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Evaluating and Predicting the Risk of Algal Blooms in a Freshwater Lake through a 4-Dimensional Approach: A Case Study on Lake Mitchell

Sumit Kumar Ghosh

EVALUATING AND PREDICTING THE RISK OF ALGAL BLOOMS IN A FRESHWATER LAKE THROUGH A 4-DIMENSIONAL APPROACH: A CASE STUDY ON LAKE MITCHELL

BY

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THESIS ACCEPTANCE PAGE

Sumit Kumar Ghosh

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

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Excessive algal growth in freshwater lakes can negatively impact ecosystems, recreation, and human health. Though algae are a natural part of freshwater ecosystems, elevated nutrient loading from anthropogenic and natural sources can lead to algal blooms. Both algae and blue-green algae (BGA) are responsible for algal blooms; however, BGA (cyanobacteria) is more dangerous. The first objective of this research was to prepare a conceptual model to understand how various environmental variables affect algae. This conceptual model was used to choose the environmental variables that help increase or decrease algae in the water environment. The second objective was to develop empirical equations to identify how the environmental variables are helping algal increase or decrease. Lake Mitchell, near Mitchell, SD, was chosen as a case study to collect the data of the environmental variables. Along with the total algae (Total algae = Chlorophyll-a + Phycocyanin), five variables: (1) conductivity, (2) temperature, (3) fluorescent dissolved organic matter, (4) ammonium, and (5) dissolved oxygen, were collected. Algae concentrations can change temporally, vertically within the water column, and spatially across lakes and thus, a four-dimensional approach was used to accurately quantify algal

presence and concentration in Lake Mitchell during the 2020 bloom season. Over four sampling events, 271 points were collected with an average of 68 points per event. Data points were collected through the entire water column (surface to bottom) using a EXO2 Multiparameter Sonde. Regression models were developed to understand the influence of collected parameters on the algal bloom growth. This research will help to understand what factors significantly influence algae in freshwater lakes through time, within the water column, and spatially across freshwater bodies. The third objective of this research was to use satellite imagery to quantify algal mass in a freshwater lake by developing a regression model. In-situ ground truth data of total algae were used from the objective two. Each sampling event data set was compared with Level-2 Sentinel-2A cloud-free satellite images taken within ±1 day of each sampling event. The regression model was developed in R studio, with the total algae (Total algae = Chlorophyll-a + Phycocyanin) data as the dependent variable and the surface reflectance value for each band as explanatory variables. This model was then calibrated (R^2=0.41) and validated, then the Raster Calculator tool in ArcGIS Pro was used to evaluate algae's spatial distribution in the study lake. An improved procedure was followed to measure the total algal mass, and a data processing procedure was introduced to prepare the empirical model. This procedure has been named “Aquatic Correction,” which improved model performance (From R^2=0.07 to R^2=0.40). Future research applications will enable lake managers to monitor lake conditions remotely and make management decisions without needing highly resource-intensive in-situ monitoring.

Chapter-1 | Introduction

Algae are a natural part of aquatic ecosystems, but can cause tremendous damage to the environment, human health, livestock, and other animals if it grows excessively which is known as algal bloom. About $100 million annually is spent in the USA to eradicate algal blooms (Griffith & Gobler, 2019). Among the various algal species, blue-green algae are considered most dangerous even though they are not actually algae at all. Blue-green algae are basically cyanobacteria but like other algal species they can perform photosynthesis, besides morphologically they have similarity with the algae.

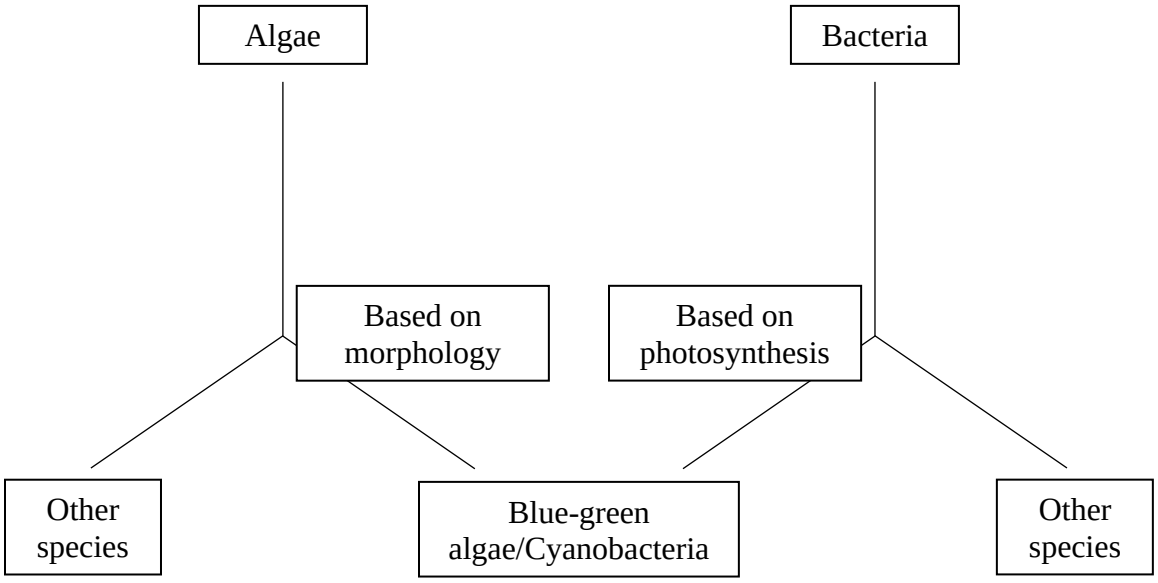

Figure 1. Simplification of Blue-green algae's nomenclature.

Different environmental variables influence algal quantity, though different species respond differently to environmental factors. While there is a significant body of research related to the threat of algal communities to environmental systems, human health, livestock, and other animals, several research gaps have been identified. These include:

(1) Insignificant understanding of the environmental parameters' influence over algae in the complex aquatic environment,

(2) Insignificant mathematical explanation of water quality parameters influence on algae, and

(3) Proper procedure has not been commonly used to remove the non-algal particles reflectance while preparing algal mass detection empirical model.

Concerning the research gaps, the three objectives of this study are:

(1) To propose a significant conceptual model of "How do environmental parameters affect algae in the complex aquatic environment?"

(2) To assess the mathematical relationship between various water quality parameters and algae.

(3) To prepare a total algal mass detecting empirical model using a novel procedure referred to as "aquatic correction".

In the first objective, the algal cycle was conceptualized with relation to several environmental components: (1) solar radiation, (2) temperature, (3) oxygen and dissolved oxygen, (4) rainfall, (5) runoff, (6) turbidity, (7) nutrients and thunderstorms, (8) saline/conductive elements, (9) dissolved organic matter, (10) carbon, and (11) wind. The

conceptual model is helpful to describe how algal species function in the aquatic environment, which supports understanding for future algae-related research. For example, if researchers wanted to make an empirical equation to identify which parameters help to increase, or decrease algal mass in a water area, then based on this conceptual model they can decide which parameters should be taken as independent variables.

In the second objective, based on the conceptual model, conductivity, temperature, fluorescent dissolved organic matter, ammonium, and dissolved oxygen were chosen to develop empirical models to identify these parameters impact on algal growth in a specific area of water. This information adds to the collective knowledge of what factors are significantly correlated with algal mass in freshwater lakes through time, within the water column, and spatially across freshwater bodies.

In the third objective, a novel procedure was developed to measure total algal mass in aquatic systems using remote sensing and aquatic correction. Aquatic correction, improved model performance through improving the data quality. Combining remote sensing with in-situ ground truthing and aquatic correction enables lake managers to develop and use tools to measure algal mass in aquatic environments.

Chapter-2 | Literature Review

2.1 Introduction to Algal Community

Algae consist of many varieties of organisms, all of which are polyphyletic, and have multiple evolutionary ancestors (Bhattacharya, 1997; Krienitz, 2009). Algae are ubiquitous across the planet (Bhattacharya, 1997); mainly living in aquatic environments, but also in soil biomes (Raven & Giordano, 2014). Most algae are photosynthetic (Krienitz, 2009) and utilize sunlight for energy production which is vital to oxygen cycling and the global food web (Guiry, 2012). The overall chemical reaction of the photosynthetic process (Yu et al., 2021) is,

$$6H_2O + 6CO_2 \xrightarrow{\text{Sun light (12 hv)}} C_6H_{12}O_6 + 6O_2 \qquad (1)$$

Which describes that the photosynthetic organisms use water, carbon dioxide, and solar radiation to produce glucose ($C_6H_{12}O_6$) and oxygen. Almost all algae are eukaryotic (Krienitz, 2009), and they are genetically (Guiry, 2012) and morphologically (Bhattacharya, 1997) diverse. Algae's cell structure varies from unicellular to multicellular (Guiry, 2012). Their body structure is homogenous and differs from more complex photoautotrophs, such as plants, since it does not consist of any roots or leaves. Algae may be found in varieties of sizes, which range from microscopic to a maximum of 80 m in length. (Taylor et al., 2009).

According to Fritsch (1935), algal communities can be broadly categorized into eleven classes. The eleven classes are: "(1) *Chlorophyceae* (*Isokontae*), (2) *Xanthophyceae* (*Heterokontae*), (3) *Chrysophyceae*, (4) *Bacillariophyceae* (Diatoms), (5) *Cryptophyceae*, (6) Dinophyceae (Peridinieae), (7) *Chloromonadineae*, (8) *Euglenineae*, (9)

Phaeophyceae, (10) *Rhodophyceae*, and (11) *Myxophyceae* (*Cyanophyceae*)". Among these eleven classes, photosynthetic (Nozaki, 2003) green colored (Sivak & Preiss, 1998) *Chlorophyceae* mostly dominate in freshwater environments (Wehr & Sheath, 2003). The eleventh class *Myxophyceae* (*Cyanophyceae*), is also called blue-green algae (Cymbaluk, 2013), is found in freshwater environment.

Blue-green algae are not algae but rather cyanobacteria (Li & Liu, 2019; WHO, 1998). According to the WHO (2003a), blue-green algae's cell structure has similarities with unicellular algae. Blue-green algae are photosynthetic, and they have blue-green pigments which are not found in other bacteria. That is why they are typically termed blue-green algae. Like other bacteria, blue-green algae are prokaryotes (USEPA, 2019), contributing about 2000 species to the ecosystem (Vincent, 2009).

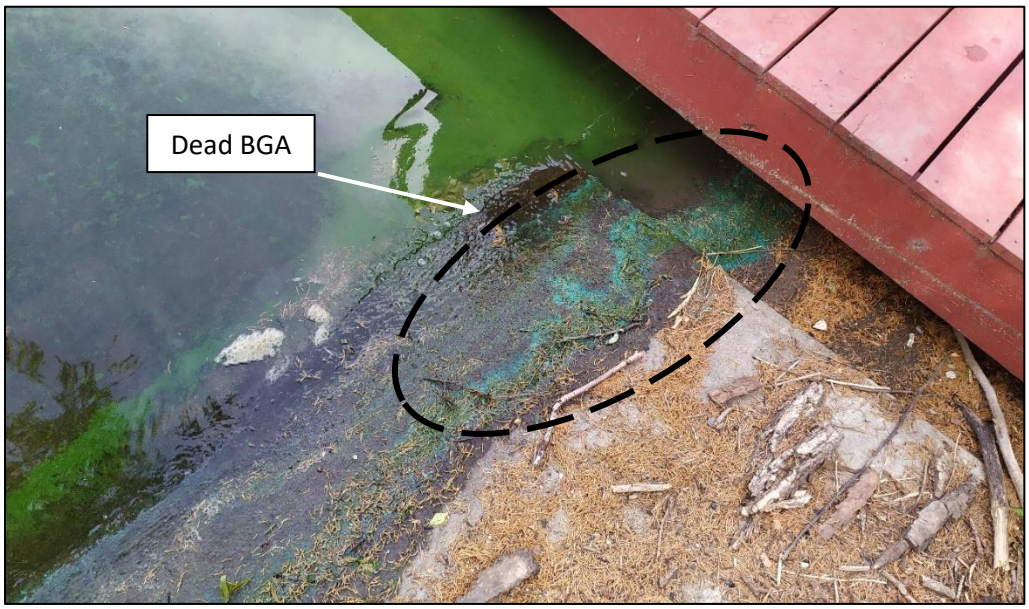

Figure 2. Blue-green algae (BGA) appear more green than blue (WHO, 2003b), but after their death, they become blue (SDSU-Extension, 2006). Photo by Sumit Kumar Ghosh.

2.2 Algal Community's Impact on Ecology, Economy, and Finance

Essentially, an algal community is not harmful if it is produced in a controlled environment. Some essential products, including fuel (Chisti, 2019), nutritive foods and beverages (Cofrades et al., 2013), and organic fertilizers (Fishman, 2021) are produced from algae. However, excessive algal growth, which is called an algal bloom, can cause harm to the aquatic environment, human health, livestock, and other animals (WHO, 2003c). Algal blooms can also cause economic losses due to decreased aquatic recreation and pisciculture, and financial losses due to aquatic management and public health related expenses (Table 1).

Table 1. Toxic algal blooms' annual economic and financial impact in the USA from 1987 to 1992. Source: Anderson et al. (2000).

Topic	Low ($)	High ($)	Average ($)	% of total
Recreation & tourism	-	29,304,357	6,630,415	13.44%
Commercial fishery	13,400,691	25,265,896	18,407,948	37.32%
Monitoring & management	2,029,955	2,124,307	2,088,885	4.24%
Public health	18,493,825	24,912,544	22,202,597	45%
Total	33,924,471	81,607,104	49,329,845	100%

Both toxic, or harmful, and non-toxic algal species can negatively impact local ecosystems and economies (USEPA, 2021a). Among algal species, the WHO (2003b) has mentioned toxicity in freshwater Dinophyceae, brackish water Prymnesiophyceae, and *Peridinium polonicum*. While freshwater algae proliferate or bloom in eutrophic water, they do not accumulate to form dense scums/blooms like some blue-green algae. That is

why blue-green algal species are considered riskier than other freshwater algal species due to their ecologic, economic, and human health impact. (WHO, 2003b).

Algal species have ecologic impacts on the aquatic environment. Increased algal blooms disturb solar radiation through the water column, which leads to increased death of underwater vegetation. This phenomenon increases the biochemical oxygen demand and depletes the water's dissolved oxygen concentration. (Brown, 1984; Wang, 1974). Dissolved oxygen depletion leads to fish death, which cascades through the aquatic food web (Hupfer & Hilt, 2008). Disturbed aquatic environments decrease recreational opportunities and tourism and increase treatment cost due to aesthetic issues like reduced transparency, discolored water, and unpleasant odor (WHO, 2003c). Along with reduced revenue from recreational activities, algal blooms also lead to reduced revenue for pisciculture. Due to *Prymnesium parvum* blooms, from 1985 to 2003, Texas lost around 17.5 million fish, worth $6.5 million (Lopez et al., 2008). Caged fish are very vulnerable to toxic algal blooms; Chile lost around $800 million due to algal toxicity-affected caged fish in 2017 (Griffith & Gobler, 2019). According to Robinson et al. (2021), South Australian tuna farmers suffered $45 million worth of damage due to toxic algae damaged tuna gills.

Along with algal communities' significant damage to the aquatic environment, algal toxins can also have significant negative consequences to humans and animals. In locations where people rely on pond/lake water as a drinking source, harmful algal blooms can increase toxins in the water source. These toxins cannot be easily removed by boiling, a traditional home treatment, since boiling water can actually burst algal cells and release additional toxins (O'Keeffe, 2019). The WHO (2003b) has mentioned skin-related health

issues due to the direct contact of blue-green algal species during aquatic recreational activities. Among the skin-related issues, skin irritation (Pilotto et al., 1997) and allergic reaction (Yoo et al., 1995) have been found as two frequent symptoms. Besides creating skin-related problems, blue-green algae's intrusion into the human body could increase risk of tumor development (Ueno et al., 1996). Along with direct algal toxic effects, the human body can also be poisoned indirectly through the algal contaminated food chain (Crush et al., 2008). McElhiney et al. (2001) reported that edible plants can contain algal toxicity due to irrigation with toxic algal contaminated water, which eventually can cause harm to human health. Besides plants, fish tissue can also be concentrated by algae-produced biotoxins, which can also be fatal after consumption (Griffith & Gobler, 2019; Hégaret et al., 2009). According to Anderson et al. (2000), expenses due to public health impairment resulting from toxic algal exposure is financially significant, averaging over $22 million annually from 1987 to 1992.

Livestock and other animals are also negatively impacted by toxic algal blooms. The first documented case of livestock being impacted by algal blooms was published in the 1870s. After that, several cases have been found for “sheep, cattle, horses, pigs, dogs, fish, rodents, amphibians, waterfowl, bats, zebras, and rhinoceroses” (WHO, 2003b). As reported in SDSU-Extension (2006), livestock affected with nervous system damaging cyanotoxins can face muscle tremors, decreased movement, and shortness of breath. Some complicated cases for livestock have been found of sudden collapse and death without showing any previous signs. A few types of animals have been affected with liver-damaging cyanotoxins that show several symptoms, which ultimately cause their death.

2.3 Water Quality Parameters' Influence on Algal Growth and Reproduction

As uncontrolled propagation of algal species can cause impairment on ecology, local economy, and human health, it is necessary to understand which environmental factors accelerate their growth and reproduction. According to Fritsch (1935), algal reproduction systems can be described under three categories. The first is "vegetative reproduction," where a part of the algal body is separated from the parent body. The second one, "asexual reproduction," is based on the algae cells' protoplasts rejuvenation. The third one, "sexual reproduction," happens in highly evolved algal species. There are still many unanswered questions on how the environmental factors influence algal growth and each of these reproduction processes; generally, any factor influencing algal growth also influences algal reproduction (Agrawal, 2012).

According to Agrawal (2012), among the environmental factors, sunlight's intensity, photoperiodism, and spectrum quality have the greatest impact on algal reproduction. For some algal species (i.e. red and brown algae), short day-length increases their reproduction. Algae need a specific photoperiod for asexual reproduction. For example, some algal species need darkness to produce zoospores and visible light to release the zoospores. Algal reproduction also depends on the specific spectral wavelength; for example, blue-green algae are reproductive under the red spectrum's wavelength. (Agrawal, 2012).

Temperature is considered another vital factor for algal reproduction and growth flexibility. Temperature affinity varies by species with some thermophilic and some thermophobic. (USEPA, 2019). Thermophilic algae grow under mesophilic condition where the temperature is between 20°C (68°F) to 45°C (113°F) (Schiraldi & Rosa, 2014).

Blue-green algae have been found to be more thermophilic than other algal organisms (Elliott, 2010). Mainly, bloom-intensive blue-green algae survive well under higher temperature conditions (Robarts & Zohary, 1987); but generally, their optimal growth has been found between 30°C (86°F) to 35°C (95°F). Davis et al. (2009) concluded, increased temperature generates the toxic microcystin producing blue-green algae more than the non-toxic microcystin producing blue-green algae. Thermophobic algae grow under the psychrophilic condition where optimum growth temperature is less than 15°C (59°F) (Kelly, 2011). Singh & Elster (2007) assessed Antarctic environment adaptative blue-green algae, where they survive the freeze/thaw cycle, and they can metabolize at near 0°C (32°F) temperature. Overall, temperature effect on algae is entirely species specific (Adenan et al., 2013; Griffith & Gobler, 2019).

Along with temperature, dissolved oxygen is also influential on the algal community (Griffith & Gobler, 2019). Griffith & Gobler (2019) indicated that algal blooms are more likely to occur with hypoxia in warmer situations. Dissolved oxygen is a measurement of free, non-compound oxygen available in the water environment, a significant limnology factor (USGS, 2020). Dissolved oxygen levels from 2 mg/L to 3 mg/L are defined as hypoxic (ESA, 2012).

Another important environmental factor, turbidity, or water cloudiness, influences water temperature, and is a significant factor for algal propagation. Due to its darker color turbid water converts a greater percentage of sun radiation into heat and can indirectly influence algae growth and propagation by increasing water temperature. (Paaijmans et al., 2008; Patel & Vashi, 2015). Turbidity is an optical characteristic of water (Swenson & Baldwin, 1965), which is measured by the amount of light scattered by the materials that

remain in the water (Woodard & Curran Inc., 2007). Varieties of elements are responsible for water's turbid condition; clay, silt, microscopic inorganic and organic matters, algal community, dissolved organic matters, and plankton are among those elements (USGS, 2021c). Hence, turbidity is a complex water quality parameter as it consists of other water quality parameters. Besides, turbidity can indirectly influence algae through the parameters included in it. Water's turbid condition happens due to the presence of total dissolved solids (less than 2 micrometer) and total suspended solids (greater than 2 micrometer) (Figure 3) (Fondriest Environmental Inc., 2021).

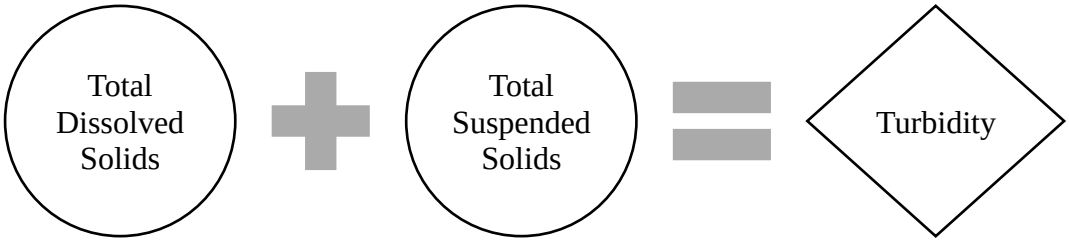

Figure 3. Flow chart for formation of turbidity, which is a dependent aquatic environmental factor.

Total dissolved solids encapsulates diverse sources, including fertilizers/nutrients, saline/conductive elements, and dissolved organic matter (USGS, 2021a) (Figure 4). Fertilizers are highly concentrated nutrients (crop macronutrients such as nitrogen, phosphorus, and potassium) containing dissolved salts (Barker, 2019). Saline elements are non-nutrient containing inorganic soluble salts (USEPA, 2021c), which conduct electricity; and conductivity measures the water's ability to pass the electricity (USEPA, 2021b). Dissolved organic matter consists of a wide variety of organic molecules, with molecular

weight ranging from less than 100 Dalton to greater than 0.3M Dalton. They are also involved in the nutrient dynamics process (Mostofa et al., 2012).

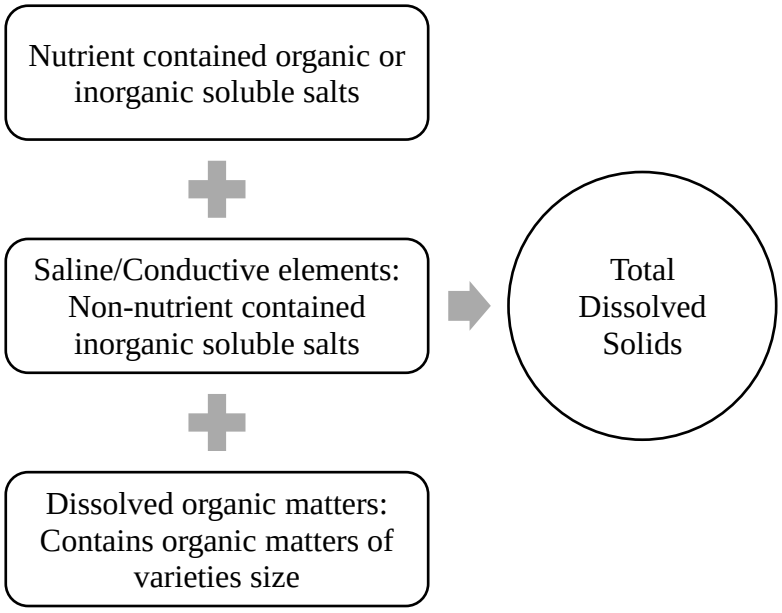

Figure 4. Flow chart for formation of total dissolved solids, which is a dependent aquatic environmental factor.

Each individual parameter included in turbidity can influence algal growth (Mueller & Helsel, 1996). Nutrients from non-point sources such as fertilizers (mostly NH_4^+ and NO_3^-) or manure or point sources such as wastewater treatment plants, are chemical compounds that are necessary for healthy ecosystems at the right concentration (Galiart, 2021). Nutrients play a significant role in vegetative growth (Mueller & Helsel, 1996). Among nutrients, nitrogen and phosphorus mainly accelerate algal growth (WHO, 2003c). The reasons behind nutrients' considerable level of availability are both naturogenic and anthropogenic. Atmospheric nitrogen is responsible for 26% of the nitrogen deposition to

the Gulf of Mexico (Figure 5) and come from anthropogenic (ammonia gas from manure, for example) and natural (lightning; Top-Crop-Manager, 2007) sources.

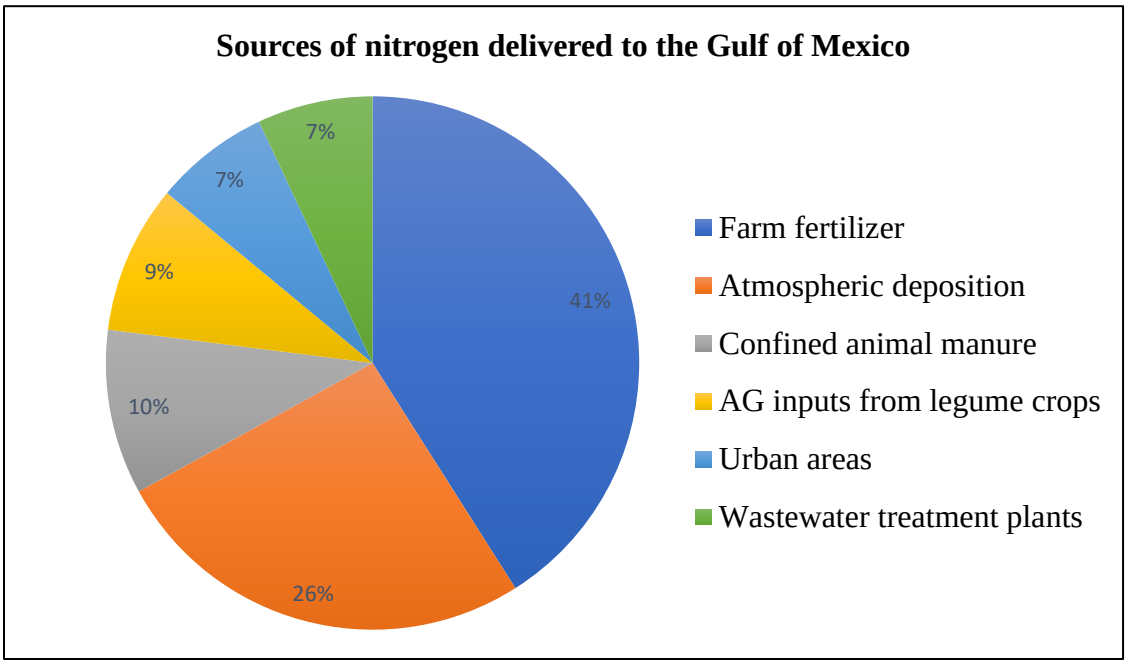

Figure 5. Nitrogen delivery sources to the Gulf of Mexico, responsible for creating toxic algal blooms in this region. This photo is adapted from USGS (2021b).

Another critical factor for microalgae growth is salinity, which has species-specific impacts (Adenan et al., 2013). Adenan et al. (2013) tested three salinity levels (20, 25 & 30%) on two types of marine microalgae (unidentified *Chlorella* species & *Chaetoceros calcitrans*). *Chlorella* species was found suitable for 25% salinity but *Chaetoceros calcitrans* was found to be productive at 30% salinity. The third constituent of total dissolved solids: dissolved organic matter, which affects algal growth, depends on how bacteria respond to dissolved organic matter provided nutrients and carbon (Klug, 2005).

2.4 Existing Algae Monitoring Processes

Due to algal blooms' potential influence on human and animal health, algae monitoring is a regular part of many state and federal agencies. Methods for monitoring include laboratory analysis, sensor-based in-situ sampling, and satellite measurement and forecasting (Smith, 2019). Currently used laboratory analysis techniques generally focus on finding algal species and concentration using chlorophyll-a as a proxy for algae concentration. Since sampling is time and personnel intensive, this method is typically employed on a relatively small scale. For in-situ algal sampling, sensors are used for monitoring at a larger scale. Several powerful sensors have been developed to collect continuous algal data, most of them use fluorescence or reflectance to measure chlorophyll-a (Xylem, 2021).

Laboratory analysis and in-situ sensor measurements are considered very accurate due to directly measuring algae presence or a component of algae presence, but these methods are challenging to scale up. Satellite forecasting presents a scalable solution for monitoring large areas (Ferdous & Rahman, 2020; Johansen et al., 2018; Olmanson et al., 2008; Page et al., 2019). Satellite forecasting enables accessible large-scale monitoring (Ferdous et al., 2019); but transferability of empirical models should be done only with calibration and validation mechanisms in place due to variable environmental conditions, geographic position, and water chemistry. Johansen et al. (2018) mentioned several empirical models; however, concerning the limitations among the empirical models, they have found Sentinel-2 based “Normalized difference chlorophyll index (NDCI)” better than other empirical models. The proposed algorithm of Sentinel-2 based NDCI is,

$$\text{NDCI} = \frac{\text{Band } 5 - \text{Band } 4}{\text{Band } 5 + \text{Band } 4} \qquad (2)$$

NDCI was first published by Mishra & Mishra (2012), which was based on 300 m spatial resolution imagery of the "Medium Resolution Imaging Spectrometer (MERIS)" satellite (ESA, 2021c). The proposed algorithm of MERIS based NDCI is,

$$C_{chl-a} \propto \frac{\text{Reflectance at 708nm} - \text{Reflectance at 665nm}}{\text{Reflectance at 708nm} + \text{Reflectance at 665nm}} \qquad (3)$$

2.5 Insight of Remote Sensing Process to Detect Algae

Current practice when preparing an empirical algal detection model, is to measure algae concentration for several point samples, and correlate that concentration with pixel reflectance. However, pixel reflectance cover a large area and depending on surface water turbidity may reflect a significant portion of the water column, not just the surface, in that area (Figure 6). In addition, a surface measurement does not accurately quantify the total algal mass, so, algal mass from the water column should be correlated with pixel reflectance. Equation 2 can be used to determine the algal mass from water volume:

$$\text{Mean concentration}\left(\frac{\text{mass}}{\text{length}^3}\right) * \text{Mean water column's depth (length)} * \text{Pixel area (length}^2) = \text{mass} \qquad (4)$$

Another thing may be possible; till now, indirectly the Equation 4 is being used for empirical model preparation. Through Equation 4, two types of empirical model preparation process typically found: (i) Algal concentration and water column's depth was assumed uniform throughout the water volume. Then, while using multiple bands, the same spatial resolution (pixel area) was used. Example: Meris-based NDCI (ESA, 2021c; Mishra & Mishra, 2012). (ii) Algal concentration and water column's depth were assumed uniform throughout the water volume. Then, while using multiple bands, the resampling technique (ESRI, 2021a) is used to match the spatial resolution if the spatial resolution is different. Example: Sentinel-2 based NDCI (Johansen et al., 2018).

Using algal mass instead of concentration might be an improved process to quantify algae by remote sensing; however, water and other non-algal particles may create disturbance to get proper algal reflectance. Algae should have a vegetation-like reflectance signature (Figure 7), but this reflectance signature should shift down due to the water particle's absorption. Also, water and other non-algal particles may distort or block actual algal reflectance (Figure 8).

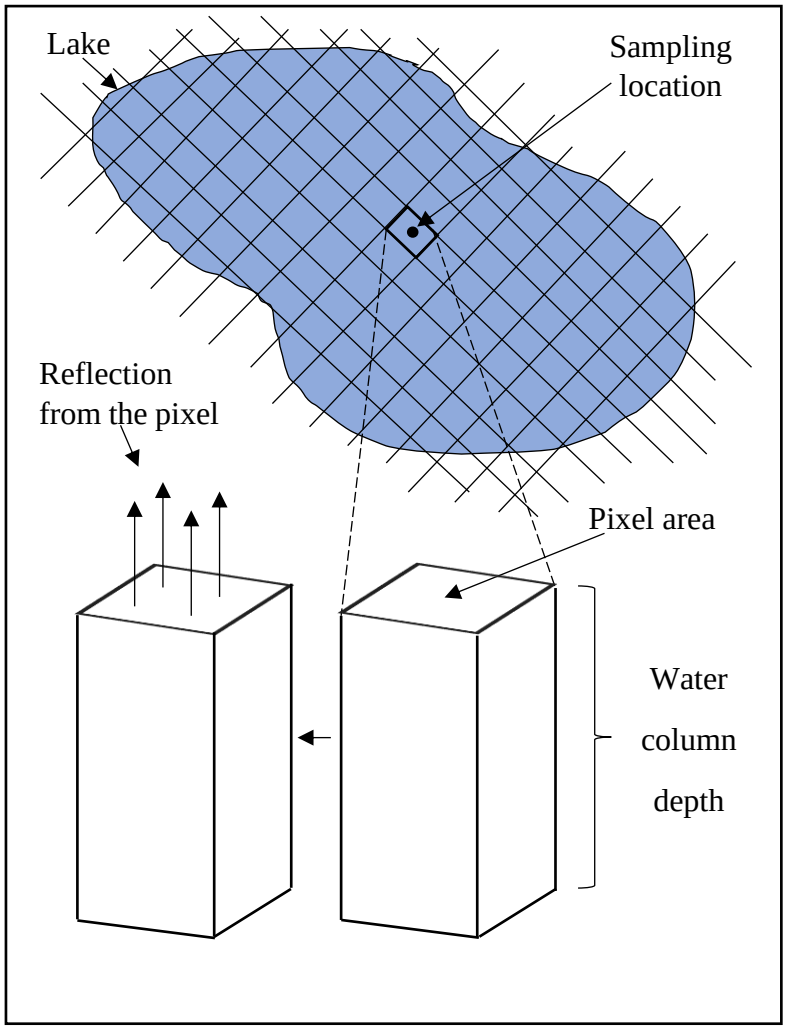

Figure 6. Illustration of "What reflectance exhibits corresponding to a pixel of a particular band?"

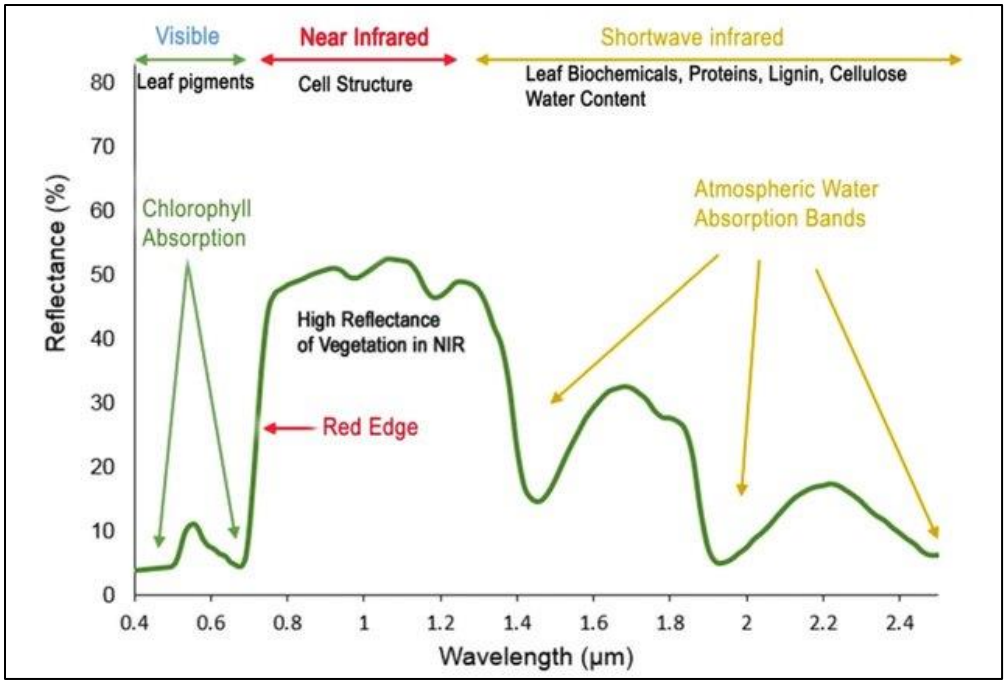

Figure 7. The spectral profile of vegetation's reflectance; This figure is adapted from Roman & Ursu (2016).

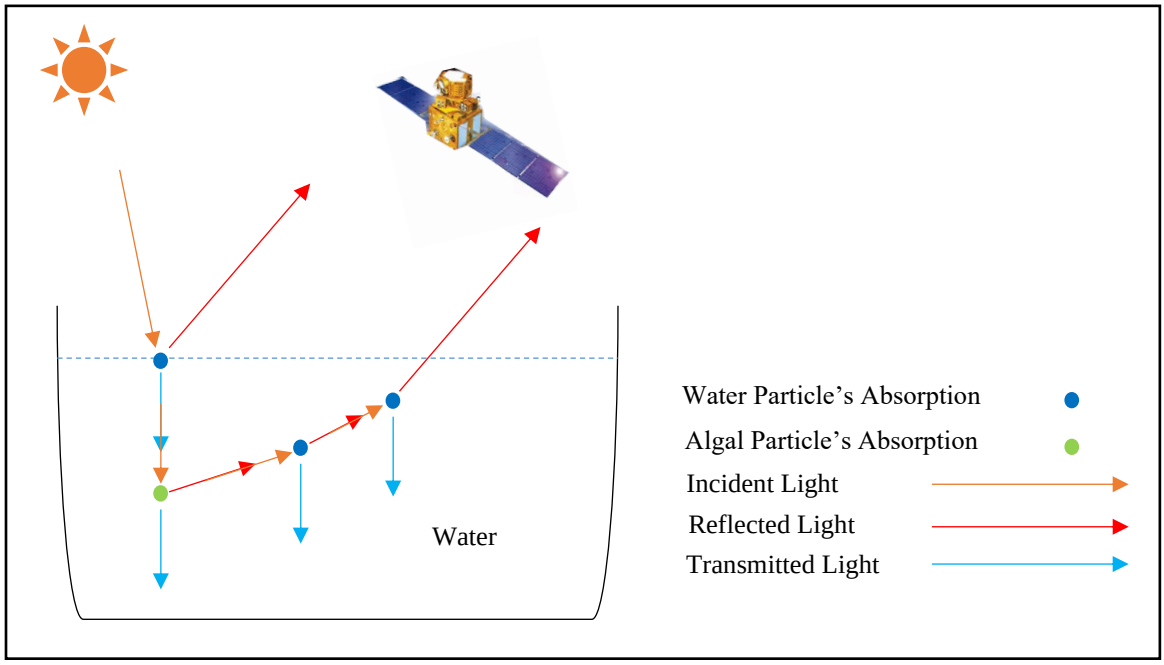

Figure 8. Illustration of "How water particles disturb to get proper reflectance from algae?"

2.6 Knowledge Gaps and Future Work

Several pieces of research have been done concerning algal growth and measurement. However, several research gaps have been found:

(1) There is insignificant understanding of the environmental parameters' effect on algae in the complex aquatic environment. In this research, a significant conceptual model of the parameters' effect on algae in the water environment was proposed which will be able to illustrate how algae function in the aquatic environment.

(2) There is insignificant mathematical explanation of the influence of water quality parameters on algae. In this research, mathematical relationship between the environmental parameters and algae was assessed.

(3) Proper procedure has not been commonly used to remove the non-algal particles reflectance while preparing an algae detection empirical model by remote sensing. For this purpose an algae detecting empirical model was prepared using a novel procedure referred to as "aquatic correction".

Chapter-3 | Conceptual Model of How Environmental Parameters Affect Algae in the Complex Aquatic Environment

3.1 Question and Assumptions of the Conceptual Model

Different environmental components influence algae growth and algae influence environmental factors. However, to give the exact answer to the question "How environmental variables affect algae in the complex aquatic environment?" is complex due to the association of lots of components. Based on some assumptions, a conceptual model might be helpful to explain this question; for this reason, a conceptual model has been prepared to understand the environmental variables effect on algae in the complex aquatic environment.

Two assumptions have been made to prepare the conceptual model:

(a) The aquatic environment contains thermophilic algal species, and an increase in temperature will lead to an increase in algal quantity.

(b) The aquatic environment contains freshwater algae and the algal species cannot survive under saline conditions.

3.2 Conceptual Model of Algal Functioning in the Aquatic Environment

Effect of Temperature on Algae (Figure 9): In a large clean freshwater vessel, solar radiation will increase water temperature, which will increase algal quantity.

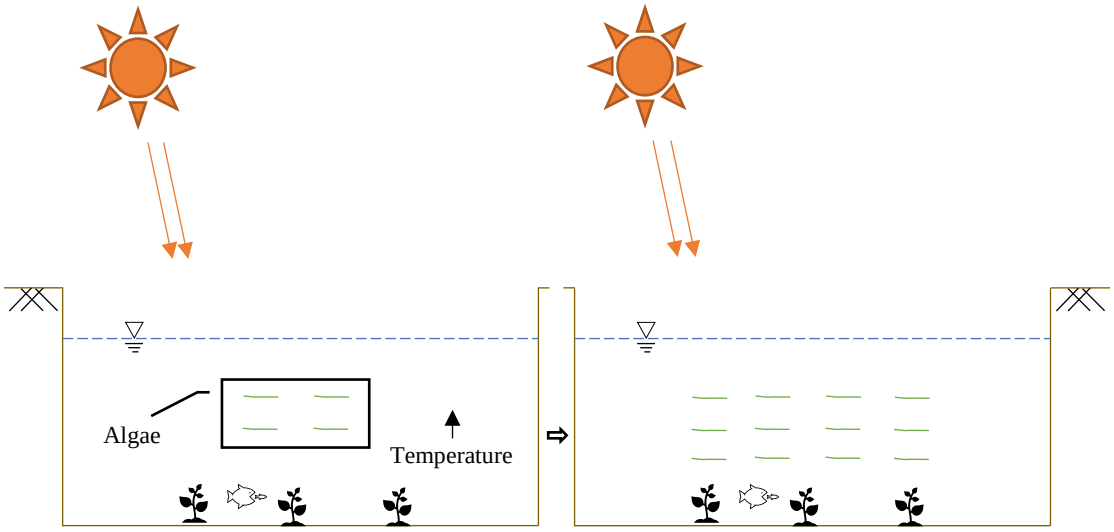

Figure 9. Effect of temperature on algal functioning in the aquatic environment.

Impact of Algae on Dissolved Oxygen (Figure 10): Algae will produce oxygen by the photosynthesis process. Among the produced oxygen, a portion will fill up the water's dissolved oxygen demand, and other portion will be included into the air. As temperature increases, water holds less dissolved oxygen and that dissolved oxygen partitions into the atmosphere. But at night during respiration algae consume oxygen and when algae naturally die it can create hypoxia (MSG, 2021).

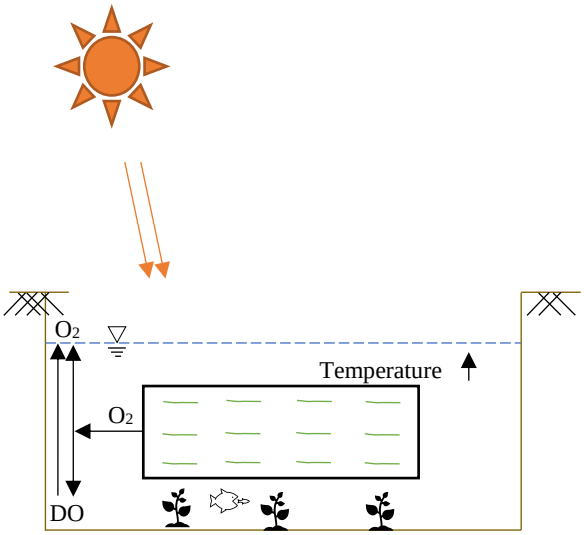

Figure 10. Algae's impact on oxygen production in the aquatic environment[1].

[1] DO: Dissolved oxygen.

Impact of Turbidity on Algae (Figure 11): In this increased algal situation algal turbidity will also increase. If rainfall occurs, then runoff will add soil into the large water vessel and will increase water's non-algal turbidity. Turbid water can increase water temperature since more solar radiation is converted to temperature. Higher water turbidity can decrease light penetration and hinder photosynthetic potential. Death of underwater vegetation through lower light penetration can result in hypoxic conditions, which might hinder algal growth as algae will not get enough oxygen during respiration. Besides the physical impact of turbidity, there is a chemical extent of turbidity due to its nature as a dependent parameter. The chemical extent of turbidity will be covered in the following scenario.

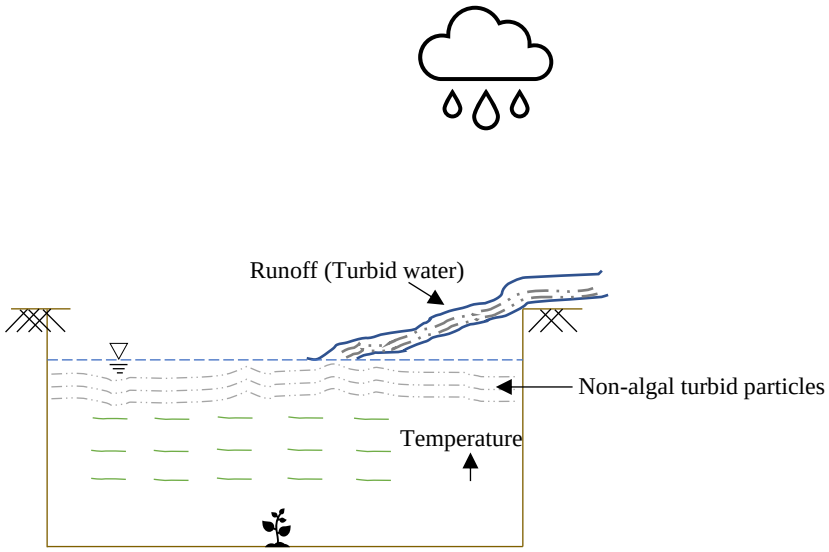

Figure 11. Turbidity's impact on algal functioning in the aquatic environment.

Impact of Nutrient on Algae (Figure 12): Turbidity is a dependent parameter that represents several environmental factors. Turbidity contains nutrients that contain organic/inorganic salts. The nutrients are an important variable for algal growth and propagation, but temperature affects algal nutrient uptake. As temperature increases, nutrient uptake by algae decreases. When temperature increases, algal species conserve nutrient resources for future use, and instead use energy derived from higher temperatures to promote growth (Cross et al., 2015). There is lacking evidence for dissolved oxygen's impact on nutrients. Thunderstorms may play another role in developing nitrogen enrichment in the water environment (Top-Crop-Manager, 2007).

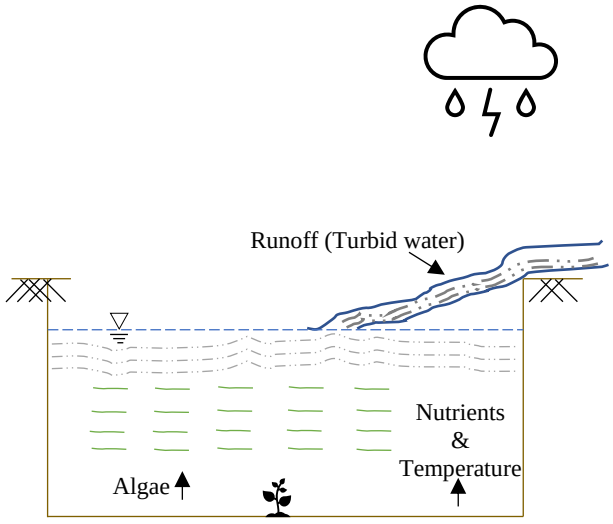

Figure 12. The impact of nutrients impact on algal functioning in the aquatic environment.

Impact of Dissolved Organic Matters on Algae (Figure 13): Turbidity also comprises of inorganic soluble salts, which can be measured by salinity/conductivity. Saline/conductive elements impact algal propagation based on species and generally have a negative impact on freshwater algal species. There does not seem to be a relationship between temperature or dissolved oxygen on salinity. However, increased salinity should decrease dissolved oxygen (USGS, 2020). Dissolved organic matter (DOM) is included in turbidity and impacts algal species by providing carbon and nutrients. There is insignificant evidence of how other environmental factors impact DOM. DOM might be helpful for algae by providing nutrients and photosynthesis associate carbon.

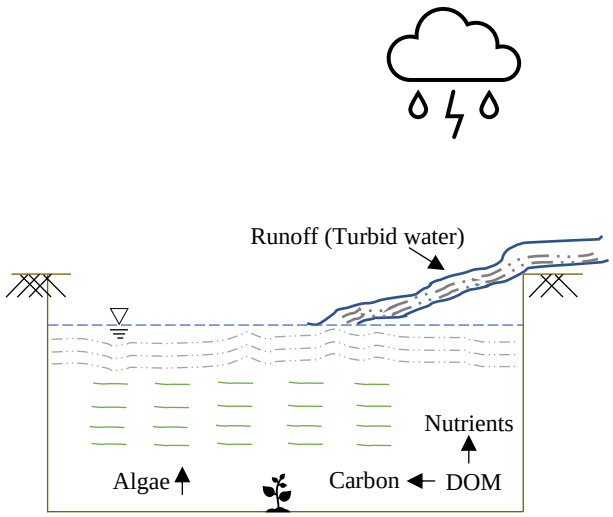

Figure 13. Dissolved organic matters' (DOM) impact on algal functioning in the aquatic environment.

Impact of Wind on Algae (Figure 14): Another environmental factor, wind, can help or disturb the algal population by mixing them or separating them. Depending on the direction of the wind, algal mass can be located on a particular portion of the water area. Wind should transport more algae on top of the water column than the bottom of the water column.

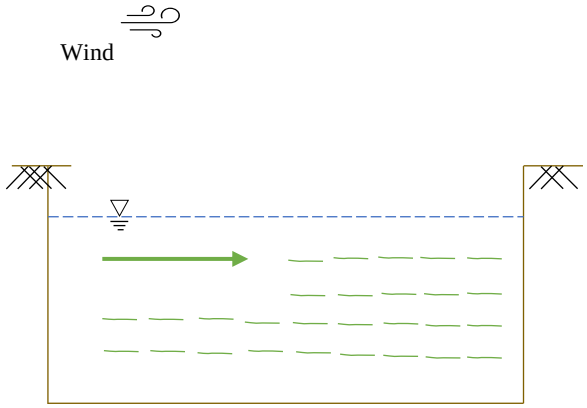

Figure 14. Wind's impact on algal functioning in the aquatic environment.

3.3 Conclusion

A conceptual model is important to understand how environmental parameters affect algae in the aquatic environment. The conceptual model will describe how the environmental variables affect algae, which might be helpful in the algae-related research. Empirical models can be built using the environmental parameters and relationships identified in this conceptual model. Algae produce oxygen during the daytime and consume oxygen during the night. So, dissolved oxygen should have an impact on the algal increase in the water. So, dissolved oxygen should be used as an independent variable in the empirical model.

The conceptual model is applicable for thermophilic freshwater algal species only. Different situations can be created due to the complex aquatic environment. So, there is likely variability of algal response against environmental parameters.

Chapter-4 | Mathematical Relationship between Various Environmental Parameters and Algae

4.1 Introduction

A conceptual model is helpful to qualitatively understand the impact of environmental parameters on algae, but mathematical models allow for quantitative relationships between parameters and algae concentration. In this chapter, the mathematical relationship between the environmental parameters and algae is presented.

4.2 Methodology

4.2.1 Study Area

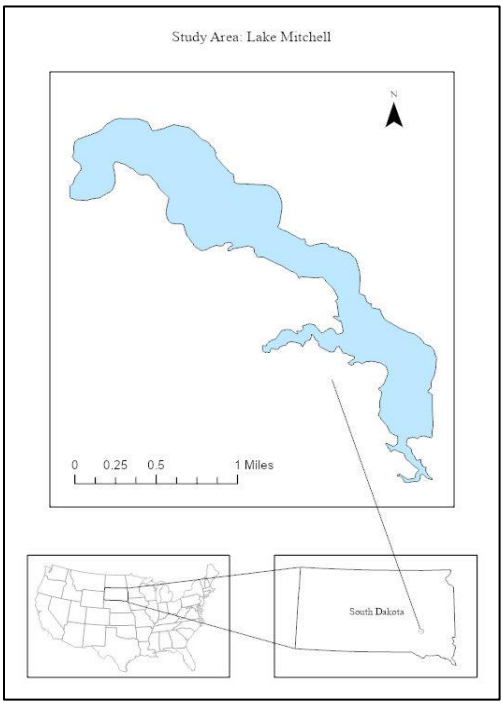

Figure 15. The study area of the research: Lake Mitchell, located near downtown Mitchell city, South Dakota, USA.

Lake Mitchell, a manmade impoundment, is located near downtown, City of Mitchell, South Dakota (Figure 15). It was constructed during the 1920s to use this lake water as a drinking water source and is approximately 280 ha in area. In addition to drinking water, it has also served as a local recreation destination. Due to sedimentation and nutrient loading, water quality in Lake Mitchell has declined and has dealt with taste and odor issues in drinking water since the mid-to-late-1990s and is no longer used as a drinking water source. Lake Mitchell is not supporting the following designated uses: domestic water supply, warmwater permanent fish life, immersion recreation, and limited contact recreation. Lake Mitchell is supporting fish and wildlife propagation, recreation, and stocking as well as irrigation waters designated uses (SDDENR, 2020). Lake Mitchell is used as recreation for locals and visitors (Mitchell-South-Dakota, 2018, 2021) but suffers from persistent algal blooms (Figure 16).

Figure 16. Algal bloom occurrence in Lake Mitchell. Photo by Sumit Kumar Ghosh.

4.2.2 Data Collection

4.2.2.1 Selection of Data Collection Process and Instrument

There are four separate dimensions of lake water quality data collection. A single point at a single time represents one dimension. The remaining points are spatial (multiple points across the lake), vertical (multiple points through the water column), and temporal (multiple sampling events at different times). Typically, lake water quality monitoring is performed over three dimensions, with samples being taken multiple times over a season at multiple points within a lake but at only one depth. Sampling or analyzing algae concentration through the entire water depth allows for a more complete analysis of the total algal mass present in the water column. The EXO2 multiparameter sonde (Figure 17) can be used to take 4-dimensional data.

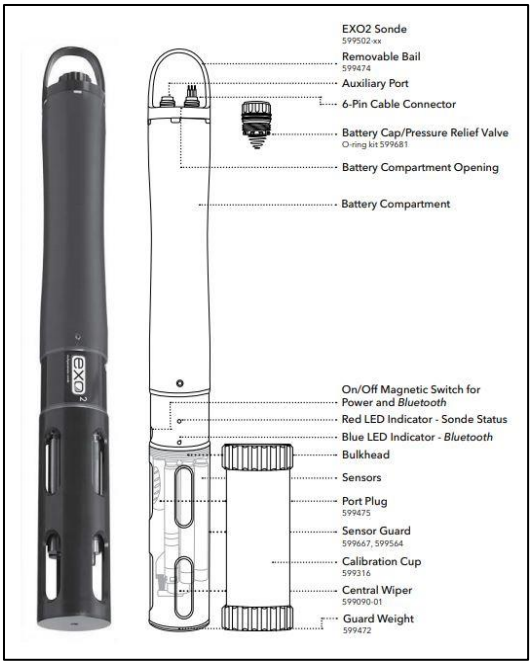

Figure 17. Data collection instrument for the research. This photo is adapted from (Xylem, 2017).

4.2.2.2 Selected Sensors for EXO2 Sonde

The Total Algae-PC sensor was selected to measure the available algae component in the water environment. Based on the following reasons, some parameters were included or excluded to be the independent variables for developing the mathematical relationship between the water quality parameters and algae:

(a) Conductivity: Being a freshwater lake, Lake Mitchell should have algal species that are conductive elements phobic, which means with increasing conductivity, the algal quantity should decrease. Concerning the effect of conductivity, it was decided to use conductivity to mathematically determine its effect on algae. The "Wiped Cond/Temp" sensor was selected to measure conductivity (Figure 18).

(b) Temperature: Lake Mitchell was studied when the lake water was not frozen, so in that condition, the thermophilic algal species should be dominant all over the lake. The thermophilic algal quantity should increase with increasing temperature. Concerning the effect of temperature, it was decided to use temperature to mathematically find out its effect on algae. The "Wiped Cond/Temp" sensor was selected to measure the value of temperature (Figure 18).

(c) Fluorescent dissolved organic matter (fDOM): As dissolved organic matter (DOM) contains nutrients and carbon, DOM should have an impact on the algae. According to Mostofa et al. (2012), fDOM is a fraction of DOM, so it was decided to use fDOM to mathematically find out its effect on algae. The "fDOM" sensor was selected to measure the quantity of fDOM (Figure 18).

(d) Ammonium: Algal quantity should increase with increasing nutrients. Concerning the effect of nutrients, it was decided to use ammonium to mathematically find

out its effect on algae. The ammonium (NH_4^+) sensor was selected to measure the quantity of ammonium (Figure 18).

(e) Dissolved oxygen (DO): Based on the conceptual model, for a lake like Lake Mitchell, algal quantity might be impacted by DO. That is why "Optical DO" sensor was selected to measure the quantity of dissolved oxygen (Figure 18).

(f) Turbidity, total dissolved solids (TDS), and total suspended solids (TSS): Based on the literature review, TSS and TDS are both parts of turbidity. Besides, TSS and TDS also consist of various components. That is why these three parameters were not used as the independent variable in the mathematical model.

So, the selected independent variables in the mathematical model were conductivity, temperature, fDOM, and ammonium. For measuring these four parameters, the "Wiped Cond/Temp," "fDOM," "Ammonium (NH_4^+)," and "Optical DO" sensors were selected. EXO2 sonde has an integral sensor to measure the water column depth.

Figure 18. Non-integral sensors used in EXO2 sonde during data collection.

4.2.2.3 Description of the Selected Sensors for EXO2 Sonde

The Total Algae-PC sensor has two excitation beams: (1) Blue excitation beam to measure the chlorophyll-a pigments, and (2) Orange excitation beam to measure the phycocyanin accessory molecules available in BGA. Though BGA contains chlorophyll-a molecules, the orange excitation beam is capable of giving a more accurate estimation of BGA. (Xylem, 2017). To get the quantity of total algal species, it was assumed that,

$$\text{Total algae molecule} = \text{Chlorophyll-a molecule} + \text{Phycocyanin molecule} \quad (5)$$

The Wiped Cond/Temp sensor has four pure nickel electrodes, two of them are current driven, and the other two measure voltage drop. Then, the voltage drop is converted into a conductance (micro-Siemens) value, and it is multiplied by the cell constant (5.1 cm^{-1} ± 10%), then finally the conductivity value is estimated. Temperature is measured by the same sensor using thermistor resistance. The fDOM sensor uses ultraviolet (UV) light to measure the fluorescent component of DOM. The Ammonium (NH_4^+) sensor uses a silver wire electrode in a custom filling solution. A polymer membrane, which selectively interacts with ammonium, separates the internal solution from the sample medium. Based on the relative quantity of ions in the sample and the internal solution, a potential (measured relative to the Ag/AgCl reference electrode) is established across the membrane of the immersed sensor. The Nernst equation is the basis of the ammonium determination in the water environment. This sensor gives ammonium quantity as nitrogen. The Optical DO sensor is based on “Dissolved oxygen quenches both the intensity and the lifetime of the luminescence associated with a carefully chosen chemical dye”. EXO2 indirectly measures the depth of each observation with a non-vented strain gauge. Depth is calculated from the subtraction of the water column’s pressure and atmospheric pressure. (Xylem, 2017).

Table 2. Overview of the used sensors in the EXO2 multiparameter sonde. Source: Xylem (2017).

Parameter	Sensor name	Sensor type	Measurement unit	Resolution
Chlorophyll-a	Total Algae-PC	Optical, fluorescence (Excitation: 470±15 nm & Emission: 685±20 nm)	µg/L	0.01 µg/L
Phycocyanin		Optical, fluorescence (Excitation: 590±15 nm & Emission: 685±20 nm)		
Conductivity	Wiped Cond/Temp	4-electrode nickel cell	micro-Siemens / cm (µS/cm)	0.0001 to 0.01 (µS/cm)
Temperature		Thermistor	°C	0.001°C
Fluorescent Dissolved Organic Matter	fDOM	Optical, fluorescence (Excitation: 365±5 nm & Emission: 480±40 nm)	Quinine sulfate units (QSU), ppb	0.01 ppb QSU
Ammonium as nitrogen	Ammonium (NH^{4+})	Ion-selective electrode	mg/L	0.01 mg/L
Dissolved Oxygen	Optical DO	Optical, Luminescence lifetime	mg/L	0.01 mg/L
Water column depth	Depth and Level	Stainless steel strain gauge	m	0.001 m

4.2.2.4 Data Collection Timeline and Sensors Calibration

Data were collected four separate days from Lake Mitchell. Sampling points were distributed over the entire lake area for each sampling event. For each sampling location, data were collected for the whole water column. In this way, a temporally, spatially, and vertically informative data set was prepared. The data set had average 67.75 sampling locations for each sampling period, and average 14.27 mean observations for each sampling location. (Table 3). Prior to each sampling period, the sensors were calibrated following the addressed process in the EXO2 user manual (Table 4). The summary statistics of the parameters are mentioned in the Table 5.

Table 3. Overview of the data collection from Lake Mitchell.

Sampling period	Sampling location	Total observation	Mean observations / Sampling location	Sampling date
1	76	1159	15	08/28/2020
2	41	500	12	09/08/2020
3	98	1271	13	09/23/2020
4	56	937	17	10/07/2020

Table 4. Calibration procedure of the used sensors. Source: (Xylem, 2017).

Sensor name	Calibration procedure of sensor
Total Algae-PC	1 point calibration using deionized water (contains 0 µg/L algal components) for both chlorophyll-a and blue-green algae (phycocyanin)
Wiped Cond/Temp	Conductivity: 1 point calibration using 1000 micro-Siemens/cm standard solution. Temperature: Not required.
fDOM	2 points calibration using 0 (Deionized water) & 300 ppb quinine sulfate units (QSU) standard solution
Ammonium (NH^{4+})	2 points calibration using 1 & 100 mg/L standard solution
Optical DO	1 point calibration using 0 mg/L standard solution
Depth and Level	1 point calibration was done to make the topwater surface level zero

Table 5. Summary statistics of the parameters.

Parameters	Sample	Minimum	Median	Mean	Maximum	Standard Deviation
Chlorophyll (µg/L)	1	2.16	3.10	3.85	25.90	2.97
	2	1.89	2.38	3.09	13.11	2.13
	3	2.47	7.99	10.48	38.63	7.86
	4	1.45	5.76	7.23	50.38	6.73
Phycocyanin (µg/L)	1	0.2	0.73	0.81	1.85	0.42
	2	0.31	0.46	0.53	0.99	0.16
	3	0.14	0.87	0.95	3.24	0.67
	4	0.31	0.70	0.80	4.56	0.58
Total Algae (µg/L)	1	2.52	3.91	4.66	27.67	3.15
	2	2.30	2.90	3.61	13.96	2.25
	3	2.71	8.73	11.43	40.71	8.36
	4	1.87	6.62	8.03	54.94	7.22
fluorescent dissolved organic matter (QSU)	1	39.01	74.65	72.44	87.06	10.64
	2	1.63	68.33	66.42	83.88	15.78
	3	27.45	76.05	70.46	85.59	14.24
	4	24.99	55.03	55.38	79.60	11.84
Ammonium (mg/L)	1	0.92	1	1.09	4.65	0.43
	2	1.85	2.11	2.22	5.57	0.55
	3	0.52	0.65	0.83	18.06	1.76
	4	1.03	1.16	1.27	5.37	0.59

Conductivity (µS/cm)	1	1262	1444	1406	1483	58.64
	2	1161	1288	1272	1304	39.66
	3	930	1147	1139	1245	44.05
	4	708.4	993.2	975.8	1046.4	66.61
Dissolved oxygen (mg/L)	1	4.46	7.44	7.35	8.48	0.66
	2	7.77	8.96	9.06	11.34	0.71
	3	8	10.02	10.15	13.54	1.47
	4	7.9	10	9.95	11.51	0.80
Temperature (°C)	1	25.20	25.82	25.83	26.60	0.31
	2	16.49	19.55	19.38	20.65	0.84
	3	18.36	19.04	19.10	20.46	0.39
	4	13.53	14.93	14.84	15.88	0.47

4.2.3 Data Processing

Before processing the data set, for the simplification of the data analysis, it was assumed that six parameters (total algae, conductivity, temperature, fluorescent dissolved organic matter, ammonium, and dissolved oxygen) were homogenously distributed in a cylindrical water volume (Figure 19).

The mean concentration of the seven parameters was used for each sampling location's water column. Then, for each sampling location, Equation-6 was used to quantify the mass/area of total algae, fDOM, ammonium as nitrogen, and DO for a homogenously concentrated volume. Mean conductivity value was used to describe the

reactivity of ions into that water volume. Mean temperature value was used to describe the mean vibration-frequency-energy of the elements that existed in the water volume.

$$\text{Mean concentration}\left(\frac{\text{mass}}{\text{length}^3}\right) \times \text{Mean water column's depth (length)} = \frac{\text{mass}}{\text{area}} \quad (6)$$

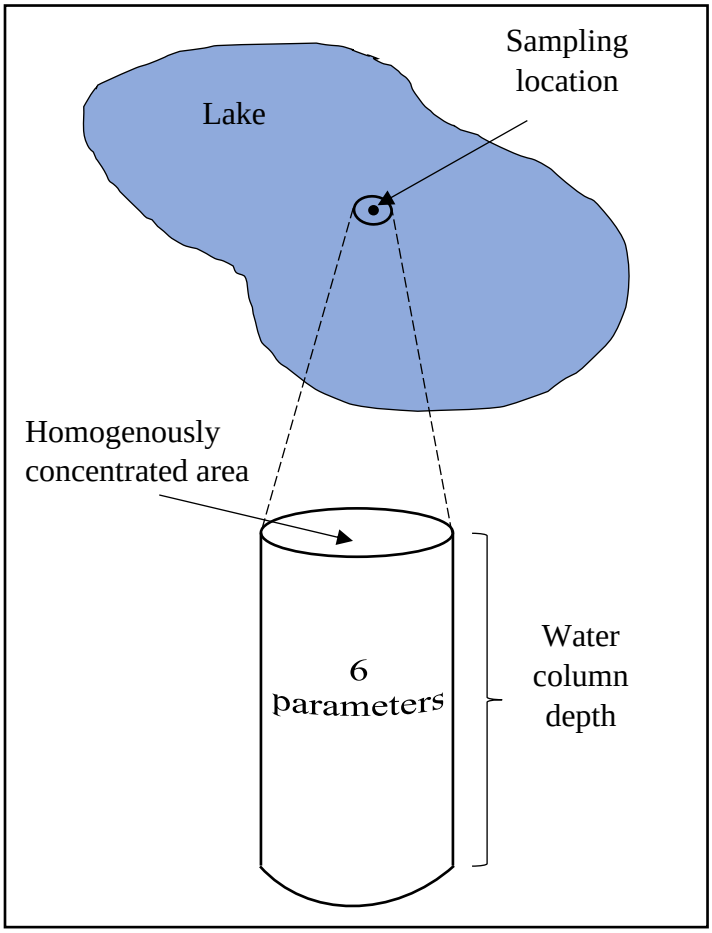

Figure 19. Conceptual model of six parameters' (total algae, conductivity, temperature, fluorescent dissolved organic matter, ammonium, and dissolved oxygen) distribution under a particular water volume.

4.3 Result and Discussion

The correlation matrices (Figure 20) is temporally inconsistent for total algae.

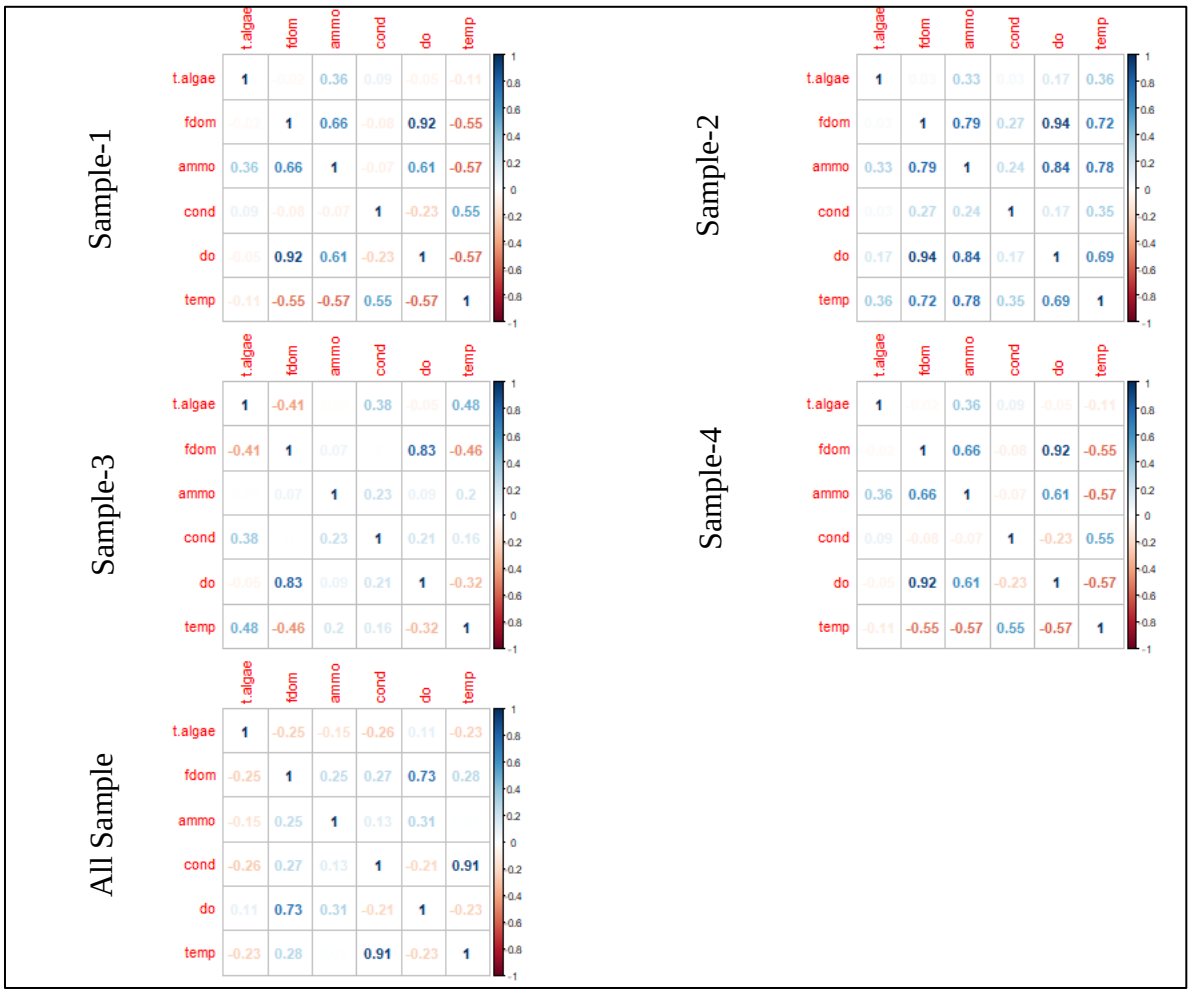

Figure 20. Correlation matrices of the parameters: total algae (t.algae), conductivity (cond), temperature (temp), fluorescent dissolved organic matter (fdom), ammonium (ammo), and dissolved oxygen (do).

Then total algal response against the five parameters (conductivity, temperature, fluorescent dissolved organic matter, ammonium, and dissolved oxygen) was assessed graphically (Figure 21 to 25) and mathematically.

From sampling period 1 to sampling period 4, the lake is losing the conductive elements, and the total algal response is not showing any particular trend throughout the conductivity range (Figure 21). Algal response against temperature is the same as conductivity (Figure 22). The lake demonstrated very little change to fDOM from sampling period 1 to 4, and the algal response is not showing any particular trend throughout the fDOM range (Figure 23). Ammonium value is consistent throughout the sampling period except for sampling period 3 which exhibited a few very high ammonium values. The total algal response does not show any particular trend throughout the ammonium range (Figure 24). Dissolved oxygen value is consistent for every sampling event. It seems like it is also not showing any particular trend (Figure 25).

The total algal response was assessed mathematically against single parameter, but no significant result was found. There was no consistent mathematical relationship between total algae and the other five parameters (Table 6). It seems like due to complex situations, single parameters are incapable of expressing the law of algae in the aquatic environment, so multiple parameters might be capable of expressing exact situations. However, based on the result in Table 7, the five parameters together also are not sufficient to express the law of algae in the aquatic environment. For developing the models the diagnostic plot and overall p-value was checked. The VIF value was checked while preparing the multiple regression model. If any parameter had a VIF>10, then that parameter was not used.

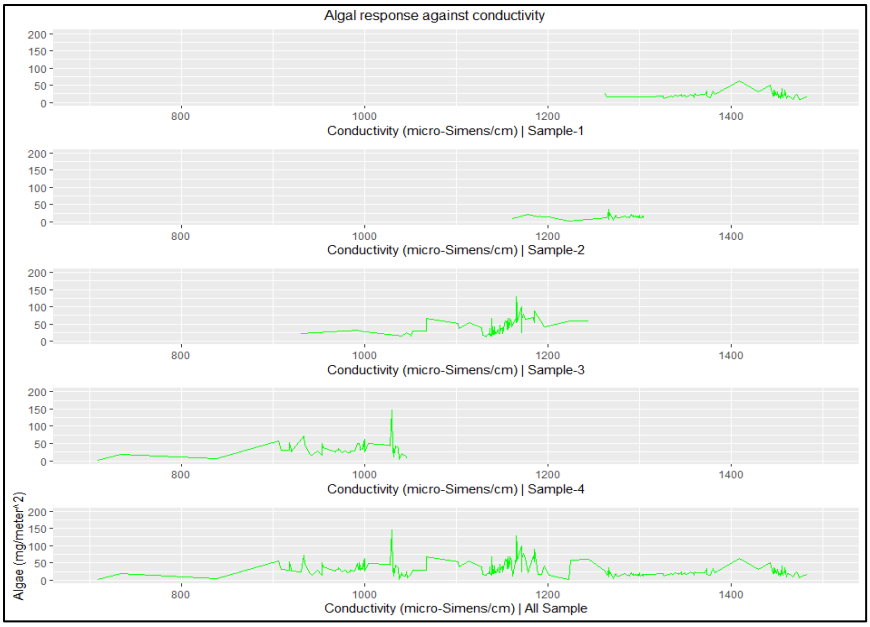

Figure 21. Total algal response against conductivity.

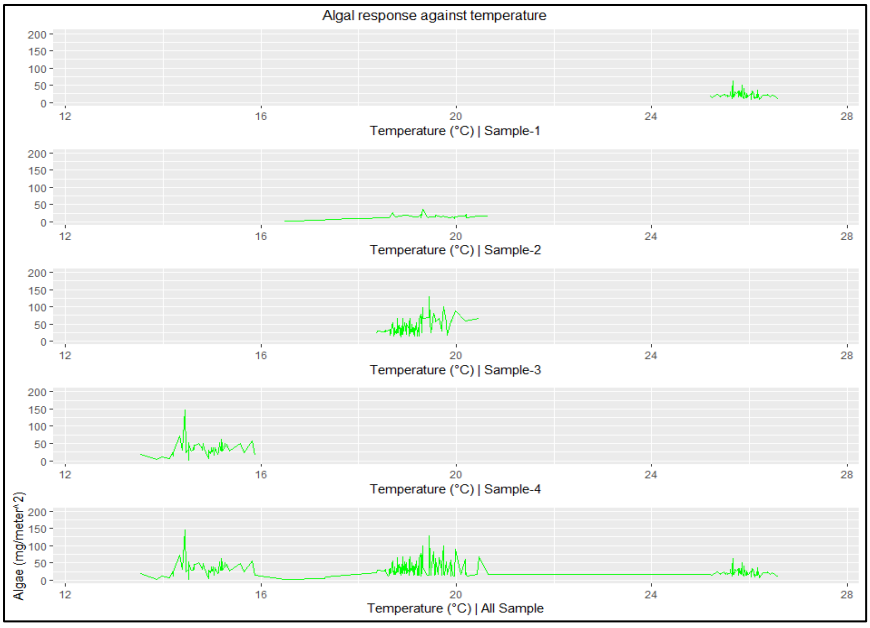

Figure 22. Total algal response against temperature.

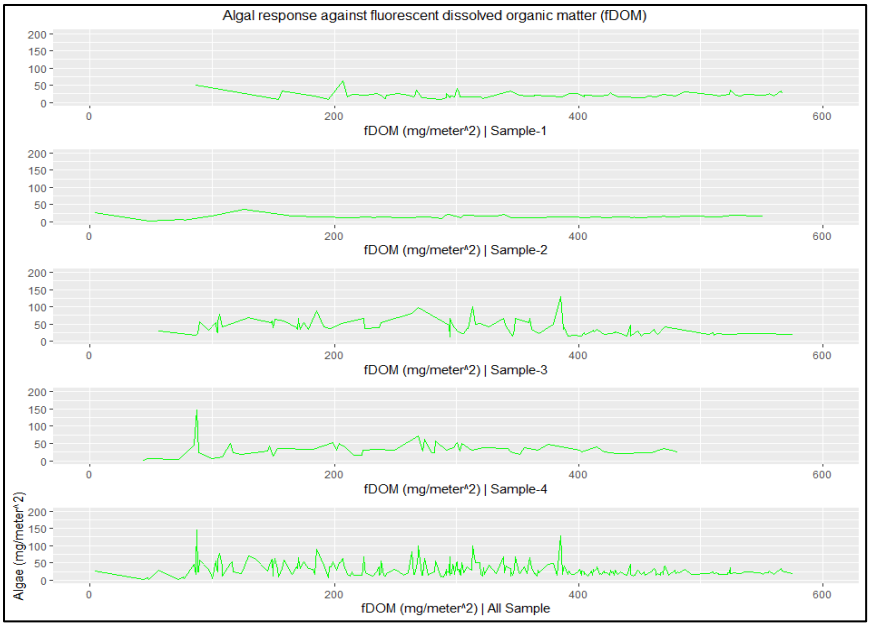

Figure 23. Total algal response against the fluorescent dissolved organic matter.

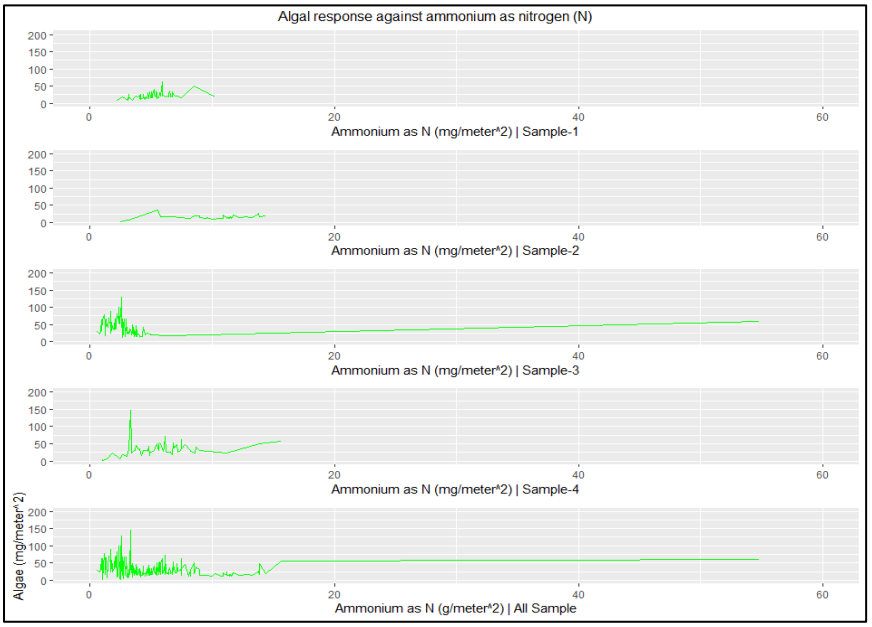

Figure 24. Total algal response against ammonium as nitrogen.

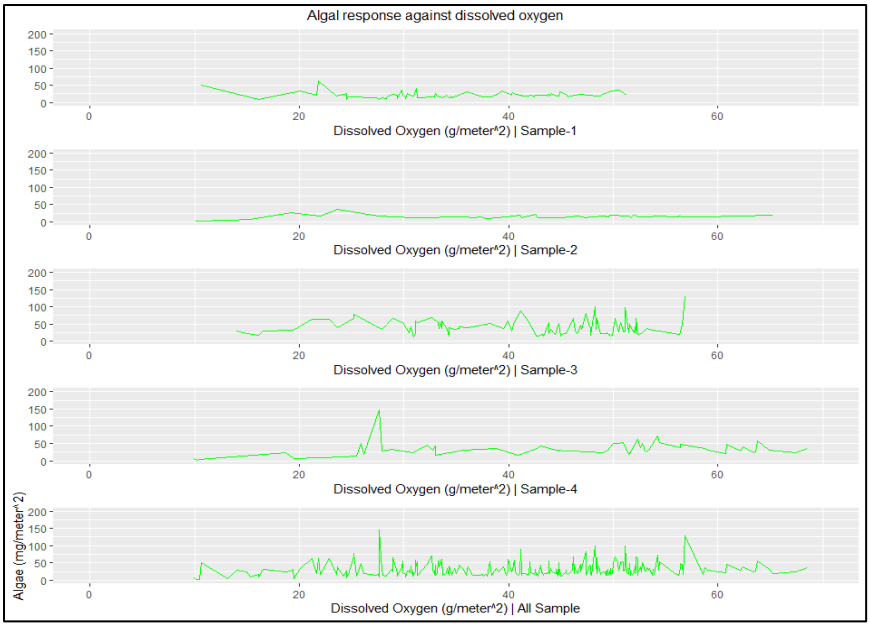

Figure 25. Total algal response against dissolved oxygen.

Table 6. The mathematical relationship of total algae with conductivity (C), temperature (T), fluorescent dissolved organic matters (fDOM), ammonium as nitrogen (A-N), and Dissolved oxygen (DO) using the simple linear regression model.

Dependent variable (mg/m^2)	Sample	Independent variable														
		C (micro-Simens/cm)			T (°C)			fDOM (mg/m^2)			A-N (g/m^2)			DO (g/m^2)		
		[2]β_o	[3]S	R^2	β_o	S	R^2	β_o	S	R^2	β_o	S	R^2	β_o	S	R^2
Total algae	1	-	0	-	-	0	-	-	0	-	9.24	2.37	0.13	-	0	-
	2	-	0	-	0	0.02	0.13	-	0	-	9.27	0.60	0.11	-	0	-
	3	-170.93	.19	0.14	-469.72	26.69	0.23	60.31	-0.07	0.17	-	0	-	-	0	-
	4	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-
	All	67.13	-.03	0.07	52.71	-1.13	0.05	41.24	-.04	0.06	33.54	-0.68	0.02	-	0	-

[2] β_o: Y-intercept
[3] S: Slope

Table 7. The mathematical relationship of total algae with conductivity (C), temperature (T), fluorescent dissolved organic matters (fDOM), ammonium as nitrogen (A-N), and dissolved oxygen (DO) using the multiple linear regression model.

Dependent variable (mg/m^2)	Sample	Y-intercept	Slope of independent variables					R^2
			C (mS/cm)	T (°C)	fDOM (mg/m^2)	A-N (g/m^2)	DO (g/m^2)	
Total algae	1	9.24	0	0	0	2.37	0	0.13
	2	0	0	3.17	-0.02	0.99	0	0.33
	3	-368.12	0.09	14.91	-0.14	0	1.50	**0.53**
	4	10.42	0	0	-0.19	0	1.61	0.26
	All	-0.66	0	0.88	-0.12	-0.80	1.28	0.30

4.4 Conclusion

The mathematical model helps to reveal the quantitative relationships between parameters and algae concentration. Algae remain in the complex aquatic environment. Besides the water quality parameters, wind and other environmental components can play a huge role in increasing/decreasing algal quantity. Maybe, for this reason, only the five water quality parameters in no way have been found capable of showing consistent behavior of algae. More parameters, like nitrate, nitrite, and phosphorus should be included to properly understand the environmental parameters' influence on the algae.

Chapter-5 | Remote Sensing and Aquatic Correction, an Improved Empirical Approach for Total Algal Mass Detection

5.1 Introduction

In this chapter, an empirical model was developed to quantify total algal mass in a freshwater lake. Also, a novel data refining approach was developed to improve remotely sensed data and its accuracy for estimating lake algal mass. This approach is called aquatic correction.

5.2 Methodology

5.2.1 Study Area

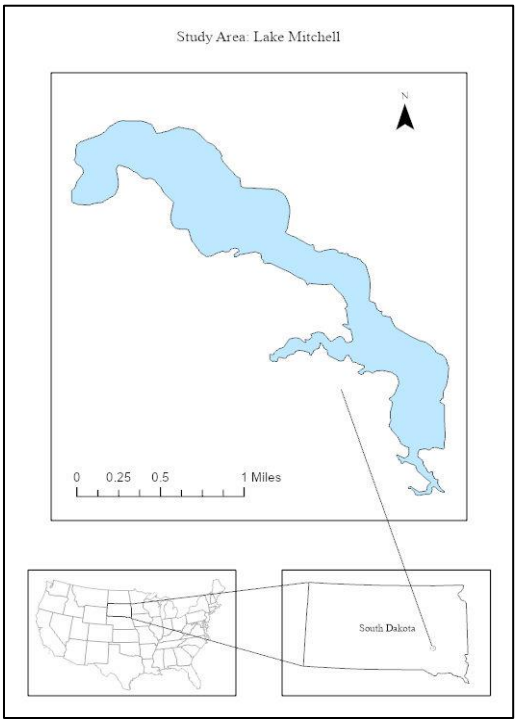

Figure 26. The research study area: Lake Mitchell, located near downtown Mitchell city, South Dakota, USA.

Lake Mitchell, a manmade impoundment, is located near the City of Mitchell, South Dakota (Figure 26). It was constructed during the 1920s to use this lake water as a drinking water source and is approximately 280 ha in area. In addition to drinking water, it has also served as a local recreation destination. Due to sedimentation and nutrient loading, water quality in Lake Mitchell has declined and has dealt with taste and odor issues in drinking water since the mid to late 1990s and is no longer used as a drinking water source. Lake Mitchell is not supporting the following designated uses: domestic water supply, warm water permanent fish life, immersion recreation, and limited contact recreation. Lake Mitchell is supporting fish and wildlife propagation, recreation, and stocking as well as irrigation waters designated uses (SDDENR, 2020). Lake Mitchell is used as recreation for locals and visitors (Mitchell-South-Dakota, 2018, 2021) but suffers from persistent algal blooms (Figure 27).

Figure 27. Algal bloom occurrence in Lake Mitchell. Photo by Sumit Kumar Ghosh.

5.2.2 Data Collection

5.2.2.1 Overview of the Data Collection Instrument

The concentration of chlorophyll-a and phycocyanin molecules was measured to calculate an estimated total algal mass. The EXO2 multiparameter sonde (Figure 28) was used to collect data for algal mass calculation. This instrument also measures water depth so algal mass could be calculated through the water column.

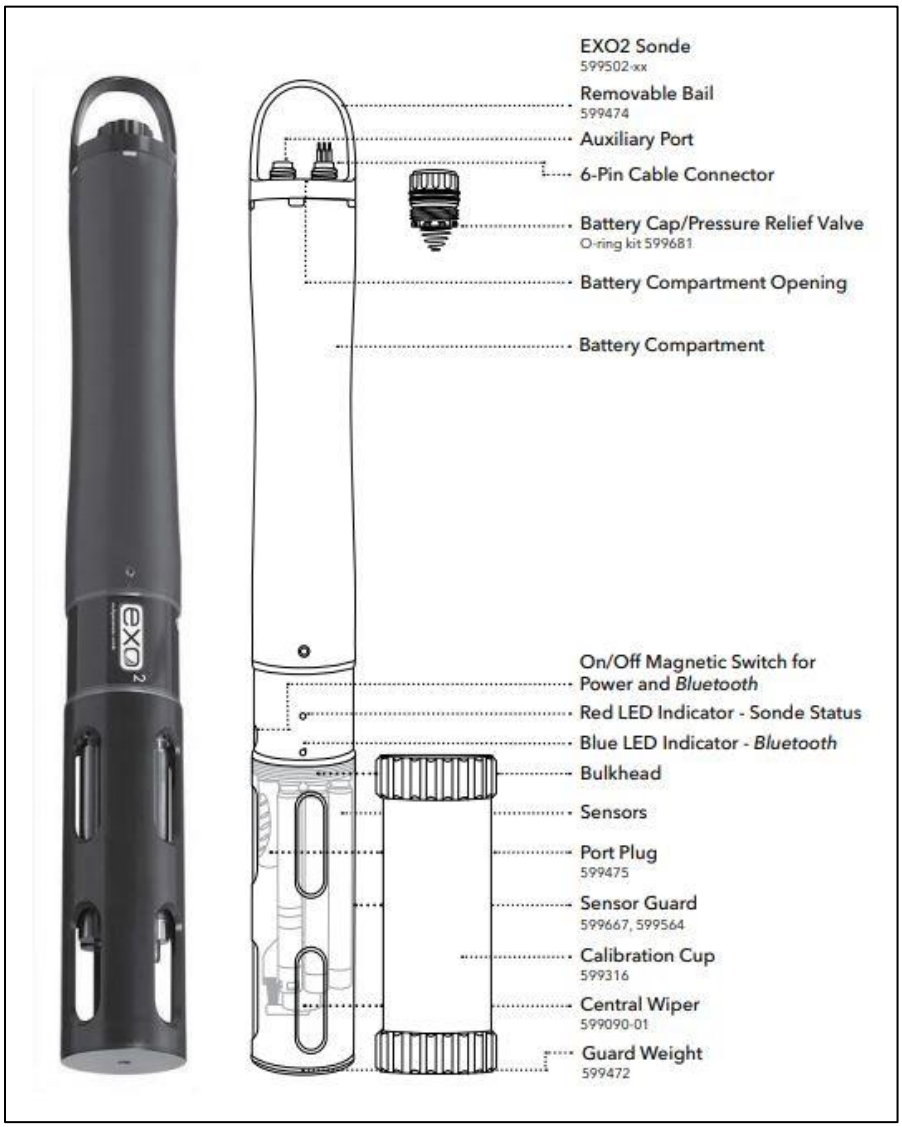

Figure 28. EXO2 instrument components. This photo is adapted from Xylem (2017).

5.2.2.2 Overview of the EXO2 Sonde's Sensors

The Total Algae-PC sensor (Figure 29) was used to measure the algal concentration using two excitation beams. A blue excitation beam measures chlorophyll-a pigments, and an orange excitation beam measures the phycocyanin accessory molecules present in BGA. Though BGA contains chlorophyll-a molecules, the orange excitation beam is capable of giving a more accurate estimation of BGA (Xylem, 2017). Total algal molecules were assumed to be composed of what was measured for chlorophyll-a and the phycocyanin molecules (Equation 7).

$$\text{Total algae molecule} = \text{Chlorophyll-a molecule} + \text{Phycocyanin molecule} \quad (7)$$

Since chlorophyll-a and phycocyanin do not make up the entire algal molecule, this likely underestimates total algal load (Ramaraj, Tsai, & Chen). However, it is a commonly used approximation (Johansen et al., 2018) and yields a direct measurement of algal presence and activity even if it is not a direct measurement of algal mass.

Figure 29. The Total Algae-PC sensor used in EXO2 sonde during data collection. Photo by Sumit Kumar Ghosh.

EXO2 measures the depth of each observation with the Depth and Level sensor, which is a non-vented strain gauge. Depth is calculated using gauge pressure (atmospheric pressure subtracted from gauge pressure) and density of water (Xylem, 2017).

Table 8. Overview of the sensors used in the EXO2 sonde. Source: Xylem (2017).

Parameter	Sensor name	Sensor type	Measurement unit	Resolution
Chlorophyll-a	Total Algae-PC	Optical, fluorescence (Excitation: 470±15 nm & Emission: 685±20 nm)	µg/L	0.01 µg/L
Phycocyanin		Optical, fluorescence (Excitation: 590±15 nm & Emission: 685±20 nm)		
Water column depth	Depth and Level	Stainless steel strain gauge	m	0.001 m

5.2.2.3 Data Collection Timeline and Sensors Calibration

Data were collected on four separate days from Lake Mitchell. Samples were collected over the entire lake area, and sampling locations were repeated if possible. For each sampling location, data were collected for the whole water column. Prior to each sampling event, the sensors were calibrated following the process detailed in the EXO2 user manual (Table 10). A Trimble Geo 7X was used to capture coordinates of the sampling locations which global navigation satellite system (GNSS) accuracy is 1 to 100 cm (Figure 30). The sampling period for ground-truthing was chosen within ±1 days of satellite image acquisition date.

Table 9. Overview of the data collection scenario from Lake Mitchell.

Sampling period	Sampling location	Mean observations per sampling location	Ground truthing date	Satellite image acquisition date
1	76	15	08/28/2020	No image due to cloud
2	41	12	09/08/2020	
3	98	13	09/23/2020	09/24/2020
4	56	17	10/07/2020	10/07/2020

Table 10. Calibration procedure of the used sensors during the data collection from Lake Mitchell. Source: Xylem (2017).

Sensor name	Calibration procedure of sensor
Total Algae-PC	1 point calibration using deionized water (contains 0 µg/L algal components) for both chlorophyll-a and blue-green algae (phycocyanin)
Depth and Level	1 point calibration was done to make the topwater surface level zero

Figure 30. Trimble Geo 7X was used to coordinate collection of the sampling locations. This photo is adapted from Trimble (2017).

5.2.2.4 Satellite Selection

The Sentinel-2A satellite was selected for remote sensing data since it provides free instant surface reflectance with a good spatial resolution of 10m and 20m (Table 11). Level 2A (Surface reflectance) satellite imagery was collected from "Copernicus Open Access Hub" (ESA, 2021a). Sample (spatial analyst) tool was used to extract the pixel value (Surface reflectance) concerning the sampling locations (ESRI, 2021b). Surface reflectance was correlated with the total algal mass under the respective pixel area. As 60m bands were designed for the atmospheric correction issue, so only 10m and 20m bands were used for this research (ESA, 2021b).

Table 11. Detail information of spectral bands for Sentinel-2A satellite. Source: USGS (2021d).

Bands no.	Band name	Central wavelength (nm)	Spatial Resolution (m)
Band 1	Aerosol	443	60
Band 2	Blue	490	10
Band 3	Green	560	10
Band 4	Red	665	10
Band 5	Vegetation	705	20
Band 6	Vegetation	740	20
Band 7	Vegetation	783	20
Band 8	Near infrared	842	10
Band 8A	Vegetation	865	20
Band 9	Water vapor	945	60
Band 10	Cirrus	1375	60
Band 11	Short-wave infrared	1610	20
Band 12	Short-wave infrared	2190	20

Table 12. Summary statistics of the parameters.

Parameters	Sample	Minimum	Median	Mean	Maximum	Standard Deviation
Band-2	3	352	430	429	505	28.05
	4	12	52.50	55.11	100	18.73
Band-3	3	425	501.5	505.3	657	43.94
	4	114	158.5	162.8	239	27.64
Band-4	3	361	432	429.1	505	26.26
	4	65	106	108.95	176	21.21
Band-5	3	405	548	559.2	960	92.35
	4	79	101	120	364	51.90
Band-6	3	334	461.5	482.4	813	93.71
	4	1	37.50	56.34	464	75.51
Band-7	3	362	473.5	495.3	822	91.42
	4	6	42.50	58.41	460	77.41
Band-8	3	353	452.5	468.3	672	76.64
	4	5	37.50	48.11	350	49.25
Band-8A	3	361	457	479	871	94.17
	4	1	36.50	56.75	567	89.79
Band-11	3	278	369.5	381.5	813	80.79
	4	47	77.50	102.07	501	87.09
Band-12	3	219	287	291	608	57.25
	4	41	73	89.59	369	54.13
Total Algae (µg/L)	3	2.71	8.73	11.43	40.71	8.36
	4	1.87	6.62	8.03	54.94	7.22

Before starting the analysis, the following process was used for pixel selection:

(a) Any pixel that was not entirely water was not used (Figure 31).

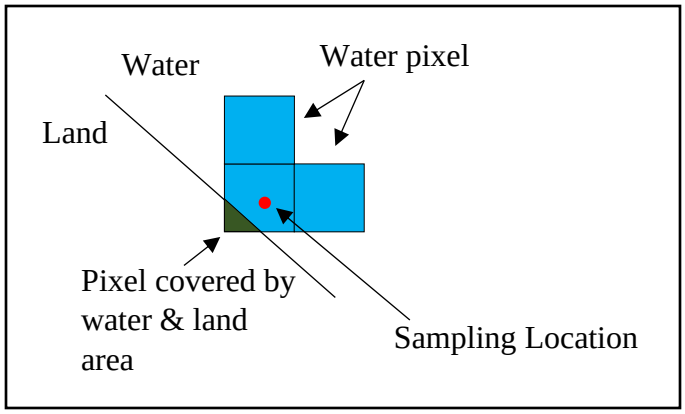

Figure 31. Illustration for a situation when pixel area is covered by both water and land.

(b) Sometimes, the sampling locations were very close to the boundary area of two pixels of varying surface reflectance (Figure 32). For those cases, it might be possible that the ground truthing data did not represent the actual surface reflectance, so those pixels were not used. Distance between sampling point and pixel boundary should be greater than the length of the boat.

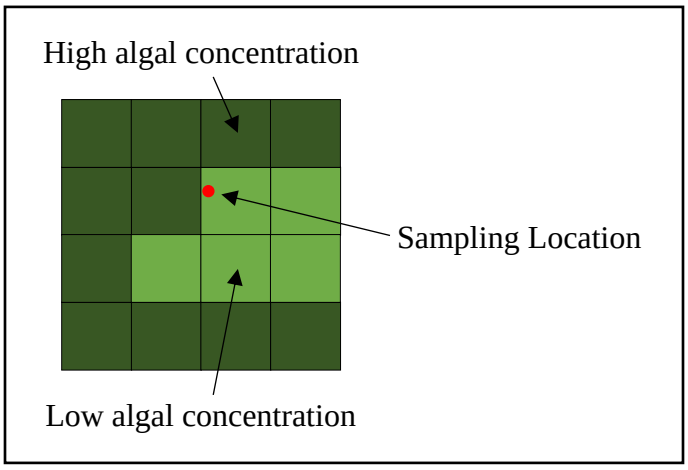

Figure 32. Illustration for a situation when a sampling location is very close to the boundary area of two pixels of varying surface reflectance.

5.2.3 Data Preparation

The mean total algal concentration in the water column was calculated from all values collected at each point. The total algal mass was calculated from Equation 2 using the mean total algal concentration in the water column multiplied by the water column depth and the pixel area that contains that sample point. Then, to prepare the total algal mass detection regression model, the algal mass was represented as a function of surface reflectance.

$$f(\text{Surface reflectance}) = \text{Total algal mass} \quad (8)$$

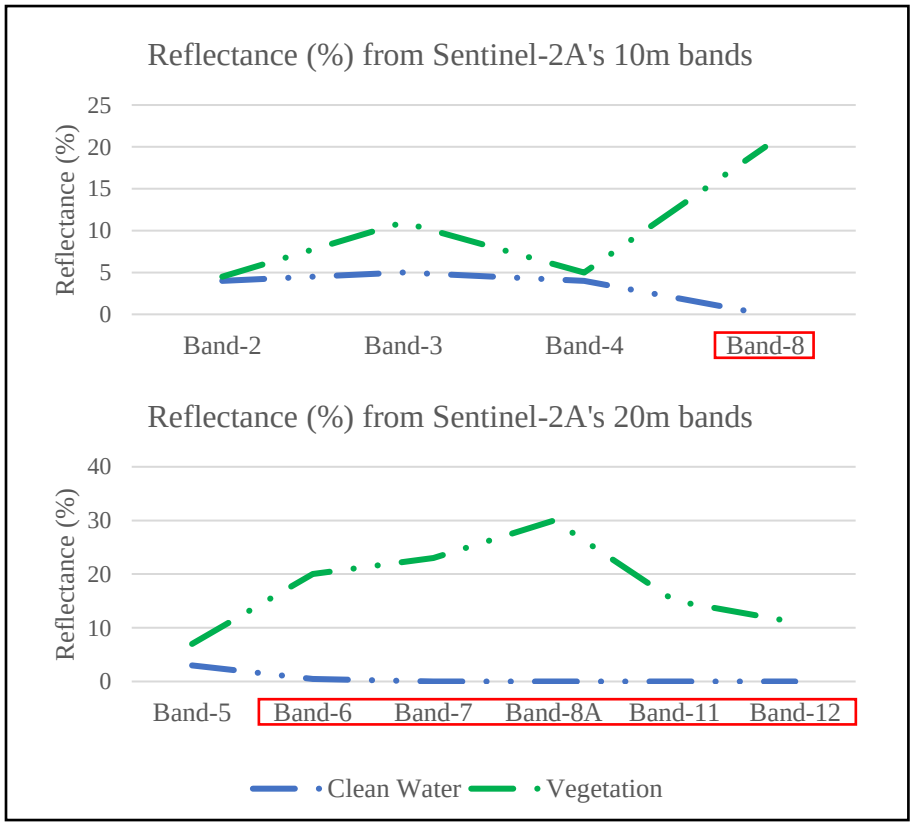

Figure 33. Illustration of surface reflectance from Sentinel-2A's 10m & 20m bands for clean water and vegetation land cover. This information is based on Sinergise (2019). The figures are not to scale.

Before developing the regression model, the spectral profile of clean water and vegetation was analyzed. It was determined that band 8 for the 10m bands and band 6 to band 12 for the 20m bands gives close to zero (0) reflectance for clean water. However, vegetation gives higher reflectance for these bands. (Figure 32). After that, the original pixel value (Surface reflectance) of each sampling location was rescaled by dividing with the special quantification value of 10000 to convert the pixel value in 0 to 1 range (Traganosa & Reinartzb, 2018), and reflectance ≤0.01 for these six bands was assumed as clean water reflectance and removed. This procedure was referred to as the "Aquatic Correction".

5.2.4 Regression Model Development

The regression model was developed with the final dataset after the aquatic correction. Under the graphical method, any band that is good to catch the algal reflectance should give an increasing reflectance trend with increasing algal mass. Based on the bands' surface reflectance performance, eligible band was chosen to estimate the algal mass. This analysis was done only among the bands of the same spatial resolution as resamples images to match the bands' spatial resolution may lead to an improper model.

5.2.5 Regression Model Evaluation Process and Implementation

After preparing the regression model, its performance was evaluated against the coefficient of determination (R^2) and root-mean-square error (RMSE). The equations of R^2 and RMSE estimation are described in Equations 9 and 10, respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{observed} - Y_i^{simulated}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{Observed} - Y^{mean}\right)^2} \qquad (9)$$

Here, $Y_i^{observed}$ is the i^{th} observation of the dataset, $Y_i^{simulated}$ is the i^{th} observation of the simulated dataset, Y^{mean} is the mean value of the observation dataset, and n is the number of the total observations (Zhong & Dutta, 2015).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i^{observed} - Y_i^{simulated})^2}{n}} \qquad (10)$$

Here, $Y_i^{observed}$ is the i^{th} observation of the dataset, $Y_i^{simulated}$ is the i^{th} observation of the simulated dataset, and n is the number of the total observations (Zhong & Dutta, 2015).

Table 13. Overview of the regression model's performance evaluation parameters. Source: Moriasi et al. (2007).

Model evaluation parameter	Range	Satisfactory value
Coefficient of determination	0 to 1	> 0.5
Root-mean-square error	-	$< \frac{1}{2} \times$ Standard deviation of measured data

In the end, the spatial distribution of the total algal mass in Lake Mitchell was determined using the empirical model in the Raster Calculator (Spatial Analyst) tool (ESRI, 2021b).

5.3 Result and Discussion

Surface reflectance was checked for both 10m and 20m spatial resolution images against the increasing total algal mass (Figure 34 & 35). For every image in Figures 34 & 35, a distinct gap was found between sampling 3 & 4 regarding the surface reflectance. This might be due to the complex water environment for which the satellite could not deliver perfect algal reflectance.

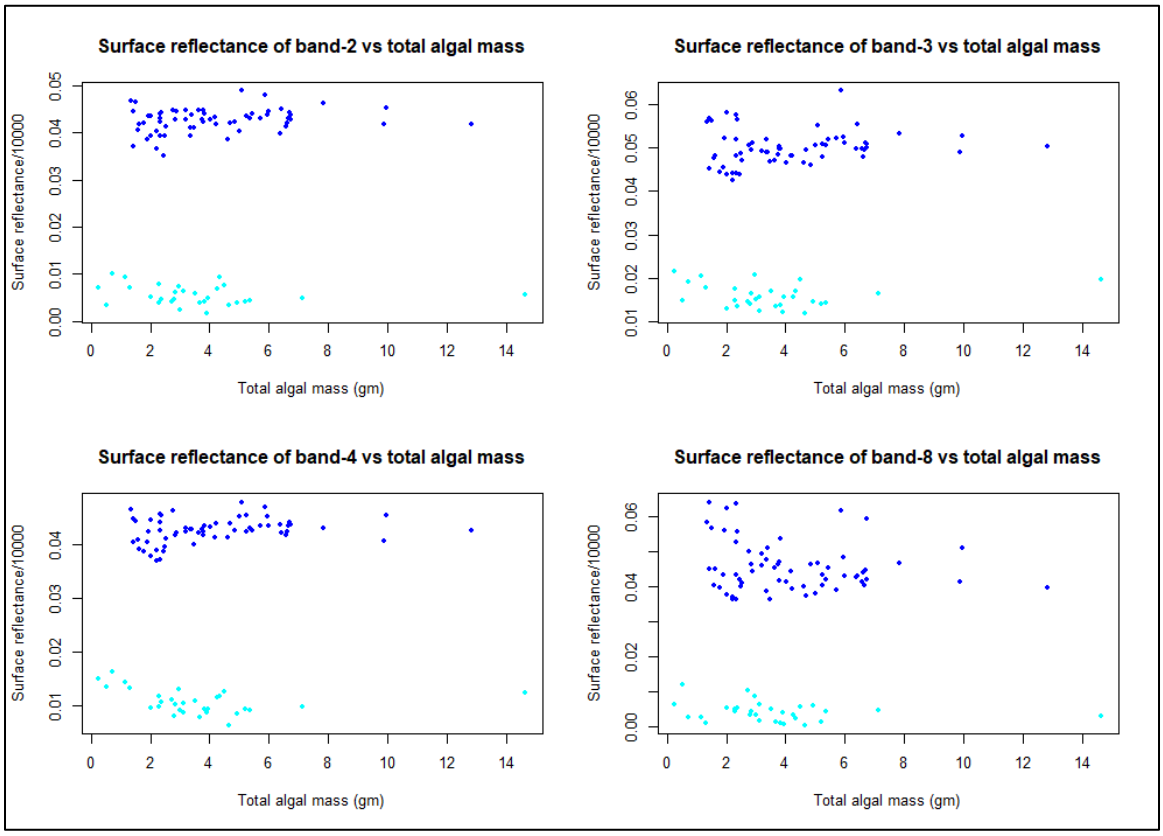

Figure 34. Surface reflectance of 10m spatial resolution images against increasing total algal mass. Blue and cyan colors represent the sampling periods 4 and 5, respectively. This figure represents the data before the aquatic correction.

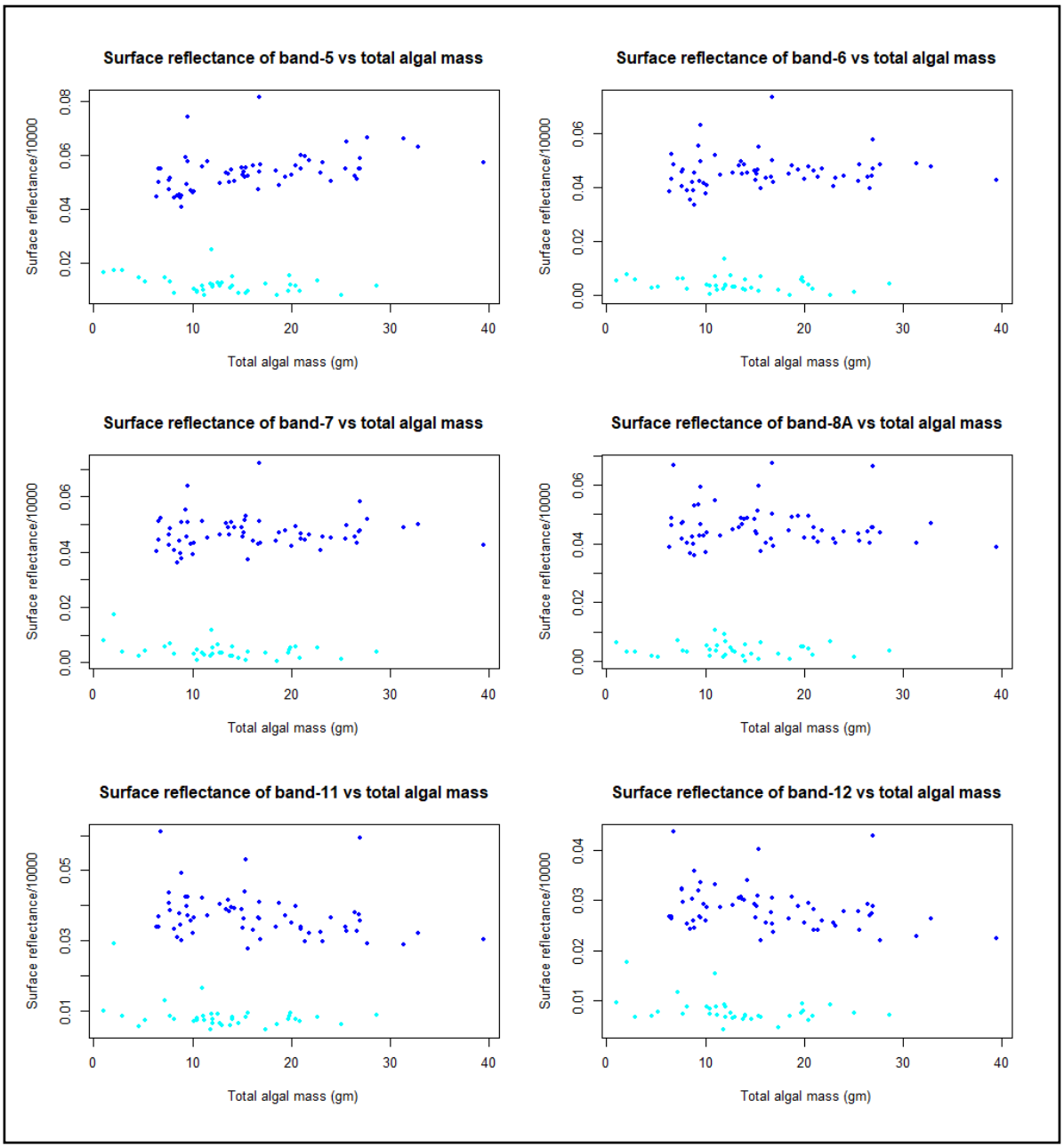

Figure 35. Surface reflectance of 20m spatial resolution images against increasing total algal mass. Blue and cyan colors represent the sampling periods 4 and 5, respectively. This figure represents the data before the aquatic correction.

After applying the aquatic correction, it was found that among the 10m and 20m spatial resolution images (Figure 36 & 37), only band-5 was found most responsive concerning its increasing trend against increasing total algal mass.

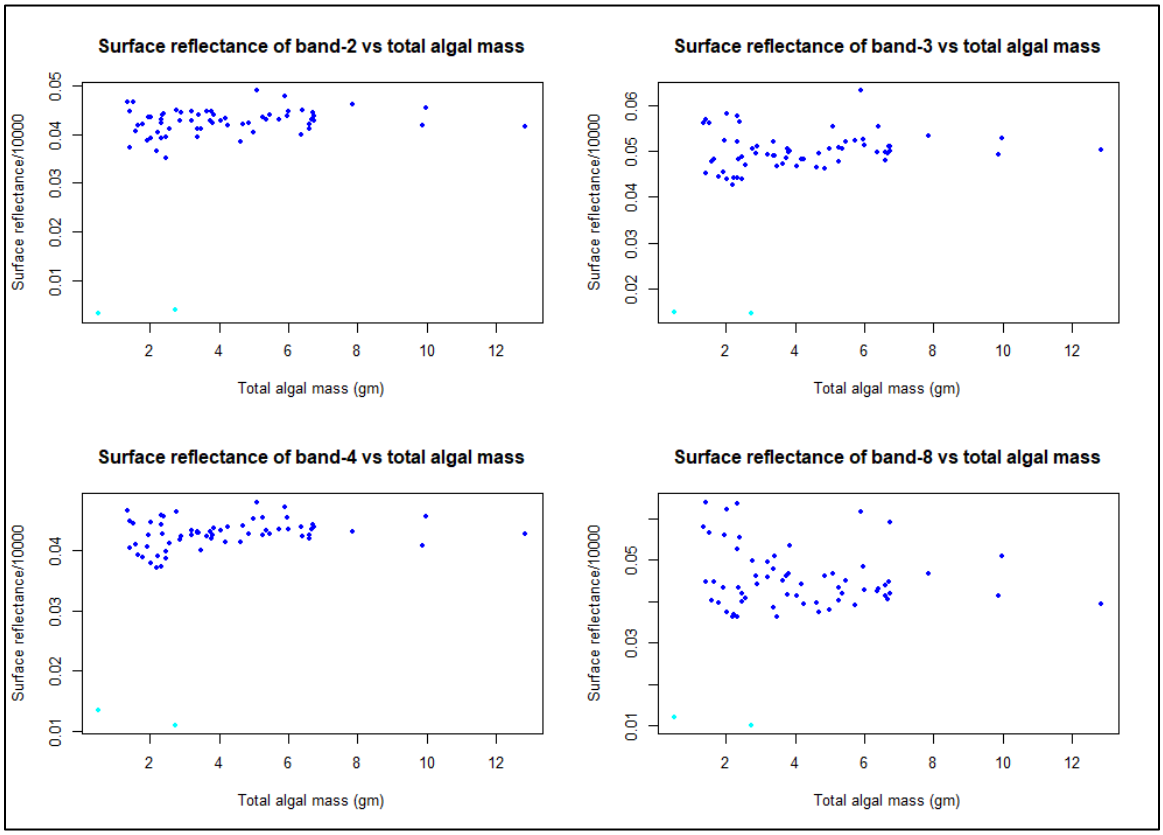

Figure 36. Surface reflectance of 10m spatial resolution images against increasing total algal mass. Blue and cyan colors represent the sampling periods 4 and 5, respectively. This figure represents the data after the aquatic correction.

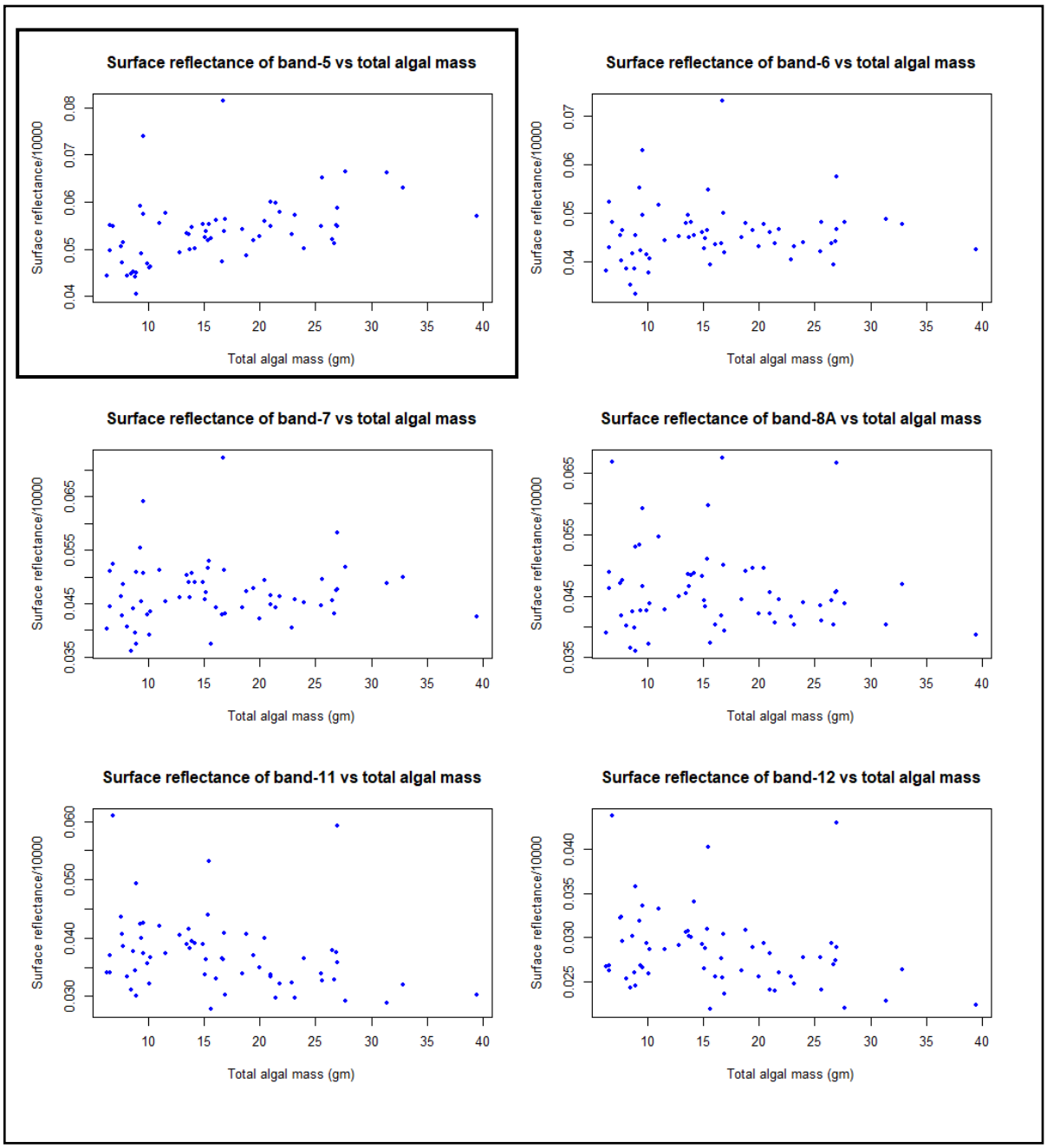

Figure 37. Surface reflectance of 20m spatial resolution images against increasing total algal mass. Blue and cyan colors represent the sampling periods 4 and 5, respectively. This figure represents the data after the aquatic correction.

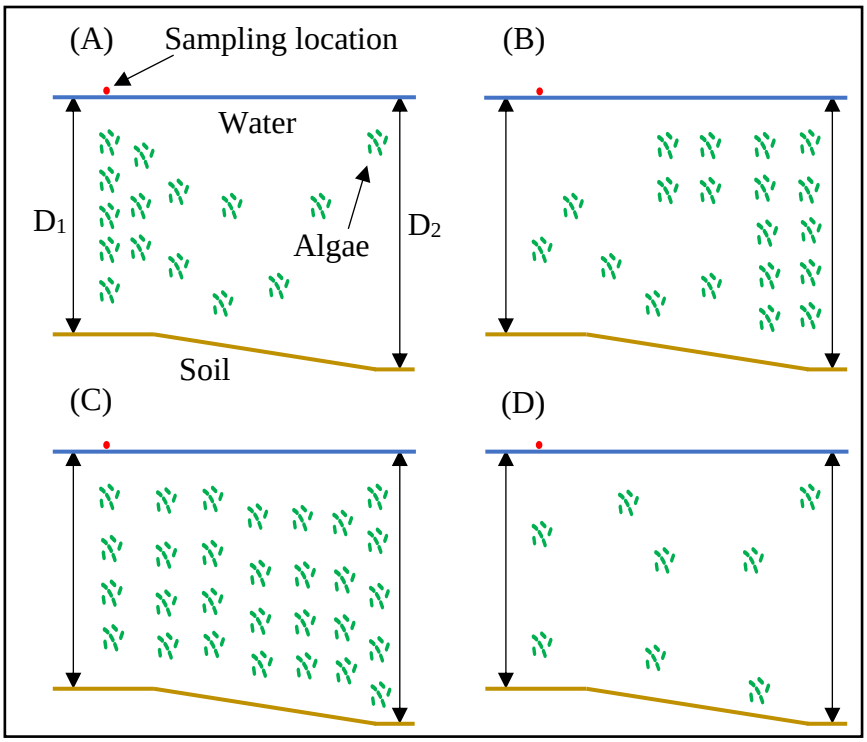

Figure 38. Illustration of sampling location's influence on total algal mass calculation. (A) will calculate high algal mass while it should be low. (B) will calculate low algal mass while it should be high. (C) and (D) should be approximately correct.

Before going to model preparation with the surface reflectance of the band-5, errors were checked raised from the total algal mass calculation. Two assumptions were taken while calculating the total algal mass from Equation 2: (1) Uniform mean total algal concentration across the whole pixel area, and (2) Uniform water column's depth across the whole pixel area. These two assumptions could cause two category errors: mean total algae per area in sampling location was higher, but other locations under that same pixel area were lower, which calculated high mass while it should be low (was indicated as E-1) and vice versa (was indicated as E-2). E-1 and E-2 phenomena are illustrated in Figure

38(A) and 38(B), respectively. Though the purpose of the aquatic correction is not to solve E-1 & E-2, by the aquatic correction process, while deleting the data of $\frac{\text{Surface reflectance}}{10000} \leq 0.01$, automatically, some E-1 got deleted. (Figure 38).

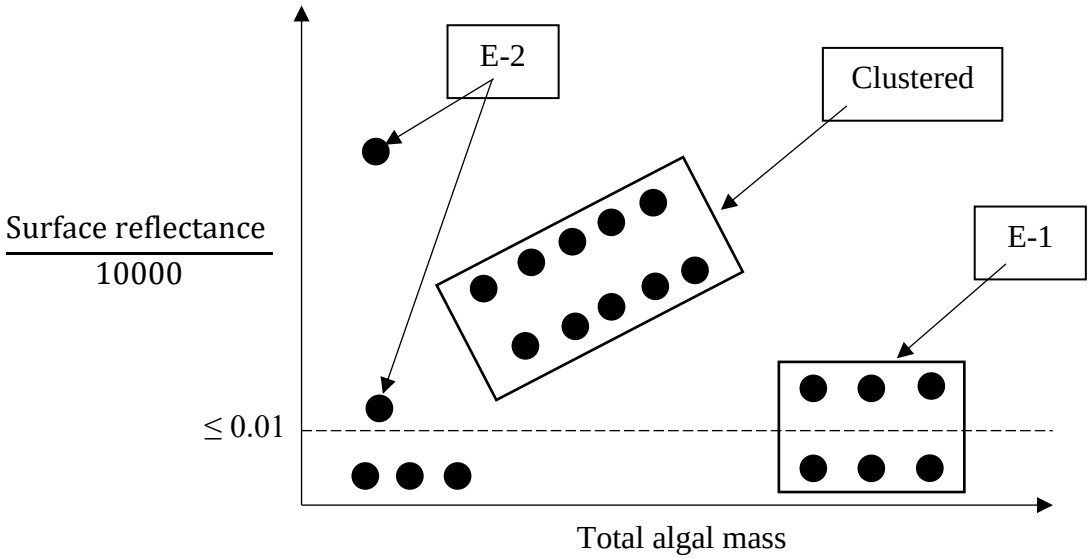

Figure 39. Illustration of E-1 & E-2 errors. E-1 & E-2 errors were created due to the limitation of the mass calculation process.

E-1 and E-2 errors were detected from the band-5's surface reflectance vs. total algal mass graph (Figure 40). Then, outliers for both surface reflectance and total algal mass were checked, and the detected E-1 and E-2 errors were matched with the outliers and deleted. After that, the other data were used for preparing the total algal mass detection empirical model.

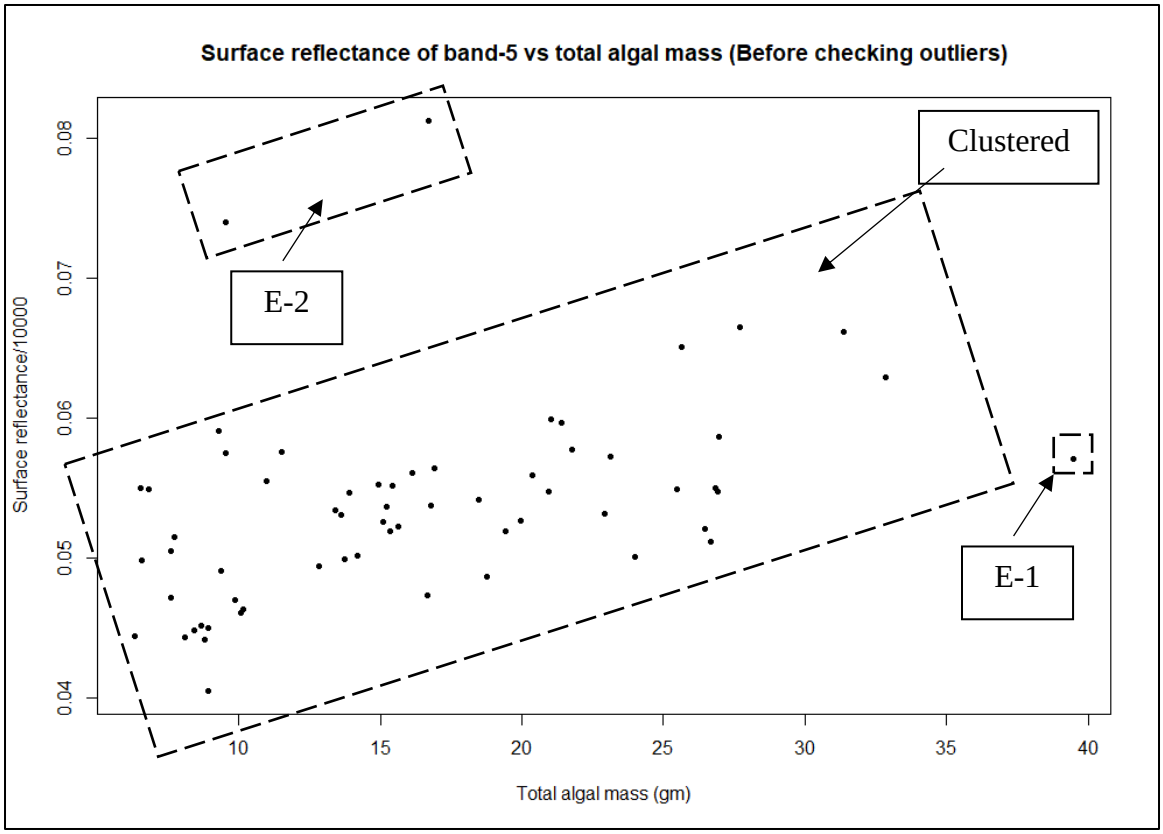

Figure 40. Categorization of the data point of the "Surface reflectance of band-5 vs total algal mass" graph into clustered, E-1, and E-2.

To conduct this research, total algal concentration was collected spatially and vertically throughout the lake, which comes with intensive data. Though this research collected more informative data than the related research like Johansen et al. (2018) and Mishra and Mishra (2012), it still faced E-1 and E-2 errors. So, the previous methodologies might face severe E-1 and E-2 errors. However, E-1 and E-2 errors might be solved with Equation 11, where n is the total number of points across the pixel area.

$$\sum_{i=1}^{i=n} \text{Mean concentration in point i's water column} * \text{Water column depth in point i} = \text{mass} \qquad (11)$$

To check the performance of the aquatic correction process, empirical models were built both for the data "before aquatic correction" and "after aquatic correction". All the data were used for making the empirical model, and it was found that the aquatic correction process developed the model's performance from R^2 = 0.07 to 0.40 (Table 14). So, this result indicates that aquatic correction improves model applicability and should be used before preparing a remote sensing-based empirical model to detect the total algal mass.

Table 14. Performance analysis of aquatic correction.

Calibration model type	R^2	RMSE	$\frac{1}{2} \times$ SD
Before aquatic correction	0.07	6.61 gm	3.45 gm
After aquatic correction	0.40	5.48 gm	3.58 gm

After doing the aquatic correction, 80% of the data were used for the empirical model's calibration, and the total algal mass detection model (Equation 12) was prepared (p-value: 8.879e-07).

$$\text{Total algal mass (gm)} = 0.07649 \times \text{Band } 5 - 23.45493 \qquad (12)$$

The R^2 of the empirical model is 0.41. The model's performance and diagnostic plot are showed in the Table 15 and Figure 41, respectively. From the diagnostic plot (Figure 41) and the Shapiro-Wilk normality test (p-value = 0.1695) it was found that the residuals are normally distributed. From the Figure 42 & 43, it has been found that for the observed mass < 18 gm, the model is mostly overpredicting the total algal mass. Then, for the observed mass > 18 gm, the model is mostly underpredicting the total algal mass. The empirical model determined the spatial distribution of the total algal mass (Figure 44).

Table 15. Performance analysis of total algal mass detection empirical model.

Model type	R^2	RMSE	$\frac{1}{2} \times SD$
Calibration	0.41	5.16 gm	3.40 gm
Validation	-	7.07 gm	3.15 gm

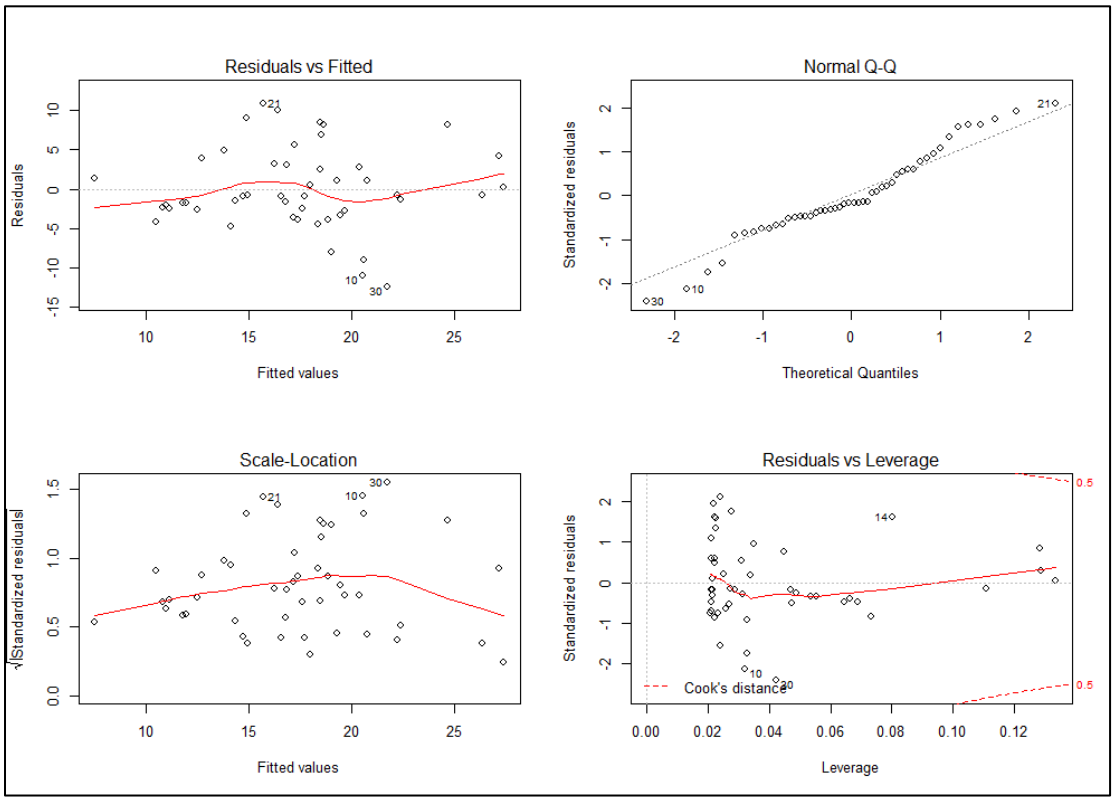

Figure 41. Diagnostic plot for the empirical model.

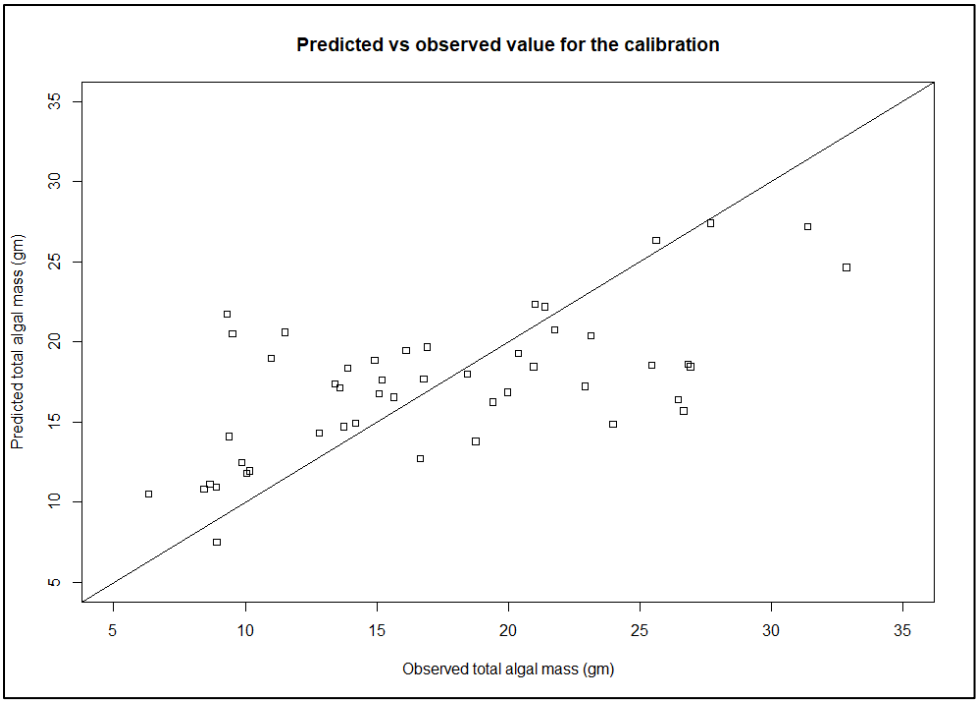

Figure 42. Predicted vs observed total algal mass for the calibration data.

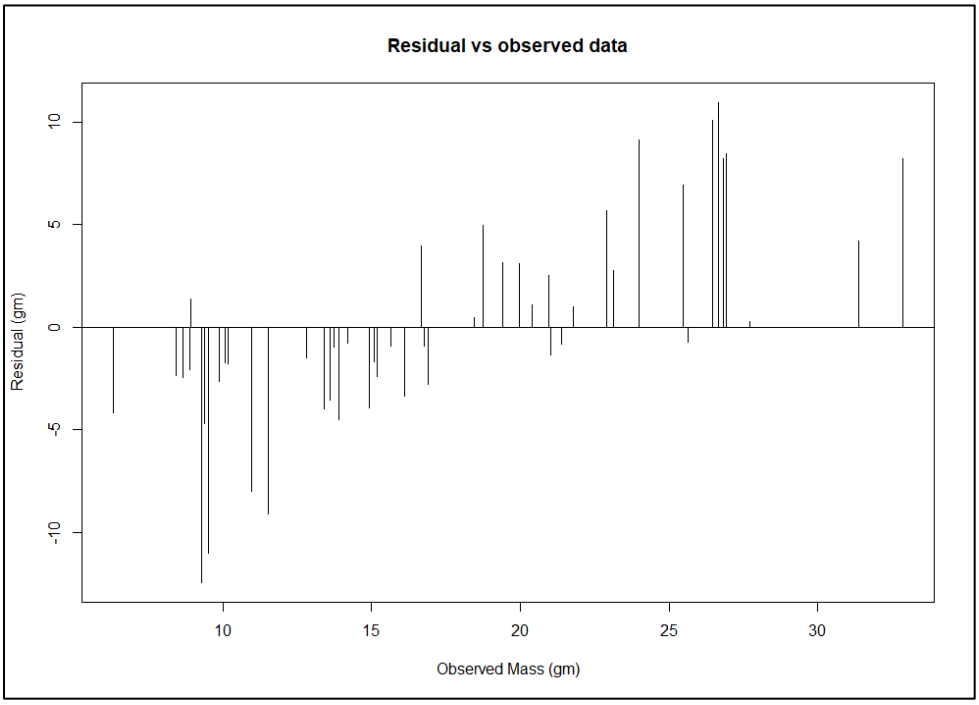

Figure 43. Plot of residual against the observed data.

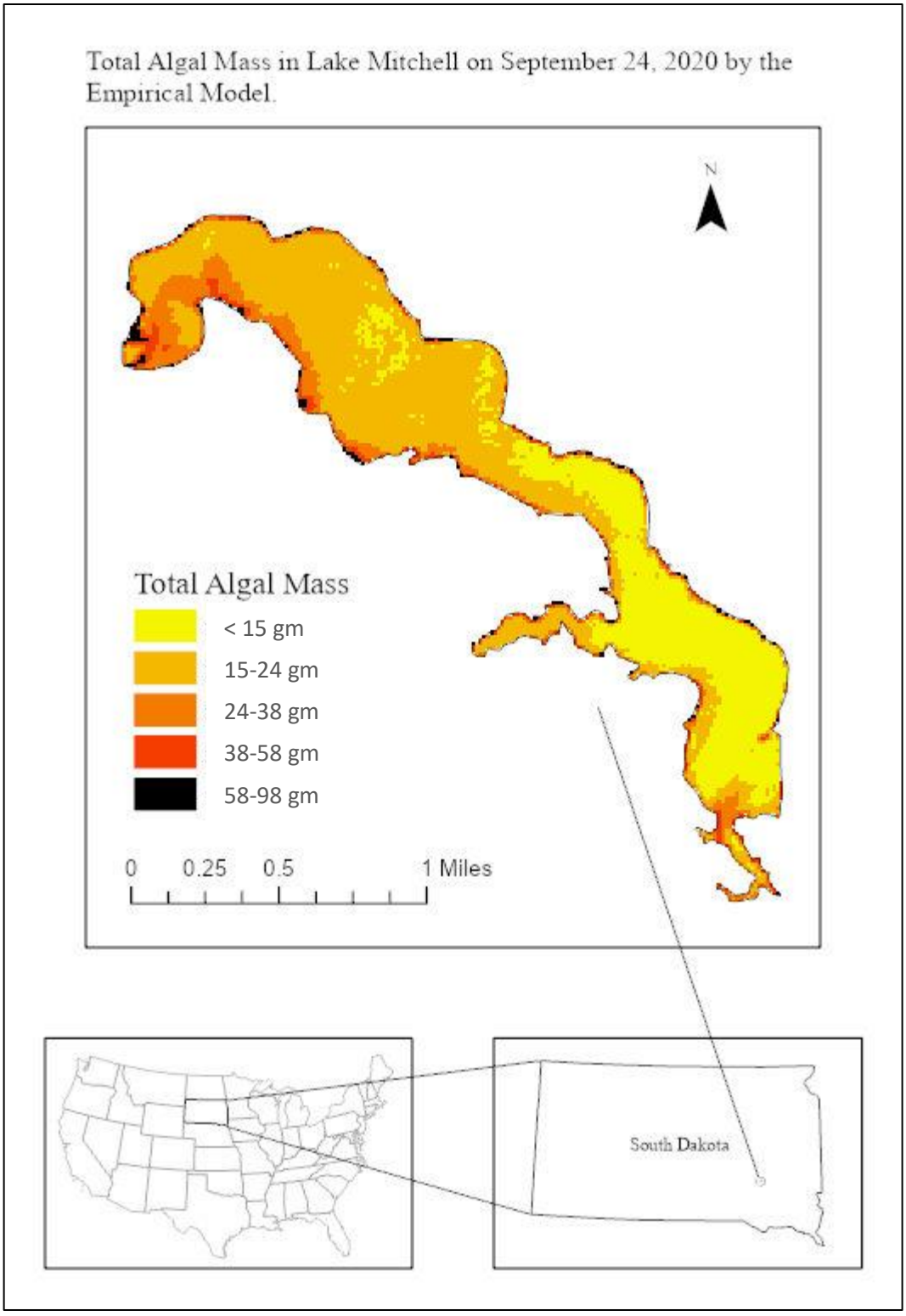

Figure 44. Total algal mass in the Lake Mitchell on September 24, 2020, by the empirical model.

5.4 Conclusion

Proper procedure is not followed to prepare an algae quantifying empirical model. Before preparing the algae quantifying empirical model, a novel procedure has been prepared. Instead of using algal concentration, algal mass should be used to make correlation with the reflectance measured from the satellite. The “aquatic correction” has improved the model performance, so this process might be a guideline for future researchers to prepare their empirical model. The total algal mass determined by the empirical model may give a relative sense of total algal mass (Where, total algal mass = chlorophyll-a mass + phycocyanin mass) in Lake Mitchell, which might be helpful to the lake manager to remotely monitor the lake conditions.

Chapter-6 | Conclusion

Algae is detrimental for ecology, local economies, and human health. Thus, it is nationally and internationally important to discover algae's environmental system. A conceptual model is essential to qualitatively understand algae, but there is insignificant conceptualization about algae. A conceptual model may also help to choose environmental parameters for the quantitative analysis, but there is insignificant quantitative understanding of algal behavior. Besides, additional factors need to be included for using remote sensing data to develop algal mass detecting empirical models.

Numbers of conceptual models can be prepared to qualitatively explain algae. In this conceptual model, eleven environmental parameters: (1) solar radiation, (2) temperature, (3) oxygen and dissolved oxygen, (4) rainfall, (5) runoff, (6) turbidity, (7) nutrients and thunderstorms, (8) saline elements, (9) dissolved organic matters, (10) carbon, and (11) wind were included. The conceptual model was prepared combining the present evidence and visualization. Later it become the foundation for the quantitative analysis where it helped to choose the environmental parameters. In the future this conceptual model might be a guideline for developing another algae related conceptual model.

The conceptual model helped to choose the five parameters (conductivity, temperature, fluorescent dissolved organic matters, ammonium, and dissolved oxygen) to quantitatively explain algae, but independently the parameters did not give any consistent

result. Even their combined effect also could not be able to explain algae. Parameters, like nitrate, nitrite, phosphorus should be included in the future for doing the quantitative research on algae.

Remote sensing has the ability to massively show the algal quantity in the water area. But the proper procedure: (1) using algal mass instead of algal concentration, (2) using aquatic correction, and (3) eliminating data error due to the mass calculation process, should be followed. This novel procedure might be a guideline for the future researchers to develop their algae detecting empirical model.

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