SŌLITUDE
LAKE MANAGEMENT

2022 Water Quality Monitoring Report

Barefoot Lakes

Firestone, CO

Submitted to:
St. Vrain Lakes Metro District
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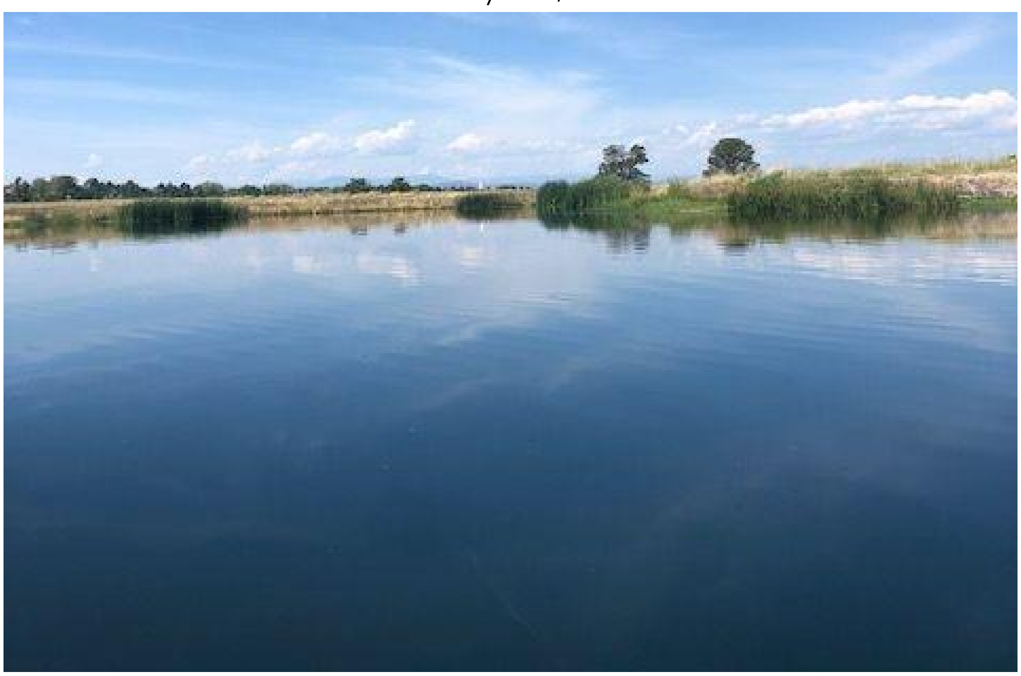

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Project Background

Barefoot Lakes is a residential development with three home builders located in Firestone, CO. The lakes are a main focal point, centered around nature, and designed for community members with walking paths and other recreational opportunities. The West Lake is approximately 30 surface acres (SA), and the larger East Lake is about 50 SA. The lakes are separated by a short section of land with large equalization pipes between them that provides water connectivity. The lakes are filled from precipitation, runoff, and St. Vrain Creek when water rights are in priority. The lakes have recently been developed for recreational purposes including paddle boarding, fishing, and non- motorized boating.

These resources have a history of nuisance algae, aquatic vegetation growth, and cyanobacteria blooms. Water quality conditions vary during different times of the year since the lakes do not have a constant water source and experience level changes. The lakes are filled from St. Vrain Creek and mutual irrigation ditches during "free river" conditions. In addition, Colorado Big Thompson (CB-T) and Windy Gap Project water can be added when water rights are in priority to make up for evaporation or seepage losses. The only other source of water is stormwater and irrigation runoff from the development above the lakes in the watershed. The lakes have high levels of productivity caused by the poor water quality, the water source, limited water exchange, high residence time, and occasional low water levels during the summer.

The lakes are home to a healthy population of aquatic life including fish, birds, amphibians, and turtles. The water quality in the lakes have been monitored for the last few years in order to establish baseline conditions and track changes over time.

Water Quality Monitoring Program and Objectives

In 2022, the water quality monitoring program included monthly events from May through September. Samples from three (3) depths (top, middle, and bottom) from each lake and a surface sample from St.Vrain Creek were collected and sent for laboratory analysis. The East Lake is slightly deeper than the West Lake, so the top sample was collected just below the surface (surface), the middle sample at two meters (2 m) and the bottom sample at four meters (4 m). In the West Lake, the top sample was collected just below the surface (surface), the middle sample at one and a half meters (1.5 m), and the bottom sample at three meters

(3 m). In addition, a multi parameter water quality monitoring probe (sonde) was used to collect profiles of temperature, pH, oxidation reduction potential (ORP), dissolved oxygen (DO), and conductivity at 1 m increments from the surface to the bottom. Water quality samples and profiles were collected in each lake, and one sample was collected from St. Vrain Creek during each monitoring event (Figure 1). Other water sources to the lakes were not significant and therefore were not sampled in 2022.

This comprehensive water monitoring program is designed to understand differences in water quality between the resources and water source and to track changes over time. Physical conditions, nutrients, chlorophyll a, E. Coli levels, and algae populations were monitored to provide detailed water quality data as well as information on conditions that could lead to potential human health risks.

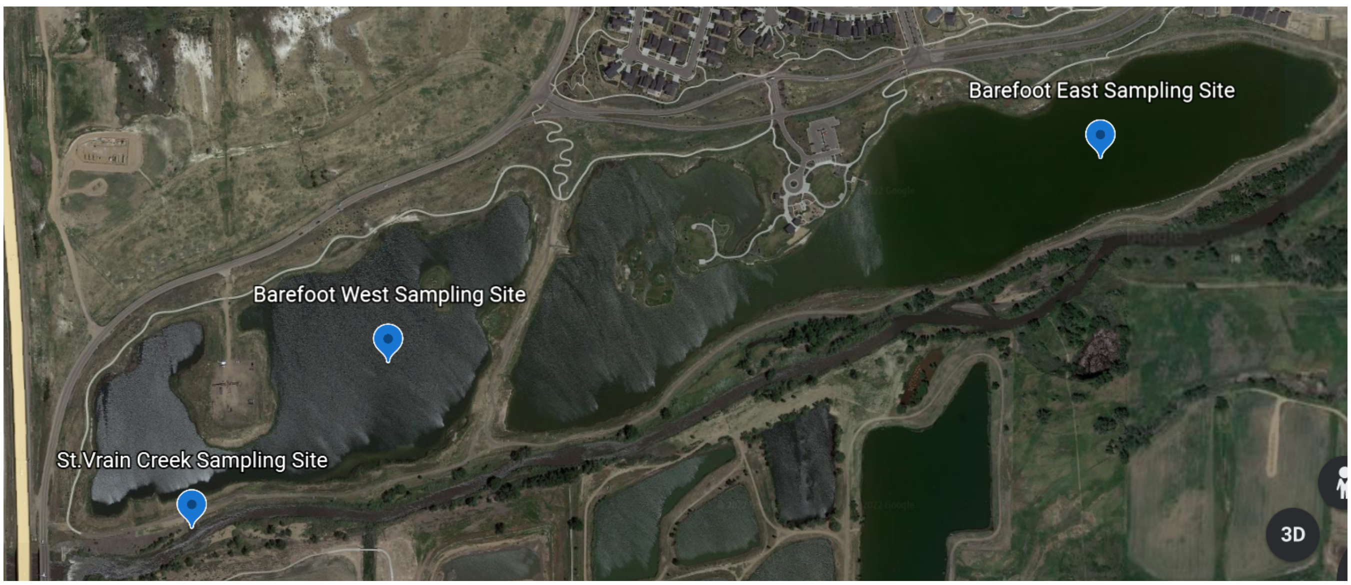

Figure 1. Water Quality Monitoring Locations

Water Quality Methods and Analyses Descriptions

The parameters analyzed in the monitoring program are useful in determining overall water quality, and suitability for aquatic life and recreational uses of the lakes. These parameters are also used to define lake trophic state and interactions between the chemical, physical, and biological components of the lake ecosystems. All analyses were conducted using approved methods described by the U.S. EPA (U.S. EPA 1993; 2014) and/or Standard Methods (Standard Methods, 1998 and other versions). A multi-parameter sonde was used for all water column profiles to measure temperature, pH, conductivity, dissolved oxygen (DO), and oxidation reduction potential (ORP). A 30cm (8 inch) black and white Secchi disk was used to measure clarity, also known as Secchi depth.

pH

The hydrogen ion activity indicates the balance of acids and bases in water and determines pH. A pH of 7 is considered neutral. A pH less than 7 is considered acidic, while a pH greater than 7 is considered basic. Most aquatic organisms survive best in waters with a pH between 6.5 and 9.0. Since pH is expressed on a logarithmic scale, each 1-unit change in pH represents a ten-fold increase or decrease in hydrogen ion concentration. Therefore, a pH of 6 would be 10 times more acidic than a pH of 7 and 100 times more acidic than a pH of 8. The pH of normal rainwater (containing no pollutants) is about 5.6. As the rainwater travels over and through rocks and soil, chemical reactions with minerals affect the pH and increase the buffering capacity of the water.

Oxidation Reduction Potential

Oxidation reduction potential (ORP) measurements are used to quantify the exchange of electrons during redox or oxidation reduction reactions. Electrical activity is reported in millivolts (mV) which is very similar to a pH probe. At the water/sediment boundary layer, microbial organisms facilitate the chemical reactions but do not actually oxidize or reduce the compounds. The redox reactions provide energy for microbial cells to carry out their metabolic processes (Wetzel 2001). The combination of microbial organisms and redox reactions are responsible for the breakdown of organic matter and development of anoxic conditions near the sediment boundary in lakes and reservoirs during the summer. Higher ORP values correlate to higher microbial decomposition activity.

Conductivity

Specific conductance, or conductivity, is the ability of water to conduct an electrical current based on the dissolved inorganic solids (positive and negative ions) present. High sediment loads do not generally increase conductivity readings since sediment particles are generally considered to be suspended rather than dissolved because of their larger size (greater than 2 microns). The geology of the area, water source and watershed affect conductivity and 50-1500 µS/cm are typical for surface water.

Dissolved Oxygen

Dissolved oxygen (DO) is the amount of oxygen gas dissolved in the water column. Oxygen enters the water column by direct diffusion at the air/water interface and is also produced during photosynthesis of algae and aquatic vegetation. Dissolved oxygen gradients provide an indication of mixing patterns and the effectiveness of mixing processes in a lake. Dissolved oxygen concentrations also have an important bearing on the physical-chemical properties of lakes and the composition of a lake's biota. Lakes impacted by heavy sediment loads may experience low DO levels since the increased turbidity caused by suspended particles can reduce light penetration and limit photosynthesis. The breakdown of organic matter or decomposition can consume large amounts of oxygen from the water column. Fish require oxygen for respiration and become stressed at levels less than 5 mg/L. Dissolved oxygen can be expressed in concentration of mg/L or in percent saturation. Dissolved oxygen saturation is directly related to temperature and capacity decreases as temperature increases.

Temperature

Water temperature affects the dissolved oxygen concentration of the water, the rate of photosynthesis, metabolic rates of aquatic organisms, as well as the sensitivity of organisms to toxins, parasites, and disease. All aquatic organisms are dependent on certain temperature ranges for optimal health. If temperatures are outside of this optimal range for a prolonged period, the organisms become stressed, and mortality is likely. Water temperature generally increases with turbidity as the particles absorb heat and the dissolved oxygen levels are reduced. Water temperature is primarily controlled by climatic conditions but can be influenced by human activities.

Transparency

Transparency is used as an indicator for primary productivity and turbidity of the water column. This measurement can be a good reference point of the overall health of an aquatic ecosystem. The measurement is based on the amount of light scattered by particles in the water column. The Secchi depth is higher when there are less particles in the water and lower with more particles in the water. This measurement is often a representation of biological productivity of the water body but is also affected by suspended sediments in the water. Secchi depths of less than 6.6 feet (2.0 meters) have traditionally been considered undesirable for recreational uses in natural lakes; however, lower clarity is usually tolerated in urban reservoirs.

Measuring the Secchi depth of a waterbody is a way to quantify water clarity and is measured when an 8” black and white disk is no longer visible as it is lowered into the water column on the shady side of the boat. The depth is measured at each location twice to verify value.

Chlorophyll a

Chlorophyll a is the green pigment that allows plants to photosynthesize. The measurement of chlorophyll a in water provides an indirect indication of the quantity of photosynthesizing phytoplankton found in the water column. It is found in all algal groups, as well as in cyanobacteria. More specifically, chlorophyll-a (chl-a) is a measurement of the portion of the pigment that was still actively respiring and photosynthesizing at the time of sampling and does not include dead biomass. In surface water, lower chl-a concentrations correspond to oligotrophic or mesotrophic conditions, where higher concentrations indicate a eutrophic or hyper-eutrophic state.

Phosphorus

Phosphorus can be found in several forms in freshwater, but the biologically available form for nuisance plant growth is soluble, inorganic orthophosphate or soluble reactive phosphorus. Organic phosphates quickly bind to soil particles and plant roots. Consequently, much of the phosphorus in aquatic systems is bound and moves through the system as sediment particles. This organic form of phosphorus is considered biologically unavailable. However, under anoxic (low oxygen) conditions, bound phosphorus can be released from bottom sediments, and the concentration of biologically available orthophosphate can increase significantly. The erosion of soil particles from steep slopes, disturbed ground, and streambeds is the primary source of phosphorus in aquatic systems. Surface runoff containing phosphorus from fertilizers, wastewater effluent and decaying organic matter will also contribute to biologically available phosphorus enrichment.

Total Phosphorus (TP) is the measure of all phosphorus in a sample as measured by persulfate digestion and includes: inorganic, oxidizable organic and polyphosphates. This includes what is readily available, potential to become available and stable forms. In surface water concentrations *<12 µg/L are considered oligotrophic; 12-24 µg/L mesotrophic; 25-96 µg/L eutrophic; and >96 µg/L hypereutrophic.*

Soluble Reactive Phosphorus (SRP) is the measure of inorganic dissolved reactive phosphorus (PO_4^{-3}, HPO_4^{-2}, etc.). This form is readily available in the water column for phytoplankton growth.

Nitrogen

Nitrogen has a complex cycle and can exist in organic and inorganic, particulate, and soluble forms. The soluble, inorganic, oxidized forms are nitrate (NO2), and nitrite (NO3) which are normally found in surface water. The reduced form is ammonia (NH4) which is normally found in low oxygen environments. Both inorganic forms are the most available for primary productivity. However, atmospheric nitrogen (N_2) can also be used as a nutrient source by some species of algae, and various other reduced forms of nitrogen can be produced by decomposition processes. Particulate and dissolved organic forms of nitrogen are not immediately available to drive algal growth but can be converted to ammonia by bacteria and fungi; and can be oxidized to form nitrites then nitrates. Surface runoff can contain inorganic nitrogen from fertilizers and organic nitrogen from animal waste, wastewater, etc.

Total Nitrogen (TN) is the quantity of all nitrogen in the water and is calculated by adding the measured forms of organic nitrogen, oxidized nitrogen, and ammonia.

Nitrates and Nitrites (NO_2+NO_3) are the sum of total oxidized nitrogen, often readily free for algae uptake.

Ammonia (NH_3-H) is a reduced form of dissolved nitrogen that is readily available for phytoplankton uptake. NH4 is found where dissolved oxygen is lacking such as in a eutrophic hypolimnion and is produced as a by-product by bacteria during decomposition.

Nitrogen/Phosphorus Levels and Ratios

Phytoplankton require both macronutrients, such as phosphorus, nitrogen, and carbon, and trace nutrients, including iron, manganese, and other minerals, for growth. Biological growth is limited by the nutrient availability within a water body, which is known as its nutrient limitation. The ratio of total nitrogen to total phosphorus in a waterbody provides insight into the nutrient limitation in the waterbody. Since many species of harmful cyanobacteria (blue-green algae) can fix nitrogen from the atmosphere, they have a competitive advantage over other algae in phosphorus-rich environments when nitrogen is limited and can become dominant over the more beneficial green algae species. Maintaining a molar Nitrogen to Phosphorus ratio (N:P) greater than 16:1, or 7:1 ratio by weight will favor a balanced phytoplankton diversity and reduce the potential for a cyanobacteria dominated environment. The ratio or total inorganic nitrogen to soluble reactive phosphorus is often more indicative of phytoplankton growth potential since these are the forms most available in the water column.

Trophic State

The Trophic state as described by Vollenweider (1970) is used as a guideline for describing water quality as it relates to the trophic state or biological productivity potential.

Oligotrophic - lack of plant nutrients, low productivity, sufficient oxygen at all depths, clear water, deeper lakes can support trout.

Mesotrophic - moderate plant productivity, hypolimnion may lack oxygen in summer, moderately clear water, warm water fisheries only.

Eutrophic - contains excess nutrients, blue-green algae dominate during summer, algae scums are probable at times, hypolimnion lacks oxygen in summer, poor transparency, rooted macrophyte problems may be evident.

Hypereutrophic - algal scums dominate in summer, few macrophytes, no oxygen in hypolimnion, fish kills possible in summer and under winter ice.

Total Suspended Solids

Total Suspended Solids (TSS) is a quantification of suspended sediment concentrations in water. Suspended solids in lakes include both organic material, such as algal cells and other microorganisms, and inorganic particulate matter, such as silt and clay particles. Algae and other organisms are commonly the main source of TSS in lacustrine environments while silt and clay are the primary source of suspended solids in lotic or groundwater samples.

Water Quality Monitoring Results

Temperature

Temperature data can indicate thermal stratification in water bodies, which occurs when there is drop in temperature and dissolved oxygen. Low oxygen levels can limit the areas aquatic life can inhabit. Minimal differences in temperature with depth was observed in the East Lake suggesting limited stratification during most of 2022 (Figure 3). A minor amount of stratification was observed in May but was much less significant the rest of the 2022 season. The West Lake did demonstrate some thermal stratification in May and June, with the most significant temperature gradient in July. The maximum difference in temperature from the top to the bottom in the West Lake was observed on July 21st with a difference of 5.9 degrees Celsius (˚C) (Figure 2) and 5.6 ˚C on May 11th in the East Lake (Figure 3). The maximum temperature recorded in 2022 was 26.6 ˚C in the West Lake on July 21st. According to CDPHE Water Quality Control Commission's Regulation 38, water bodies that have water quality standards must maintain a temperature standard of 26.3 ˚C for a maximum weekly average temperature (MWAT) and a 29.5 ˚C for a daily maximum temperature (DM) from the months of April to December for warm water lakes (CDPHE, 2016). The temperature readings for both lakes were well within these parameters and no concerns were determined from this data.

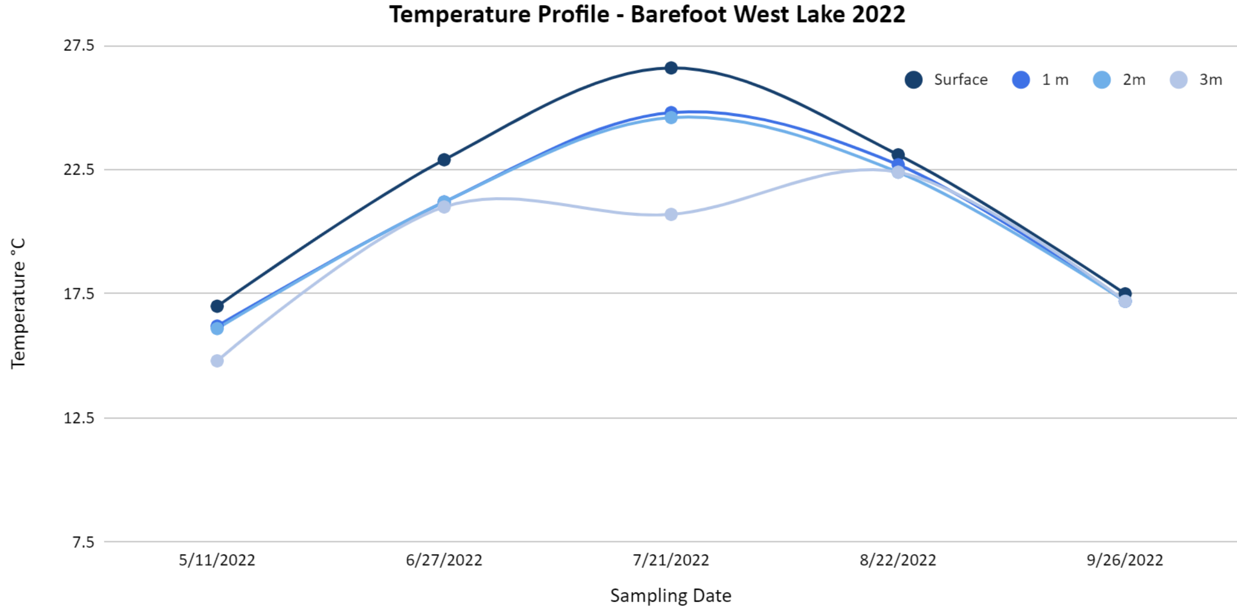

Figure 2. Temperature Profile, Barefoot West Lake, 2022.

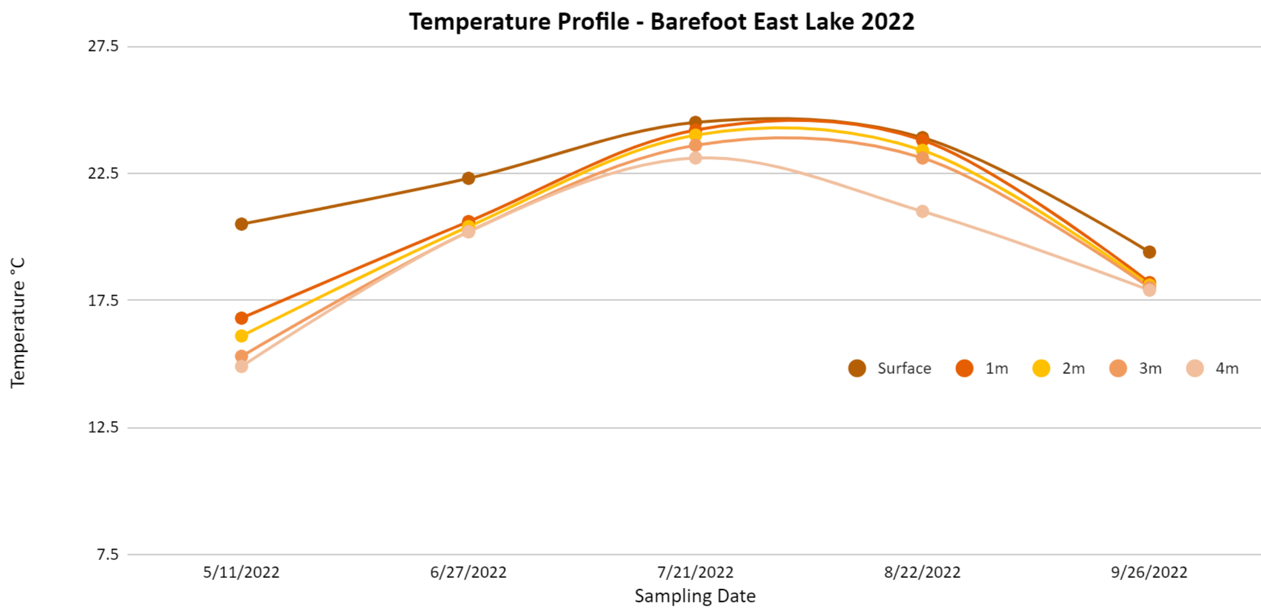

Figure 3. Temperature Profile, Barefoot East Lake, 2022.

Dissolved Oxygen

In water bodies with water quality standards, Colorado Department of Public Health and Environment (CHPHE) Water Quality Control Commission's Regulation 38 for warm water reservoirs requires that dissolved oxygen (DO) levels are 5.0 mg/L or above near the surface (CDPHE, 2016). The DO may be less than 5.0 mg/L near the bottom as long as there is a refuge with DO levels greater than 5.0 mg/L available for aquatic life.

Figure 4 and Figure 5 illustrate the DO profiles in both lakes and St. Vrain Creek during 2022. The dissolved oxygen measurements were typical with higher values near the top (photic zone) which decreased with depth. The profiles demonstrated a significant decrease in DO concentrations below 2-3m throughout the season. The East and West Lakes had DO values below 5.0 mg/L from June through August at depth.

The East Lake had DO concentrations below 5.0 mg/L all season from 2m to the bottom. Dissolved oxygen levels in July and August decrease significantly, but return to optimal levels above 2m in September. The West Lake maintained sufficient DO 2m and above May through July. In August, DO concentrations decrease, but remain ideal above 1m the entire season.

When adequate DO is limited to the upper portion of the water column, fish kills are a greater risk, especially when it coincides with elevated water temperatures. Periods of low dissolved oxygen indicate high microbial activity or decomposition in the sediments, which further reduces DO concentrations. A portion in the water column of both lakes remained above 5.0 mg/L giving refuge to fish that could not survive in the anoxic depths.

As seen in Figure 4, the DO concentrations in the St. Vrain Creek ranged between 8.03 mg/L and 10.62 mg/L which is suitable for aquatic life.

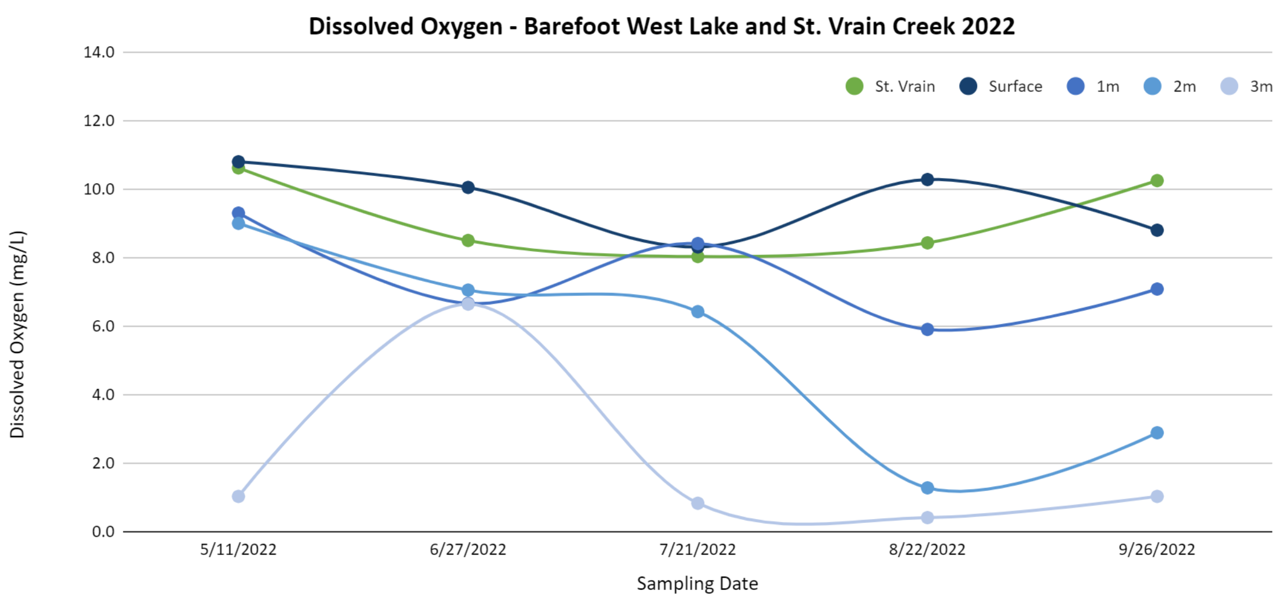

Figure 4. Dissolved Oxygen Profile, Barefoot West Lake and St. Vrain Creek, 2022.

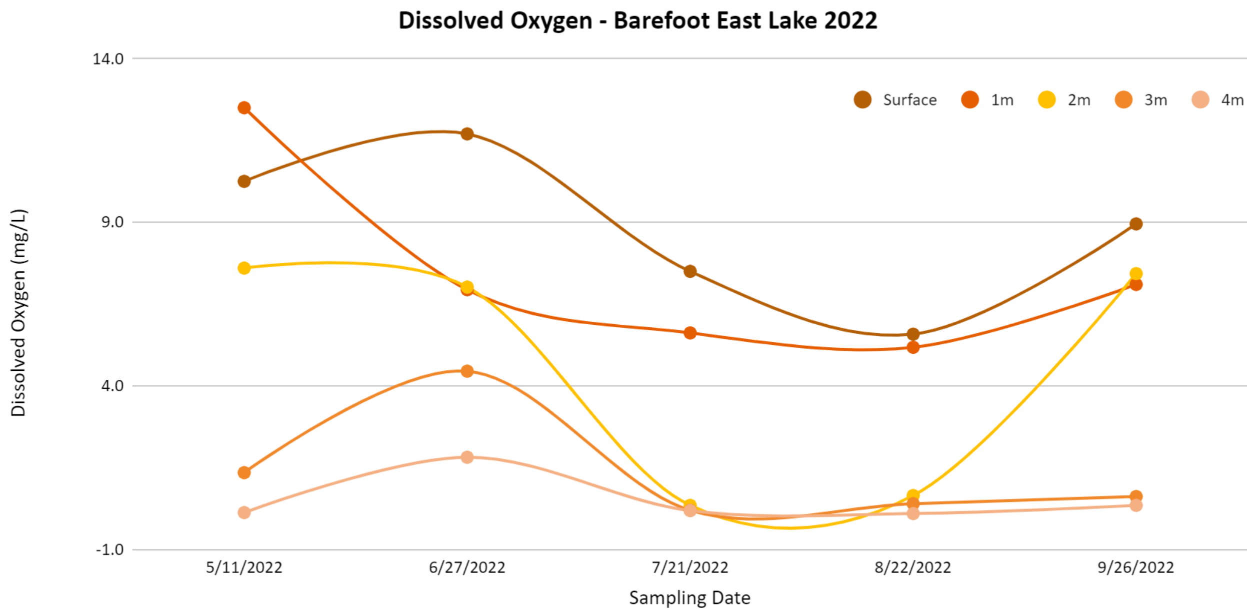

Figure 5. Dissolved Oxygen Profile, Barefoot East Lake, 2022.

pH

The pH in the West Lake (Figure 6 and Figure 7) ranged from 8.0 to 8.8 with an average of 8.34. The pH of the East Lake ranged from 7.9 to 8.8 with an average of 8.30 during the monitoring period. The highest pH values were seen at the surface pH and decreased with depth.

In water bodies with water quality standards, CDPHE Water Quality Control Commission's Regulation 38 standard range for pH is 6.5-9.0 (CDPHE, 2016), because values above or below can be harmful to fish and other aquatic organisms over time. In both lakes, no pH values above 9 or below 6.5 were measured the entire season.

The higher pH values measured in the lakes can likely be attributed to the higher levels of productivity. During the daylight, photosynthesis occurs in the photic zone, and carbon dioxide (CO_2) is pulled from the water causing the alkalinity and pH to increase. In the evening, the opposite occurs as plants and algae respire releasing CO_2 into the water and lowering pH. All monitoring events were completed during the daytime when pH levels may be elevated.

The pH in St. Vrain Creek remained relatively constant through the season ranging from 7.4 to 8.6 with an average of 8.18 (Figure 6). The lower pH values in the St. Vrain are due to the constant flowing water, cooler temperatures, higher dissolved oxygen concentrations, and less productivity.

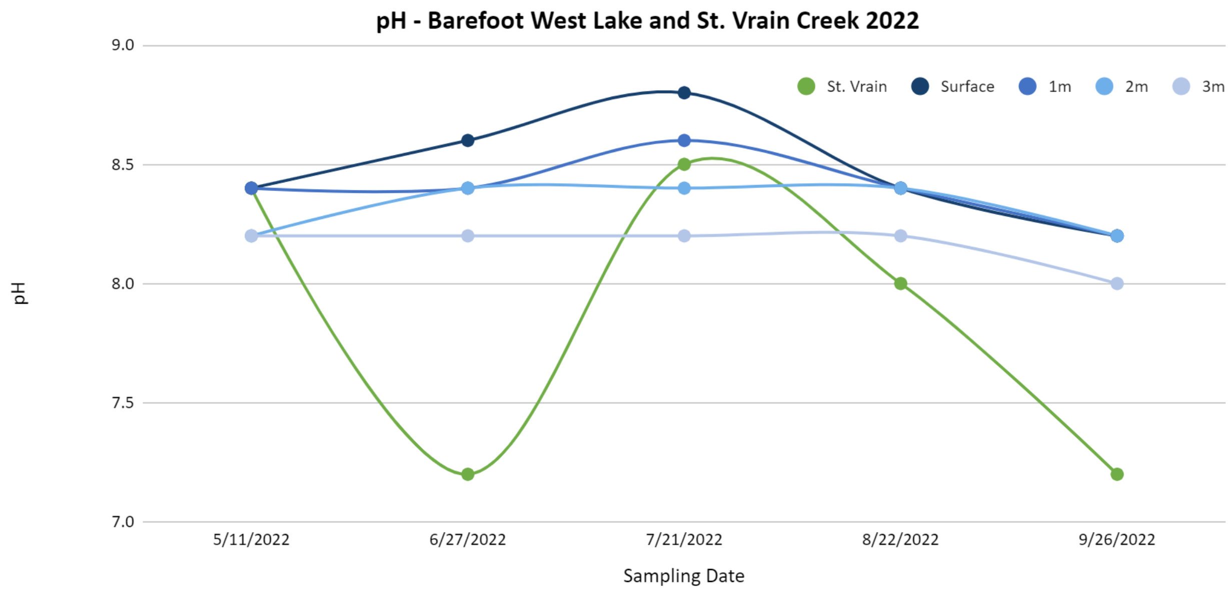

Figure 6. pH Profile, Barefoot West Lake and St. Vrain Creek, 2022.

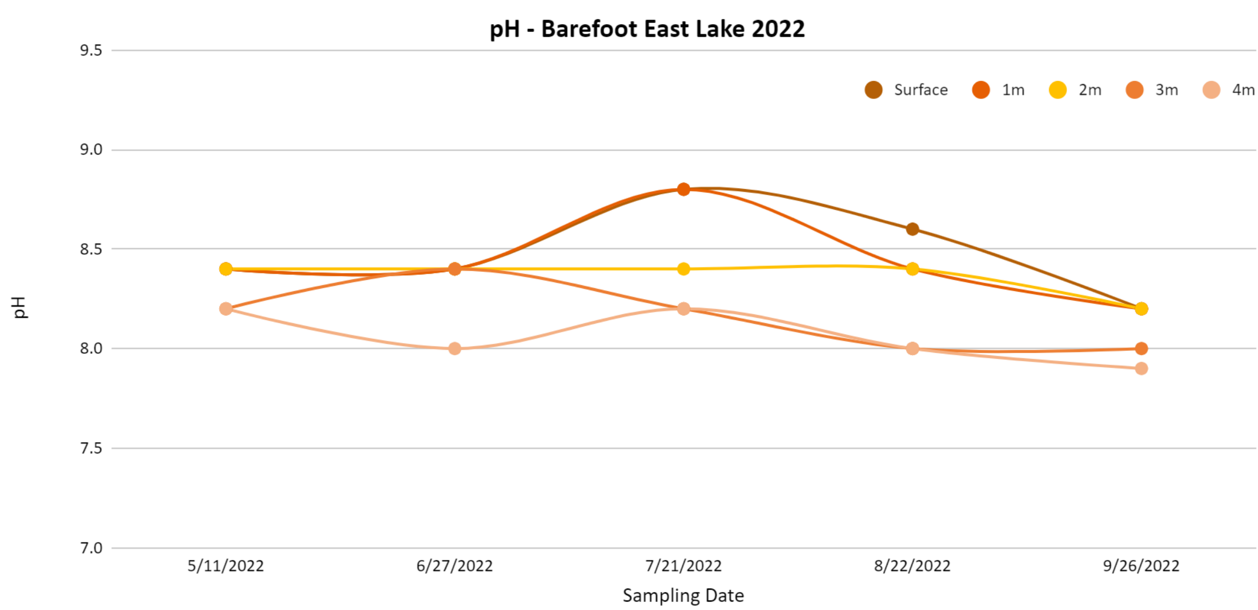

Figure 7. pH Profile, Barefoot East Lake, 2022.

Oxidation Reduction Potential

The Oxidation Reduction Potential (ORP) in the West Lake had a minimum value of -206 mV at 3 m in August and a maximum of 262 mV 2m below the surface in July of 2022 (Figure 8). In the East Lake the ORP ranged from -262 mV at 3 m in July to a maximum of 236 mV at 1 m in June (Figure 9). In St. Vrain Creek, the ORP ranged from 202 mV in September to 254 mV in July (Figure 8).

Higher ORP values indicate an oxidative environment and high potential to break down organic matter in the water. Low and negative values indicate a reducing environment and correlate to lower dissolved oxygen concentrations and higher microbial decomposition activity that is usually present at deeper sites and in the sediments.

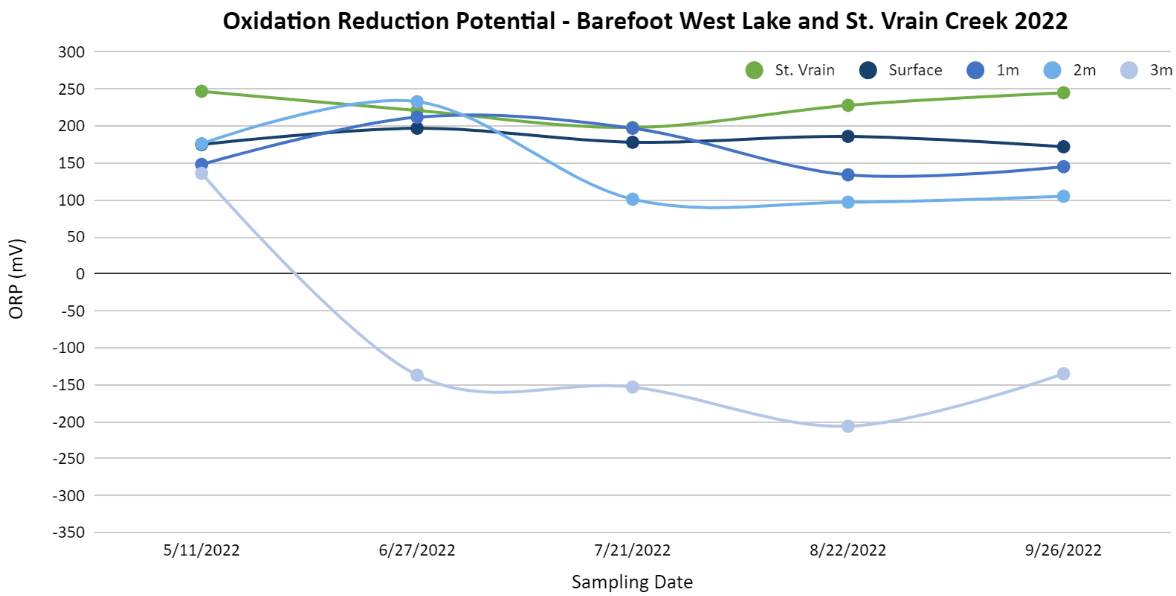

Figure 8. Oxygen Reduction Potential (ORP), Barefoot West Lake and St. Vrain Creek, 2022.

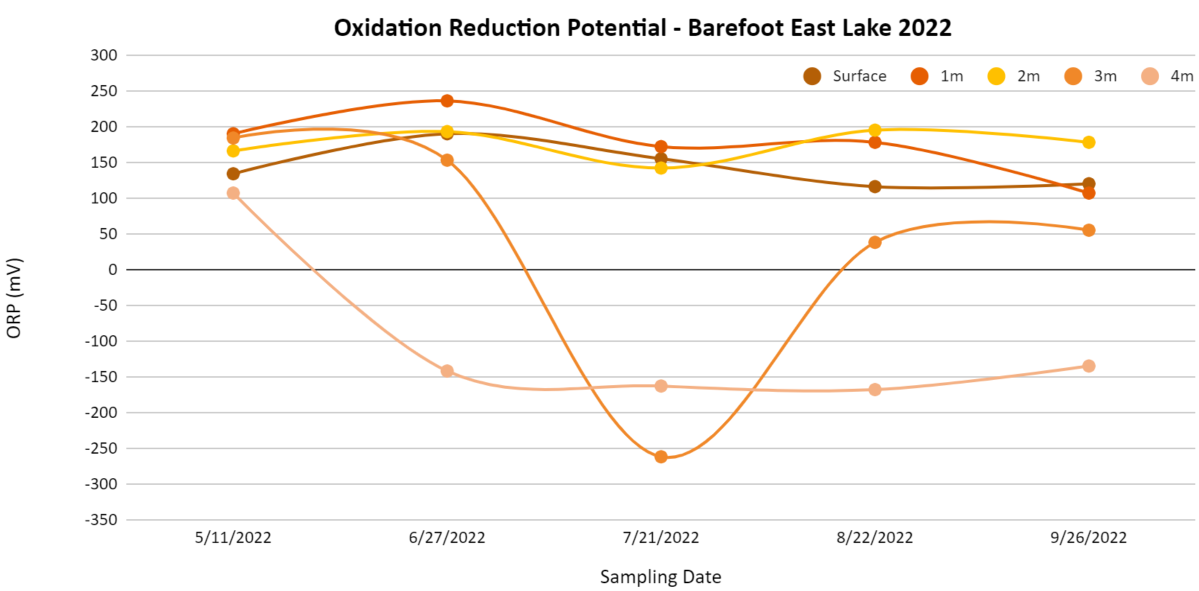

Figure 9. Oxygen Reduction Potential (ORP), Barefoot East Lake, 2022.

Conductivity

The East Lake conductivity ranged between 1,065 µS/cm and 2,880 µS/cm, with an average value of 1,926 µS/cm (Figure 11), which is lower than the 2021 average (2,491 µS/cm). The West Lake conductivity ranged between 1,053 µS/cm and 2,875 µS/cm with an average value of 2,167 µS/cm (Figure 10) which is slightly lower than the 2021 average (2,208 µS/cm).

St. Vrain Creek demonstrated greater variability in conductivity through the season with values ranging from 622 µS/cm to 1,165 µS/cm with an average value of 825 µS/cm. This is a similar trend to what was observed in previous years.

Conductivity is a measure of the dissolved solids, including salts, in the water and can be a measure of pollution. In this case, it appears that the conductivity in both lakes increases in the summer when the lake levels decrease due to evaporation and seepage. Water loss due to evaporation can increase conductivity, as the same amount of dissolved solids exist in less volume of water, therefore concentrations increase. It would be helpful to examine correlations between lake filling activities and changes in water quality such as conductivity. The variability of the levels in St. Vrain Creek can directly be attributed to the constituents in the watershed and water sources that feed the river (wastewater treatment plants, agricultural runoff, stormwater, etc.).

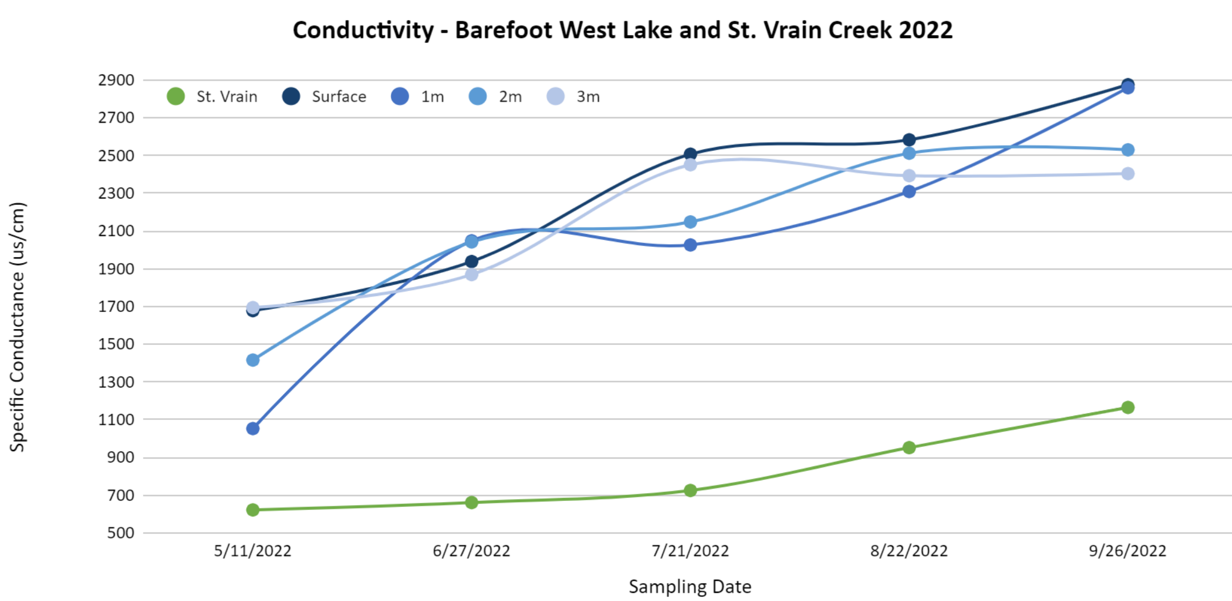

Figure 10. Conductivity, Barefoot West Lake, 2022.

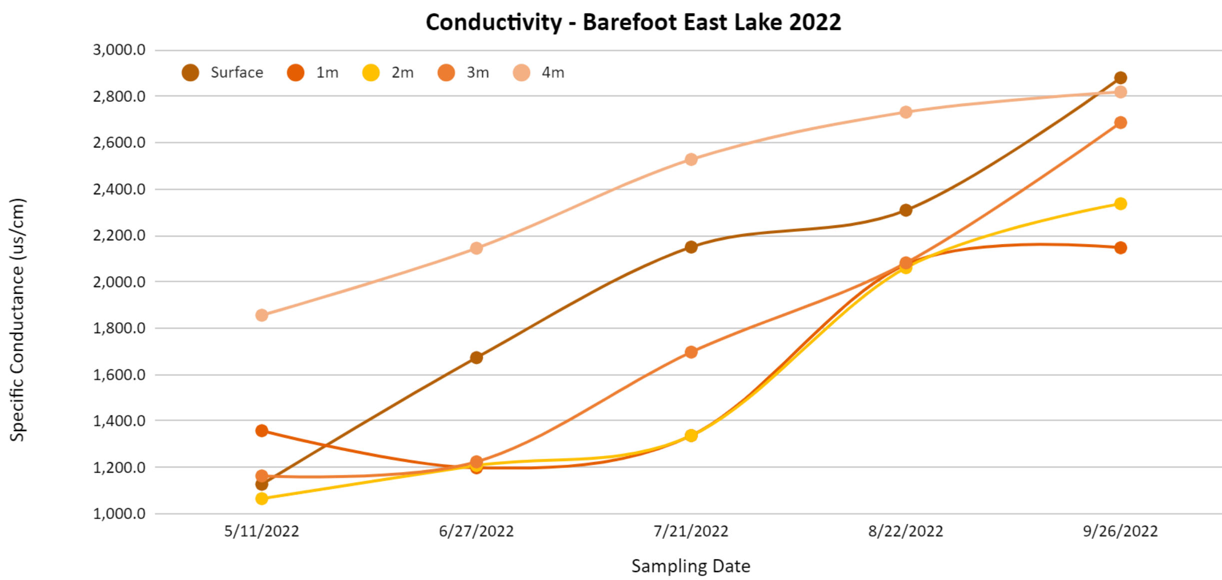

Figure 11. Conductivity, Barefoot East Lake, 2022.

Transparency

The Secchi depth in both Barefoot Lakes were low as the season progressed, representing high productivity, reduced clarity and eutrophic to hyper-eutrophic conditions throughout the year (Figure 12). The maximum Secchi depth in the East Lake was 0.54m in May and the minimum was 0.3m in June and August.

Secchi depth measurements were lower in the West Lake with a maximum of 0.45m from May to July and a minimum of 0.3m in August and September. The lower Secchi depth correlated to higher chl-a concentration in both lakes late in the season. In addition to productivity, inorganic particles can also directly affect Secchi depth by scattering light and negatively affecting water clarity. This can be observed in August and September when Total Suspended Solids was high decreasing transparency (Figure 12).

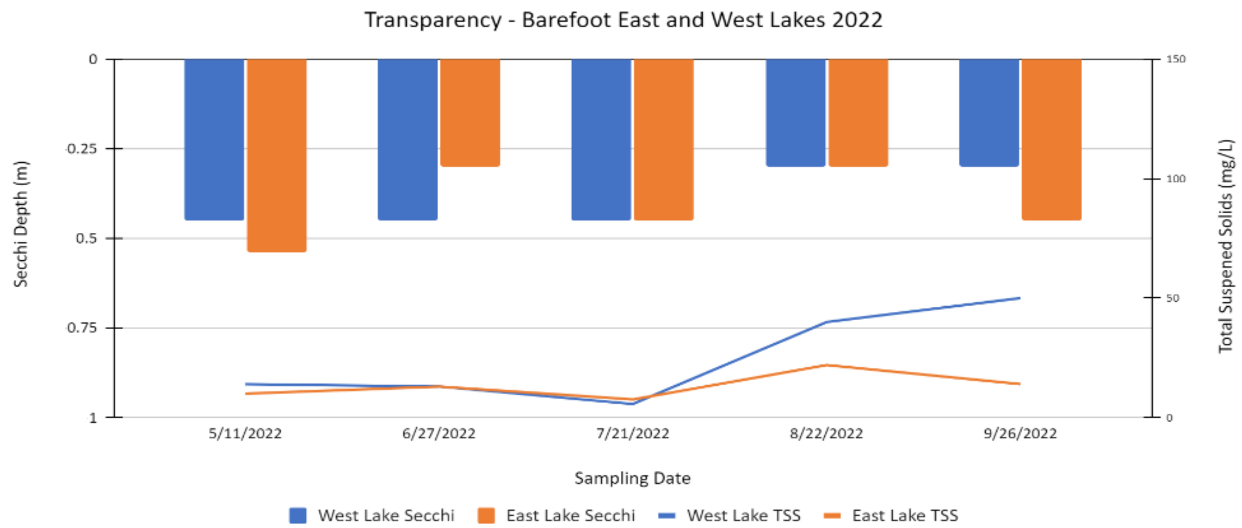

Figure 12. Transparency, Barefoot East and Barefoot West Lakes, 2022.

Chlorophyll a

Each sample collected was analyzed for Chlorophyll a (chl-a) concentrations in both lakes and St. Vrain Creek. In 2022, the chl-a densities in the West Lake ranged from a minimum of 21 µg/L at 2m in May to a maximum 143 µg/L at 2m in August. The chl-a concentrations in the East Lake ranged from a minimum of 11 µg/L at the surface in May to a maximum of 310 µg/L at the bottom in September, and St. Vrain Creek ranged from 4.8 µg/L to 16 µg/L. (Figure 13 and Figure 14). The surface chl-a concentrations in the West Lake ranged from 24 µg/L to 137 µg/L with an average of 66.4 µg/L, and in the East Lake ranged from 11 µg/L to 284 µg/L with an average of 148.4 µg/L. The chl-a concentrations were higher in the West Lake than the East Lake in May and June but were significantly lower in July, August, and September. These lower concentrations could be attributed to the aquatic dye shading the water column and limiting photosynthesis of organisms producing chl-a (algae). The highest values were observed in August and September when seasonal algal growth is typically at its peak due to the warmest temperatures of the year.

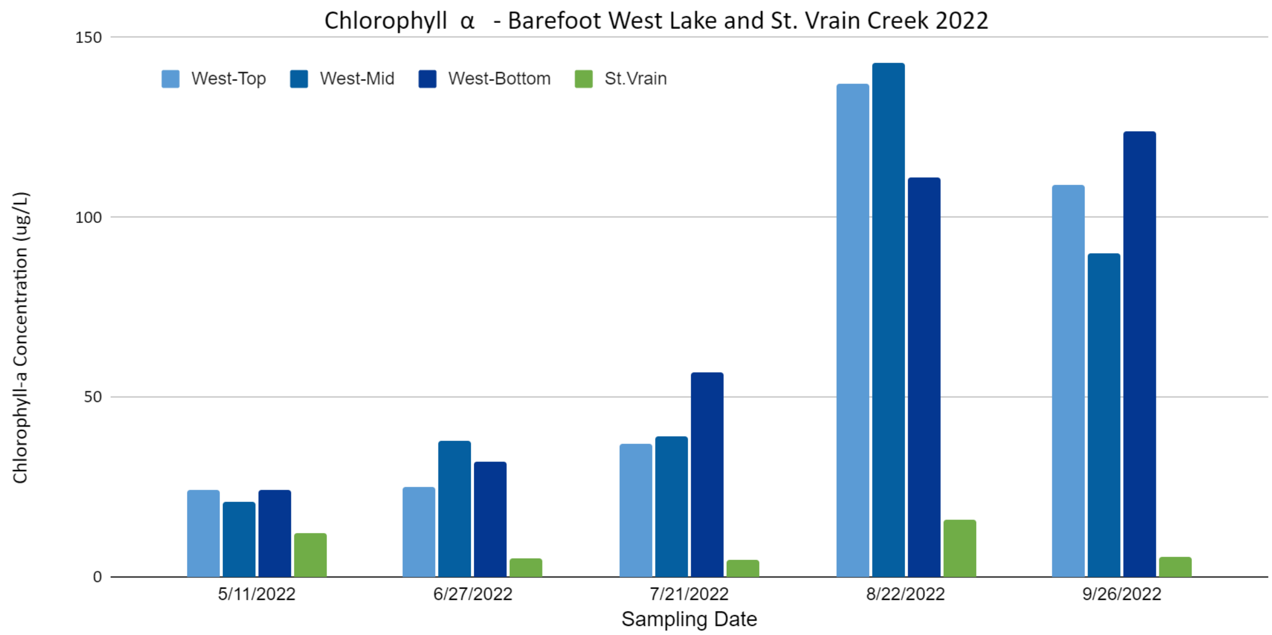

Figure 13. Chlorophyll a Concentrations, Barefoot West and St. Vrain Creek, 2022.

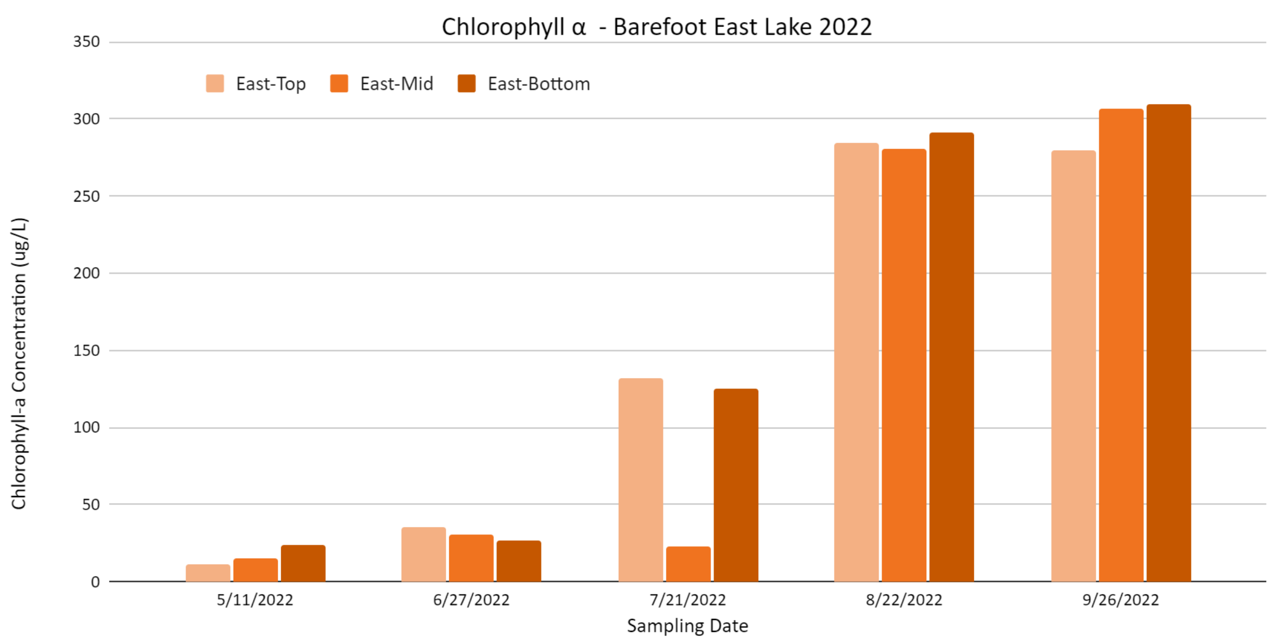

Figure 14. Chlorophyll a Concentrations, Barefoot East, 2022.

Translating the effects of chlorophyll-a concentrations on water quality into terms that are meaningful to most recreational lake users is a complex task. Walmsley and Butty (1979) proposed some typical relationships between maximum chlorophyll-a concentrations and observed impacts (Table 1) to describe lake user perception of water quality.

Table 1. Impact of Chlorophyll a Concentrations on Perceived Water Quality

Chlorophyll a Concentration	Nuisance Value
0 to 10 µg/L	No problems evident
10 to 20 µg/L	Algal scums evident
20 to 30 µg/L	Nuisance conditions encountered
Greater than 30 µg/L	Severe nuisance conditions encountered

During 2022, minimal surface scums were observed, but both lakes experienced nuisance conditions including green, cloudy, murky, and/or off-color water. Throughout most of the season the chlorophyll-a concentrations were greater than 30 µg/L at various depths, indicating severe nuisance conditions.

Phosphorus

Monthly samples were analyzed for total phosphorus (TP) concentrations at three depths (top, middle, and bottom) in both lakes and in St. Vrain Creek. The monthly mean TP concentrations in the East Lake ranged between 0.164 mg/L and 0.299 mg/L with a mean value of 0.223 mg/L (Figure 16). The TP concentrations were slightly lower in the West Lake and ranged from 0.090 mg/L to 0.166 mg/L with a mean value of 0.119 mg/L (Figure 15). The TP concentrations in St. Vrain Creek were very high all season, ranging from 0.475 mg/L to 0.931 mg/L with a seasonal average of 0.731 mg/L (Figure 16). Based on the data observed, it appears that the high nutrient concentrations in the lakes are likely the result of internal loading from the sediments, external loading from the water source, and potentially runoff from the watershed.

Internal nutrient release of phosphorus from bottom sediments occurs when the bottom of the lake becomes anoxic (low DO concentrations). The sediment phosphorus load accumulates over time from external sources and is geochemically transformed and released when the sediment surface becomes anoxic (Nürnberg and LaZerte, 2008). The low DO concentrations in both the East and West Lake sustained conditions for internal release of phosphorus from the sediments.

The high concentrations of TP in the bottom samples suggest the East Lake may have experienced internal loading from the sediments throughout the season which was more significant in June and July reflecting when DO concentrations at the bottom were the lowest. The West Lake displayed a similar trend but had significantly higher TP concentrations at the bottom than the surface in June, August, and September.

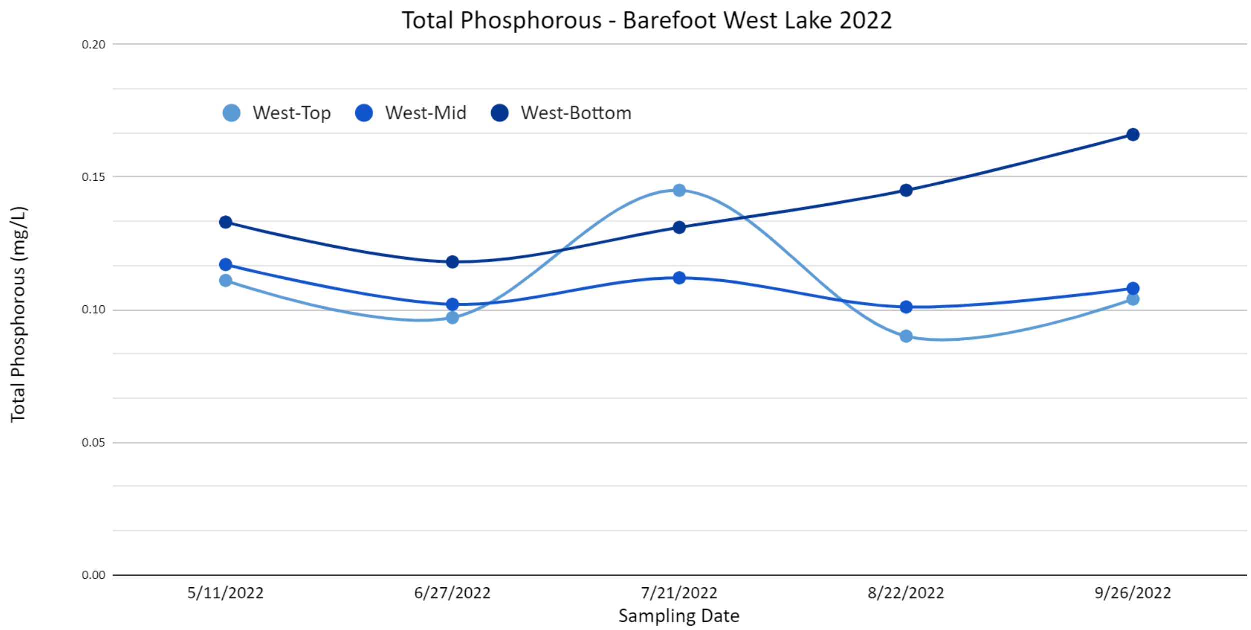

Figure 15. Total Phosphorus, Barefoot West Lake, 2022.

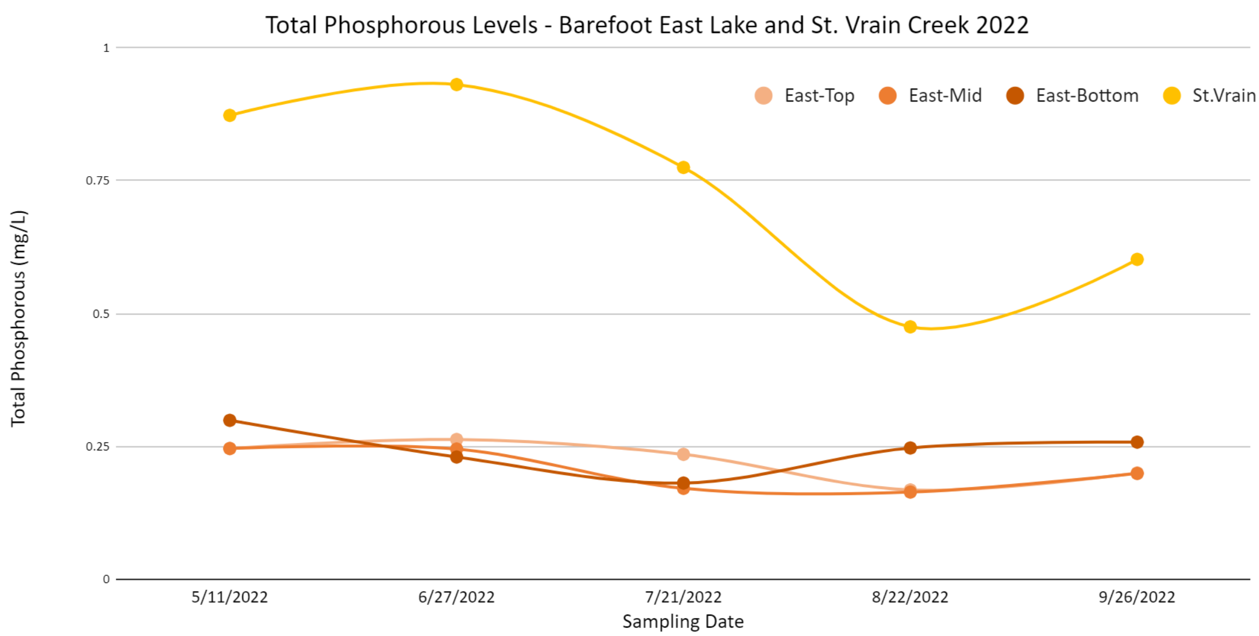

Figure 16. Total Phosphorus, Barefoot East Lake and St. Vrain Creek, 2022.

Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) was consistently present during the 2022 sampling period in both lakes. SRP levels can indicate primary productivity potential since this form is most readily available for uptake by algal cells. The SRP concentration in the West Lake varied between 0.004 mg/L to 0.021 mg/L with a seasonal average of 0.007 mg/L (Figure 17). The East Lake demonstrated values between 0.005 mg/L and 0.059 mg/L with an average of 0.024 mg/L (Figure 18). The SRP concentrations in St. Vrain Creek mimicked TP levels with high concentrations ranging from 0.206 mg/L to 0.477 mg/L with a seasonal average of 0.325 mg/L (Figure 17). In comparison to TP, the significantly lower levels of SRP indicated that the majority of the available forms of phosphorus were being utilized in the water column by primary productivity or algal growth. The high SRP and low chl-a concentrations in the East Lake in May and June indicates that a higher amount of the available forms of phosphorus were likely present due to the low productivity observed.

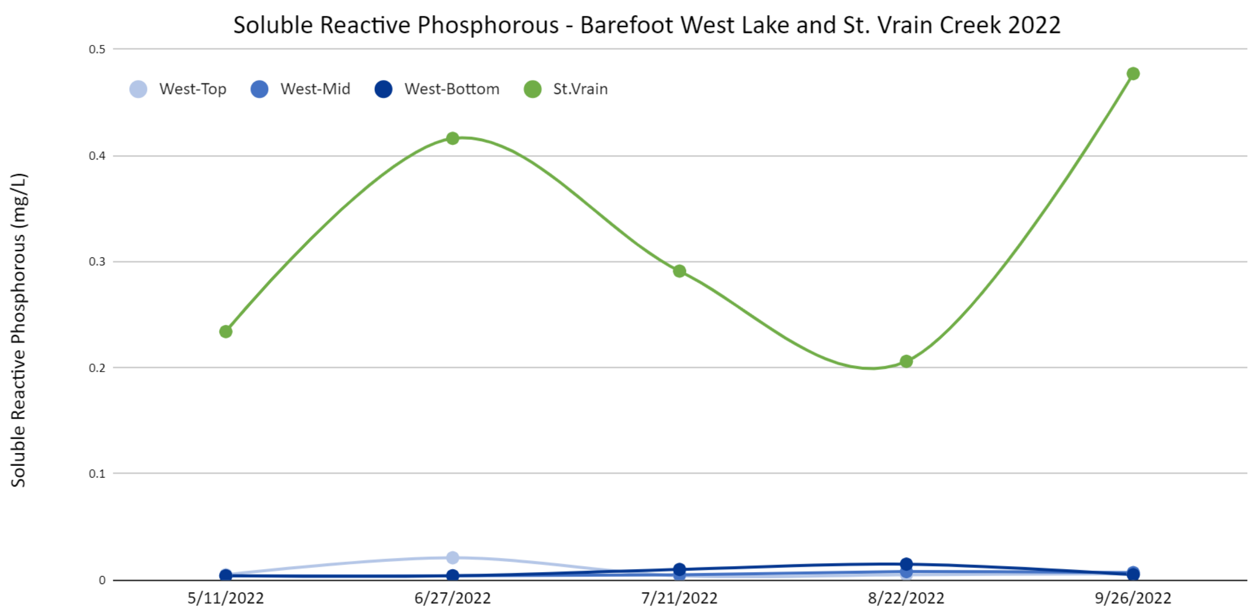

Figure 17. Soluble Reactive Phosphorus, Barefoot West Lake and St. Vrain Creek, 2022.

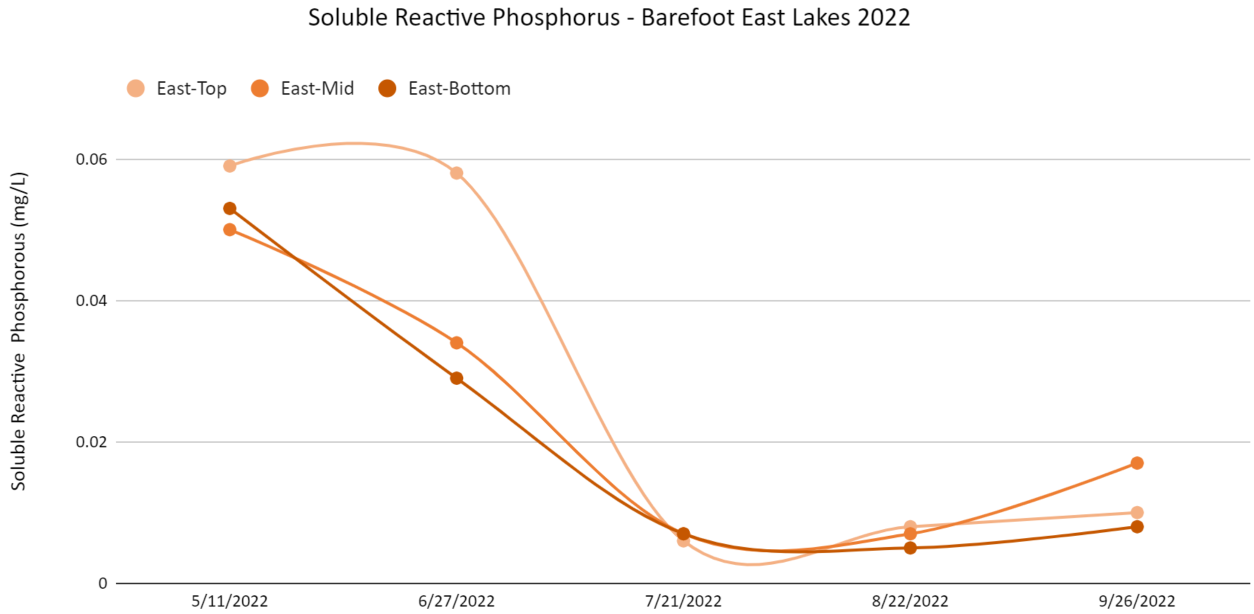

Figure 18. Soluble Reactive Phosphorus, Barefoot East Lake, 2022.

Nitrogen

The total nitrogen (TN) concentrations in Barefoot East Lake ranged from 2.16 mg/L to 4.68 mg/L, with an average of 3.51 mg/L (Figure 20). TN concentrations in the West Lake ranged from 2.04 mg/L to 4.93 mg/L, with an average of 3.12 mg/L (Figure 19). The St. Vrain Creek TN concentrations ranged from 1.93 mg/L in September to 2.93 mg/L in June, with an average of 2.52 mg/L (Figure 19). During the 2022 sampling season, the TN concentrations in both lakes varied during the season with increasing trends until mid-season where nitrogen steadily decreased. The water quality and nutrient concentrations in St. Vrain Creek are directly impacted by upstream watershed activities, releases, discharges, and agriculture.

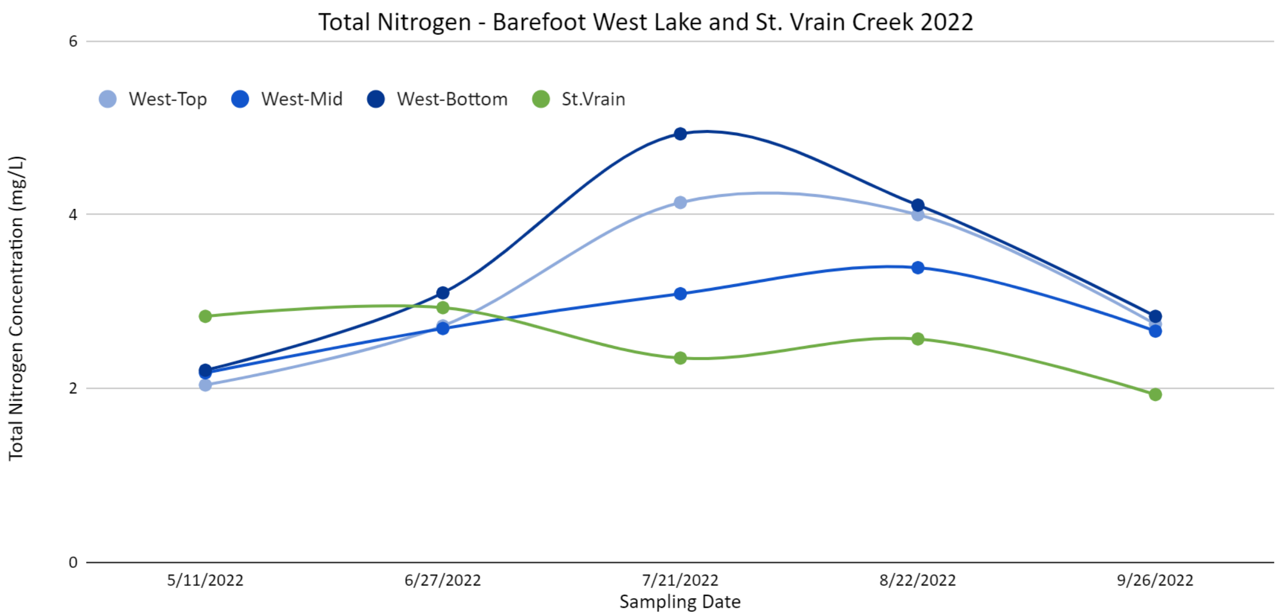

Figure 19. Total Nitrogen Concentrations, Barefoot West Lake and St. Vrain Creek, 2022.

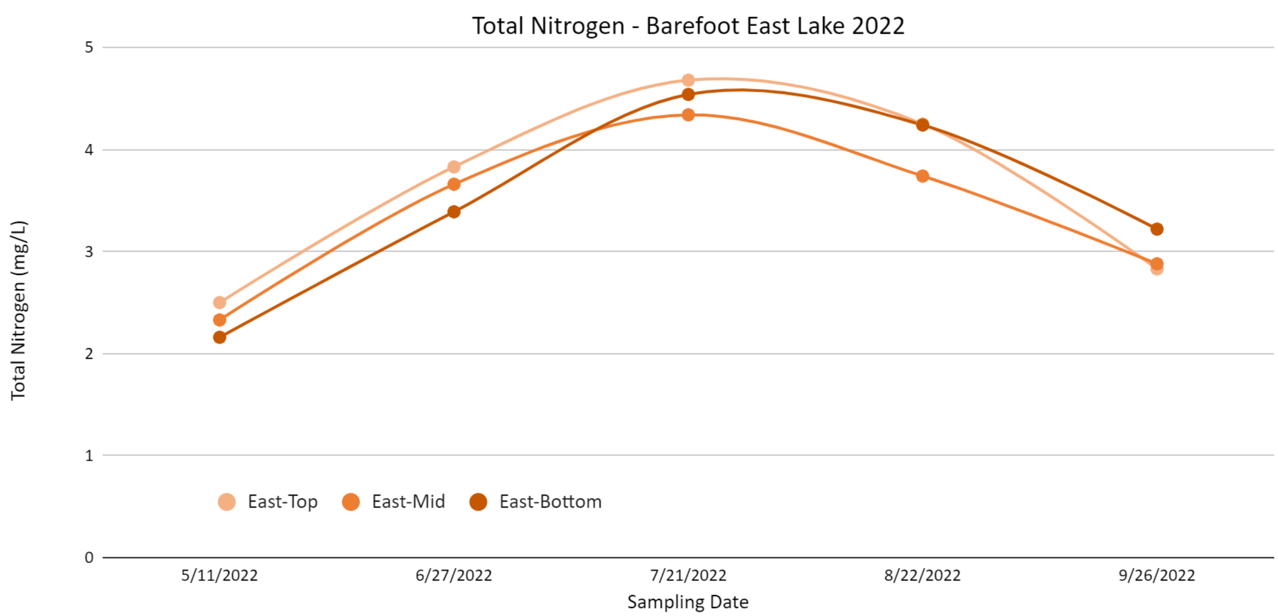

Figure 20. Total Nitrogen Concentrations, Barefoot East Lake, 2022.

Figure 21 and Figure 22 represent the total inorganic nitrogen (TIN) concentrations composed of nitrate, nitrite, and ammonia for the Barefoot Lakes in 2022. Higher levels of TIN were seen in July in the West Lake and in June in the East Lake. The nitrate/nitrite concentrations were incredibly similar to ammonia levels. Nitrate/nitrite had concentrations ranging from 0.005 mg/L to 1.590 mg/L with an average of 0.196 mg/L. Ammonia levels reflected nitrate/nitrite concentrations in that they ranged from 0.005 mg/L to 1.680 mg/L with a mean value of 0.295 mg/L. High values of ammonia were seen in the bottom samples from the East Lake in June and July which reached a maximum of 0.959 mg/L on the surface in June. The highest concentration of 1.680 mg/L was seen in the West Lake bottom sample in July. Elevated ammonia in the deep areas of a lake indicate high microbial activity and decomposition of organic matter. St. Vrain Creek also had concentrations of ammonia as high as 0.101 mg/L but overall were fairly low, likely due to conversion of ammonia to nitrate from microbial activity in the water. From this data, a conclusion can be drawn that in June on the East Lake and July on the West Lake productivity was high but quickly declined.

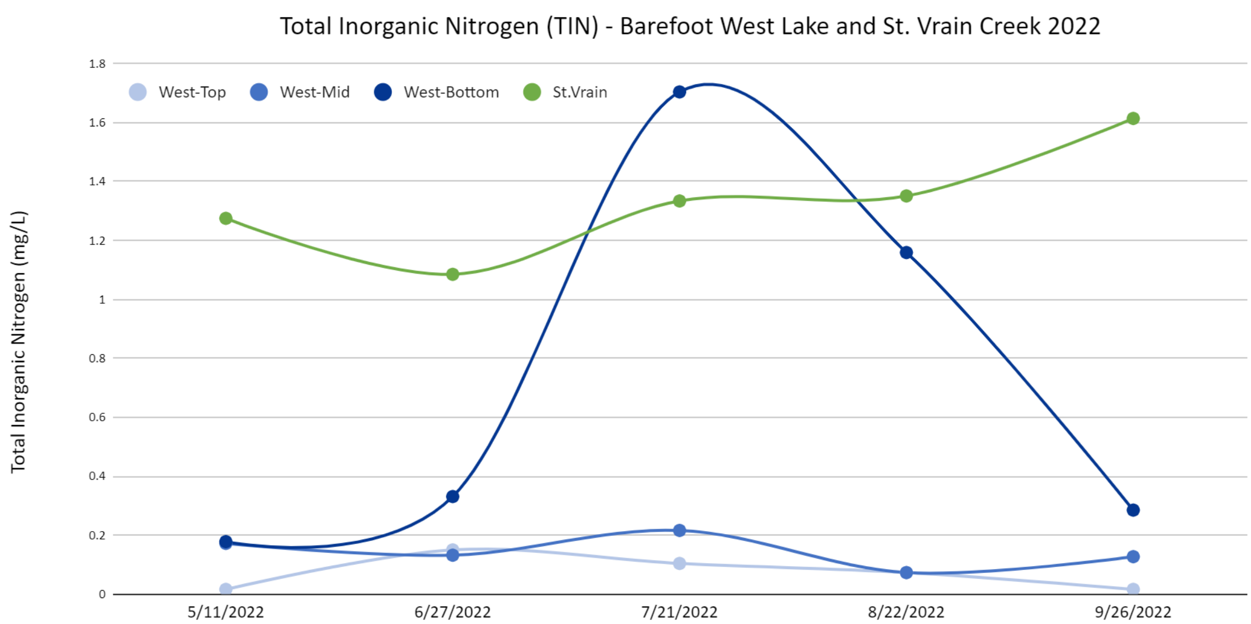

Figure 21. Total Inorganic Nitrogen, Barefoot West Lake and St. Vrain Creek, 2022.

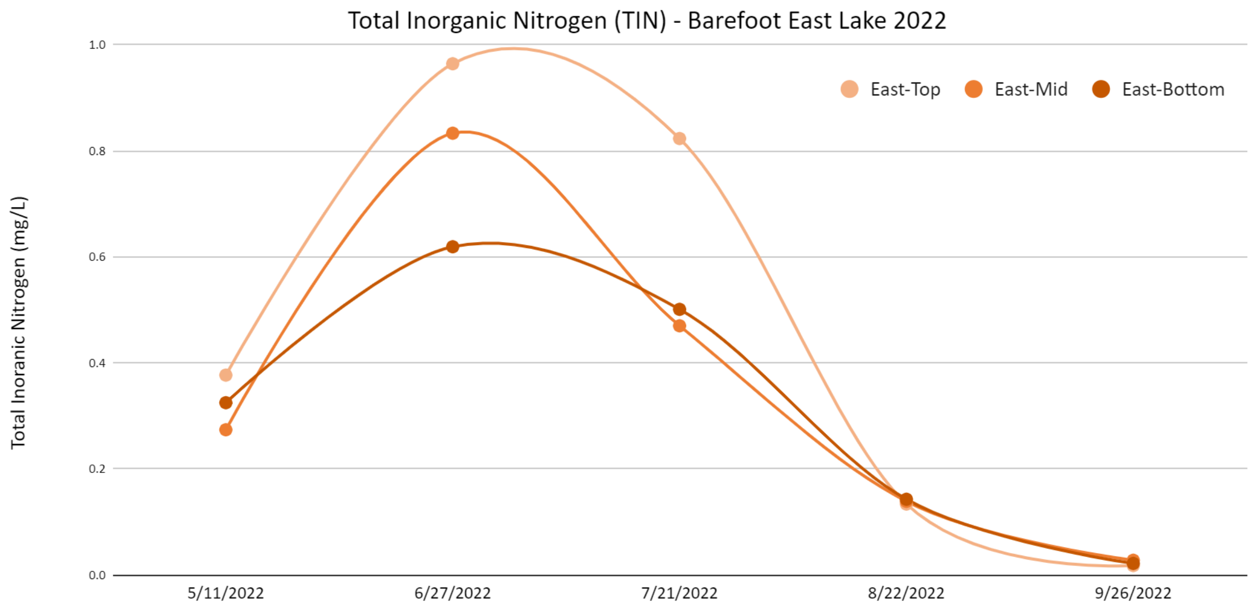

Figure 22. Total Inorganic Nitrogen, Barefoot East Lake, 2022.

Nutrient Ratios

Nutrient ratio calculations provide insight into nutrient limitation.

Figure 23 and Figure 24 represent the nutrient ratios of total nitrogen to total phosphorus (TN:TP) and total inorganic nitrogen (NO2+NO3+NH4) to soluble reactive phosphorus (TIN:SRP). The dotted gray line indicates the mass ratio of nitrogen to phosphorus indicating whether nitrogen or phosphorus is likely the limiting factor in algal growth. The TN:TP ratios indicate that total phosphorus was the limiting nutrient in both lakes throughout the sampling season. The TIN:SRP ratios indicate that inorganic nitrogen, the forms of nitrogen readily available for uptake by algae, was limiting in the West Lake all season except July and August. TIN was limited in the East Lake only during the May and September monitoring visits. In all calculations, when concentrations of the nitrogen forms were below the minimum reporting limit (MRL), values were calculated based on half of the MRL, and any values of SRP below the reporting limit were calculated at 0.001mg/L due to the lower MRL.

Based on the data and the correlation to the concentrations of chl-a, it appears that the available forms of phosphorus were the main limiting nutrient in both lakes with more nitrogen available in the East Lake. Examining the nutrient ratios over time provides insight to the phytoplankton diversity in the lakes. The populations are examined in more detail in the Phytoplankton section below. Cyanobacteria thrive in phosphorus rich aquatic systems and can fix nitrogen from the environment when nitrogen is limiting. Any future increases of nutrients into the lakes will likely translate to an increase in blue-green algae blooms because Cyanobacteria outcompete other forms of algae species.

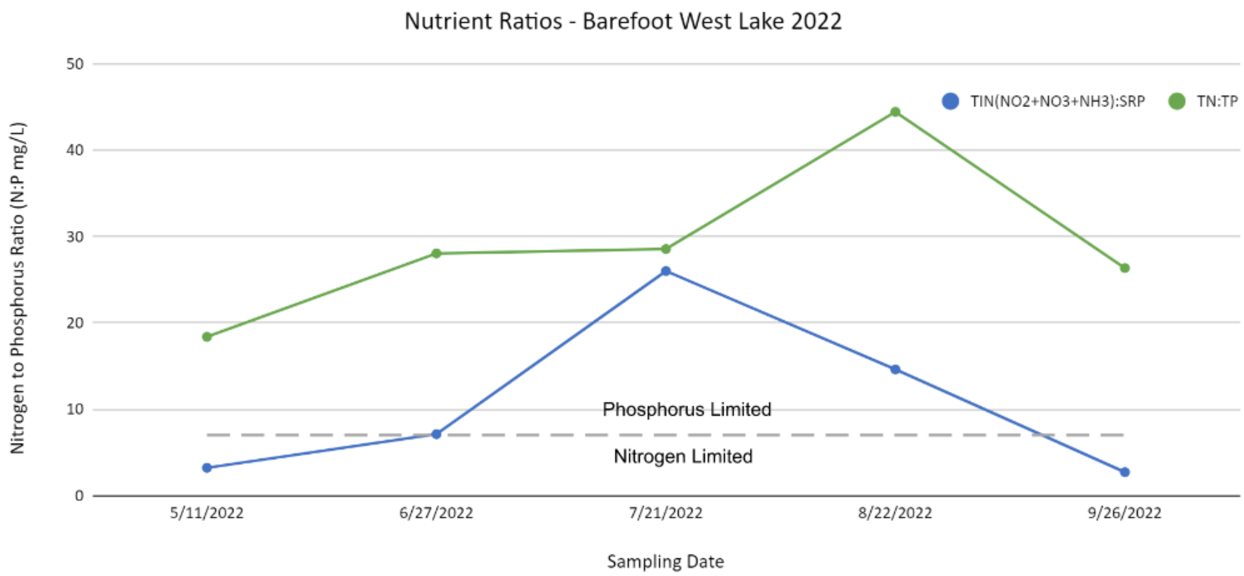

Figure 23. Nutrient Ratios in Photic Zone, Barefoot West Lake, 2022.

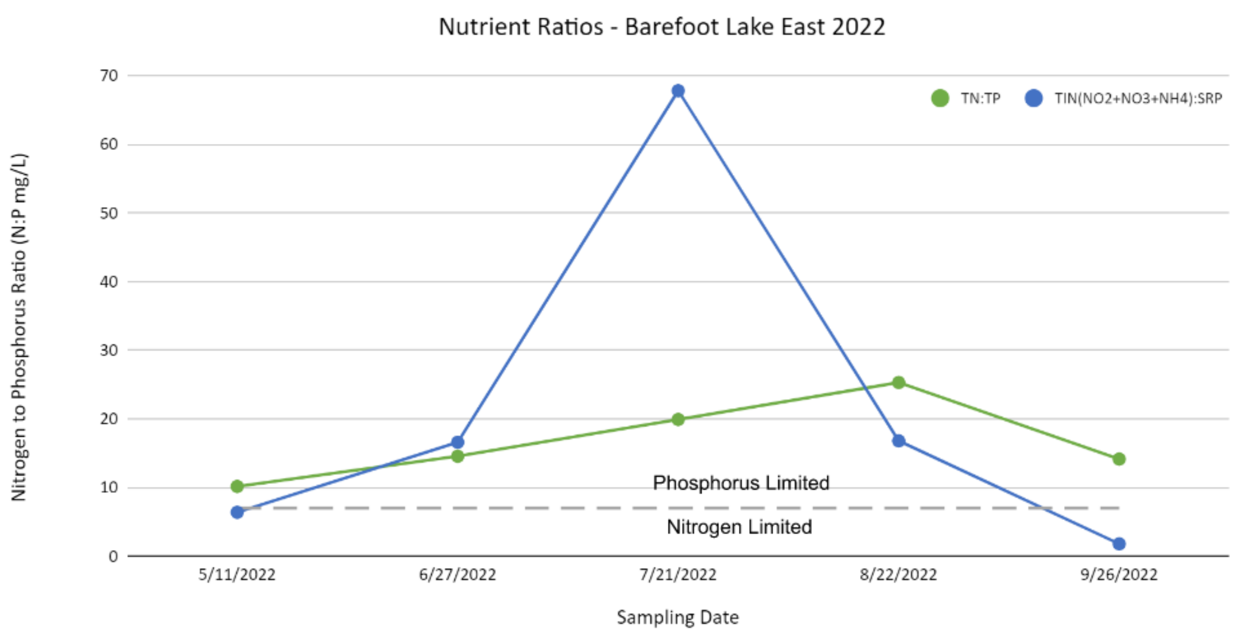

Figure 24. Nutrient Ratios in Photic Zone, Barefoot East Lake, 2022.

Trophic State Analysis

A lake's trophic state is a relative expression of its biological productivity. Elevated values for the Trophic State Index (TSI) are indicative of higher productivity. Table 2 presents a comparison of the Barefoot Lakes to the EPA trophic state criteria and the Carlson Trophic State Index. Mean seasonal values (May-Sept) from the photic zone or surface samples are represented. Secchi depth, Chlorophyll a, and total phosphorus all indicate that both Barefoot Lakes are in the hypereutrophic range according to the EPA criteria.

Table 2. Comparison of Barefoot Lakes Monitoring Data to Trophic State Criteria 2022.

Trophic State	Characteristic				
	Total P (mg/L)	Chlorophyll-*a* (µg/L)	Secchi Depth (m)	Carlson Trophic State Index	Relative Productivity
Oligotrophic	< 0.005	< 2.0	> 8	<35	Low
Mesotrophic	0.005 -0.030	2.0 - 6.0	4 – 8	35-50	Moderate
Eutrophic	0.030 - 0.100	6.0 - 40.0	2 – 4	50-70	High
Hypereutrophic	> 0.100	> 40.0	< 2	>70	Excessive
Barefoot Lakes (West)	**0.223**	**148.4**	**0.4**	**78**	**Excessive**
Barefoot Lakes (East)	**0.119**	**66.4**	**0.4**	**73**	**Excessive**

Comparisons of monitoring data indicates the St. Vrain would be considered hypereutrophic with mean TP values of 0.739 mg/L and oligotrophic in regard to chl-a with mean concentrations of 8.74 µg/L. The St. Vrain Creek is the main water source for these lakes and is likely one of the main contributors to the poor water quality.

Using the Carlson index (1977), which puts the values on a 0 to 100 scale, a TSI of less than 35 indicates oligotrophic conditions, a TSI between 35 and 50 indicates mesotrophic conditions, and a TSI greater than 50 indicates eutrophic conditions. Hypereutrophic, or excessively productive lakes, have TSI values greater than 70. Higher TSI values are associated with increased probabilities of encountering nuisance conditions, such as excessive macrophyte growth, algae scums, or possible cyanobacteria blooms. The index is composed of three separate indices based on observations of total phosphorus concentrations, chlorophyll a concentration, and Secchi depths from a variety of lakes. Total phosphorus was chosen for the Barefoot Lakes index because water quality results indicate that total phosphorus is the nutrient limiting algal growth in Barefoot Lakes when compared to total nitrogen. Chlorophyll a is a plant pigment present in all algae and is used to provide an indication of the algal biomass in a lake. Secchi depth is a common measure of the transparency of lake water and is typically only used in trophic state analyses when water quality data is not available.

Figure 12 illustrates the correlation between water clarity and total suspended solids. The low Secchi depths are affected by both biological turbidity and inorganic suspended solids in the lakes. Chl-a concentrations substantially increased in the latter half of the season, which is in direct correlation with the lower Secchi readings and high TSS values also seen at the same time.

Figure 25 and Figure 26 display the historic trophic state index from 2017 to 2022 using the Carlson Trophic State Index values for Secchi depth, Chlorophyll a, and total phosphorus over the last six years. The West Lake had significant decreases in TSI values for Secchi depth and Chlorophyll-a from 2020 to 2021, with a slight decrease in total phosphorus. During the 2022 season, TSI values for Secchi depth and Chlorophyll-a returned to similar levels as 2020 with a slight increase in TP from 2021. Total Phosphorus is continuing to decrease slightly over the years which indicates that the nutrient remediation treatments that are completed each year are slowly working. The East Lake Secchi depths and Chlorophyll-a TSI values have increased over the past three years with the largest increase in Chlorophyll a from 2019 to 2020 and the values only slightly increasing during the 2022 season. Total phosphorus had decreased in the East Lake from 2019 to 2020 but saw a minor increase during the 2021 and 2022 season. This data follows the trend of increased planktonic blooms sustained over longer periods of time for the past few years.

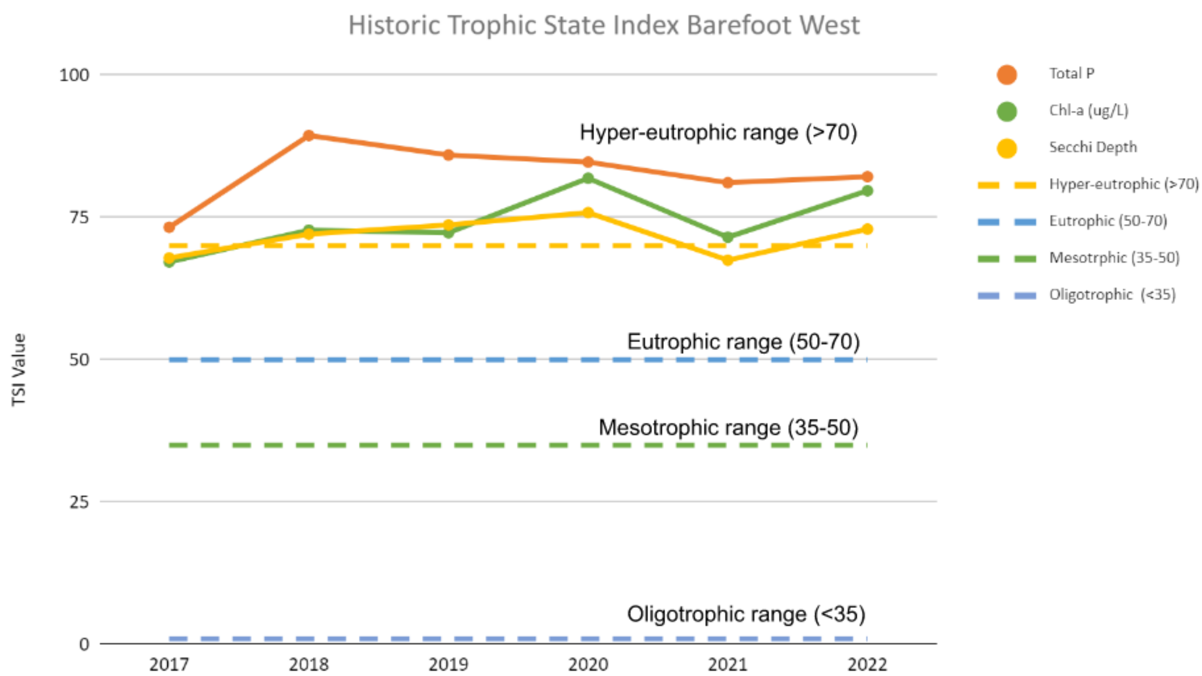

Figure 25. Historic Trophic State Index, Barefoot West

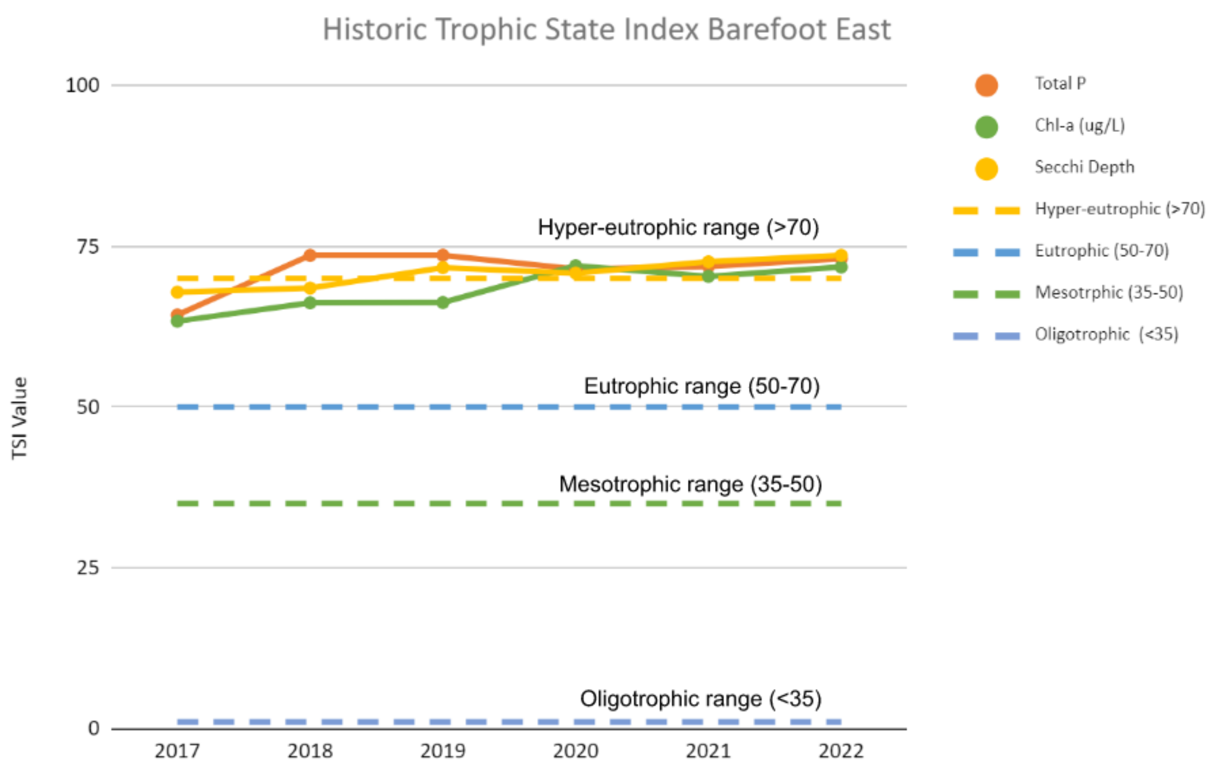

Figure 26. Historic Trophic State Index, Barefoot East.

Coliform Bacteria and E. Coli

Coliform are bacteria present in the environment by excretion from warm-blooded animals and are generally harmless. E. Coli is one type of fecal coliform which are usually harmless, but some strains can cause human illness. The total Coliform concentrations were below the 2,419.2 MPN/100ml threshold from June to September and measured below the 2,419.2 MPN/100ml threshold in St. Vrain Creek from June to August in 2022 (Table 3).

Table 3. Coliform Levels for Barefoot Lakes and St. Vrain Creek, 2022.

Coliform Bacteria						
	Units	5/11/2022	6/27/2022	7/21/2022	8/22/2022	9/26/2022
West-Top	MPN/100 mL	228.2	>2419.2	>2419.2	>2419.2	>2419.2
East-Top	MPN/100 mL	59.1	>2419.2	>2419.2	>2419.2	>2419.2
St. Vrain	MPN/100 mL	980.4	>2419.2	>2419.2	>2419.2	1986.3

E. Coli counts are reported in the most probable number (MPN)/100mL sample and were at or less than the detection limit (1.0 MPN/100mL) in June of both lakes. The West Lake saw higher values in both May and August with the highest value seen in August at 32.3 MPN/100ml. E. Coli concentrations were highest in the St. Vrain samples with 387.3 MPN/100mL seen in August. Although the Barefoot Lakes do not have designated swimming areas, recreation does now occur on the West Lake. Colorado Department of Public Health 5 CCR 1003-5 requires that all public swim beaches be tested weekly for E. Coli and must be closed if concentrations exceed 235 organisms per 100 ml (235 MPN/100ml). No sample during 2022 from the lakes indicated levels that neared this threshold. However, values from the St. Vrain Creek samples were above the threshold in August (Table 4).

Table 4. E. Coli Levels for Barefoot Lakes and St. Vrain Creek, 2022.

E. Coli						
	Units	5/11/2022	6/27/2022	7/21/2022	8/22/2022	9/26/2022
West-Top	MPN/100 mL	9.6	<1	1	32.3	6.2
East-Top	MPN/100 mL	3.1	<1	3	3.1	1
St. Vrain	MPN/100 mL	137.1	172.2	127.4	387.3	28.2

Phytoplankton

Phytoplankton are photosynthetic organisms that are the primary producers in aquatic systems forming the base of aquatic food chains. Phytoplankton are grazed upon by zooplankton and herbivorous fish. A healthy lake should support a diverse assemblage of phytoplankton, in which many algal groups are represented.

Phytoplankton samples collected within the East and the West Lakes from the photic zone were analyzed to identify and quantify the populations present and assess biological conditions in Barefoot Lakes. A healthy lake should support a diverse assemblage of phytoplankton, in which many algal groups are represented. Phytoplankton populations in Barefoot Lakes were very diverse, with anywhere between 10 to 30 species present on most sampling dates within each lake.

Cyanophytes, or cyanobacteria, are responsible for the majority of nuisance algal blooms that occur in freshwater ecosystems. They have the ability to use atmospheric nitrogen as a nutrient source and regulate their position within the water column by altering their buoyancy with the use of gas vacuoles. These characteristics give cyanobacteria a competitive advantage over other groups of phytoplankton. Nuisance blooms of cyanobacteria usually occur in neutral to alkaline waters that are still, relatively warm, and have low N:P ratios. Some species of cyanobacteria can produce toxins, the most common toxin forms being *Microcystis*, *Cylindrospermopsis*, anatoxins and saxitoxin (US EPA, 2019a). Although there is variability between species, stress conditions often are indicated in the factors that induce toxins.

Nuisance blooms of Bacillariophyta (diatoms) are not as common as nuisance cyanobacteria blooms; however, when they do occur, it tends to be during the late spring or early summer months when water temperatures are still relatively low. Diatoms usually grow better in unpolluted water so they can be useful in monitoring water quality. Chlorophytes (green algae) are unicellular or colonial photosynthetic organisms that reside in most lakes, ponds, and even puddles. Green algae are important in aquatic ecosystems by providing energy (food) to many larger organisms like zooplankton and fish.

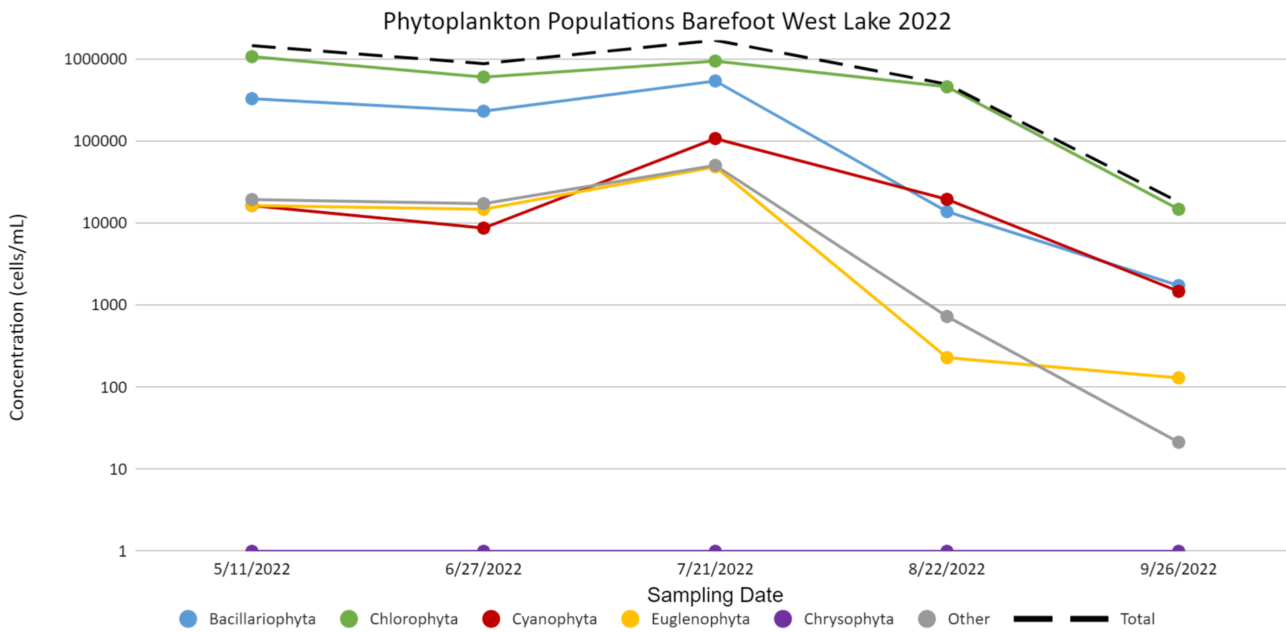

Figure 27. Phytoplankton Concentration, Barefoot West Lake, 2022.

*For graph formatting and the usage of a logarithmic scale, phytoplankton populations displayed as 1 are 0.

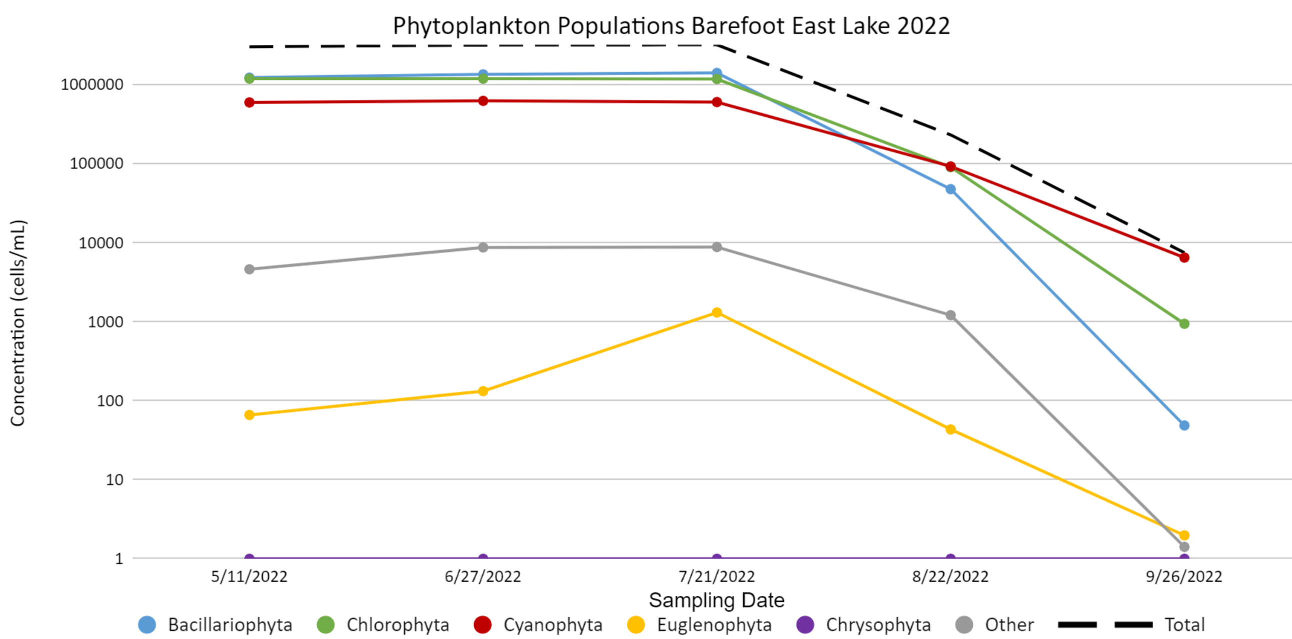

Figure 28. Phytoplankton Concentrations, Barefoot East Lake, 2022.

*For graph formatting and the usage of a logarithmic scale, phytoplankton populations displayed as 1 are 0.

There were diverse populations of algae throughout the season in both lakes as seen in Figure 27 and Figure 28. Chlorophytes were present in high numbers throughout the year, and Bacillariophytes, Euglenophytes, and other photosynthetic organisms were also present in both resources. No Chrysophyta species were identified in either lake during 2022. Total algal counts were highest for both lakes in July. In the East and West Lakes, the Cyanophytes population was lower and Chlorophytes and Bacillariophyta were responsible for most of the total algae.

In the East Lake, Bacillariophyta were the highest algal species represented in May, June, and July. However, in the West Lake, green algae were the dominant algae present followed by Bacillariophyta throughout the season with the exception of August and September when an increase in Cyanophyta occurred. For graph formatting and the usage of a logarithmic scale, phytoplankton populations displayed as 1 are 0 in Figure 27 and Figure 28.

Since cyanobacteria blooms are a major concern in resources with public access and recreation, the populations were examined in more detail to determine risks of potential human health concerns related to toxin production. The East Lake had higher cyanobacteria cell counts the entire season compared to the West Lake. *Dolichospermum sp (Anabaena)*[1] was the most abundant (71%) cyanobacteria present in the East Lake. The most common species in the West Lake was *Aphanizomenon sp.* which accounted for approximately 41% of the cyanobacteria composition, with *Dolichospermum sp (Anabaena)*[1] the second most abundant at 33% (Figure 29) (US EPA, 2019b). Other species identified in the West Lake included *Oscillatoria sp.* at 25%, *Aphanothece sp.* at 16%, and *Chrysococcus sp.* at only 1%. *Phormidium sp.* accounted for 23% and *Oscillatoria* sp. estimated only 3% of cyanobacteria identified in 2022 (Figure 29). *Dolichospermum sp (Anabaena)*[1] made up about 67% of the total algae composition in both lakes.

Oscillatoria can produce Microcystin-LR, which acts as a hepatotoxin, and has the ability to produce Anatoxin-a, which acts as a neurotoxin. *Dolichospermum sp.* have the ability to produce Cylindrospermopsin which acts as a hepatotoxin, as well as Anatoxin-a and Microcystin-LR. *Raphidiopsis sp.*[2], previously known as *Cylindrospermopsis,* was found at 0% in both lakes due to a low density in the East Lake and none detected in the West. This species is a concern due to the fact that these organisms have the ability to produce Cylindrospermopsin and Anatoxin-a (Li, 2016). Chrysococcus is not currently listed to produce cyanotoxin on the Contaminant Candidate List (CCL) issued by the EPA (US EPA, 2019a, p. 3).

[1] Cyanobacteria taxonomy is continuously being revised. The genus *Anabaena* has been renamed to *Dolichospermum*.

[2] Cyanobacteria taxonomy is continuously being revised. The genus *Cylindrospermopsis* has been renamed to *Raphidiopsis*.

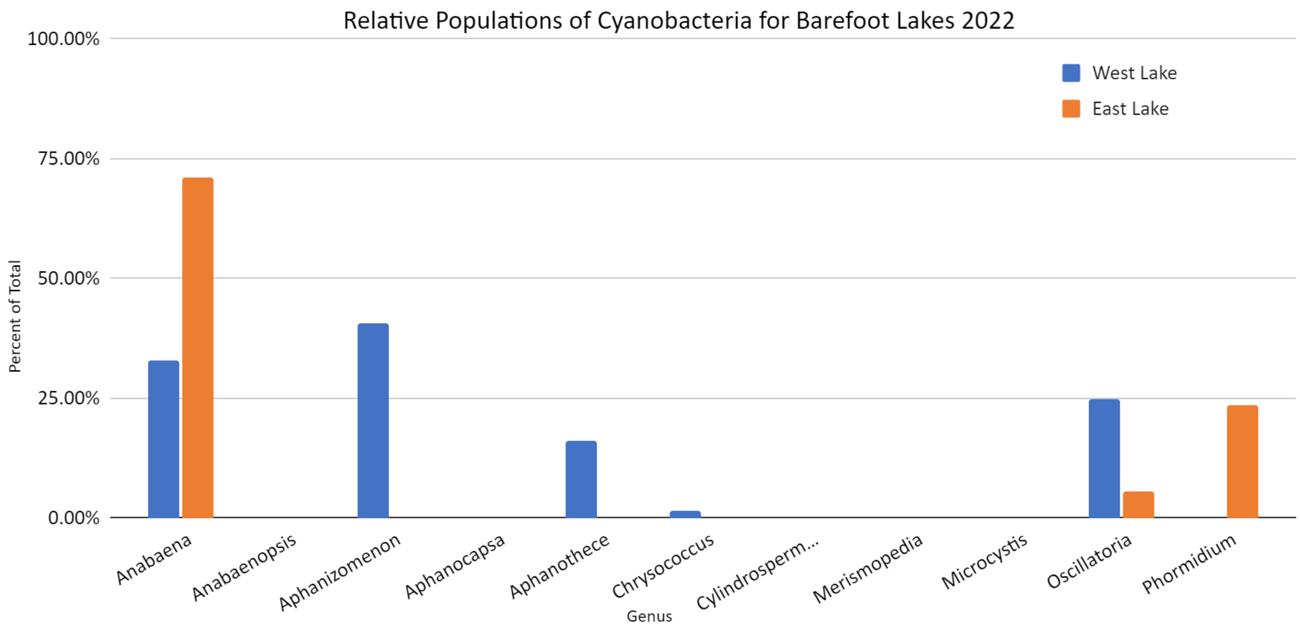

Figure 29. Relative Cyanobacteria Populations, Barefoot Lakes, 2022.

Table 5. Recreational Guidance/Action Levels for Cyanobacteria, Chlorophyll a, and Microcystin (WHO, 2003)

Relative Probability of Acute Health Effects	Cyanobacteria (cells/mL)	Chlorophyll a (µg/L)	Estimated Corresponding Microcystin Levels (µg/L)
Low	< 20,000	< 10	< 10
Moderate	> 20,000 – 100,000	10 – 50	10 – 20
High	100,000 – 10,000,000	50 – 5,000	20 – 2,000
Extreme	> 10,000,000	> 5,000	> 2,000

The World Health Organization (WHO) published a series of guideline values for recreational exposure to cyanobacteria that progress in severity and the probability of health effects as densities increase of total cyanobacteria concentrations by cell counts and the concentrations of chlorophyll a (Table 5) (US EPA, 2019b, p. 19). This table is recognized and referenced by the EPA in the Recommendations for Cyanobacteria and Cyanotoxin Monitoring in Recreational Waters.

Throughout the year, Barefoot East Lake cyanobacteria concentrations ranged between 6,492 cells/mL to 624,580 cells/mL which represents a low to high risk. Overall, the East Lake fell into the low-risk category in September as concentrations were below 20,000 cells/mL. Chlorophyll a levels in the photic zone also ranged between 11 µg/L to 284 µg/L which fell between the low to high-risk category.

The Barefoot West Lake saw lower cyanobacteria counts ranging between 1,468 cells/mL in September to 106,721 cells/mL in July. West Lake would maintain the low-risk category for 2022 season during the months of May, June, August, and September but July presented high cyanobacteria concentrations of 106,721 cells/mL which would classify it in the high-risk category. The West Lake saw higher values of chlorophyll a in the photic zone ranging between 24 µg/L to 137 µg/L representing moderate to high risk depending on the month. Based on the WHO and EPA guidelines, no direct body contact recreation should be allowed in either of the Barefoot Lakes.

Discussion

The results of the water quality analyses of the Barefoot Lakes indicate that both lakes are hypereutrophic, with high nutrients, low transparency, and high chlorophyll-a concentrations. The conditions support high levels of primary productivity and diverse phytoplankton populations. Minor Cyanobacteria blooms occurred throughout the season in both lakes. Most nutrient data reflected the results collected in 2021.

Generally, the 2022 weather pattern as the season progressed was warm and dry similar to 2021. In addition to the water quality, the weather likely played a significant role in the increased productivity in the lakes. The algae and cyanobacteria blooms remained moderate to high with most productivity midseason when temperatures are high.

The East Lake experienced thermal stratification in May and August while the West Lake established a temperature gradient from May through August with the most differences occurring in July. Dissolved oxygen concentrations remained in healthy conditions all year in both lakes 1m and above. Below 2m, DO concentrations fluctuated between ideal and reduced levels throughout the season. Based on the low dissolved oxygen levels at the bottom which corresponded to increases in phosphorus at deeper depths, it appears that internal loading of nutrients from the anoxic sediments remains a major factor in the lakes.

Overall, the water quality was slightly better in the West Lake than the East in regard to nutrients and algae populations but both lakes still suffered from severely impaired water quality. A full lake phosphorus inhibiting treatment is suggested for the East Lake to improve and sustain the water quality. By decreasing phosphorus in the water column and sediment, all other nutrients will conform to ideal parameters. Algae growth will in turn diminish with less free reactive phosphorus to bind to.

In the West Lake, available or usable forms of nitrogen were limited during the beginning and end of the season. The East Lake began the season with high concentrations of available nitrogen but greatly reduced by July. In nitrogen limited environments, cyanobacteria populations can flourish due to their ability to fix nitrogen from the environment.

The East Lake contained higher densities of chlorophyta and bacillariophyta until September when a cyanophyta increase occurred. Chlorophyta remained the dominant algae phylum in the West Lake all season. Of the cyanobacteria that were present, *Oscillatoria* and *Anabaena* are at higher risk of producing toxins when dense blooms occur.

With low total Coliform concentrations in both lakes throughout the season, E. Coli levels do not present a major risk to human health. It is suggested as a precaution to continue minimizing human contact with the water bodies. Recreational activities such as paddleboarding and kayaking can resume with no concerns, however, swimming is still not advised.

Continuing to monitor water quality and phytoplankton populations over time will help to further understand seasonal variability and establish significant trends. Based on the water quality data collected this year, a full lake phosphorus inhibiting treatment will be applied to the East Lake. This treatment will cause no harm to the ecosystem but will improve all aspects of water quality. If major improvements are observed from visual observation and water quality results of the East Lake, then a phosphorus inhibiting treatment will be applied to the West Lake. Regular algaecide treatments will proceed to continue reducing phosphorus, nitrogen, and Cyanophyta. The addition of dye limits light penetration and algae growth, and will continue to be added to both water bodies in 2023. SŌLitude Biologists will also implement bacteriacide treatments to reduce E. Coli accumulation. Both lakes should remain "no contact" water bodies. Recreation should be limited if accumulations of algae, scums or severely off-color conditions of the water are observed. In addition, if cyanobacteria blooms are visible, toxin analysis may be recommended to provide guidance on public safety for lake visitors.

SŌLitude Lake Management will continue to monitor and implement recommendations in the annual maintenance service to help further improve the water bodies. SŌLitude Lake Management® appreciates the opportunity to work on Barefoot Lakes to maintain water quality and appearance for the community and safety of the environment.

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