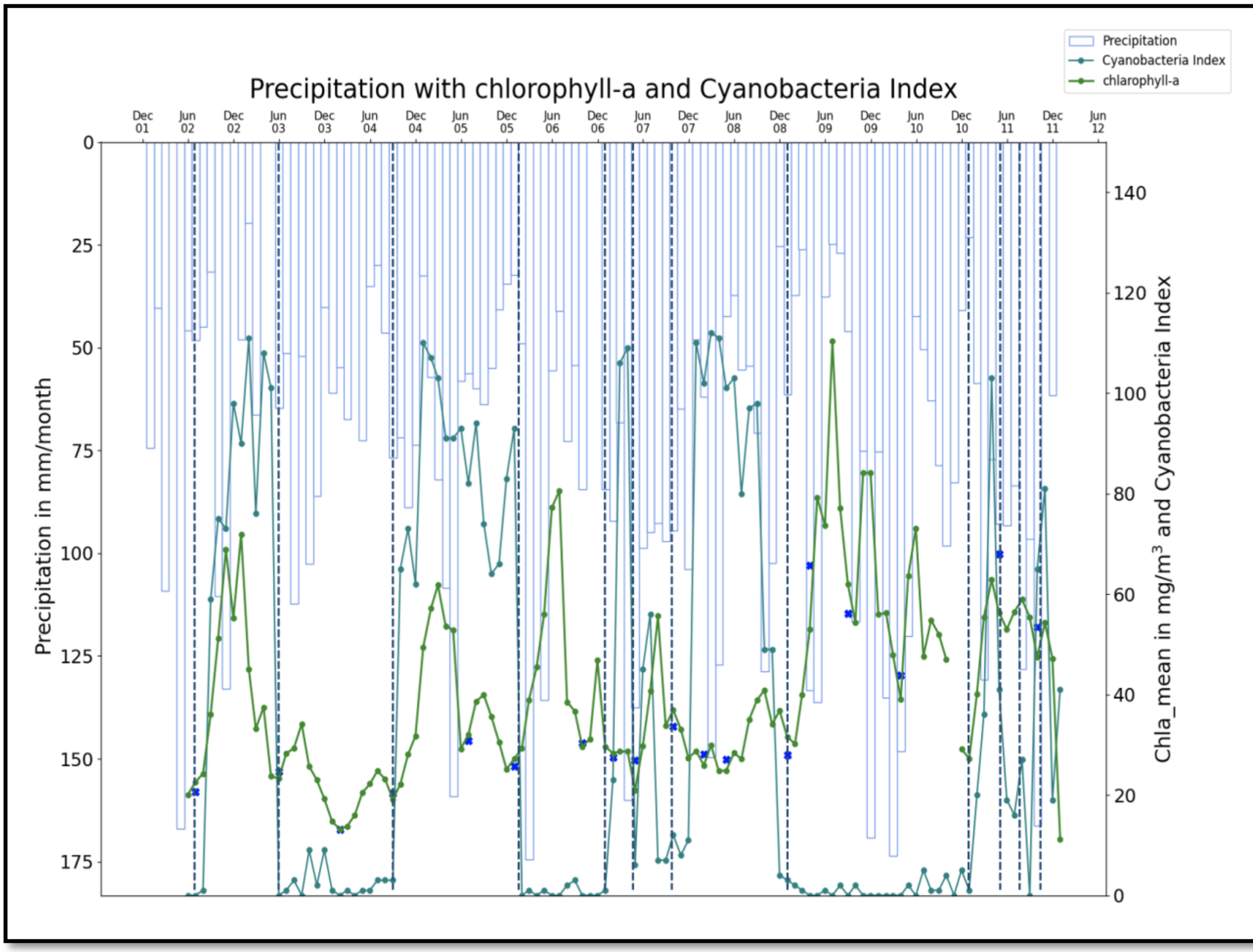

Figure 28 Chlorophyll-a and Cyanobacteria index with precipitation

Sr.no	Year	Growth Window	Seasons	Average Bloom Intensity mg/m^3	Average Bloom Extent km^2	Bloom Severity mg/m^3 km^2	Average LSWT K	Average Precipitation mm/month
1	2002-2003	August-April	Start in dry season, end in wet season	48	87.8	4176	295.3	68.2
2.	2004-2005	September 2004-December2005	Dominated by wet season	43	85	3655	294.7	69
3	2007	January-March	Dry Season	32	79	2528	296.1	81.6
		May -July	Wet Season	45	36	1620	294	108.4
4	2007-2008	December 2007- October 2008	Dominated by wet season	32	92	2944	294.6	70.4
5	2011	January-March Dominated	dry season	56	53	2968	295.1	70.8
		June -October	dry season	65	37	2405	294.3	100.5

Table 6 Average Lake surface water temperature and Precipitation during growth window with bloom indices

According to table 6 the average lake surface water temperature during the cyanobacterial growth in each year is between 294K-296K. It is observed that growth period with same bloom intensity of 32 mg/m^3 with almost similar precipitation levels has highest and lowest lake surface water temperature values. Highest Lake surface water temperature was observed in January-March 2007 growth period, but the bloom intensity was lowest during this growth window. In the same year, in the next growth window, the lowest water temperature was recorded with increased bloom intensity. These observations show that there is no definite correlation observed between the increase in lake surface water temperature and average chlorophyll-a concentration or bloom intensity during the growth windows.

According to the results in the table 6,2002-2003 growth window had highest bloom severity (4176 mg/m^3 km^2) and lowest average precipitation (68.2 mm/month). The 2004-2005 growth window also experienced similar precipitation levels as 2002-2003 growth window and therefore it was second most sever bloom detected over lake Naivasha. High precipitation levels reduce the cyanobacteria biomass and thus reducing the cyanobacterial extent over the lake. Growth window of 2007-2008 had the highest bloom extend but the average precipitation was low due to which this growth window experienced third most sever bloom event. Similar results were observed 2002-2003 and 2004-2005 growth window the average precipitation is less in January-

March(70.8mm/month), and it increased by 30mm/month in May-June. The average bloom extend decrease by 43 km^2 with increase in average precipitation as the high precipitation levels reduced the cyanobacterial biomass which reduced the bloom extent. However, the bloom intensity increases in wet season. During the dry season of January to March of 2011, the bloom intensity was high. In the June- October growth window, high average precipitation was observed even though the growth window was dominated by dry season. This was because, the month of August despite being a dry month, experienced 128mm/month precipitation.

4 DISCUSSION

4.1 VERIFICATION

The results for verifying if the Lake CCI derived chlorophyll-a concentration was similar to chlorophyll-a absorbance measured in the lake, show no correlation. There are various reasons for the low r-square value. The first reason could be the day of the in-situ data available. The in-situ absorbance was available only for 23 September 2010. In this month the reflectance data from which the lake CCI derived chlorophyll-a show large variability due to turbidity as seen from fig 14. The second reason could be the number of location points. In general, both in-situ and satellite observation have substantial uncertainties, but the random uncertainties average out if the data points are more in number leading to reliable statistics.11 location with uncertainties cannot provide reliable statistics. The third reason could be the location of the in-situ data. According to fig 7 in-situ observation are in the northern region of the lake and the satellite detects the chlorophyll-a concentrations for the whole lake. These location would have been good representative if the chlorophyll-a concentrations were homogenous, but the satellite data detected variations in the chlorophyll-a concentrations. The fourth reason could be the algorithm developed to retrieve chlorophyl-a concentration. The different algorithm which estimates the concentration use the reflectance recorded at the sensor. There is the possibility that the Lake CCI algorithms overestimated the chlorophyll-a concentrations. The fifth reason for low correlation could be due to atmospheric interference. Even though Lake CCI do best to provide atmospherically corrected data, there still could be uncertainties possibly arising due absorption and scattering by water vapor, aerosols which could affect atmospheric signal. The absorption and scattering by water vapor, aerosols etc. can be source of uncertainties in case of in-situ observations also.

4.2 DATA LIMITATIONS

This study explores the idea of using lake CCI data variables to analyze the spatiotemporal variations in lake surface water temperature, chlorophyll-a and use lake water reflectance to detect presence of cyanobacteria. The variables are atmospherically corrected for the water pixel only and therefore the areas at the shore of the lake where there is a chance of contamination by land pixel is excluded from the algorithm which might have affected the results of this study. The cyanobacterial bloom extend depends on pixel area and not the fraction of the pixel there the bloom extend might be different. The temporal density of the lake surface water temperature observation is lower for the initial years because data for those years was obtained only from earlier ERS-ATSR which had a lesser temporal coverage. Overall, the results show low variability in the data except for year the 2009-2010. The GPM-IMERG has overestimated the precipitation levels in few months due to which the results might differ.

4.3 INVESTIGATION OF EXISTENCE OF TRENDS IN LAKE SURFACE WATER TEMPERATURE AND PRECIPITATION PATTERNS

RQ1- Is there increase in lake surface water temperature and changes in precipitation patterns in the years from 2002 to 2011?

The study found no evidence that surface water temperature of lake Naivasha is increasing between 2002-2011, but according to the figure of worldwide satellite-derived warm-season lake surface water temperature (LSWT) trends from 1996 to 2018 in(Woolway et al., 2020) the lake surface water temperature has increased by 0.2 °C decade^{-1}. However, this trend was not observed in this study. This could be because there is a lot of natural variability in the observation recorded for lake surface water temperature. The trend shows slight upward movement from 2009 but it cannot be definitely said that the trend is increasing. A longer timeseries of in needed to justify it. The main reason for not detecting any significant increasing trend in lake Naivasha's water temperature is a short time series. The other reason could be the location of lake Naivasha, according to (Woolway et al., 2020) in general, lakes in the colder regions where mean temperature below -0.4°C in winters are warming more quicky than lake in the region with warm winters.

The study did not detect any drastic changes in the precipitation pattern for lake Naivasha between 2002-2011. Studies indicate that the average precipitation patterns have not changed for the past between 1960-2010(Odongo et al., 2015). However,(Ayugi et al., 2016) have concluded that compared to 1991-1999, the precipitation levels have decreased in 2000-2010 in entire Kenya. (Awange et al., 2013)not only reported a decrease in total annual rainfall from 1960 to 2010 but also in all the seasons between 2002-2010 for Lake Naivasha. The decline in seasonality trend between 2002-2011 was also observed in this sudy.The monthly climatology detected a bimodal precipitation patterns during the entire time series. The bimodal distribution pattern corroborate with the previous studies done by (Camberlin and Okoola, 2003; Yang et al., 2015) for entire Kenya region. Lake Naivasha basin is located in Kenya which in the Intertropical convergence zone (ITCZ)(Camberlin and Okoola, 2003; Veenvliet, 2014). Intertropical convergence zone is a region near equator where the trade winds from north and south hemisphere converge. The intense solar heating in this region warms the air, making it humid and buoyant. The converging winds rises the buoyant air resulting in cloud formation and precipitation. Due to lack of air movement, this region has been called doldrums by sailors.(Daoxian, 2013; Rosenberg, 2020; Waliser and Jiang, 2015). The ITCZ, is the driving factor for seasonality of the precipitation observed in this region. Apart from this, Kenya experiences the monsoon winds, subtropical high pressure, the tropical cyclones, the trade winds phenomenon which are associated with either with high or low precipitation(Ayugi et al., 2016).Due to the presence of Mount Kenya and Nyandarau range, during the monsoon season, the monsoon winds cast a rain shadow over lake Naivasha due which the spatial distribution of the precipitation varies from 600mm/year in the town area to 1700mm/year over the mountain ranges. (Becht et al., 2005; Veenvliet, 2014)

4.4 DETECTION OF HARMFUL ALGAL BLOOMS BY ESTIMATING CHLOROPHYLL-A AND PHYCOCYANIN USING REMOTE SENSING ALGORITHM.

RQ2- Are the harmful agal blooms of cyanobacteriapresent on Lake Naivasha in the year 2002 to 2011?

In the fig 21, between 2002-2011,the presence of cyanobacteria was detected in all the years except 2006, 2009 and 2010. Historical records report that cyanobacteria are present in lake Naivasha since 1974. According to(Kalff and Watson, 1986), a shift from diatoms species in lower biomass to green algae species in moderate biomass to peak biomass of cyanobacteria between 1970 and 1980 was observed. In 2005, blooms dominated by toxin producing species of cyanobacteria called Microcystis were first observed over lake Naivasha.(Harper, 2006; Harper et al., 2011) and its presence has been recorded in many studies since then(Ballot et al., 2009; Krienitz et al., 2013; NYANGOYA, 2018; Raffoul et al., 2020). In this year other species of cyanobacteria present over lake Naivasha were *Aphanocapsa, chroococcus, Cyanocatena,* (Krienitz et al., 2013). This study also detected the presence of cyanobacteria in the entire year of 2005. The cyanobacteria index used in this study, detected presence of cyanobacteria in 2002-2003.(Krienitz et al., 2013) reported the presence of green algae bloom *Botryococcus terribilis* also called as oil-alga. This bloom also had species of cyanobacteria called *Chroococcus limneticus*. Since cyanobacteria index detects phycocyanin, it showed the presence of cyanobacteria in these months. This study also reported the presence of other species of cyanobacteria such as *Aphanocapsa, Cyanocatena, Microcystis spp* over Lake Naivasha. In 2007 (Murakaru, 2010) observed green scums over lake Naivasha by the end of 2007 and start of 2008 which corresponds to the findings of this study. (Krienitz et al., 2013) reported occurrence of cyanobacteria species of *Aphanocapsa, Chroococcus, Coelomorum, Microcystis aeruginosa, Microcystis spp, Planktothrix, Cyllindrospermopsis* in the same year. In 2011 (Krienitz et al., 2013) recorded the presence of cyanobacteria species *Aphanocapsa, Chroococcus, Coelomorum, Microcystis aeruginosa, Microcystis spp, Planktothrix, Cyllindrospermopsis* which confirms the findings of this study for that year.

Literature review showed that in the year 2006, the cyanobacterial blooms of species *M.aeruginosa* and coccoid cyanobacteria were recorded in the Elsamere region near the southwestern part of the lagoon which is towards the shoreline(Ballot et al., 2009; Krienitz et al., 2013)of lake. Lake CCI algorithm could not record the reflectance data for this region due to presence of land pixels therefore cyanobacteria index could not detect phycocyanin in this region. (Raffoul et al., 2020) recorded that there were Cyanobacterial blooms in 2009 and 2010 too, but in this study, due to high turbidity, the reflectance data for these two years was inconsistent and highly variable due to which the cyanobacterial bloom was not detected in this time of the year by cyanobacteria index.

4.5 ANALYSIS OF HARMFUL ALGAL BLOOMS OF CYANOBACTERIA GROWTH PERIOD AND DETERMINING EFFECTS OF PRECIPITATION AND LAKE SURFACE WATER TEMPERATURE DURING THE GROWTH PERIOD

RQ-3 What is the growth period of Cyanobacterial bloom and is Lake surface water temperature and precipitation affecting the growth of harmful algal blooms in lake Naivasha?

The results of this study show that the surface water temperature of lake Naivasha is stable between 293.2K(20.6°C) and 295.6 K (22.6°C). Even though there is no increasing trend, it is observed that the lake surface water temperature of Naivasha is at an ideal temperature for the cyanobacteria to dwell for some time on the lake as the growth of phytoplankton other than cyanobacteria reduces once the water temperature increases between 15°C to 25°(288K to 298 K). In their study (M & M, 2015; Smucker et al., 2021) reported that the cyanobacteria thrive when the water temperature raised between 20°C (293K) to 27°C (300K) and the growth rate of diatoms decreases during the same temperature range. According to the study done by (Deng et al., 2014) *Microcystis*, a species of cyanobacteria grows rapidly when the water temperature is above 16°C (289 K) and that water temperature above 20°C (293K) is ideal from full bloom development.
The outcome of the study showed a stronger relationship between the rate of change chlorophyll-a concentration and precipitation than lake surface water temperature and chlorophyll-a in Lake Naivasha. Cyanobacteria index detected the presence of cyanobacteria in wet season as well as dry season. During high precipitation levels, the cyanobacterial biomass is flushed out which reduces the cyanobacterial biomass.(Reichwaldt and Ghadouani, 2012).This relationship between increased mean precipitation and reduction in cyanobacterial biomass was observed in this study as the bloom extend decreased in one of the growth windows of 2007 and 2011 when the mean precipitation was high(table 6). Exact opposite situation, where lower mean precipitation having higher cyanobacterial bloom extent was observed in rest of the growth windows. However, the high precipitation levels bring in more nutrients input to already nutrient rich lakes via surface runoffs which increases the concentration of chlorophyll-a(Reichwaldt et al., 2015; Reichwaldt and Ghadouani, 2012). (Ndungu et al., 2013) observed increasing nutrient load from nearby agricultural area with high precipitation causing increase in chlorophyll-a concentration in Lake Naivasha between 2002-2010 .This was situation was observed in the growth window which showed high mean precipitation, had average chlorophyll-a concentration higher leading high bloom intensity. Lower precipitation levels lead to intensification of nutrients in the lake, and which again increases chlorophyll-a concentrations and may also favor the increase of toxin levels produced by cyanobacteria. (Kleinman et al., 2006; Reichwaldt et al., 2015; Reichwaldt and Ghadouani, 2012).This relationship between lower precipitation and higher concentration of chlorophyll-a was observed in almost all of the growth windows of this study. Lower mean precipitation levels growth widows have high bloom intensity. (Raffoul et al., 2020) reported that nutrient inputs followed by precipitation causes cyanobacteria growth, increasing the production of cytotoxin over lake Naivasha. The study also reported that during dry season, high concentrations of microcystin toxin were observed.

5 CONCLUSION

The main questions this study sets out to answer were whether lake surface water temperature was increasing and were precipitation pattern changing over lake Naivasha and if so, how were they affecting the occurrence of cyanobacterial blooms and finally understand which them is the main driver for the bloom intensity, bloom extend and bloom severity.

RQ1- Is there increase in lake surface water temperature and changes in precipitation patterns in the years from 2002 to 2011?

The study concluded that the surface water temperature of lake Naivasha is not increasing or decreasing steadily or rapidly. The location might be the probable reason for a not detecting any significant increase in lake surface water temperature.

In case of precipitation, the study does not indicate any changes in monthly average precipitation patterns but saw a slight decline seasonal trend which was confirmed by literature. The study also did not observe any changes in the bimodal precipitation distribution pattern. The location of lake Naivasha might be the reason for not observing any sudden precipitation changes.

RQ2- Are the harmful agal blooms of cyanobacteriapresent on Lake Naivasha in the year 2002 to 2011?

The cyanobacteria index did detect the presence of phycocyanin over lake Naivasha in most of the years in the time period considered for this study and literature does indicate the cyanobacteria blooms were present those years. Nevertheless, it could not detect the blooms present in other years due variability in the reflectance data and Lake CCI algorithms not detecting the shoreline areas.

RQ-3 Is the Lake surface water temperature and precipitation affecting the growth of harmful algal blooms in lake Naivasha?

The investigations of this study show that increase in water temperature does not have any effects on chlorophyll-a concentrations and occurrence of cyanobacteria. However, the lake surface water is at ideal temperature for the full bloom development of certain species of cyanobacteria. Precipitation has a stronger influence on the bloom indices. Lower precipitation enhances the bloom extend as there is no flushing of the cyanobacterial bloom and increases the cyanobacterial intensity due to concentration of nutrients in the lake Naivasha. Higher precipitation levels do reduce the bloom extent but increases the bloom intensity due addition of nutrients from surface runoffs.

6 RECOMMENDATIONS

This study attempted to determine the relationship of lake water temperature and precipitation with cyanobacterial bloom using remote sensing data. The study will give better results for trend of precipitation and lake surface water if the time series is longer than ten years. Investigation of nutrient inflow into the lake will benefit the determination of growth window. The nutrient levels could be determined by means laboratory analysis or by investigation changes in land use and land cover changes by remote sensing techniques. Since the cyanobacterial index in this study was ineffective during high turbid conditions, a different algorithm determining phycocyanin concentrations might give better results. Since MERIS gives data between 2002-2012, use of MODIS sensor with a different phycocyanin detecting index might be effective to determine a longer time series for cyanobacterial bloom. As phycocyanin concentration in the Lake Naivasha were not determined in this study, the in-situ concentrations will help to validate the chosen remote sensing algorithms. More situ data needed for verification of Chlorophyll-a and phycocyanin with the remote sensing algorithms.

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