

Monitoring Algal Abundance and Water Quality in Arizona Reservoirs Through Field
Sampling and Remote Sensing.

by

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ABSTRACT

Safe, readily available, and reliable sources of water are an essential component of any municipality's infrastructure. Phoenix, Arizona, a southwestern city, has among the highest per capita water use in the United States, making it essential to carefully manage its reservoirs. Generally, municipal water bodies are monitored through field sampling. However, this approach is limited spatially and temporally in addition to being costly. In this study, the application of remotely sensed reflectance data from Landsat 7's Enhanced Thematic Mapper Plus (ETM+) and Landsat 8's Operational Land Imager (OLI) along with data generated through field-sampling is used to gain a better understanding of the seasonal development of algal communities and levels of suspended particulates in the three main terminal reservoirs supplying water to the Phoenix metro area: Bartlett Lake, Lake Pleasant, and Saguaro Lake. Algal abundances, particularly the abundance of filamentous cyanobacteria, increased with warmer temperatures in all three reservoirs and reached the highest comparative abundance in Bartlett Lake. Prymnesiophytes (the class of algae to which the toxin-producing golden algae belong) tended to peak between June and August, with one notable peak occurring in Saguaro Lake in August 2017 during which time a fish-kill was observed. In the cooler months algal abundance was comparatively lower in all three lakes, with a more even distribution of abundance across algae classes. In-situ data from March 2017 to March 2018 were compared with algal communities sampled approximately ten years ago in each reservoir to understand any possible long-term changes. The findings show that the algal communities in the reservoirs are relatively stable, particularly those of the filamentous cyanobacteria,

chlorophytes, and prymnesiophytes with some notable exceptions, such as the abundance of diatoms, which increased in Bartlett Lake and Lake Pleasant. When in-situ data were compared with Landsat-derived reflectance data, two-band combinations were found to be the best-estimators of chlorophyll-a concentration (as a proxy for algal biomass) and total suspended sediment concentration. The ratio of the reflectance value of the red band and the blue band produced reasonable estimates for the in-situ parameters in Bartlett Lake. The ratio of the reflectance value of the green band and the blue band produced reasonable estimates for the in-situ parameters in Saguaro Lake. However, even the best performing two-band algorithm did not produce any significant correlation between reflectance and in-situ data in Lake Pleasant. Overall, remotely-sensed observations can significantly improve our understanding of the water quality as measured by algae abundance and particulate loading in Arizona Reservoirs, especially when applied over long timescales.

DEDICATION

“The mountains are calling and I must go and I will work on while I can, studying incessantly.” I would like to dedicate this work to my father, Robert Russell, who made my pursuit of a Master’s Degree possible, and whose passion for the outdoors and wild places inspired me to study sustainability.

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INTRODUCTION

Safe, readily available, and reliable sources of water are an essential component of any municipality's infrastructure, and water security is one of the major concerns of urban authorities (Grafton et al., 2011; Yigzaw & Hossain, 2016). Municipal water systems have a broad range of essential uses, serving not only residential, but also industrial, commercial, institutional, and public clients (Mayer et al., 1999). Stake-holders have diverse sets of needs affected by both long-term factors such as economic conditions, population demographics, and water conservation activities as well as short-term factors, such as seasonal weather patterns and the timing of peak demand (Corbella & Pujol, 2009). The greater Phoenix metropolitan area has a unique set of water-related requirements and limitations due to its location in an arid environment (Larson et al., 2009). Water use varies widely within the United States, but some of the highest rates are seen in southwestern cities such as Phoenix, Arizona (Sokol, 2005).

Municipal water supplied to the Phoenix metropolitan area is categorized as effluent wastewater, ground water, surface water, and Colorado River water by the Arizona Department of Water Resources (2016). Forty percent of water comes from groundwater sources, nineteen percent comes from surface water sources including the Gila River, the Verde River, the Little Colorado River, the Salt River, the Aqua Fria River, and a variety of additional small rivers and streams. Finally, twenty-nine percent comes from the Colorado River (Arizona Department of Water Resources, 2016). Surface waters make up a substantial part of the municipal water supply, but these sources can vary

dramatically from year to year and by season (Arizona Department of Water Resources, 2016). In order to combat this issue, an extensive system of reservoirs and canals have been constructed, with the most notable being the reservoirs located on the Salt, Verde, Gila, and Aqua Fria Rivers as well as the Central Arizona Project reservoirs, which store water from the Colorado River (Arizona Department of Water Resources, 2016). Among these reservoirs are Lake Pleasant, Saguaro Lake, and Bartlett Lake. These are particularly important as Lake Pleasant is the major storage location for Arizona's allotment of Colorado River water, and Saguaro Lake and Bartlett Lake are the terminal reservoirs for the Salt River and the Verde River, respectively.

Each of the Phoenix metro reservoirs has a varied and unique ecology. They range from relatively deep and oligotrophic, as is the case for Lake Pleasant, to relatively shallow and eutrophic, as seen in Saguaro Lake (Sawyer, 2011) and Bartlett Lake. These differences in physical properties are due to a variety of factors both biotic and abiotic. Trophic interactions, both top-down and bottom-up, also play a role in determining the composition of the algal community and level of turbidity (Sawyer, 2011; Weis & Post, 2013). The community structure of each reservoir has important implications for water treatment and management strategies.

In addition to the ways algal communities can impact the physical properties of water bodies, they can also alter their chemical composition. Many species of algae are capable

of producing toxic and noxious compounds (Pelley, 1998). Cyanobacteria in particular are capable of producing compounds that impact the taste and odor of municipal water (Tarrant & Neuer, 2009), they are also among the algae that can produce compounds that are harmful to wildlife and potentially humans (Wiedner et al., 2007; Hudnell, 2008). Noxious algal blooms can also impact food webs and ecosystems functions (Moustaka-Gouni et al., 2006). They can contaminate food and have other adverse health effects on people (Moore et al., 2008). They can also poison wildlife and fish (Christoffersen, 1996; Moustaka-Gouni et al., 2006; Grover et al., 2012). For these reasons, it is imperative to have a good understanding of the structure of the algal communities in reservoirs in addition to other more traditionally monitored parameters.

Many of the parameters used to better understand water quality, such as chlorophyll-a concentration, total suspended sediment, algal community composition, dissolved oxygen, and temperature are monitored through extensive field sampling (Bocharov et al., 2017; Navratil et al., 2011; Zhang & Angelidaki, 2012). Field sampling and observation is also generally how the onset of algal blooms is observed (Burford et al., 2007). There have been periods of sampling activities at Lake Pleasant, Saguaro Lake, and Bartlett Lake, from 2007 to 2010, undertaken by previous members of the Neuer Lab. The records generated offer unique benchmarks against which we can compare current data, with an eye towards long-term changes and trends in the reservoirs of interest.

However, despite the value of what can be learned through field sampling activities there are some drawbacks. Sampling can be both labor intensive and expensive. Field sampling has the added issue of being limited temporally and spatially, and thus only allowing for a limited picture of the parameter of interest. Remotely-sensed data derived from satellites can potentially allow for a more complete picture of parameters of interest in real time (Gerace et al., 2013). Given the negative impacts associated with algal blooms and high levels of suspended matter, the ability to remotely monitor reservoirs for these parameters has the potential to provide more advanced warning for both environmental and water processing issues.

ALGAE IN SUBTROPICAL RESERVOIRS

The algal communities found in reservoirs are broadly similar to those found in natural lakes (Reynolds, 1999). The physical structure of the aquatic environment, as well as the availability of nutrients and grazer communities play a role in shaping the algal community composition (Reynolds, 1980). Algal community composition is partially dependent on the natural community, which inhabited the river prior to damming, but also by species' ability to adapt to the environments within a reservoir that are characterized by its chemical, physical, and biological factors (de Souza et al., 2016).

The community structure of algae in subtropical water bodies is also generally influenced by seasonal variation, namely changes in light and temperature, in addition to biotic

factors such as grazing pressure, and hydrological factors (Kuo & Wu, 2016). For example, a study conducted in the subtropical Feitsui Reservoir, located in Taiwan, found that seasonal changes in light availability and temperature affect the composition of phytoplankton more strongly than nutrients (Chien et al., 2009).

The reservoirs of interest are located in a subtropical climate region. Subtropical climates are characterized by hot summers and mild winters (Belda et al., 2014). Water will remain thermally and chemically stratified for the majority of the summer, spring, and sometimes into autumn (Bertone et al., 2015). Under stratified conditions, a transitional layer (metalimnion) separates the water column into the epilimnion and the hypolimnion, with the level of nutrients in the epilimnion remaining relatively low (Zhang & Chan, 2003; Bednarz et al., 2011; Bertone et al., 2015). During destratification, when the water is well mixed vertically, most of the chemical and biological constituents have similar concentrations throughout the entire water column (Nürnberg, 1988).

Predictive models have shown that subtropical reservoirs may experience intensified thermal stratification due to rising temperatures, resulting in a higher probability of deep-layer hypoxia and an increased risk of algae blooms and eutrophication (Chang et al., 2015). Lower water levels in subtropical reservoirs due to little precipitation and increased demand may result in more water level fluctuations and overall lower water

levels, which have been shown to drive shifts between clear-water and turbid states in some lakes (Yang et al., 2016).

The algal community composition and abundance varies widely between reservoirs and by season (Sawyer, 2011). Some lakes exhibit relatively diverse algal communities and relatively few blooms, while others have frequent blooms that are dominated by one species of algae. For example, in one eutrophic subtropical lake in Florida, algal abundance has been demonstrated to peak during the warmer summer months, with cyanobacteria including *Planktothrix*, *Cylindrospermopsis*, *Planktolyngbya*, *Microcystis*, *Aphanizomenon* and *Anabaena* dominating the phytoplankton community during warmer months and other phytoplankton taxa including chlorophytes, diatoms, dinoflagellates, and cryptophytes increasing their relative contribution to phytoplankton biomass during colder months (Sriifa et al., 2016).

HARMFUL ALGAL BLOOMS

Harmful algal blooms (HABs) occur when populations of algae grow rapidly producing blooms. Blooms are classified as harmful when they produce toxins or result in other harmful effects on people and organisms that interact with the body of water experiencing a bloom. Cyanobacteria are often responsible for HABs and the presence of taste-and-odor compounds in drinking water supplies (Wnorowski, 1992; Rashash et al., 1996; Tarrant et al., 2009; Tarrant & Neuer, 2009; Tarrant et al., 2010), but other species

of algae have been known to create harmful blooms. Another particularly problematic species is *Prynesium parvum* or golden algae (Sager et al., 2008).

CYANOBACTERIA

Cyanobacteria (commonly referred to as blue-green algae) inhabit a wide range of environments, both aquatic and terrestrial, and in most cases are not harmful to humans. However, in aquatic systems, in some conditions, they can reach high population densities and form blooms or mats (Svirčev, 2013). These can be considered harmful when they lead to a reduction in aquatic diversity, interfere with drinking water treatment, or produce toxins (known as cyanotoxins) (Codd, 2000; Gantar & Svircev, 2008; Metcalf & Codd, 2012; Svirčev et al., 2013). Cyanotoxins can present acute health risks to humans and are generally a danger in drinking water and bodies of water where recreational activities take place (Yoo et al., 1995; Chorus and Bartram, 1999; Falconer & Humpage, 2005).

An additional concern with the proliferation of cyanobacteria is the production of taste and odor-causing compounds. Taste-and-odor compounds can cause concerns among the public over water quality (Graham et al., 2008). These compounds are responsible for malodorous and undesirable-tasting water, which can require additional treatment raising treatment costs and discouraging recreational activities.

Aquatic cyanobacteria grow optimally in warm temperatures (Srifa et al., 2016) and are often found in eutrophic environments (Svirčev et al., 2013). This makes them of particular interest as there has been an increase in both global temperature and in the prevalence of eutrophication as a direct result of human activities such as rapid population increase, urbanization, and environmentally harmful agricultural practices (Svirčev, 2009). Both eutrophication and warming temperatures are expected to continue into the future, and as a result, cyanobacterial blooms are expected to remain a pressing issue (Paerl & Paul, 2012; Paerl & Otten 2013).

PRYMNESIUM PARVUM

Prymnesium parvum (commonly known as golden algae), is a species of alga frequently associated with fish kills. It is a haptophyte alga found worldwide that is tolerant of large variations in temperature and salinity (Lundholm & Moestrup 2006; Baker et al., 2007, 2009; Roelke et al., 2010). The algae are single-celled and ellipsoid in shape, and they range in size from 8 to 11 µm in length (Green et al., 1982). *Prymnesium parvum* (golden algae) is a mixotroph and can support growth through both autotrophy and heterotrophy (Roelke et al., 2016). Golden algae are known to produce a number of toxins including ichthyotoxin, which adversely affects gill-breathing organisms (Ulitzer & Shilo, 1966). While the formation of a bloom does not always mean that the algae will begin producing toxins, it does appear that toxicity is enhanced by nutrient-limited conditions, pH greater than 7, and temperatures below 30°C (Dafni et al., 1972; Granéli & Johansson, 2003).

Documented blooms in the western hemisphere began in the mid 1980's, with the first confirmed bloom occurring in Texas in 1985 on the Pecos River (James & Delacruz, 1989). By the early 2000's blooms were occurring with increasing frequency and had been reported in 15 additional U.S. states including Arizona (Sager et al., 2008). Today blooms are known to occur in all southern regions of the U.S. as well as in some northern regions (Roelke et al., 2016).

Fish kills due to golden algae are a serious concern. As of 2009 over 34 million fish fatalities were attributed to golden algae in Texas alone, with economic losses estimated to be in the tens of millions (Southard et al., 2010). Blooms can also have a negative impact on lake-related recreational activities. Arizona reservoirs along the Salt River, such as Saguaro Lake, Canyon Lake, Apache Lake, and Roosevelt Lake are also recreation and fishing areas. Fish kills in these lakes can mean a loss of revenue due to a decrease in recreational activities in addition to their other deleterious ecological effects. For example, some lake-goers were deterred from entering the waters of Canyon Lake because of an observed fish kill due to golden algae in 2007 (Markham, 2007).

REMOTE SENSING AND MONITORING

Field sampling as a means to monitor algal communities and level of suspended sediment is widely practiced, but it also both time consuming and expensive. The use of remotely-

sensed data for monitoring these water quality parameters can ameliorate some of the issues that come with field sampling. There is a plethora of freely available remotely-sensed satellite data, making this approach to monitoring less expensive. It also provides more complete spatial data for entire bodies of water. New remotely sensed data are generated daily in some cases, and datasets go back many years, allowing for more complete temporal knowledge. The newest generation of sensors, with better radiometric sensitivity and finer scale, are opening up new possibilities for monitoring small inland water-bodies.

Landsat data have been used to estimate chlorophyll-a concentration since the 1980's with varying levels of success (Bacharov 2017). Algorithms have been continuously developed and improved over time, and monitoring water quality through remote-sensing has become more and more prevalent. For example, Ritchie et al. (2003), Hellweger et al. (2004), Ali et al. (2014), Dogliotti et al. (2015), Doña et al. (2015), and Harvey et al. (2015) all developed algorithms to generate estimates of water quality parameters of interest such as chlorophyll-a concentration, turbidity, and concentration of suspended sediment in coastal waters and lakes. Studies have utilized remotely-sensed data for monitoring a number of water quality parameters in Arizona reservoirs specifically, (Tarrant & Neuer, 2009; Tarrant et al., 2010; Lau, 2018). The estimates generated from these algorithms can be used to infer a considerable amount of information about the algal communities in water bodies. Researchers have even successfully used remotely-

sensed data to detect cyanobacterial algal blooms (Bresciani et al., 2011; Matthews et al., 2010; Vincent et al., 2004).

Remotely-sensed data are currently being used to study algal blooms in Lake Erie (Vincent et al., 2004; Zhang et al., 2017; Ali et al., 2016; Wang et al., 2017; Ho et al., 2017). There, researchers have successfully used Landsat data for the early detection of a large *Mycrocystis* bloom, which occurred in 2002 (Vincent et al., 2004). This supports the utilization of remote sensing technologies for detecting and classifying waterborne constituents (Lekki et al., 2013).

Previously, the Neuer Lab has explored the use of remotely-sensed satellite data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua satellite and the Medium-Resolution Imaging Spectrometer (MERIS) aboard the European Space Agency's Envisat satellite to detect and monitor total suspended matter and chlorophyll-a (a proxy for algal biomass) in multiple Arizona reservoirs (Tarrant et al. 2009, 2010). MERIS is no longer operating, and so is not a viable data source for the scope of this study. MODIS is still operating and was designed with an appropriate spectral coverage to monitor water quality from space. It generates daily coverage, making it ideal for capturing dynamic changes in water quality. However, there are some limitations that come with using these sensors. The spatial resolution is not ideal for the relatively small inland reservoirs. Since the previous study, the availability of remote

sensing capabilities by satellites have improved substantially. Data that used to be quite expensive to obtain is now freely available in many cases, allowing for a wider range of options in terms of available sensors.

MODIS is effective for monitoring water that has reflectance properties dominated by phytoplankton and its associated materials such as open ocean, as well as optically complex waters that contain significant levels of inorganic suspended matter and color-dissolved organic matter such as coastal and inland waters (Gerace et al., 2013), making it a good candidate to monitor the reservoirs of interest. However, due to its relatively coarse spatial resolution (500 meters), MODIS is not ideal for monitoring small spatially complex inland water bodies. MODIS can provide a valuable monitoring resource but may best be used in combination with additional data sources.

Landsat 8's Operational Land Imager (OLI) offers a much finer spatial resolution (30 meters), which is better suited to small optically complex water bodies. This finer resolution eliminates the problems with pixel contamination that are encountered in near-shore MODIS data. OLI has both the spectral and radiometric resolution necessary for monitoring water quality of relatively small water bodies (Gerace et al., 2013), however the temporal resolution is not as good as MODIS, with coverage every two weeks rather than daily. However, this coverage can be improved by also using data from Landsat 7's Enhanced Thematic Mapper Plus (ETM+). Landsat 7 was launched in 1999 and is still

generating data every 16 days, in an 8-day offset with Landsat 8. The use of data generated by both sensors is simplified by the USGS Analysis Ready Dataset (ARD), which integrates images from all of the Landsat missions. These data are atmospherically corrected, and all surface reflectance values are normalized to the same range, making these data very user-friendly. ARD surface reflectance images originating from Landsat 7 and Landsat 8 are generated every eight days and have a 30-meter pixel resolution.

There are a multitude of approaches when it comes to correlating remotely-sensed reflectance data with *in-situ* data. Both empirical and analytical algorithms are widely used, in addition to hybrid “semi-analytical” and “semi-empirical” versions. Empirical are sometimes favored for their simplicity and have been used with good result in small lakes with cyanobacteria-dominant blooms (Matthews et al., 2010).

METHODS

STUDY SITES

Data were collected at Saguaro Lake (Figure 1), Bartlett Lake (Figure 2), and Lake Pleasant (Figure 3). All three lakes serve as reservoirs for municipal water for the greater Phoenix metropolitan area. Sampling took place from March 2017 to March 2018 at all three lakes. Additional sampling was undertaken by previous members of the Neuer Lab at Saguaro Lake from March 2007 to December 2009, at Bartlett Lake from February 2008 to November 2009, and at Lake Pleasant from July 2008 to February 2010.

BARTLETT LAKE

Bartlett Lake was created with the construction of Bartlett Dam, which took place from 1936 to 1939 (AZ Department of Fish and Game 2007). It is the terminal reservoir on the Verde River, located downstream of Horseshoe Reservoir. It is approximately 77 kilometers northeast of Phoenix. The lake's average depth is 30 meters. The water level experiences large fluctuations due to draw-down in the summer months. The lake is turbid, with relatively low visibility (with *Secchi* depths ranging from 20 cm to 2 m) (Parks & Baker, 1996).

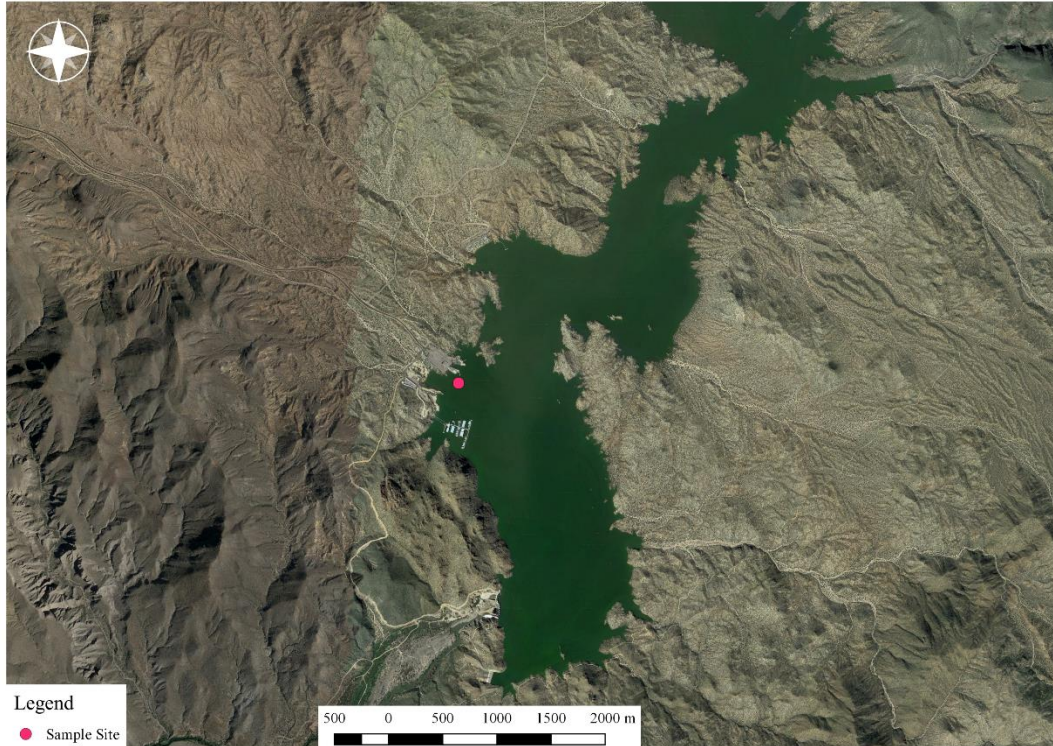


Figure 2. Bartlett Lake with sampling site from March 2017 to March 2018 indicated in red.

LAKE PLEASANT

Lake Pleasant is one of Arizona’s largest reservoirs. It was initially a smaller reservoir, which was created by damming the Aqua Fria River in 1927. The reservoir was used for agricultural irrigation (Maricopa County Parks). In 1973 construction began on the Colorado Project Aqueduct, which diverted Colorado River water in to the lake. In 1994 the construction of the New Waddell Dam increased the lakes capacity three-fold

(Maricopa County Parks). While the lake is still fed partially by the Aqua Fria, its main source of water is now the Colorado River.

Lake Pleasant is located approximately 82 kilometers northeast of Phoenix. The lake's average depth is 21 meters, but the depth fluctuates considerably, with waters being drawn down in the summer months and re-charged in the winter. Lake Pleasant is relatively oligotrophic, and its water has good visibility much of the year.

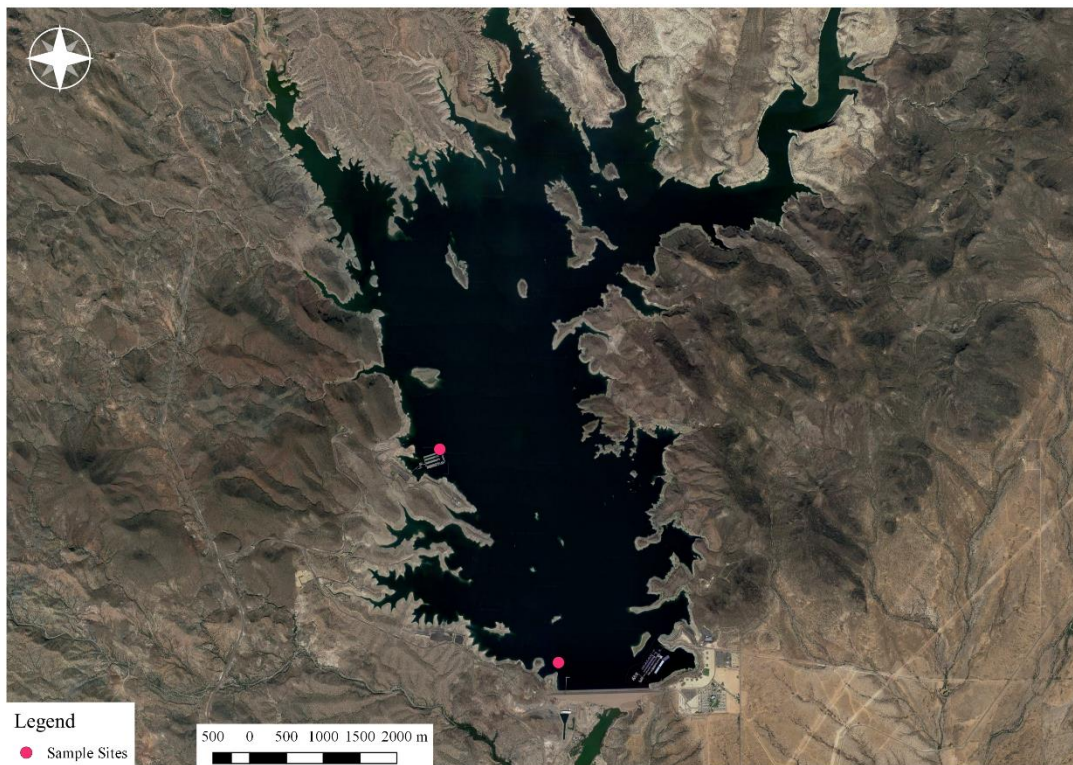


Figure 3. Lake Pleasant with sampling sites from March 2017 to March 2018 indicated in red.

SAGUARO LAKE

Saguaro Lake is the terminal reservoir in the Salt River Reservoir system, which originates at Roosevelt Lake and flows through Apache Lake, Canyon Lake, and finally Saguaro Lake. It is located east of the Phoenix metropolitan area. It was created with the construction of the Stewart Mountain Dam between 1928 and 1930 (Arizona Department of Fish and Game 2007).

Saguaro Lake has a surface area of 512 hectares, an average depth of 27 meters, and a surface elevation of 459 meters (AZ Department of Fish and Game 2007). Previous studies from the Neuer Lab showed that the reservoir's depth is held fairly consistent. It is comparatively eutrophic and its algal community is generally dominated by cyanobacteria and Prymnesiophytes during summer months.

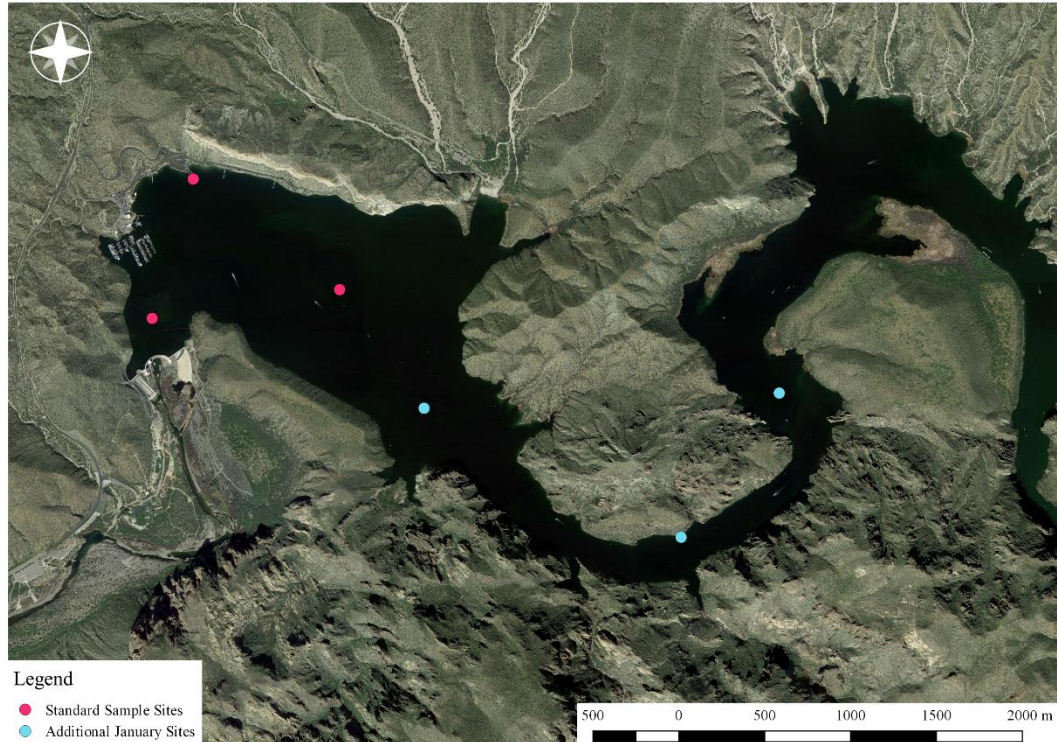


Figure 1. Saguaro Lake with regular sampling sites from March 2017 to March 2018 indicated in red and additional sampling sites during this same period indicated in blue.

FIELD SAMPLING

Field sampling was carried out monthly over a 13-month period (from March 2017 to March 2018) at the three study sites (Lake Pleasant, Saguaro Lake, and Bartlett Lake). In all three lakes, samples were collected at surface level at pier sites. In Lake Pleasant and Saguaro Lake, samples were also collected mid-reservoir at three depths using a small fishing boat: surface, 3 meters, and the estimated bottom of the euphotic zone. A *Secchi* depth was taken to visually measure water transparency, which can be used as a coarse measure of underwater light penetration. Underwater light penetration has a known

relationship with euphotic depth, and *Secchi* depth can simply be multiplied by two to estimate the depth of the euphotic zone (Luhtala & Tolvanen, 2013).

Temperature and dissolved oxygen was measured using a YSI model 85 handheld oxygen, conductivity, salinity, and temperature probe. The probe was factory calibrated in March 2017. The oxygen sensor was calibrated prior to each sampling trip to the correct altitude with the probe exposed to 100 percent humidity in order to ensure accurate dissolved oxygen readings. Dissolved oxygen readings are subject to an error of approximately ± 0.3 mg/l. Temperature readings are subject to an error of ± 0.1 °C.

Total suspended sediment was calculated using the gravimetric method for non-filterable residue by filtering at least 100 mL of sample in replicate through pre-weighed Whatmann GF/F filters, which were then dried at 105° C in an oven for at least 24 hours and re-weighed. Chlorophyll-a, a proxy of phytoplankton biomass, was quantified by filtering 50-250 mL of water through 25 mm GF/F filters in replicates, which were extracted in 90% acetone overnight at 4°C. The extracted chlorophyll-a was then read on a Turner Designs TD-700 fluorometer. The fluorometer was calibrated using three standard concentrations of chlorophyll-a (100 μ g/L, 10 μ g/L and 5 μ g/L) diluted from a chlorophyll-a stock solution (Sigma, 10,000 μ g/L). Phytoplankton abundance was determined by filtering sample volumes from 5 to 20 mL onto 0.22 μ m black polycarbonate filters. Each volume was preserved with 0.1-0.2 mL of 50%

Gluteraldehyde and stained with 1 mL of a solution of DAPI (4',6-Diamidino-2-phenylindole dihydrochloride, 1 mg/100m). The filters were then fixed on glass slides and examined via epifluorescence microscopy under blue light and UV excitations. Algal cells were identified to a class level based on the records of previous members of the Neuer Lab, and Wehr's Freshwater Ecology of North America (2015). At least 40-100 cells were counted for each taxon and errors in the cell counts were calculated as 95 percent confidence intervals based on the number of cells counted as in Lund et al. (1958). Filamentous cyanobacterial cell counts were estimated by measuring the length of a filament and dividing by the average length of one cell. Biovolumes were calculated by assigning geometric shapes best-suited to each type of algal cell (Hillebrand et al., 1999).

To determine zooplankton abundance samples are collected with vertical net casts at each mid-reservoir sampling site. A 15 cm towable net with a 75 µm mesh size is cast between 5 and 30 meters. Samples were preserved in 2% final volume formalin solution. Prior to fixation zooplankton are anesthetized with CO₂. The zooplankton samples were not further analyzed within the scope of this thesis.

SATELITTE DATA ANLYSIS

Landsat Surface Reflectance Analysis Ready Data (ARD) were obtained for the period of the study (March 2017 to February 2018) from the USGS portal at <https://earthexplorer.usgs.gov>. The data obtained for this time period originated from

both Landsat 7 and Landsat 8 sensors. The surface reflectance ARD come pre-processed to allow for direct use without additional atmospheric or quality control corrections needed. ARD tiles were visually inspected to ensure they contained no clouds over the study sites.

The ARD images were then loaded into R and reflectance values were pulled at the coordinate of each sampling site. In order to reduce the risk of land contamination or other visual anomalies interfering with the accuracy of the reflectance values, sampling site coordinates that were located near the shore were adjusted to locations 100 meters away from the shore and towards the center of the water body, and a thirty-meter buffer was applied around all sampling site coordinates. All pixels that fell at least fifty percent inside the buffer were averaged together.

Surface reflectance data generated were then compared with the *in-situ* chlorophyll-a concentrations and *in-situ* total suspended sediment. Surface reflectance values were matched with *in-situ* data by date, including exact matches (*in-situ* data taken the same day as the satellite reflectance data were generated) and plus or minus one day matches (*in-situ* data that were taken one day prior-to or one day after the satellite reflectance data were generated).

Surface reflectance data were correlated with *in-situ* data using a variety of different methods including single-band, multi-band, and band-ratio comparisons along with empirical and semi-analytical algorithms for deriving chlorophyll-a and total suspended sediment estimates from surface reflectance. The best performing method for each individual lake was selected based on r-squared values.

Once the best-performing algorithm was identified for each water body, it was applied to all pixels within the bounds of the lake to generate mapped chlorophyll-a and TSS estimates for the entire water body during summer, spring, fall, and winter seasons. Additional surface reflectance ARD were downloaded for the period of time between field sampling activities undertaken by the Neuer Lab (2009 to 2017) and appropriate algorithms applied to estimate chlorophyll-a concentrations and total particulates in the reservoirs during the years when no field sampling took place.

RESULTS

In the following sections, I will describe water quality parameters including temperature, dissolved oxygen, and algal abundance of abundant taxonomic groups, as well as chlorophyll-a and suspended sediment concentration collected from March 2017 to March 2018. These data are then compared with a congruous data generated from 2007 to 2010, with a focus on long-term trends and unique developments in the relevant water quality parameters.

I will also show the best performing algorithms that predict chlorophyll-a and suspended sediment concentrations from remotely-sensed data. The best performing algorithms were applied to generate time series data for the interim field sampling periods.

MARCH 2017 TO MARCH 2018 SAMPLING PERIOD

BARTLETT LAKE

Over the year-long sampling period, Bartlett Lake showed the highest peaks in chlorophyll-a concentration and levels of suspended sediment of all the study sites (Figure 4). It also generally had the highest algal abundances (Figure 5) and biovolume of algal cells (Figure 6). Chlorophyll-a concentrations peaked in June 2017 and March 2018 at approximately 150 $\mu\text{g/L}$ and 210 $\mu\text{g/L}$ respectively. The peak in chlorophyll-a concentration in March 2018 was accompanied by a peak in suspended sediment of 27.20

mg/L. The chlorophyll-a concentrations and suspended sediment values were closely correlated ($R^2 = 0.92$). The highest surface temperature was recorded in September 2017 at approximately 30 °C. The lowest dissolved oxygen level was recorded in December 2017 at approximately 51 percent saturation.

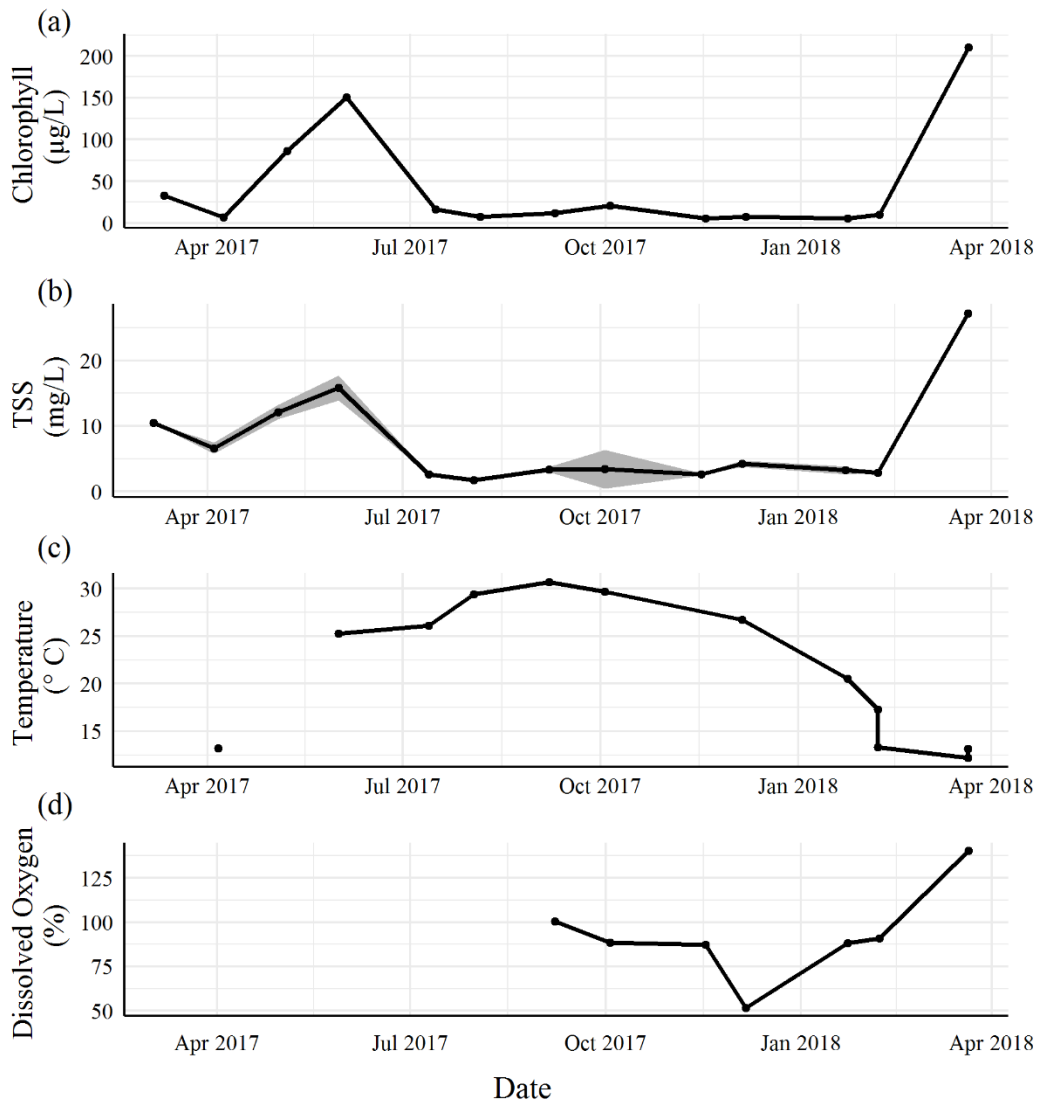


Figure 4. Trends in key water quality parameters in Bartlett Lake (a) chlorophyll-a concentration ($\mu\text{g/L}$) (b) total suspended sediment in (mg/L), (c) surface temperature ($^{\circ}\text{C}$), and (d) dissolved oxygen at the surface (percent saturation). (a) and (b) 95% confidence intervals indicated in grey. Note data gaps in (c) and (d).

The algal community composition was generally dominated by filamentous cyanobacteria in Bartlett Lake, with peak levels in June 2017 at approximately 4.5×10^5 cells/ml. There was also a high abundance of diatoms in October 2017 at approximately 5.0×10^4 cells/ml. These peaks in abundance are reflected in the biovolume measurements (Figure 6).

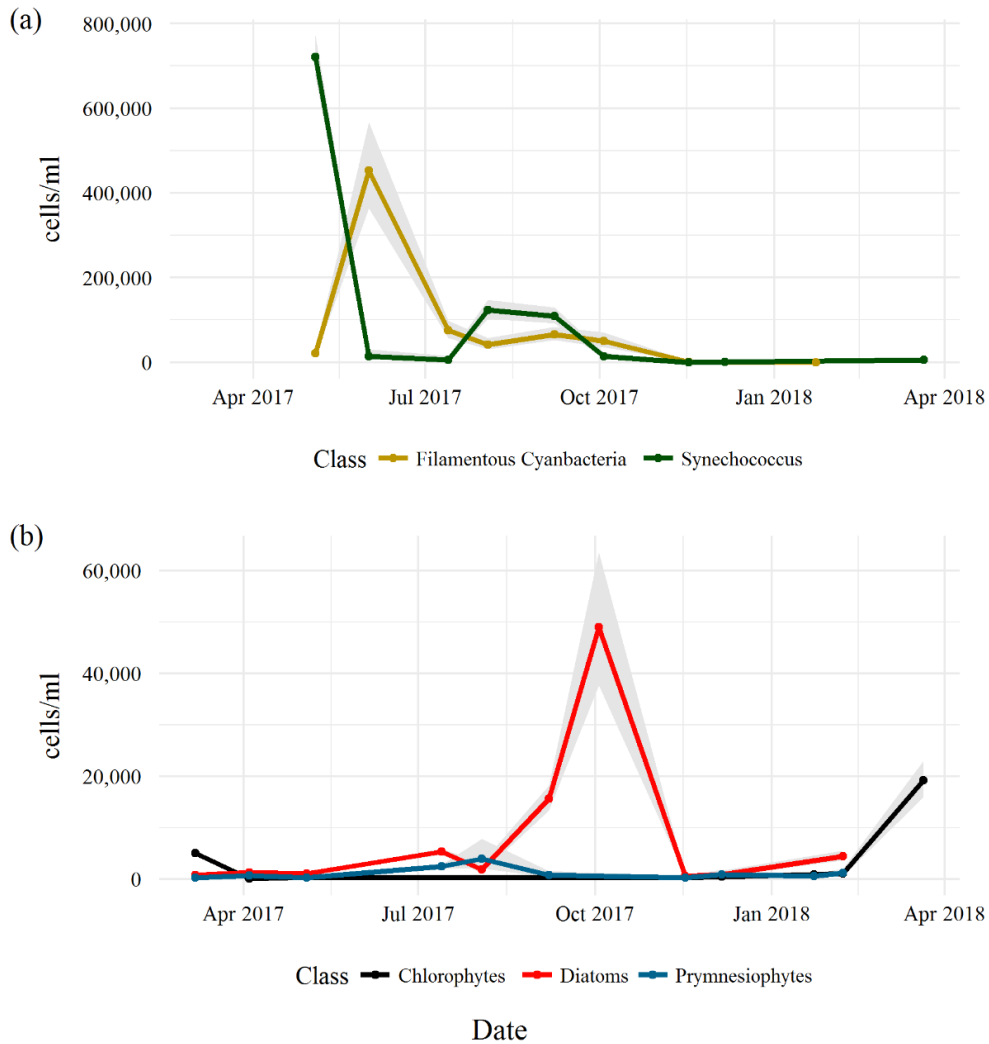


Figure 5. Algal abundances by class in Bartlett Lake from March 2017 to March 2018 plotted on two different axes (a) algae with the greatest abundance (cells/ml). (b) algae with relatively smaller abundance (cells/ml). 95% confidence intervals in grey.

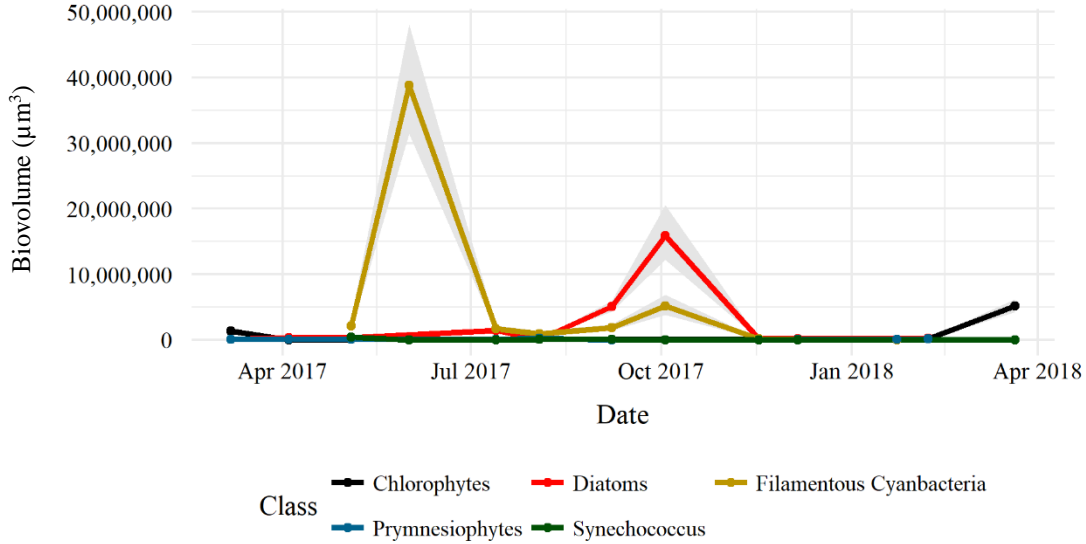


Figure 6. Algal biovolumes (μm^3) by class in Bartlett Lake from March 2017 to March 2018. 95% confidence intervals in grey

LAKE PLEASANT

Over the one-year sampling period dissolved oxygen and temperature was measured along a vertical profile to 60 m depth. The water temperatures increased from March 2017 until August 2017, at which point water temperatures began decreasing through March 2018. The opposite trend is observed in dissolved oxygen, with levels decreasing from March 2017 to August 2017 and then increasing through March 2018. Lake Pleasant experiences stratification in the summer months and destratification in the winter (Figure 7).

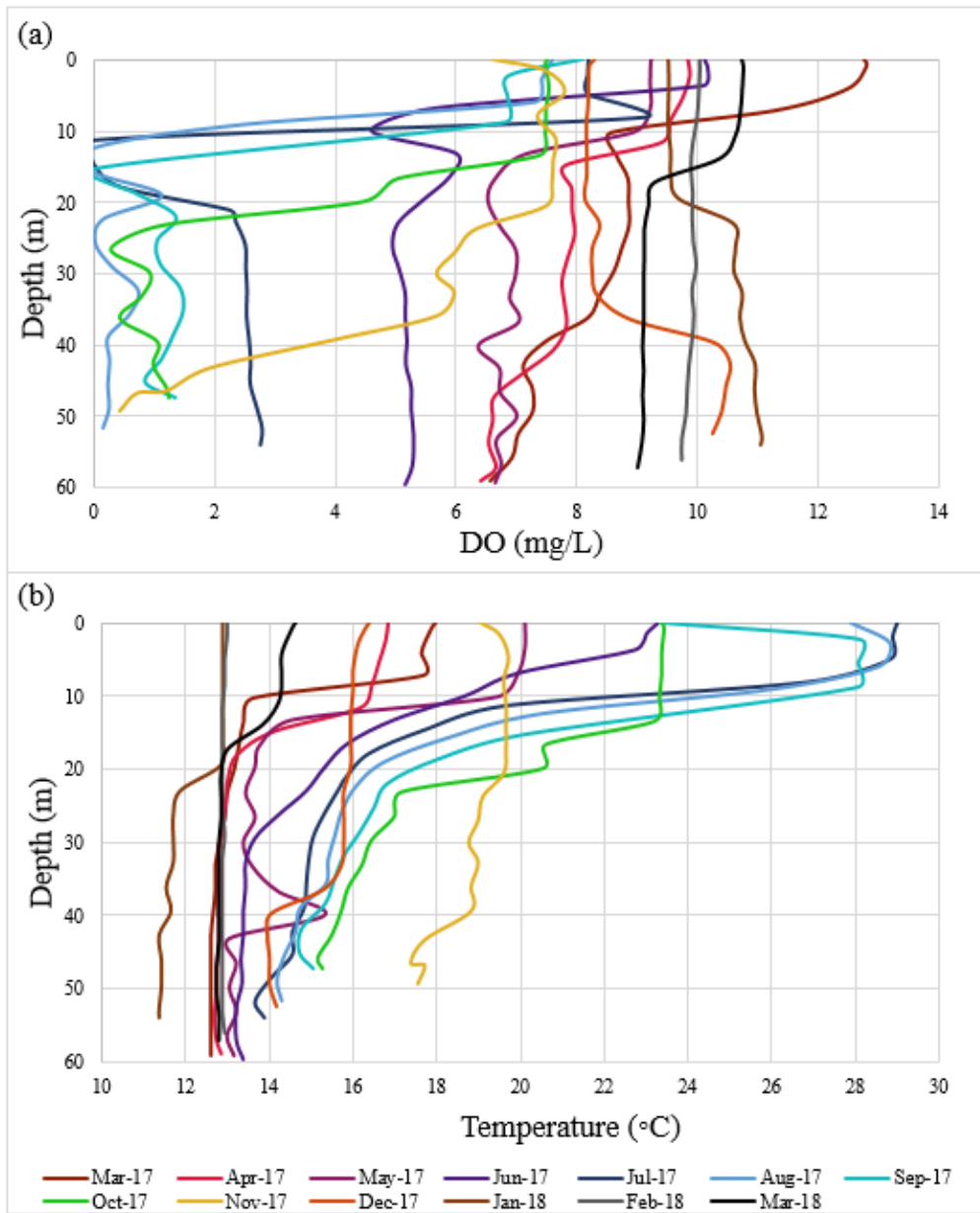


Figure 7. (a) Dissolved oxygen (mg/L) and (b) temperature ($^{\circ}\text{C}$) at depth in Lake Pleasant from March 2017 to March 2018.

Over the study period, Lake Pleasant showed the lowest levels of chlorophyll-a and suspended sediment compared to the other two study sites (Figure 8). Chlorophyll-a peaked in June 2017 at approximately 8 µg/L. Suspended sediment peaked in July 2017 and February 2017 at 2.9 mg/L and 2.8 mg/L respectively. The highest temperature was seen in July 2017 at approximately 29 °C and the lowest was observed in January 2018 at 12.89 °C. The lowest dissolved oxygen value was approximately 75 percent saturation in November 2017.

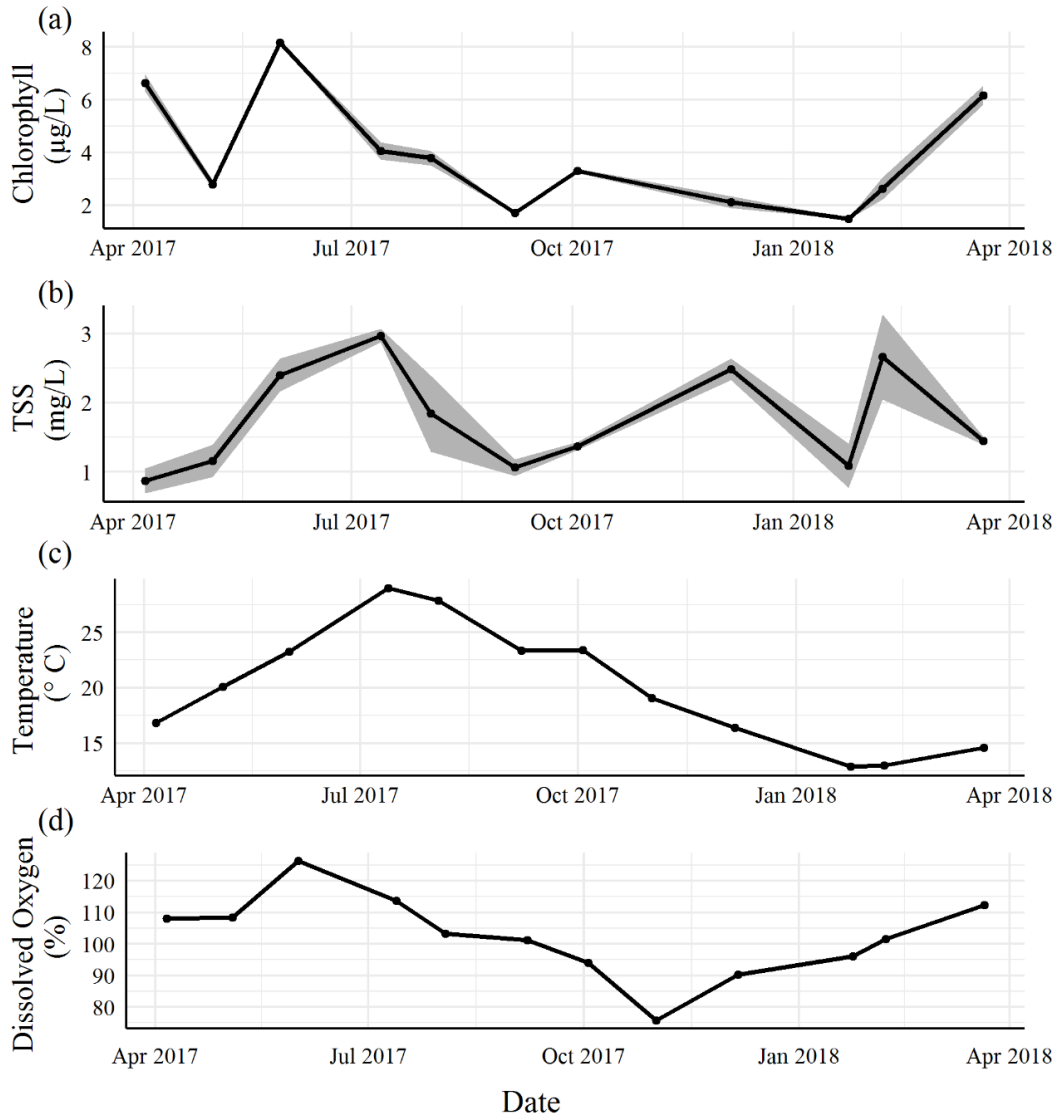


Figure 8. Trends in key water quality parameters in Lake Pleasant (a) chlorophyll-a concentration ($\mu\text{g/L}$) (b) total suspended sediment (mg/L), (c) surface temperature ($^{\circ}\text{C}$), and (d) shows dissolved oxygen at the surface (percent saturation). (a) and (b) 95% confidence intervals in grey.

In comparison with other study sites, algal abundances in Lake Pleasant were low (Figure 9). As a result, relatively lower biovolumes were also observed in Lake Pleasant (Figure 10). Peaks were observed in filamentous cyanobacteria, with the largest in June 2017 at 8.5×10^3 cells/ml. *Synechococcus* peaked in August 2017 at approximately 8.0×10^4

cells/ml. This was followed by a peak in diatoms in July and August 2017 at about 7.0×10^3 and 8.0×10^3 cells/ml respectively, which was reflected in the biovolume which was about $2.5 \times 10^6 \mu\text{m}^3$ in that month due to diatoms - the highest peak in biovolume of any algae observed in the study period.

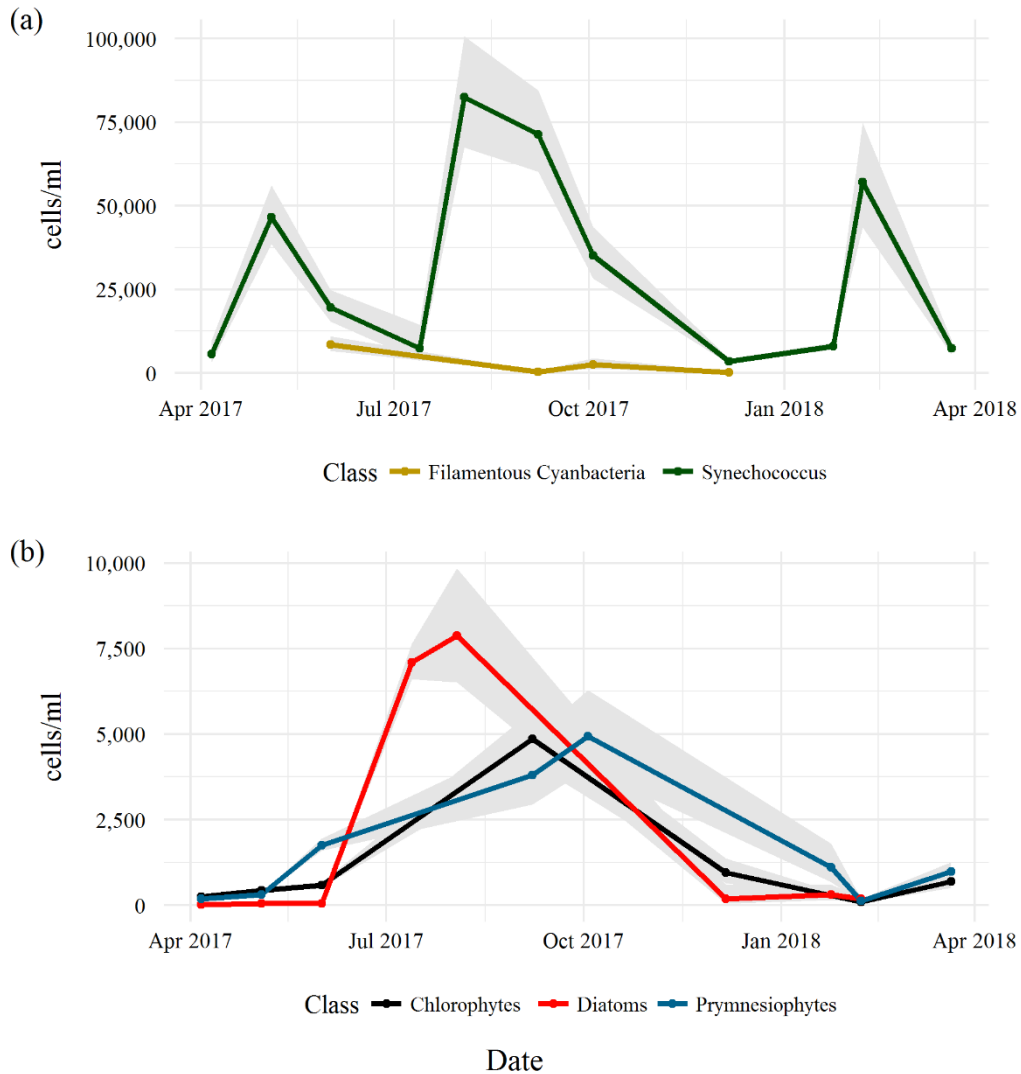


Figure 9. Algal abundances by class in Lake Pleasant from March 2017 to March 2018 plotted on two different axes. (a) algae with the greatest abundance (cells/ml). (b) algae with relatively smaller abundance (cells/ml). 95% confidence intervals indicated in grey.

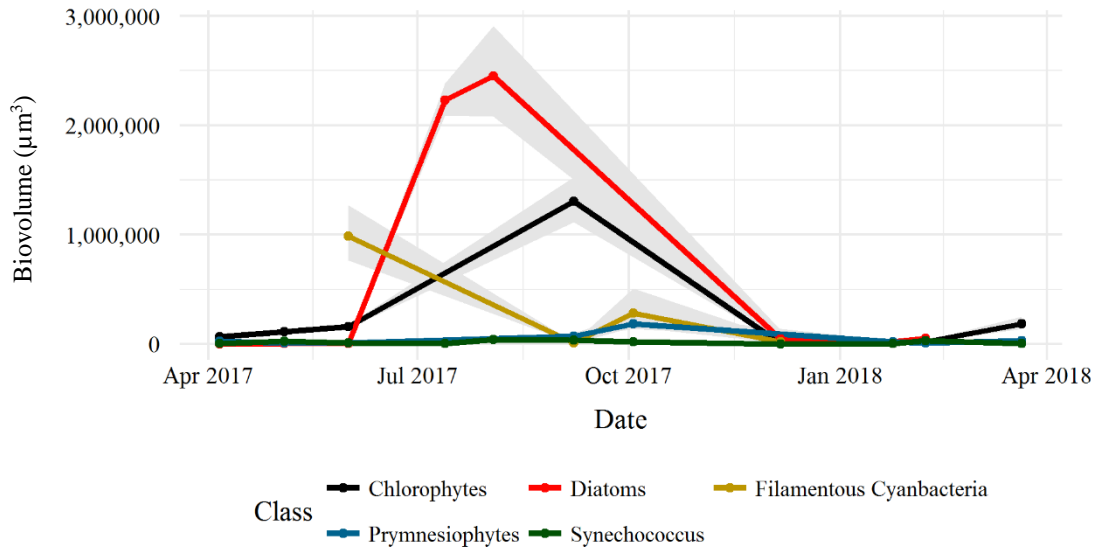


Figure 10. Algal biovolumes (μm^3) by class in Lake Pleasant from March 2017 to March 2018. 95% confidence intervals indicated in grey

SAGUARO LAKE

In Saguaro Lake the water temperatures at depth increased from March 2017 until July 2017, at which point water temperatures began decreasing through March 2018. The opposite trend was observed in the dissolved oxygen. With levels decreasing from March 2017 to September 2017 and then increasing through March 2018. Saguaro Lake also experiences stratification in the summer months and mixes in the winter (Figure 11).

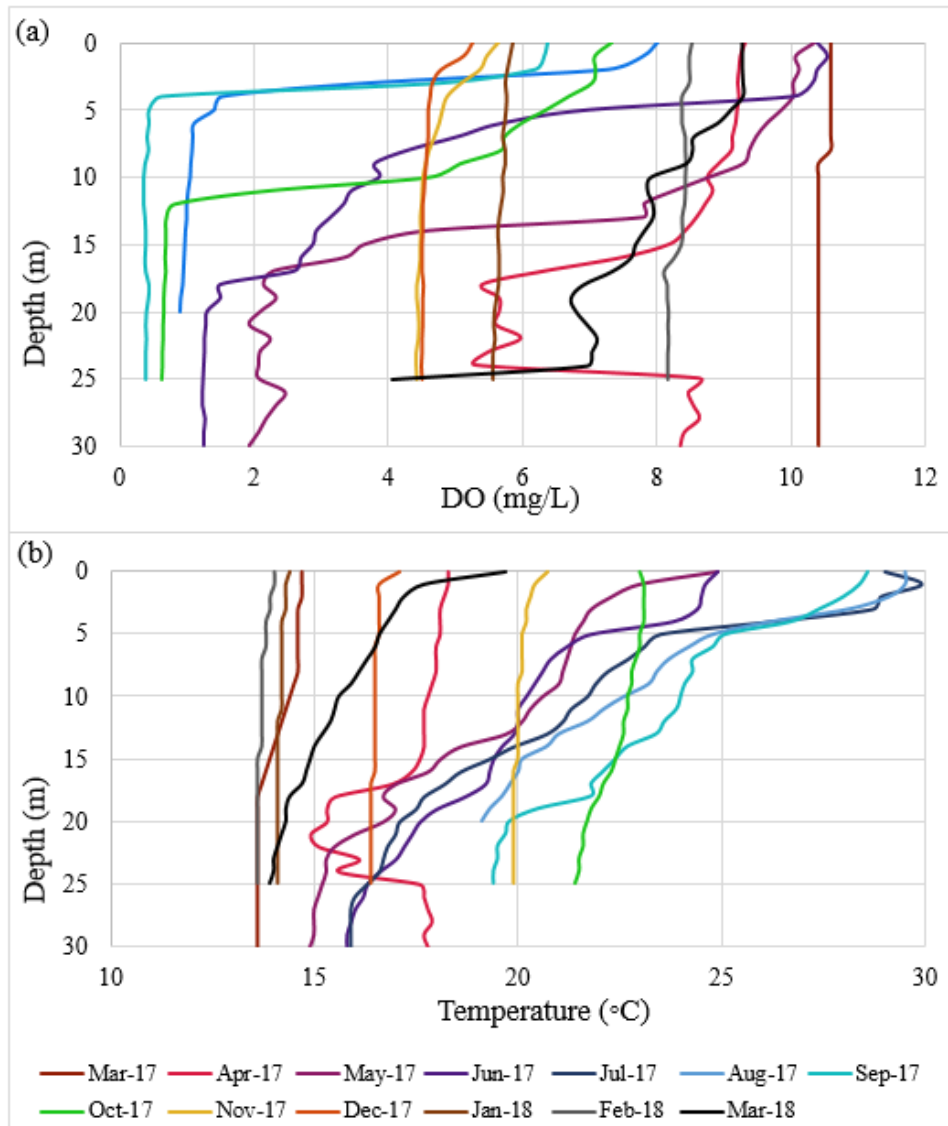


Figure 11. (a) dissolved oxygen (mg/L) and (b) temperature (°C) at depth in Saguaro Lake from March 2017 to March 2018.

Saguaro Lake showed the moderate levels of chlorophyll-a and suspended sediment, falling between the ranges of Bartlett Lake and Lake Pleasant (Figure 12). Chlorophyll-a peaked in August 2017 at approximately 44 $\mu\text{g/L}$. Suspended sediment peaked simultaneously at approximately 6 mg/L. The chlorophyll-a concentration showed a

moderate correlation with the level of suspended sediment ($R^2 = 0.63$). The highest surface temperature was also occurred in August 2017 at approximately 30 °C and the lowest was observed in February 2018 at approximately 14 °C respectively. The lowest dissolved oxygen occurred in December 2017 and was approximately 58 percent saturation.

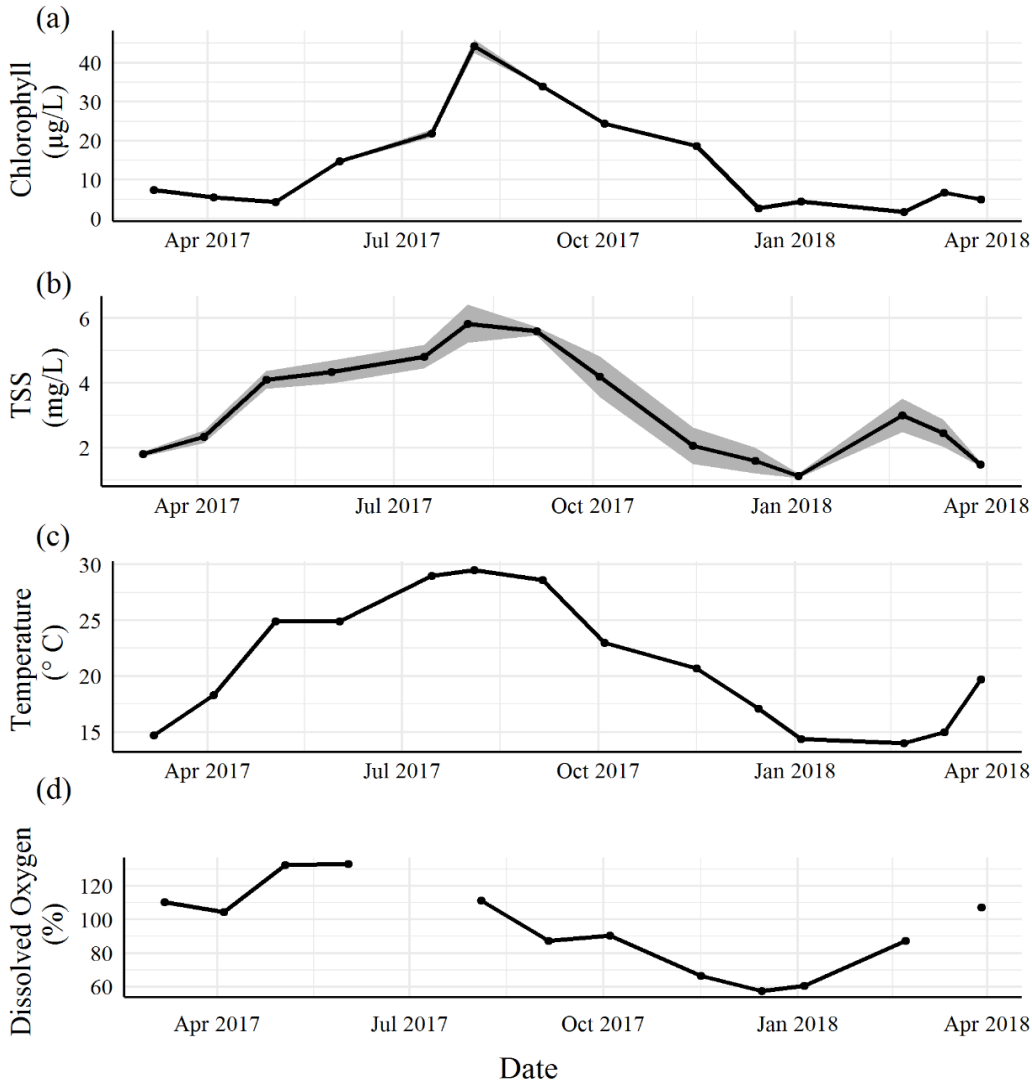


Figure 12. Trends in key water quality parameters in Saguaro Lake (a) chlorophyll-a concentration ($\mu\text{g/L}$) (b) total suspended sediment (mg/L), (c) surface temperature ($^{\circ}\text{C}$), and (d) dissolved oxygen at the surface (percent saturation). (a) and (b) 95% confidence intervals indicated in grey. Note data gaps in (d).

Saguaro Lake showed moderately high algal abundances in comparison to the other sites. The algal community was generally dominated by filamentous cyanobacteria, which reached their highest peak at approximately 5.7×10^4 cells/mL in August 2017, this peak in abundance is reflected in the biovolume. In Saguaro Lake filamentous cyanobacterial biovolume was moderately well-correlated with chlorophyll-a concentration ($R^2 = 0.54$) throughout the course of field sampling (March 2017 to March 2018). Prymnesiophytes were also a relatively abundant class of algae, reaching approximately 1.7×10^4 cells/mL in August 2017, but their biovolume was much lower compared to that of the cyanobacteria (Figure 14).

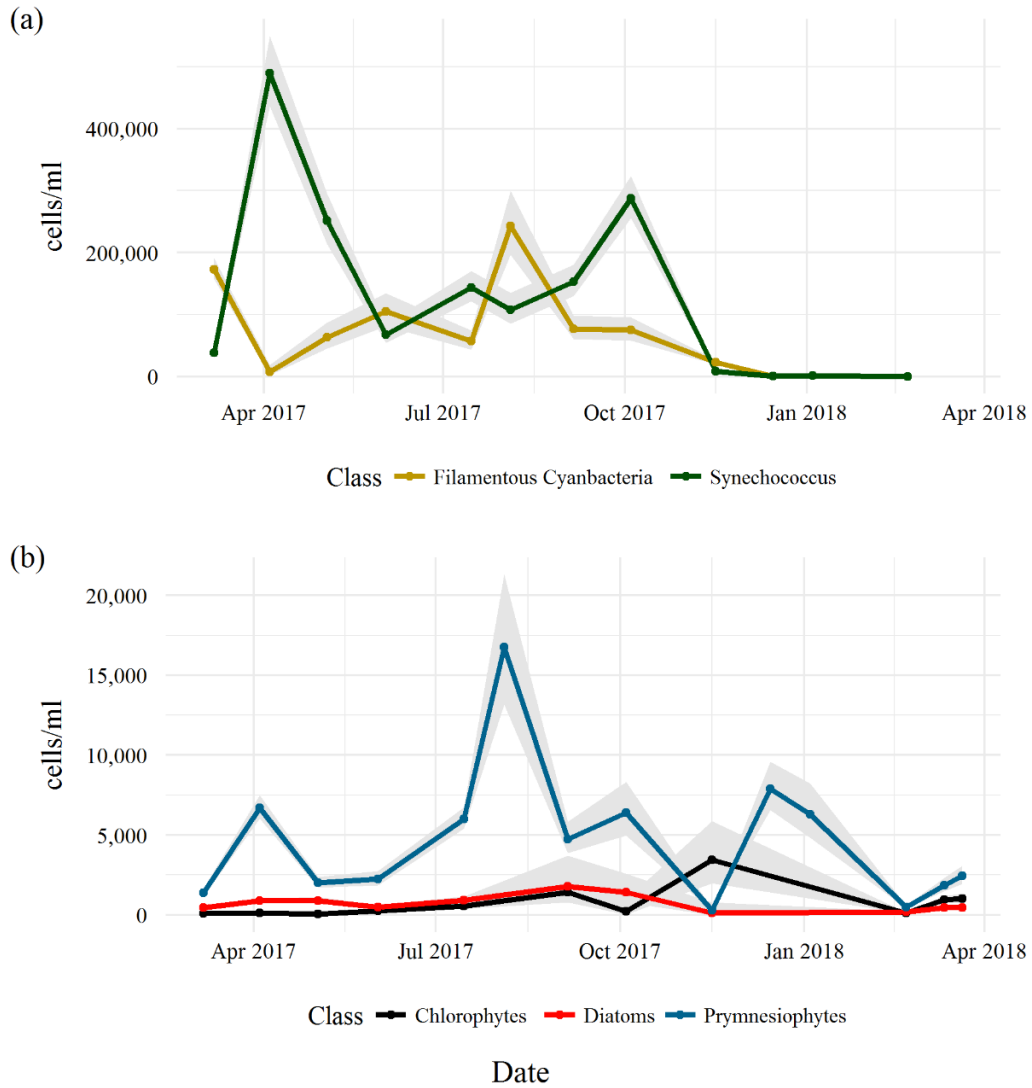


Figure 13. Algal abundances by class in Saguaro Lake from March 2017 to March 2018 plotted on two different axes. (a) algae with the greatest abundance (cells/ml). (b) algae with relatively smaller abundance (cells/ml). 95% confidence intervals in grey.

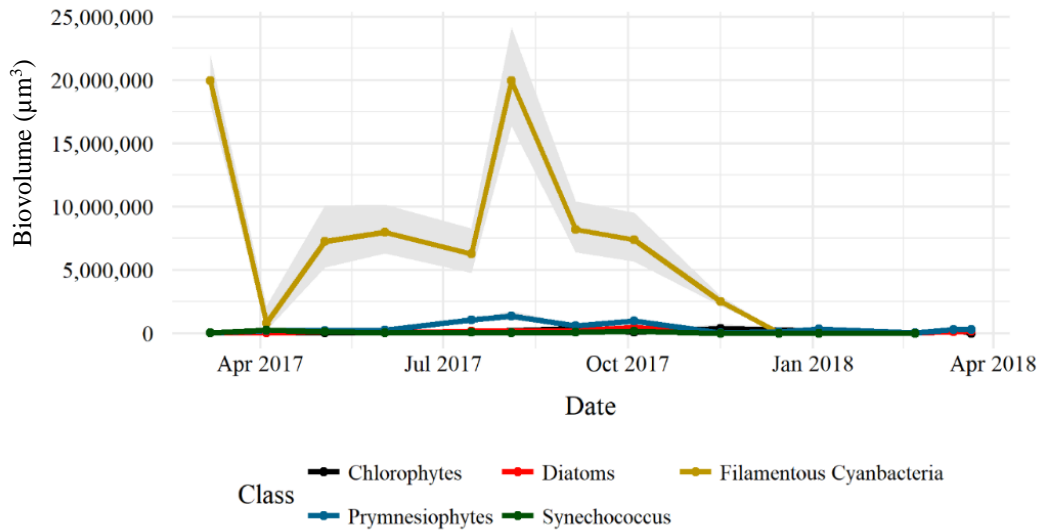


Figure 14. Algal biovolumes (μm^3) by class in Saguaro Lake from March 2017 to March 2018. 95% confidence intervals in grey.

ALGAL ABUNDANCE OVER TIME

Ranges in algal abundance observed between March 2017 and March 2018 were relatively consistent with ranges of the historical sampling periods for each study site. There were some interesting deviations from previously observed algal abundances. In Bartlett Lake, there was a previously unobserved peak in diatoms in October 2017 (Figure 15). The peak abundance of 4.9×10^4 cells/ml was approximately five times higher than any previously recorded. A similarly unprecedented abundance was seen in filamentous cyanobacteria in June 2017. Its peak value of 4.5×10^5 cells/ml was also a fivefold increase from the next most abundant value recorded (Figure 15). In Lake Pleasant, there was an unusually high peak in the abundance of diatoms in August 2017 at 7.9×10^3 cells/ml. This peak was more than tenfold any that had previously been

recorded (Figure 16). Saguaro Lake showed the least variation from previously recorded algal abundances of all the study sites (Figure 17).

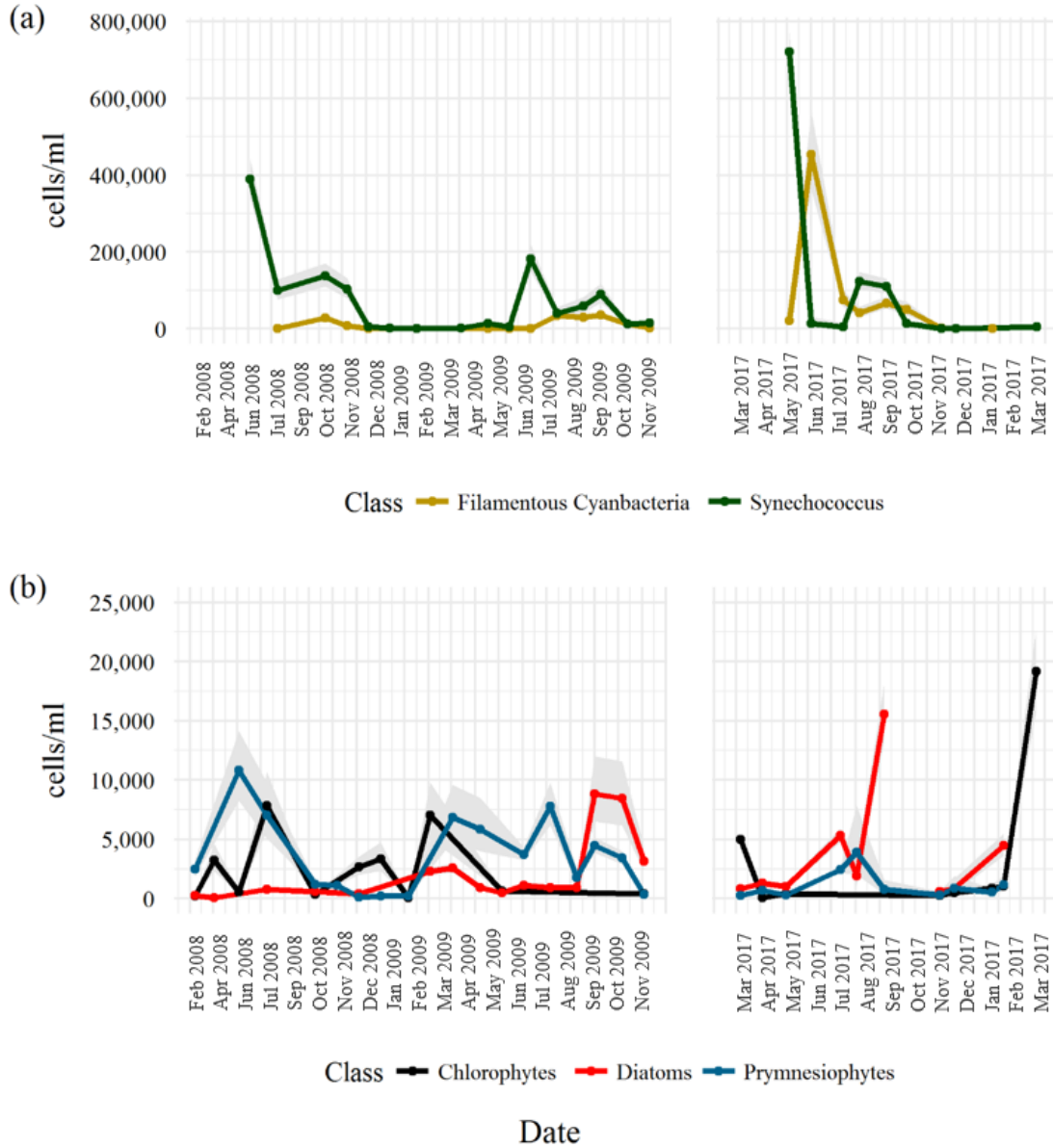


Figure 15. Algal abundance in Bartlett Lake from February 2008 to November 2009 and from March 2017 to March 2018.

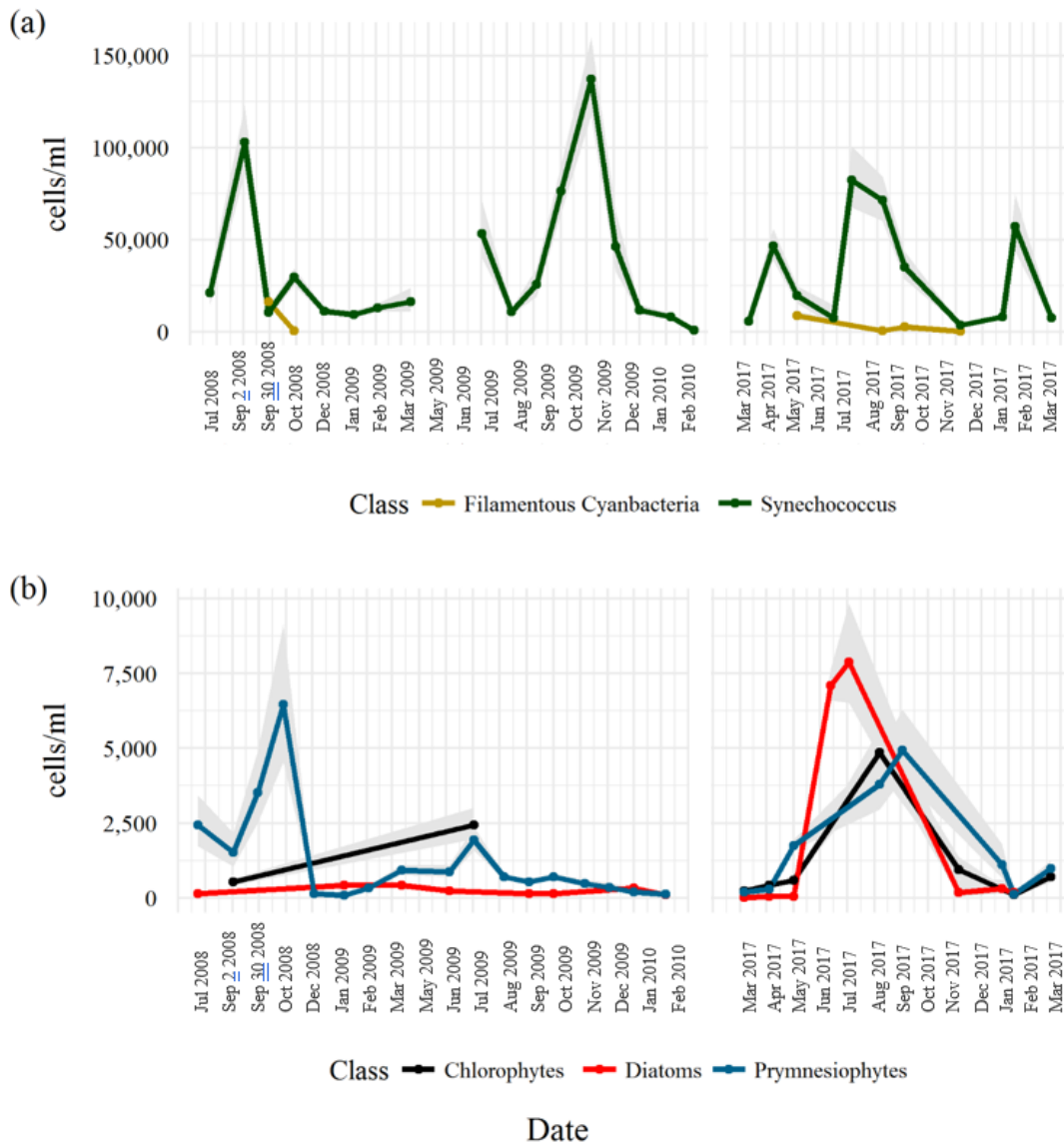


Figure 16. Algal abundance in Lake Pleasant from July 2008 to February 2010 and from March 2017 to March 2018.

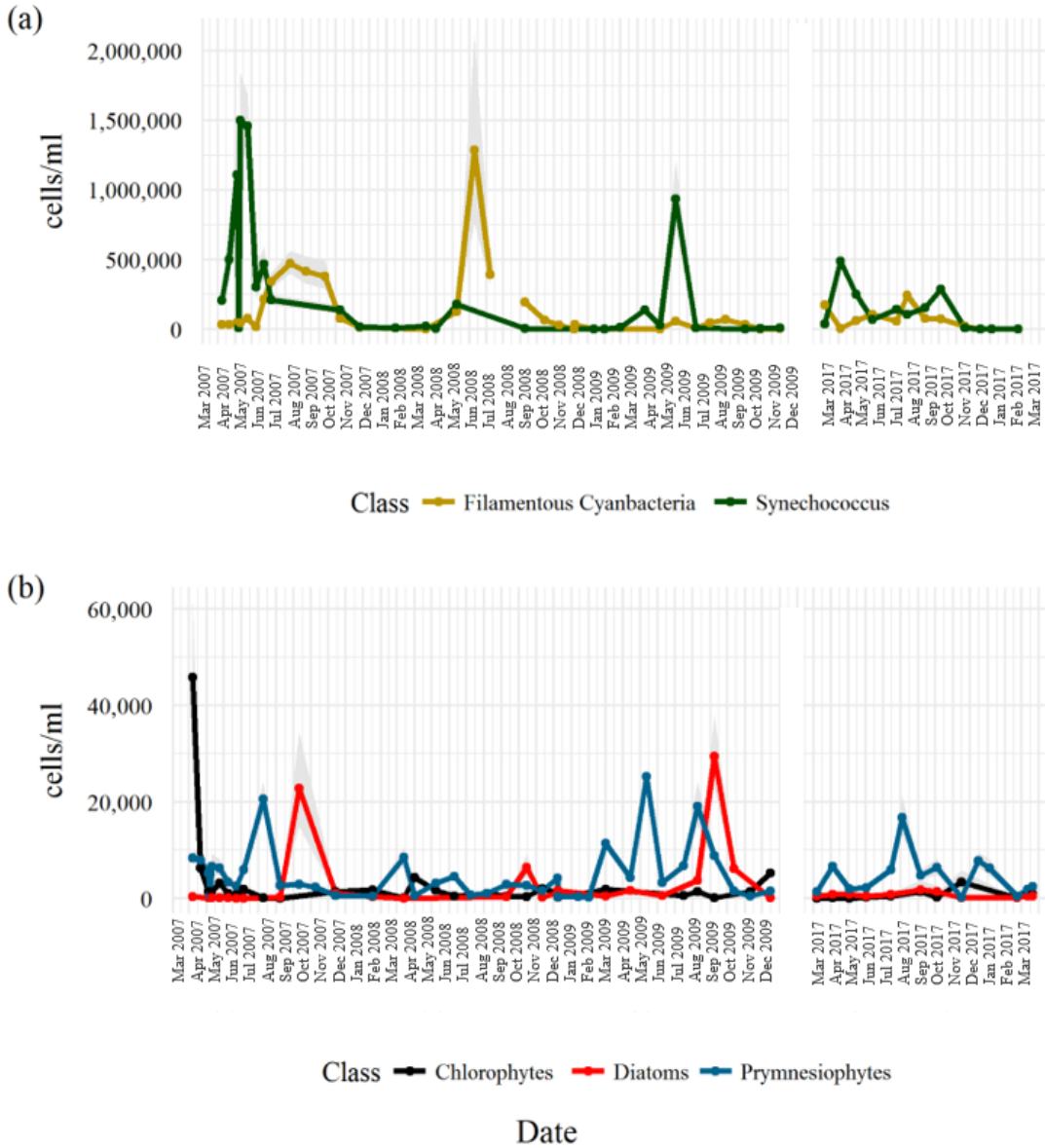


Figure 17. Algal abundance in Saguaro Lake from March 2007 to December 2009 and from March 2017 to March 2018.

REMOTE SENSING

ALGORITHM SELECTION

For each lake, *in-situ* data were matched with surface reflectance data generated by both Landsat 7 and Landsat 8 sensors by date. Both exact date matches and dates that matched plus or minus one calendar day were used in algorithm development. The surface reflectance data were then correlated with the *in-situ* data. Each site had a different number of comparison points.

Various empirical band combination algorithms were chosen due to their relative simplicity and ease of use, and because they generally perform well when there is adequate number of *in-situ* comparison points. Band ratios were selected from previous studies (Hellerger et al., 2004; Tarrant & Neuer, 2009; Tarrant et al., 2010; Ali et al., 2014; Dogliotti et al., 2015; Ali et al., 2016; Ho et al., 2017) and applied to the reflectance data generated at each lake. The most commonly used bands are the blue, green, red, and near-infrared. These bands were compared with *in-situ* chlorophyll-a concentration and level of suspended sediment individually and in various combinations. Frequently used band combinations include green/red, blue/green, red/blue, near-infrared/red, and red minus near-infrared.

All of these band algorithms were considered to estimate both chlorophyll-a concentration and total suspended sediment based on surface water reflectance in the

reservoirs. Overall, empirical algorithms utilizing two band combinations were the best estimators. None of the single-band, three-band, or four-band algorithms tested performed well (all $R^2 < 0.30$). When all the sites were grouped and compared with a variety of multi-band combinations, the blue/green band ratio was the best predictor of suspended sediment and the red/blue band ration was the best predictor of chlorophyll-a concentration.

Each lake experiences different ranges of suspended sediment and chlorophyll-a concentration. These differences may be reflected in unique optical properties of each site. Therefore, the sites were each also considered individually in order to tailor empirical algorithms to each one. Initially, the relationship between the reflectance band ratios and the *in-situ* parameters were fitted with liner trend-lines, but R^2 values improved in all cases when a second order polynomial lines of fit were used.

The *in-situ* chlorophyll-a concentrations and levels of suspended sediment in Bartlett Lake both had the best correlation with the red/blue band ratio, with R^2 values of 0.47 and 0.88, respectively (Table 1). *In-situ* suspended sediment concentration in Lake Pleasant correlated the best with the near infrared minus the red band, with an R^2 of 0.52 (Table 1) however, it should be noted that this relationship was not significant at a 95% confidence level according to the Pearson correlation test. None of the band combinations performed well in estimating chlorophyll-a concentration in Lake Pleasant. In Saguaro Lake, the

blue/ green band ratio was the best estimator of both chlorophyll-a and suspended sediment concentrations, with R^2 values of 0.43 and 0.56, respectively. Table 1 summarizes the R^2 and p-values for the grouped and individual sites.

	Green/Blue		Red/Blue		Red-NIR		(Blue-Red)/Green	
	R ²	P-Value	R ²	P-Value	R ²	P-Value	R ²	P-Value
All Sites Chlorophyll-a	0.33	4.7E-05	0.50	7.4E-05	0.11	0.13	0.48	1.6E-04
All Sites Suspended Sediment	0.55	1.1E-07	0.43	2.8E-05	0.19	2.1E-03	0.47	2.6E-05
Bartlett Chlorophyll-a			0.47	0.03				
Bartlett Suspended Sediment			0.88	7.2E-04				
Pleasant Chlorophyll-a					0.30	0.45		
Pleasant Suspended Sediment					0.52	0.11		
Saguaro Chlorophyll-a	0.43	3.3E-04						
Saguaro Suspended Sediment	0.56	6.2E-05						

Table 1. Summary of the R^2 and p-values for correlations between *in-situ* chlorophyll-a and total suspended sediment values and various Landsat band combinations. Sites are first combined and then considered independently. All R^2 values are for second order polynomial equations of fit. P-values are calculated using the Pearson correlation test to determine if correlations are significant.

In Bartlett Lake, there are ten points of comparison for chlorophyll-a concentration and twelve for suspended sediment concentration between March 2017 and March 2018.

Figure 18 illustrates the relationship between *in-situ* chlorophyll-a and the red/blue band ratio in Bartlett Lake ($R^2 = 0.47$). Figure 19 illustrates the relationship between *in-situ* suspended sediment concentration and the red/blue band ratio in Bartlett Lake ($R^2 = 0.88$). Both of these relationships are significant according to the Pearson correlation test (p-value = 0.03 and p-value = 7.2×10^{-4} , respectively).

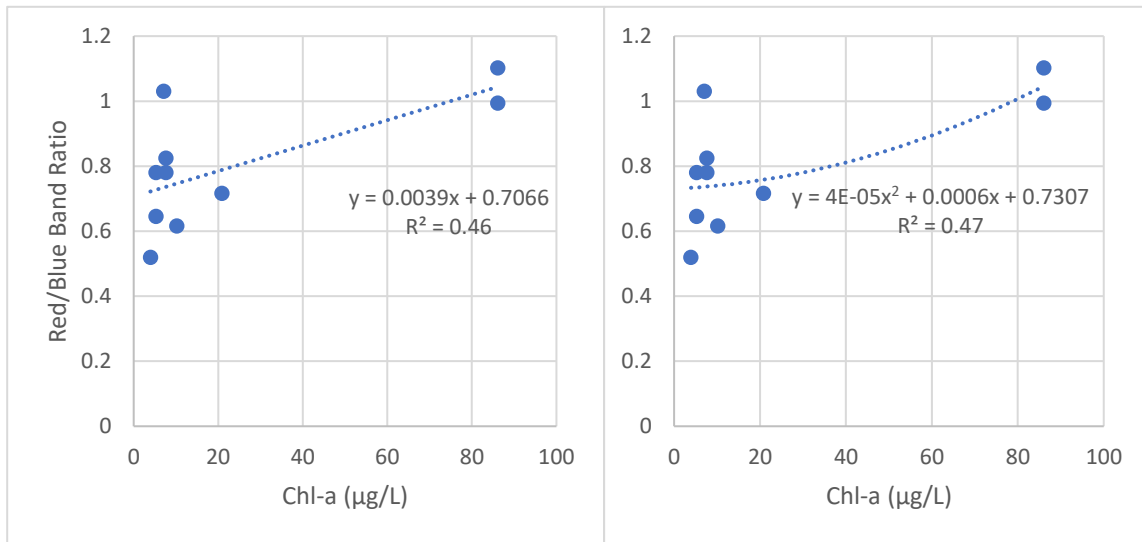


Figure 18. Correlation between the red/blue Landsat band ratio and *in-situ* chlorophyll-a concentration in Bartlett Lake. The graph on the left shows a linear fit and the graph on the right shows a second order polynomial fit.

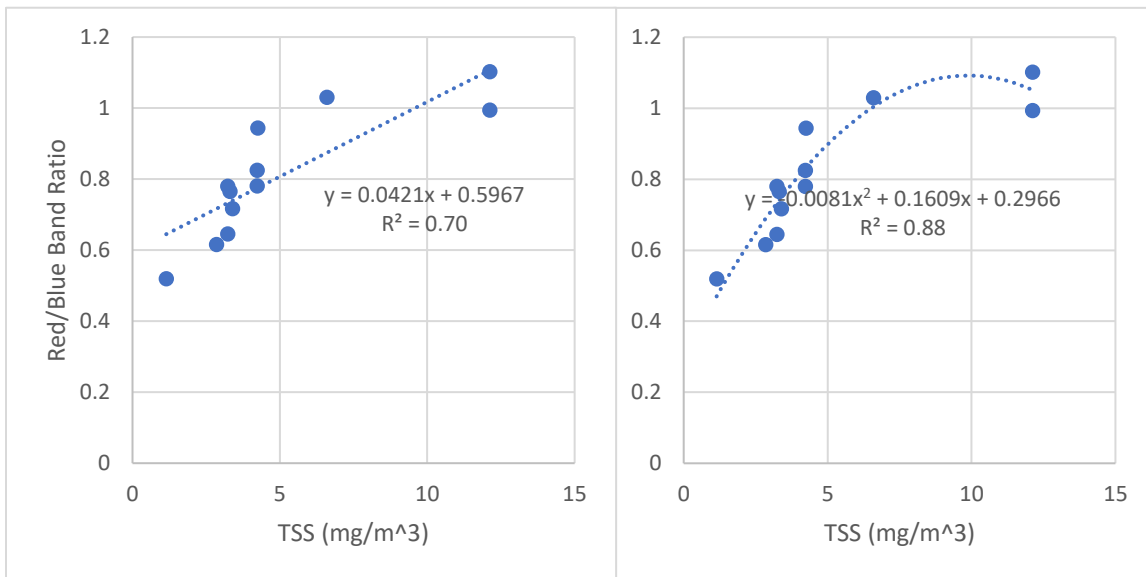


Figure 19. Correlation between the red/blue Landsat band ratio and *in-situ* suspended sediment concentration in Bartlett Lake. The graph on the left shows a linear fit and the graph on the right shows a second order polynomial fit.

For Lake Pleasant, there were 13 data points of comparison between March 2017 and March 2018. However, even the best-performing algorithms did not produce any

significant correlations, with p-values of 0.45 and 0.11 for the red-near infrared band relationship versus chlorophyll-a and suspended sediment, respectively.

In Saguaro Lake, there are 19 data points of comparison between March 2017 and March 2018. Figure 20 illustrates the relationship between *in-situ* chlorophyll-a and the blue/green band ratio in Saguaro Lake ($R^2 = 0.43$). Figure 21 illustrates the relationship between *in-situ* suspended sediment concentration and the blue/green band ratio in Saguaro Lake ($R^2 = 0.56$). Both of these relationships are significant according to the Pearson correlation test ($p = 3.3 \times 10^{-4}$ and $p = 6.2 \times 10^{-6}$, respectively).

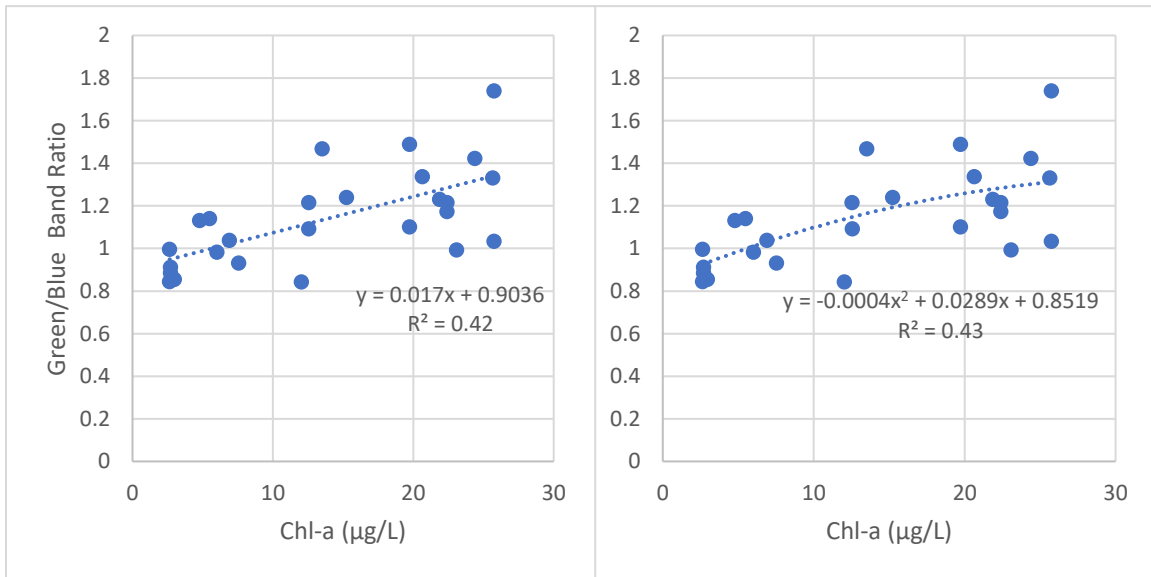


Figure 20. Correlation between the green/blue Landsat band ratio and *in-situ* chlorophyll-a concentration in Saguaro Lake. The graph on the left shows a linear fit and the graph on the right shows a second-order polynomial fit.

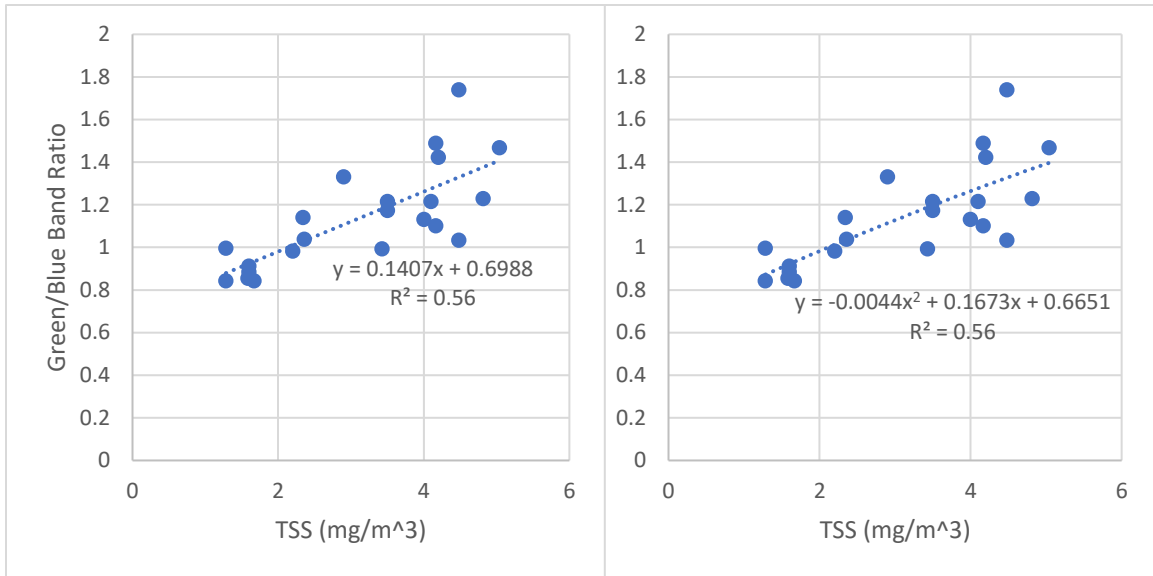


Figure 21. Correlation between the green/blue Landsat band ratio and *in-situ* suspended sediment concentration in Saguaro Lake. The graph on the left shows a linear fit and the graph on the right shows a second order polynomial fit.

ESTIMATES ACROSS STUDY PERIODS

The best performing algorithms were identified and applied to historical Landsat 7 data from January 2007 to December 2017. *In-situ* data from 2007-2009 and March 2017 to February 2018 were overlaid with these estimates (Figure 22-23). Due to the inferior performance of all the algorithms applied to Lake Pleasant data, no long-term estimates were generated for this site.

In Bartlett Lake, chlorophyll-a concentration estimates did not seem to show much of a seasonal pattern, with peaks occurring at different times of the year and to different magnitudes (Figure 22a). When comparing the estimated with the *in-situ* chlorophyll-a

concentration, it becomes apparent that the algorithm tended to over-estimate. The estimated suspended sediment concentration seemed to peak during the first half of the year, although the peaks were of varying magnitude (Figure 22b). The *in-situ* suspended sediment data matches the estimates reasonably well, with the most notable issue being some slight over-estimations.

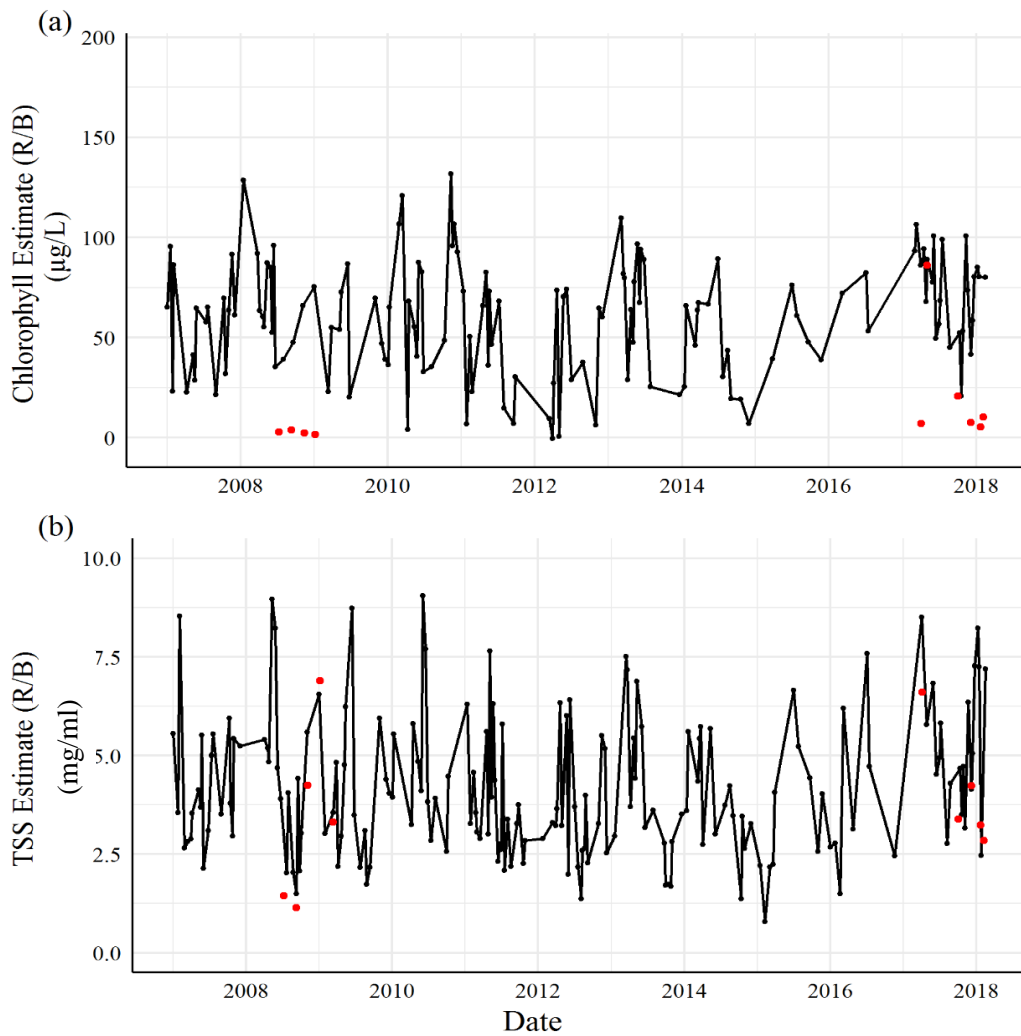


Figure 22. Estimates of chlorophyll-a and suspended sediment concentrations based on the red/blue Landsat band ratio in Bartlett Lake from 2007 to 2017. Reflectance data were derived from Landsat 7's sensors. *In-situ* data collected on the same day or plus or minus one day of the satellite overpass are overlaid in red.

In Saguaro Lake, chlorophyll-a concentration tended to peak during the summer months (Figure 23a). During 2009 and from 2013 to 2017, there is a decrease in the magnitude of the peaks in chlorophyll-a concentration. The estimated chlorophyll-a concentration is reasonably well-matched with the *in-situ* values, however there are some *in-situ* points, which were not captured in the estimates, notably the highest recorded *in-situ* chlorophyll-a value. The concentration of suspended sediment showed clear peaks in value during the summer in 2007, 2008, and 2009, with the peak of the greatest magnitude estimated in 2007 (Figure 23b). From 2009 onward, estimated peaks in suspended sediment did not appear to occur during a particular season, with some years having no obvious peak in magnitude. The *in-situ* suspended sediment concentrations were relatively well-matched with the estimated values.

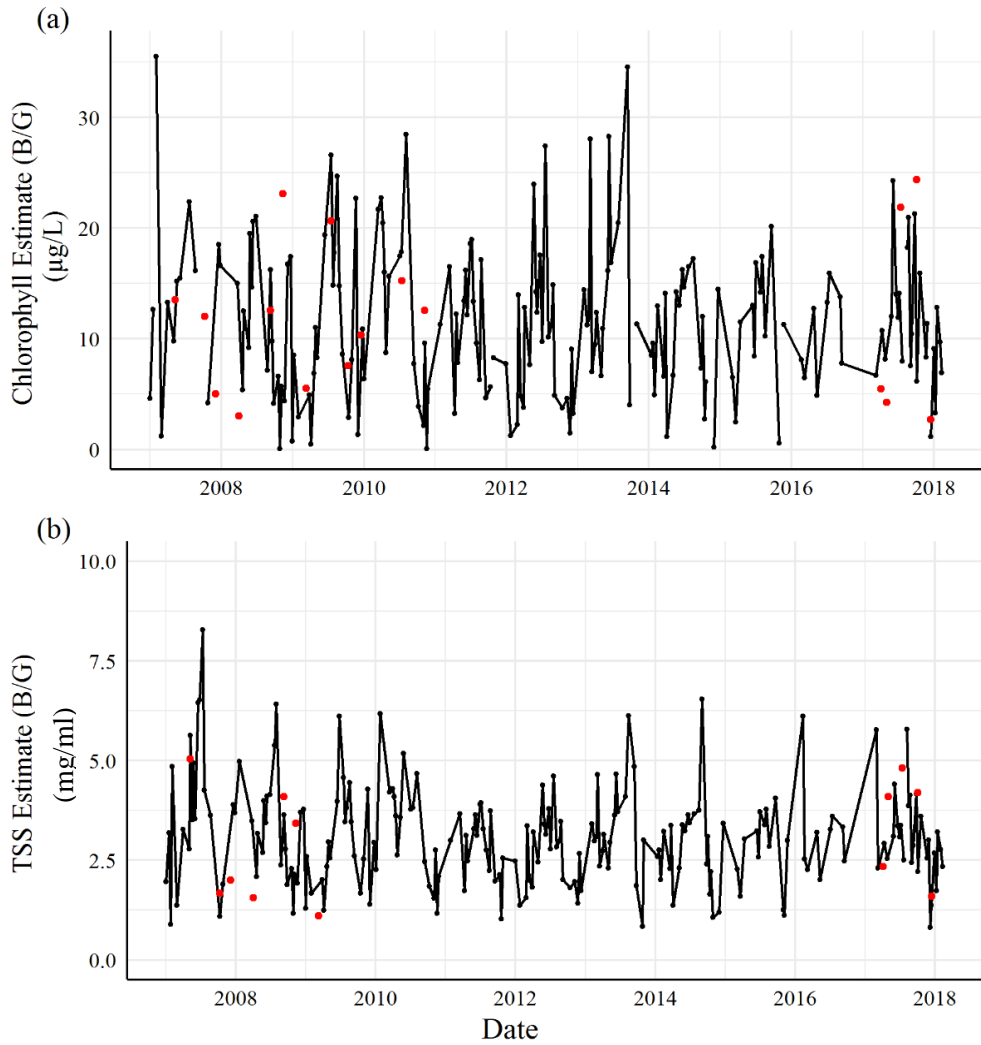


Figure 23. Estimates of chlorophyll-a and suspended sediment concentrations based on the blue/green Landsat band ratio in Saguaro Lake from 2007 to 2017. Reflectance data were derived from Landsat 7's sensors. *In-situ* data collected on the same day or plus or minus one day of the satellite overpass are overlaid in red.

DISCUSSION

I found that algal abundances tended to increase with warmer temperatures in all three reservoirs. Prymnesiophytes and filamentous cyanobacteria were generally the most abundant in the summer. During the cooler months, algal abundance was comparatively lower in all three lakes, and there was more even distribution of abundance across algae classes. I found that the algal communities in all three reservoirs were relatively stable, with one exception, that of the abundance of diatoms, which showed a marked increase in Lake Pleasant and Bartlett Lake.

When working with surface reflectance data, I found that two-band combinations were the best-estimators of chlorophyll-a concentration (as a proxy for algal biomass) and total suspended sediment concentration. The resulting empirical algorithms performed reasonably well to estimate *in-situ* parameters in Bartlett Lake and Saguaro Lake but did not perform well in Lake Pleasant.

TRENDS IN ALGAL ABUNDANCE

In Bartlett Lake during the 2017 to 2018 sampling period chlorophyll-a and suspended sediment peaked simultaneously. This could indicate that much of the suspended sediment was made up of algal cells. The peak in chlorophyll-a also coincided with a peak in filamentous cyanobacteria. However, this peak did not coincide with the highest

recorded surface temperature, which is interesting since filamentous cyanobacteria are known to thrive in warmer temperatures (Berger et al., 2007; Peeters et al., 2007; Paerl and Huisman, 2009).

One possible explanation for the abundance of filamentous cyanobacteria peaking independent of surface temperature is that the cells were concentrated by the draw-down of the lake during the summer months. Reduction of lake depth has been shown to increase the density of filamentous cyanobacteria in subtropical reservoirs (Yang et al., 2016). The peak in filamentous cyanobacteria was the largest recorded throughout the course of monitoring. This hypothesis is supported by SRP water-level data recorded at Bartlett Dam from June 12th, 2017 until present. Water levels were relatively low in June, with a water surface elevation recorded at 1788 feet above sea-level on June 15th. Water level then increased through July, peaking at 1796 feet above sea-level, and then slowly began to decrease again, not reaching levels that were similarly low to those in June until October 2017 (SRP 2018).

Diatom abundance also reached historically high levels in Bartlett Lake in 2017. Small pennate diatoms (8-16 μm in length) reached high levels in comparison with all previously recorded field sampling data. It is possible that previous diatom blooms occurred but simply were not captured by field sampling or that there were some changes

in environmental factors, which were conducive to higher diatom abundance, such as changes in temperature, rainfall, or nutrient availability.

However, it is also possible that the peak could be due to the introduction of a new species, which was not present during the time span of the earlier field sampling. There are many recorded cases of non-native diatoms being introduced in lakes. Mills et. al (1993) documented the introduction of 16 non-native species of diatoms into the great lakes. Often, upon the introduction of an invasive species, that organism will rapidly reproduce and reach relatively high abundances or “bloom”. It is possible that an invasive diatom has established itself in Bartlett Lake since the time of the last field study, and its rapid population growth immediately following introduction is responsible for the high abundance observed.

In Lake Pleasant, during the 2017-2018 study period, peaks in chlorophyll-a concentration did not tend to peak at the same time as the suspended sediment load. Relatively low algal biomass in Lake Pleasant may mean that it is not a significant contributor to the total suspended sediment. Chlorophyll-a concentration did, however, tend to be highest when surface-dissolved oxygen was high. It is possible that these high oxygen levels can be attributed, in part, to the photosynthetic algae responsible for the high chlorophyll-a levels.

Overall Lake Pleasant had the lowest algal abundance and the most even distribution of abundances across classes of algae. This low algal abundance has been demonstrated to be due to top-down control (Sawyer, 2011). The one exception being the high abundance of diatoms seen in August 2017. These diatoms were also small pennate diatoms (8-16 μm in length). Similarly, in Lake Pleasant this peak could be due to an introduced species, potentially the same species that may have been introduced to Bartlett Lake. It is well-documented that recreational boats can be vectors for non-native aquatic species (Hirsch et al., 2016) and that lakes located geographically close to one another are more likely to experience species transfer (Rahel, 2007).

In Saguaro Lake during the 2017 to 2018 sampling period, chlorophyll-a and suspended sediment also tended to peak together, though the association ($R^2 = 0.63$) was not as closely matched as in Bartlett Lake ($R^2 = 0.92$). Algal cells certainly contributed to total suspended sediment in Saguaro Lake, but were not the only significant contributor, causing some association but not a perfect match in peaks. One study conducted at Bafa Lake in Turkey, which has concentrations of chlorophyll-a similar to those found in Saguaro Lake, found a weak ($R^2 = 0.41$) but significant correlation between total suspended sediment and chlorophyll-a concentrations (Koçak et al., 2017).

Chlorophyll-a concentration generally correlated positively with temperature, with highest temperature coinciding with a peak in filamentous cyanobacteria biovolume,

which generally dominate in Saguaro Lake in terms of abundance and biovolume. Filamentous cyanobacteria are known to do well at high temperatures (Srifa et al., 2016, Huisman et al., 2018), so this co-occurrence of chlorophyll-a and high temperature is consistent with the algal community composition of Saguaro Lake. This trend is particularly interesting from a water quality standpoint because of the potential of filamentous cyanobacteria to produce taste and odor compounds, which are troublesome for water managers (Westerhoff et al., 2005; Izaguirre & Taylor, 2007; Yang et al., 2008). Chlorophyll-a concentration was observed to correlate with filamentous cyanobacteria biovolume reasonable well ($R^2 = 0.54$). Understanding that peaks in chlorophyll-a concentration that occur in the warmest part of the year are likely due to the high biovolume of filamentous cyanobacteria can be helpful in terms of monitoring. Measuring chlorophyll-a is simpler and faster than identifying species of algae. Chlorophyll-a can also be monitored using remotely-sensed data. In Saguaro Lake, an empirical algorithm was able to predict chlorophyll-a concentration from a two-band ratio reasonably well (r-square of 0.43). Thus, using the algorithm tailored to Saguaro Lake along with temperature data or with a consideration of the time of year, the occurrence of filamentous cyanobacteria blooms can likely be observed via remote sensing. Analysis Ready Data originating from Landsat 7 and Landsat 8's sensors are available for download 16 days after the image is taken, so the timeframe is reasonable to assess the severity and duration of blooms.

ALGORITHM PERFORMANCE

When *in-situ* data from all the lakes were grouped together and compared with various band combinations, the estimates were less closely correlated than when each lake's *in-situ* data were considered individually. This is likely due to the unique optical properties of each lake. Lake Pleasant is oligotrophic and the range of observed chlorophyll-a and TSS values are quite low in comparison with the other two lakes. On the other end of the spectrum, Bartlett Lake is quite eutrophic and has a high range of chlorophyll-a and suspended sediment values. Saguaro Lake fell somewhere in the middle. Likely due to these differences, certain band ratios such as blue/green performed well in one site, but poorly in another. Considering the sites separately allowed for the selection of band combinations that were better suited to their unique ranges of chlorophyll-a and suspended sediment. The drawback to this approach is the reduced sample sizes. However, the majority of comparisons still produced significant correlations.

The best performing band ratio in Bartlett Lake was red/blue. This makes sense for a eutrophic lake as the red bands perform better in waters with high algal biomass (Ali et al., 2014) than the blue or green bands alone. The algorithm, when applied to historical satellite data produced chlorophyll-a estimates, which were in the range of those observed during the study period. However, when comparing the estimates against *in-situ* data, it is apparent that this particular algorithm is over-estimating the chlorophyll-a concentration. It is possible that the algorithm's failure to capture these low *in-situ* chlorophyll-a values is due to the species composition in Bartlett Lake at the time of the

satellite observation. In the instances where the *in-situ* values fell well below the estimates, the algal abundance tended to be dominated by filamentous cyanobacteria. Due to the unique optical properties of filamentous cyanobacteria, namely the presence of accessory pigments like phycobilins with an absorption range of 520 to 670 nm (Seppälä et al., 2007), it is possible that the simple two-band red to blue ratio is over-estimating because of higher values in the yellow to red ranges when compared with the blue range.

It is well known that complex optical properties of productive lakes and coastal waters can prove challenging when it comes to accurately estimating chlorophyll-a concentration from remotely-sensed data (Yi, 2013). Suspended sediment concentrations matched the estimations much more closely, but the algorithm still over-estimated some values, although the discrepancy was smaller compared to chlorophyll-a. In these types of waters, it may be necessary to build much more complex analytical and semi-analytical algorithms specifically tailored to the site in order to increase the reliability of the estimations. In Bartlett, the simpler two-band ratio performed moderately well, but in the future it may be necessary to devote more resources to creating a more complex algorithm.

For Saguaro Lake, a lake with algal biomass that was comparatively lower than Bartlett Lake, the blue/green band ratio performed the best. This ratio tends to perform better in waters with lower CDOM and chlorophyll-a concentrations, becoming less effective as

these two values increase (Ali et al., 2013). Since Saguaro Lake showed much lower overall levels of chlorophyll-a and suspended sediment, it makes sense that this particular ratio performed better for that lake. The estimations of both chlorophyll-a and suspended sediment matched the *in-situ* values reasonably well, without a trend of either over or under-estimation.

Lake Pleasant was the most difficult site in which to identify an effective algorithm to estimate chlorophyll-a or suspended sediment. The near-infrared band minus the red band was ultimately the most effective at estimating chlorophyll-a and suspended sediment, but the correlations were not strong and ultimately not significant. This failure to produce accurate estimates from remotely-sensed data could be due to a plethora of issues, the most likely being that there was simply not enough *in-situ* data to build a reliable empirical algorithm.

All of the band combinations chosen for this study have also been applied to other water bodies, and with varying degrees of success (Hellerger et al., 2004; Tarrant & Neuer, 2009; Tarrant et al., 2010; Ali et al., 2014; Dogliotti et al., 2015; Ali et al., 2016; Ho et al., 2017). The nature of empirical algorithms is that they are dependent on the amount and quality of the *in-situ* data used to build them. Specific bands tend to perform better in certain conditions. For example, the red and near-infrared bands generally produce better results in water with high levels of colored organic dissolved matter, while the blue band

performs better in more oligotrophic waters (Ali et al., 2016). By considering the lakes individually, selecting the appropriate band combinations, and using equations of fit tailored to each site, I was able to build algorithms that produced reasonable estimates of chlorophyll-a concentration and suspended sediment in two out of the three reservoirs.

Previous studies have been able to achieve similarly satisfactory results in Arizona Reservoirs using reflectance data derived from MODIS and MERIS (Tarrant & Neuer, 2009; Tarrant et al., 2010). However, these sensors have a relatively coarse spatial resolution, and the bandwidths are slightly different than the Landsat sensors used in this study. Therefore, it is not feasible to simply apply the same algorithms to data produced by Landsat 7 and 8's sensors. Ultimately the band combinations (red and red minus near-infrared) used by Tarrant et al. (2009; 2010) were not the most effective estimators when applied to the Landsat reflectance data.

The best-performing band combination in Saguaro Lake, the green/ blue band ratio, was initially developed for ocean waters and was not specifically created for use with Landsat data. It generally performs best when chlorophyll-a concentrations are below 6 $\mu\text{g/L}$ (Ali et al., 2013). Although, chlorophyll-a concentration values did reach much higher levels in Saguaro Lake, they remained below 10 $\mu\text{g/L}$ for half of the time of the study.

The best-performing band combination in Bartlett Lake, the red/blue band ratio, was initially developed for use with the Landsat Thematic Mapper for monitoring turbid

inland lakes (Lathrop, 1992). Therefore, its good performance in Bartlett Lake, which is comparatively turbid, is not surprising.

In general, empirical algorithms using various band combinations are a powerful tool for use in this type of study. They are relatively simple, and easily tailored to specific sites. However, there are draw-backs to this approach. Many of the commonly-used band combinations were created using sensors with slightly different bandwidths and may not perform as well when used with data derived from Landsat sensors. This approach is also dependent on the quality and quantity of *in-situ* data available for a site. There are cases where they do not perform well, such as in Lake Pleasant. In such cases empirical approaches may act as a good starting point, but ultimately it may be necessary to collect more field data or to apply more complex semi-analytical and analytical algorithms.

INSIGHTS FROM ESTIMATES

The algorithms identified through comparisons with *in-situ* data were applied beyond the field sampling period to gain greater insight into how chlorophyll-a and suspended sediment have varied in the past. These estimates helped to illustrate long term trends and changes in the interim between field sampling periods. Algorithms were applied to Landsat 7 data from January 2007 to December 2017.

In Bartlett lake these estimates showed that values from the 2017 to 2018 study period fell within the historical ranges of chlorophyll-a and suspended sediment. Chlorophyll-a concentration peaks at irregular intervals, with some years having much higher peaks than others. Some years also have much more variation in the concentration of chlorophyll-a than others. This could be indicative of Bartlett Lake having less stability in terms of its algal community composition, with different groups dominating over different intervals and a less regular succession taking place. The suspended sediment seems to regularly peak in early to mid-year although the peaks are of different magnitudes. From 2010 to 2017, the peak suspended sediment values were comparatively lower. This may be due to lake draw-down concentrating sediment, more rainfall within the watershed carrying sediment into the lake, or perhaps more frequent dust storms depositing dust particles into the water.

In Saguaro Lake, chlorophyll-a and suspended sediment have sometimes co-occurring peaks, which was also seen in the field data collected from 2017 to 2018. The chlorophyll-a and suspended sediment concentrations again fall within the estimated historical range. The estimates show that in 2013, the chlorophyll-a concentration might have been unusually high, with the lake following years experiencing lower values. Chlorophyll-a concentrations show less regular peaks than suspended sediment, which like in Bartlett Lake, seems to peak from the beginning to middle of each year. Although chlorophyll-a concentration was much lower overall than in Bartlett Lake, suspended sediment was within the same range.

FUTURE DIRECTIONS

This research demonstrates the advantages of building algorithms tailored to individual lakes, especially when they range from oligotrophic to eutrophic and vary in volume and amount of draw-down. The main challenge to this method is validating the algorithms with *in-situ* data. In the future, additional field data could be invaluable in refining the algorithms, especially for Lake Pleasant, where simple band-combinations did not perform well. Additional *in-situ* data can also allow us to glean more information about the algal community structure in addition to overall ranges of chlorophyll-a and suspended sediment. Chlorophyll-a concentration is often used as a proxy for algal biomass. However, this measure does not account for accessory pigments, which will vary based on the overall algal community composition and will therefore be different in each lake's unique environment. Accessory pigments may change the color of a lake in a way that is not directly correlated to chlorophyll-a concentration, and therefore result in different lakes with the same chlorophyll-a concentrations having different reflectance values for a given band, based on the species of algae present.

These algorithms could also be applied to detect the early warning signs of noxious blooms, with consideration of the physical changes preceding a bloom, including impact of temperature and precipitation. These physical parameters in addition to the concentration of chlorophyll-a and suspended sediment and the timing of peaks in these values can be related to the severity and toxicity of blooms.

Finally, these algorithms could be applied on a much longer time scale to investigate any long-term trends. Landsat data are available going back decades and understanding changes in water bodies over longer timescales would allow managers to make inferences about the future and to plan accordingly.

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