Water quality and limnological monitoring of Skaneateles Lake, 2019

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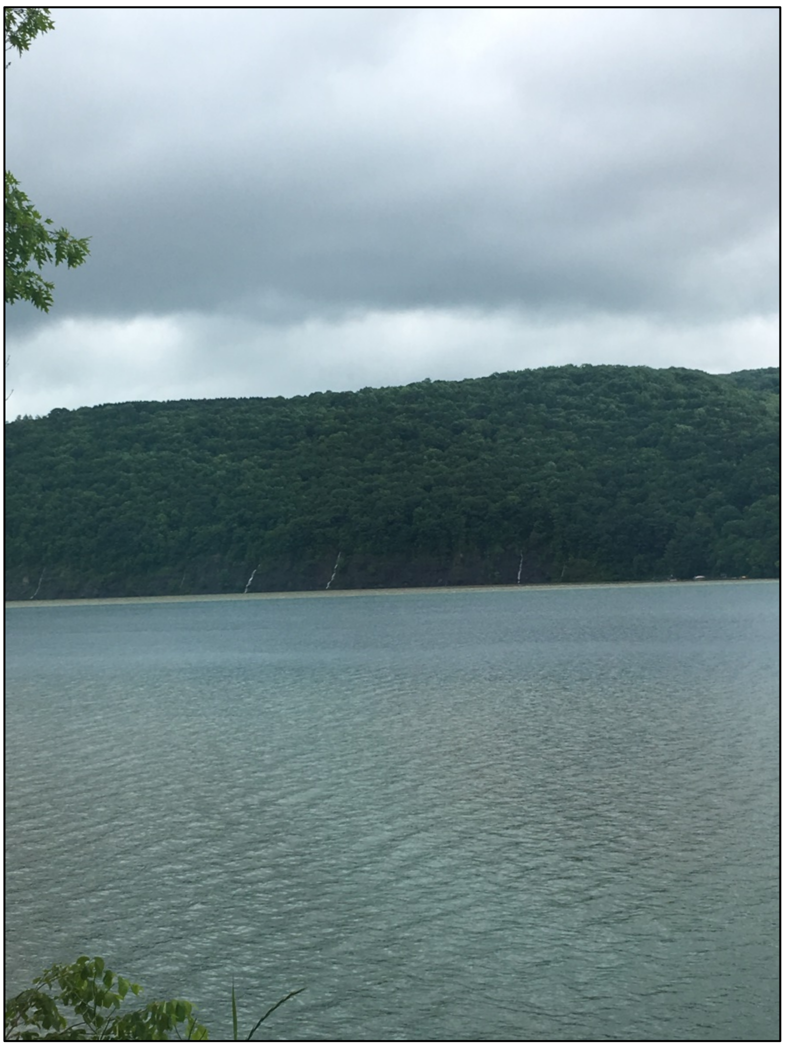
Cover image: Skaneateles Lake, June 19, 2019

Image below: Skaneateles Lake, June 20, 2019



Abstract

Skaneateles Lake is an important natural resource in Central New York; it supplies water to the city of Syracuse, supports recreational opportunities, and provides ecological value that benefits local businesses and property values. Due to its regional importance, continued monitoring and proper management are vital. On behalf of the Town of Skaneateles, water quality parameters and optical characteristics were monitored from June to October at the centrally-located, long-term monitoring site (TOS 2/Site 2) in 2019. All measurements of common metrics of trophic state (total phosphorus, chlorophyll *a*, Secchi disk) were supportive that the lake remains oligotrophic. In addition to the common trophic indicators, measurements of phosphorus fractions (total dissolved phosphorus and soluble reactive phosphorus), particulate organic carbon, and algal community composition were taken at various depths of the water column. Concentrations of the various phosphorus fractions were generally low at all depths, suggesting that phosphorus release from the sediments is not a major source of phosphorus to the water column of Skaneateles Lake. According to FluoroProbe measurements, the algal community in the pelagic zone was dominated by green algae (chlorophytes) and diatoms (bacillariophytes); however, cyanobacteria were present at low concentrations in September. Microcystin concentrations were measured in September and October; all results were less than the reporting limit for the test and well below guidance values related to potential health effects. The information gained through this program will be beneficial to the development of a nine element watershed plan and water quality model.

1. Introduction

1.1. Lake characteristics

Skaneateles Lake is located in central New York within Onondaga, Cortland, and Cayuga counties (Figure 1a); this area is known as the “Finger Lakes” region due to the presence of eleven long, narrow lakes formed by a receding glacier. The lake is the second most easternmost Finger Lake (Figure 1b) and approximately 19 km south-southwest of Syracuse, NY and 8 km east of Auburn, NY. The lake is oriented along a north/northwest and south/southeast axis, and the Village of Skaneateles lies at the northern end of the lake, at the outflow. Of the eleven Finger Lakes, Skaneateles Lake is the third deepest (maximum = 90.5 m, mean = 43.5 m), has the fourth largest volume (1563×10^6 m^3), and has the fifth smallest surface area (35.9 km^2; Schaffner and Oglesby 1978). Exact lake volume estimates vary by researcher and institution (e.g., Schaffner and Oglesby 1978, Figure 2c). More than 80% of the volume of the lake is associated with depths greater than 10 m (Figure 2).

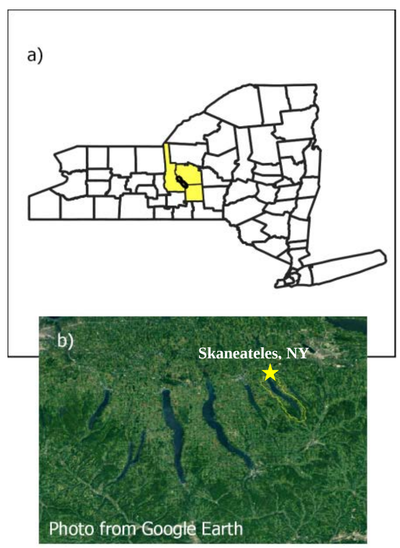


Figure 1. Skaneateles Lake and watershed location within (a) New York, and (b) Finger Lakes region.

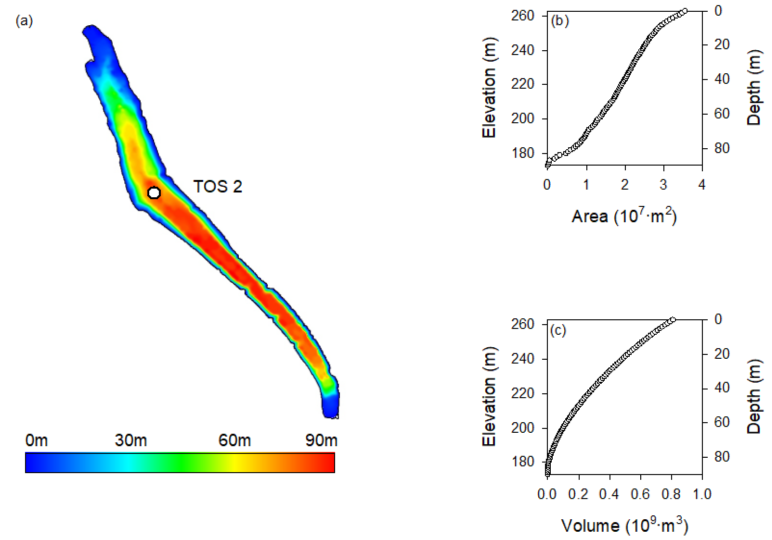


Figure 2. Skaneateles Lake morphometry: (a) bathymetric map with long term sampling location, (b) contour area as a function of elevation and depth, and (c) volume as a function of elevation and depth. Based on bathymetric data collected by Scholz and others from Syracuse University.

1.2. Watershed characteristics

Relative to size of the lake, Skaneateles has a small watershed (154 km^2) and the lowest watershed to lake surface area ratio of the Finger Lakes (4.3). As others have noted, the small watershed limits the amount nutrient inputs that would affect the trophic state and water quality of Skaneateles Lake (Oglesby and Schaffner 1978, Perkins et al. 2009). The watershed is primarily agriculture lands (36 %) and forested (34%) with very little residential and commercial development (Table 1; Figure 3). The lake has a long hydraulic retention time, meaning the water flushes from the basin relatively slowly. On a completely mixed basis, it flushes once every 18 years, the second slowest of the Finger Lakes (Schaffner and Oglesby 1978). There is no primary inlet, but many small tributaries provide hydrologic inputs. A single natural outflow, Skaneateles Creek, is located at the northern end of the lake.

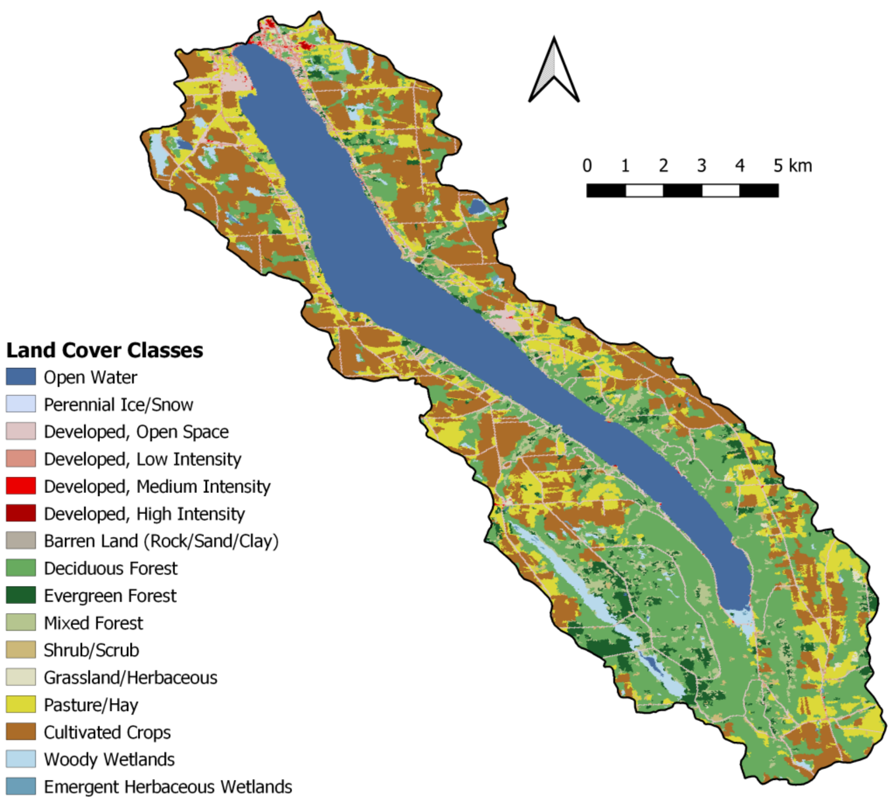


Figure 3. Skaneateles Lake watershed landcover (NLCD 2016, StreamStats 2019).

Table 1. Skaneateles watershed landcover from greatest to least area (NLCD 2016, StreamStats 2019).

Land cover class	Area (km^2)	Percentage
Deciduous Forest	50.16	26.6
Cultivated Crops	43.82	23.2
Open Water	36.12	19.2
Pasture/Hay	24.24	12.9
Developed, Open Space	9.92	5.3
Evergreen Forest	7.09	3.8
Mixed Forest	6.22	3.3
Woody Wetlands	4.99	2.6
Shrub/Scrub	2.77	1.5
Developed, Low Intensity	1.88	1.0
Grassland/Herbaceous	0.72	< 1
Emergent Herbaceous Wetlands	0.35	< 1
Developed, Medium Intensity	0.22	< 1
Developed, High Intensity	0.08	< 1
Barren Land (Rock/Sand/Clay)	0.02	< 1
Perennial Ice/Snow	0.00	< 1

1.3. Lake use, condition, and management

Skaneateles Lake is classified by New York State as an AA waterbody; with the highest rating, water from the lake can be used for potable purposes and, therefore, must meet certain water quality regulations set by the New York State Department of Health (NYSDOH). The City of Syracuse uses the lake as its primary source of water, and maintains an active watershed management program (i.e. Skaneateles Lake Watershed Agricultural Program) in order to protect water quality. Two intakes located in the northern end of the lake, approximately 1.3 and 2 km south of the Village of Skaneateles, withdraw the drinking water. Low turbidity levels allow the city to not filter the water withdrawn from the lake (i.e. filtration avoidance).

Along with being used as a source of drinking water, Skaneateles Lake provides opportunities for a wide range of recreational activities. The aesthetic quality of the lake attracts tourism to the area, benefiting businesses within the Town and Village of Skaneateles. Locals and tourists alike enjoy swimming, boating, and diving during the summer. Additionally, angling is very popular because of the presence of warm-, cool-, and cold-water fisheries. The New York State Department of Environmental Conservation (NYSDEC) maintains an active fish stocking program, stocking 20,000 rainbow trout (*Oncorhynchus mykiss*) and 9,000 Atlantic salmon (*Salmo salar*) annually (NYSDEC 2019a). The Skaneateles Lake Association (SLA) has contributed to the management of Skaneateles by initiating the invasive species prevention and Eurasian watermilfoil (*Myriophyllum spicatum*) control programs (SLA 2018a,b).

Although Skaneateles Lake is known for its naturally pristine water, active management efforts are necessary to protect water quality. Harmful algal blooms (HABs) occurred in the lake during the early fall of 2017 and in 2018, HABs were reported for five weeks between August 10th and October 5th (NYSDEC 2019b). Harmful algal blooms often form noxious surface scums and may contain toxin-producing cyanobacteria that can affect the health of people, pets, and aquatic animals. Not all cells within a bloom produce toxins, nor are toxins constantly produced; however, caution should always be exhibited when coming into contact with a potential HAB. Although toxins (i.e. microcystin) were detected in Skaneateles Lake, the toxins were not detected in public water supplies. Algal blooms are often influenced by nutrient (phosphorus and nitrogen) availability, warm temperatures, and quiescent conditions. The lake has not been treated with copper sulfate, a commonly used algicide for control of taste and odor causing algae, since 1972. In 2017, the NYSDEC developed a Harmful Algal Bloom Action Plan for Skaneateles Lake. This document outlined current conditions, sources of pollutants triggering HABs, future projects to manage water quality and reduce HABs in the lake, and monitoring recommendations (NYSDEC 2017). An estimated 80% of nonpoint source phosphorus loading is attributed to agricultural land within the watershed, but more information is needed. The development of a nine-element (9E) watershed plan, which outlines sources of nonpoint source pollution and best management practices to meet water quality goals, is expected to occur in the near future.

1.4. Previous studies

Due to the importance of Skaneateles Lake as a natural resource, it has been studied and monitored for decades by various agencies, organizations, and individuals including the NYSDEC and Citizens Statewide Lake Assessment Program (CSLAP), Finger Lakes Institute (FLI), and Upstate Freshwater Institute (UFI; Table A.1.). In addition, the City of Syracuse and Onondaga County Water District monitor several standard drinking water parameters (i.e. bacteria, turbidity, organic and inorganic chemicals).

Upstate Freshwater Institute has been monitoring Skaneateles for many years, dating back to the 1980s. More recently, UFI monitored water quality parameters on behalf of the Town of Skaneateles frequently between 2004 and 2008, then has been monitoring on a three-year cycle since 2011. The latest monitoring report was completed in 2017 (UFI 2017). During the 2017 study, two sites were monitored and water quality parameters examined included: nutrient concentrations (i.e. phosphorus and nitrogenous compounds), vertical profiles of physical and chemical parameters (i.e. temperature and dissolved oxygen), and vertical profiles of phytoplankton community composition. Two sites were monitored in 2017, one near the water intakes at the north end of the lake and the other a main lake site that has been used as a long term monitoring location. The lake was deemed as oligotrophic, and water quality conditions were similar to those in 2014. Despite the nutrient-poor trophic status, 2017 had the highest average total phosphorus (TP) concentrations, chlorophyll *a* (Chl-*a*) concentrations, and Secchi depth (measured in meters) values since the early 1970s (Table A.1.). The phytoplankton community differed between sites 1 (near the intakes) and 2 (long term monitoring site). The contribution of cyanobacteria to the overall Chl-*a* concentration was low at site 2 but increased at site 1 and near shore. Several recommendations regarding future monitoring efforts were made to support effective management and protection of this natural resource.

1.5. Objectives

The goal of the 2019 monitoring program was to collect limnological information that will support management considerations for Skaneateles Lake.

Specific objectives of this study include:

1) Report current limnological conditions and trophic state.
2) Add to the record of data and compare selected metrics of water quality to current conditions.
3) Collect data to support future development of 9E management plan and water quality model, which will guide management efforts to maintain pristine condition of the lake.

2. Methods

Data were collected approximately monthly from mid-June to early-October 2019 (n = 6) at the site that has been used as the long-term monitoring site, known as TOS2 or Site 2 in previous studies and reports (Figure 2a). This location is considered representative of the pelagic conditions in Skaneateles Lake per previous monitoring efforts (UFI 2017).

2.1. Field measurements

On each sampling date, the following field data were collected: Secchi depth and vertical profiles of temperature, specific conductance, chlorophyll *a*, dissolved oxygen, pH, turbidity, and optical properties (Table 2). Profiles were obtained utilizing two profiling instruments, a YSI Series 6600 multi-probe datasonde (YSI 2011) and a SeaBird rapid profiling instrument (SeaBird Electronics Model 25-03). Measurements from the YSI sonde were recorded at 1 m intervals from the surface to 20 m depth and at 10 m intervals between 30 and 60 m. The SeaBird is a rapid profiling instrument that has several sensors that measure multiple parameters simultaneously from the surface to the bottom (75 m). On 19 June 2019, a 50 m profile was completed with the SeaBird due to the short length of cable used. See Table 2 for instrument resolution and data use. See appendix (Table A.2.) for instrument specification and range of detection.

Table 2. Field measurements, instruments, and depth resolution used for 2019 Skaneateles Lake monitoring.

Parameter	Vertical Resolution (m)	Instrument
Temperature (T)	0.25	profiles with SeaBird[a]
Specific Conductance (SC)	0.25	profiles with SeaBird[a]
Chlorophyll *a* (Chl-*a*)	0.25	profiles with SeaBird[a]
Dissolved oxygen (DO)	as necessary to depict structure[b]	YSI 6600 with datalogger
pH	as necessary to depict structure[b]	YSI 6600 with datalogger
Secchi depth	0.10	black and white quadrant disk
Turbidity (Tn)	0.25	profiles with SeaBird[a]
c_{660}[c]	0.25	profiles with SeaBird[a]
k_d[d]	0.25	profiles of PAR with SeaBird[a]

(a) SeaBird is a rapid profiling instrument package with several sensors on a common frame used to measure multiple water quality parameters simultaneously; (b) 1 m depth intervals from 0 to 20 m and 10 m depth intervals from 30 to 60 m; (c) $\mathbf{c}_{660}$ is the beam attenuation coefficient at a wavelength of 660 nm; a more sensitive measure of turbidity; (d) k_d is the attenuation coefficient for PAR; a fundamental delimiter of the depth range of photosynthesis; will be calculated (Beer's Law) from downwelling irradiance profile.

2.2. Laboratory measurements

On each sampling date, water samples were collected at multiple depths and analyzed for multiple analytes including: total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), chlorophyll *a* (Chl-*a*), and particulate organic carbon (POC). See Table 3 for specification of laboratory analytical methods. From the measured TP, TDP, and SRP concentrations (that were above detection limits), particulate phosphorus (PP) and dissolved organic phosphorus (DOP) were derived. The algal community was assessed via a FluoroProbe (bbe Moldaenke 2017). This instrument is designed to distinguish various algal groups including: “green” algae (Chlorophyta and Euglenophyta), “brown” algae (Bacillariophytoa, Chrsophyta, and Dinophyta), “bluegreen” algae (Cyanophyta), and “red” algae (Cryptophyta). The summation of the four groups provides an overall total measure of chlorophyll-*a*, and can indicate the dominant algal group. See Table 4 for the complete list of analyses performed at select depths. See appendix (Table A.2.) for FluoroProbe instrument specification and range of detection.

Table 3. Laboratory analytical methods used for 2019 Skaneateles Lake monitoring. "SM" refers to Standard Methods (Rice et al. 2012).

Analysis	**Method No.**
Phosphorus, Orthophosphate (Soluble Reactive Phosphorus as P; SRP)	SM 4500-P G -2011
Phosphorus, Total, Total Dissolved (as P; TP, TDP) low range	SM 4500-P F-H -2011
Particulate organic carbon (as C; POC)	SM 5310 B -2011
Chlorophyll *a* (Chl-*a*) (fluorometric)	EPA 445.0 (USEPA 1997)
Algal toxins, Cyanotoxin automated assay system (CAAS)	EPA 701 (EPA 2015)
Algal classification, FluoroProbe	bbe Moldaenke 2017

Table 4. Specification of analytes analyzed at depth of collection during 2019 Skaneateles Lake monitoring.

Depth (m)	**TP**	**TDP**	**SRP**	**Chl *a***	**POC**	**FluoroProbe**[(a)]
0[(b,c)]	X	X	X	X	X	X
9[(c,d)]						X
20	X	X	X	X	X	
50			X			
75[(e)]	X	X	X			

(a) in addition to the FluoroProbe, microcystins were analyzed on 2 of last 3 sampling dates; (b) samples were collected just below the surface; (c) quality control samples were taken at 0 m. FluoroProbe quality control samples were taken at 9 m on 9/9 and 10/1; (d) FluoroProbe analyses at 9 m began on 9/9; (e) samples were collected approximately 1 m off the lake bottom.

2.3. Trophic State Index (TSI)

The Trophic State Index (TSI) was developed by Carlson (1977) as a quantifiable method to understand trophic state. Trophic state index values between 0 and 100 are calculated using 1 or more of the three most common trophic indicators (TP, SD, and Chl *a*; Table 5). Typically, eutrophic waterbodies have TSI values greater than 50, whereas TSI values of oligotrophic waterbodies are less than 40. (Carlson 1977, Carlson 1991) This index allows changes in trophic state, as a result of anthropogenic changes or management efforts within the watershed or waterbody, to be evaluated over time.

Table 5. Trophic State Index (TSI) can be calculated using three water quality parameters. Values ranges are associated with trophic state classifications (Carlson 1977).

Water quality parameter	TSI equation	Classification and Common Parameter Ranges	
Chlorophyll *a* (Chl-*a*; µg/L)	$TSI\ (\mathrm{Chl}a) = 9.81 \times \ln \mathrm{Chl}a\ + 30.6$	Oligotrophic:	< 2.6 µg/L
		Mesotrophic:	2.6 – 7.3 µg/L
		Eutrophic:	> 7.3 µg/L
Total phosphorus (TP; µg/L)	$TSI\ (TP) = 14.42 \times \ln TP\ + 4.15$	Oligotrophic:	< 12 µg/L
		Mesotrophic:	12 – 24 µg/L
		Eutrophic:	> 24 µg/L
Secchi depth (SD; m)	$TSI\ (SD) = 60 - 14.41 \times\ \ln SD$	Oligotrophic:	> 4 m
		Mesotrophic:	4 – 2 m
		Eutrophic:	< 2 m

3. Results and Discussion

3.1. Thermal stratification

3.1.1. Background

Thermal stratification, or the layering of the water column according to temperature, is commonly observed in north temperate lakes and reservoirs. Basin morphometry (Ford and Stefan 1980), hydrology, lake discharge, the extent of light penetration (Stefan and Ford 1975, Effler and Owens 1985, Harleman 1982), and meteorological conditions (Effler et al. 1986) can influence the features of thermal stratification including: the onset of stratification and "turnover", vertical dimensions of layers, and temperature of the individual layers. Waterbodies can be classified based on the number of times thermal stratification is broken (i.e. dimictic, monomictic, polymictic). Although waterbodies may be considered to have certain thermal regimes, various features of stratification differ from year-to-year because of the sensitivity of thermal stratification to environmental conditions (Effler et al. 1986). Thermal stratification is often manifested as a warm, well-mixed layer (the epilimnion) separated from a cold, more dense, and deep layer (the hypolimnion) by a narrow layer with a steep temperature change (the metalimnion). The density gradient of the metalimnion limits vertical exchange between the epilimnion and the hypolimnion during the stratification period, which promotes vertical differences in various constituents pertinent to limnology and water quality (Wetzel 2001).

Thermal stratification greatly influences the biological and chemical conditions of a waterbody. The layers can limit the presence and metabolic rates of various organisms due to individuals' thermal, dissolved oxygen, or nutrient requirements (Chapra 1997). The epilimnion is often where most primary production occurs due to ample sunlight and temperatures optimal for plant and algal growth (Davies et al. 2009). Under stratified conditions, the hypolimnion (bottom layer) can become partially or fully anoxic, depending on the dimensions of the layer and amount of primary productivity in the upper waters. Anoxic conditions can trigger chemical reactions that release nutrients from the sediments and contribute to nutrient loading (See sections 3.2. and 3.3.). Vertical mixing within and between stratified drives the cycling of materials, such as phosphorus, throughout the water column (Powell and Jassby 1974, Effler and Field 1983).

Specific conductance (SC) is an aggregate measure of ionic content; for example, higher SC values are observed where concentrations of primary ionic species (i.e. Ca^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3) are higher. These ionic species can originate from minerals that are naturally and unnaturally found within the watershed, as well as from decomposition of organic materials within the basin (Wetzel 2001). Some ions are biochemically "conservative" whereas others are more "dynamic". Concentrations of conservative ions (e.g., Cl^{-}, Na^{+}, K^{+}) tend to experience small fluctuations throughout the year due to being used biotically. The concentrations of dynamic ions are strongly influenced by limnological conditions and metabolic processes within waterbodies (Wetzel 2001). For example, in alkaline, hardwater systems, calcium carbonate ($CaCO_3$) can precipitate out of solution and attach to picoplankton to form small crystals, referred to as "whiting events" (Kalff 2002). Whiting events cause increased SC in the hypolimnion and decreased SC in the epilimnion (Wetzel 2001).

3.1.2. 2019 results

Distinct thermal stratification was evident during the 2019 monitoring period (Figure 4). Weak thermal stratification was observed by mid-June, with temperatures of 15 °C at the surface and < 10 °C at depths below 30 m (Figure 4a). Strong but shallow (epilimnion depth of ~ 10 m) stratification was developed by early July (Figure 4b). From July to the beginning of October, well-defined vertical layers were present. A progressive increase in the thickness of the epilimnion (from 10 to nearly 20 m) and sharpening of the vertical temperature gradients of the metalimnion were observed after the onset of strong stratification in early July (Figure 4b-f). Skaneateles Lake is a monomictic lake, meaning that it only experiences one mixing or turnover event annually (autumn-spring) and is thermally stratified during one portion of the year (spring-autumn). Other regional lakes such as Otisco Lake are dimictic, with thermally stratified layers during the open water season (summer) and under ice cover (winter). During the winter, Skaneateles Lake rarely has complete ice cover, therefore it experiences one, prolonged mixing event throughout the cold season. This mixing regime influences the way that materials are utilized in Skaneateles Lake throughout the year.

Specific conductance remained between 280 and 290 µS/cm at all depths over the monitoring period (Figure 4). Between June and the beginning of July (Figures 4a,b), specific conductance was relatively uniform from the surface to the bottom of the depth profiles. By the end of July and onward, specific conductance within the epilimnion decreased (Figure 4c-f). This observation in the upper waters is commonly attributed to the loss of Ca^{2+} and HCO_3^- from seasonal precipitation of $CaCO_3$ or "whiting" (Wetzel 2001). Specific conductance within the hypolimnion was relatively constant, and only slightly increased towards the end of the monitoring period.

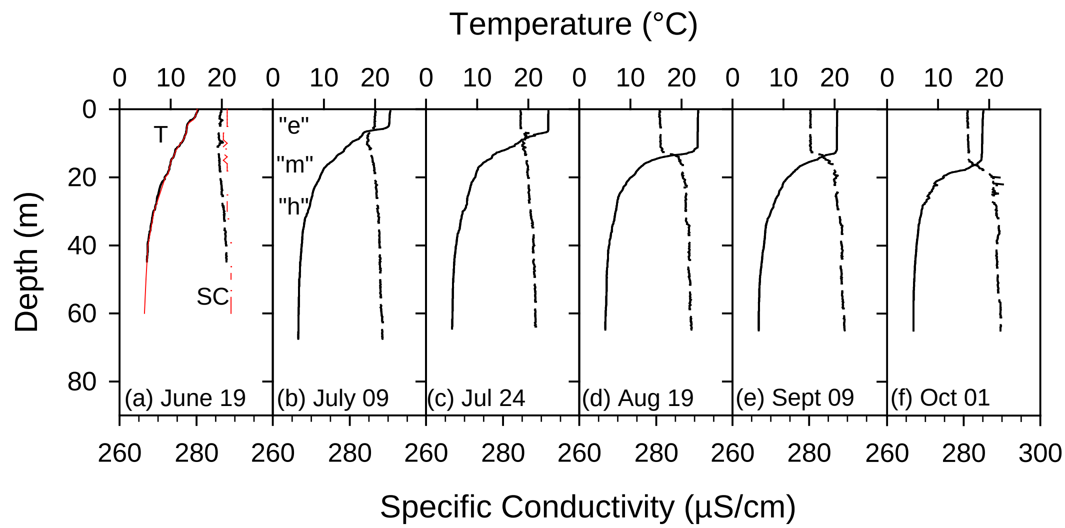


Figure 4. Vertical profiles of temperature (°C, solid line) and specific conductance (µS/cm, dashed line) during 2019 at TOS 2 site: (a) June 19, (b) July 9, (c) July 24, (d) August 19, (e) September 9, (f) October 1. Profiles made using SeaBird; profile on June 19th supplemented with YSI measurements shown with red line.

3.1.3. Comparison to previous studies

Even though the features of thermal stratification may appear to be the same from year to year, there are slight inter-annual differences that can show how the lake and the watershed are changing over time. In 2017, the onset of stratification was in early June, and temperatures in both the epilimnion and at 30 m (the hypolimnion) were similar to those observed in 2019 (Figure 5a,b). The depth of the epilimnion has remained in the 10-20 m range since the 2000s (Effler et al. 2007).

The specific conductance of the epilimnion and hypolimnion were both higher in 2019 than in past years (Figure 5c,d). Although the trend of decreasing specific conductance within the epilimnion over the summer months is in keeping with previous years, the overall measurements were slightly higher (at least 5 µS/cm) in 2019 (Figure 5c). Similarly, in the hypolimnion the specific conductance was at least 3 µS/cm higher during 2019 than it was in 2017 (Figure 5d). Inter-annual differences are to be expected, but it is important to note these differences in case a systematic increasing trend emerges in the future. Many regional surface waters are experiencing increased salinization (increase of total dissolved solids) that could alter the aquatic ecosystem and nutrient cycling due to anthropogenic activities (Kaushal et al. 2017). Natural tributary inputs, whiting events, winter road salt usage, precipitation, and land-use changes can influence the SC within these two layers (Kaushal et al. 2017, 2018).

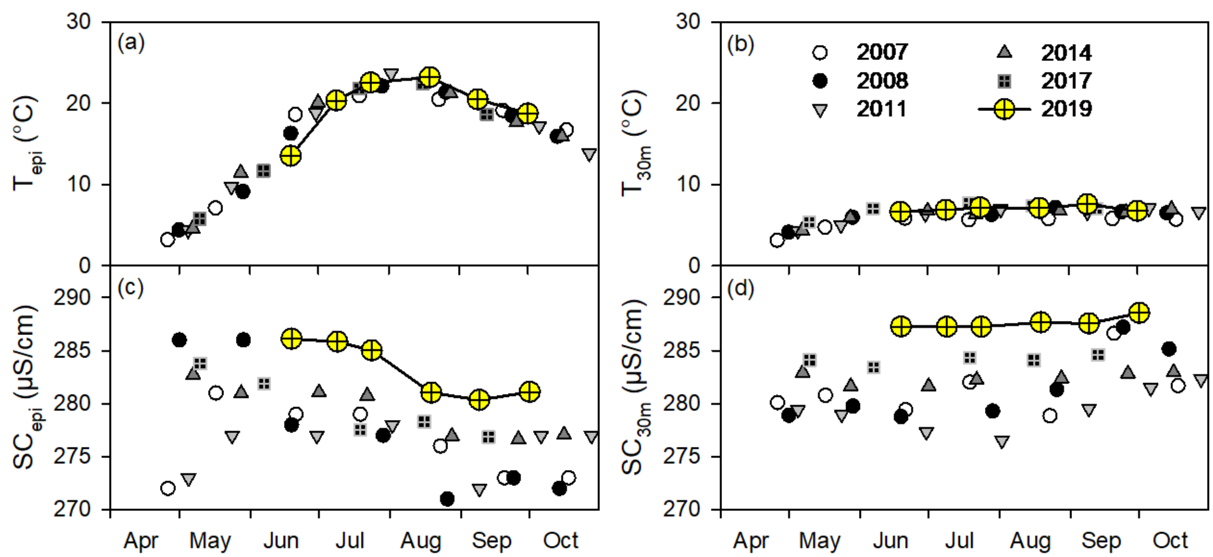


Figure 5. Time series plots of previous studies (2007, 2008, 2011, 2014, and 2017) and 2019 study for TOS 2/Site 2: (a) epilimnetic (0-10 m) temperature (°C), (b) hypolimnetic (30 m) temperature, (c) epilimnetic specific conductance (µS/cm), (d) hypolimnetic specific conductance.

3.2. Dissolved oxygen

3.2.1. Background

Dissolved oxygen (DO) is an important limnological characteristic that influences chemical processes and biological systems. Dissolved oxygen within the water column is introduced via atmospheric conditions (i.e. wind turbulence) and as a byproduct of photosynthesis. The DO within the water column is used by organisms for respiration and the decomposition of organic materials. Under thermal stratification, there is little vertical mixing (See Section 3.1.1), and the hypolimnion is isolated from sources of DO. The rate of DO depletion in the hypolimnion is dependent on utilization by organisms, temperature of the water column, and the dimensions of thermal stratification (Wetzel 2001). Areas of the hypolimnion can eventually become low in oxygen (hypoxic) or without any oxygen (anoxic) if the rate of DO depletion is high or prolonged. Under these conditions, redox reactions at the sediment-water interface can potentially release nutrients that were bound to the sediments into the hypolimnion, which can then be transported throughout the water column upon turnover.

Because of this relationship between hypolimnetic anoxia and nutrient release from the sediments, the rate of DO depletion in the hypolimnion has been connected to primary production (Hutchinson 1938, Mortimer 1941). Hypolimnetic DO and the areal hypolimnetic oxygen deficit (AHOD) are important to monitor when assessing trophic state. Additionally, Skaneateles Lake supports cold water fisheries, or fish species that require low temperatures; typically these fish have high DO requirements and must reside within the hypolimnion due to thermal constraints.

3.2.2. 2019 results

Dissolved oxygen is more soluble in cold water, which can lead to high concentrations of DO within the hypolimnion and lowered DO concentrations in the epilimnion throughout summer stratification (Figure 6b-e). This pattern is described as “orthograde”, and is a common characteristic of oligotrophic lakes (Wetzel 2001). There was a slow, progressive depletion of DO within the hypolimnion due to metabolic and decompositional processes between the end of July and October (Figure6c-f). Dissolved oxygen concentrations within the hypolimnion most likely continued to decrease until turnover occurred; however, the rate of DO depletion was insufficient to result in hypoxic or anoxic conditions. The estimated AHOD was low in 2019 (-311 $mg/m^2/d$), and was similar to rates calculated in previous years (-456 to -241 $mg/m^2/d$; Effler et al. 2008, 2009, 2015; UFI 2017). During the monitoring period, pH values of the water column ranged between 7.4 and 9.6; hardwater lakes, such as Skaneateles Lake, commonly are more alkaline than softwater lakes due to the presence of carbonates and bicarbonates (Wetzel 2001). The pH values were mostly consistent with those observed during previous studies, but some of the deeper measurements were higher than previously observed (Figure 6a,b,d). It is unclear whether these higher values are real or due to a pH probe malfunction.

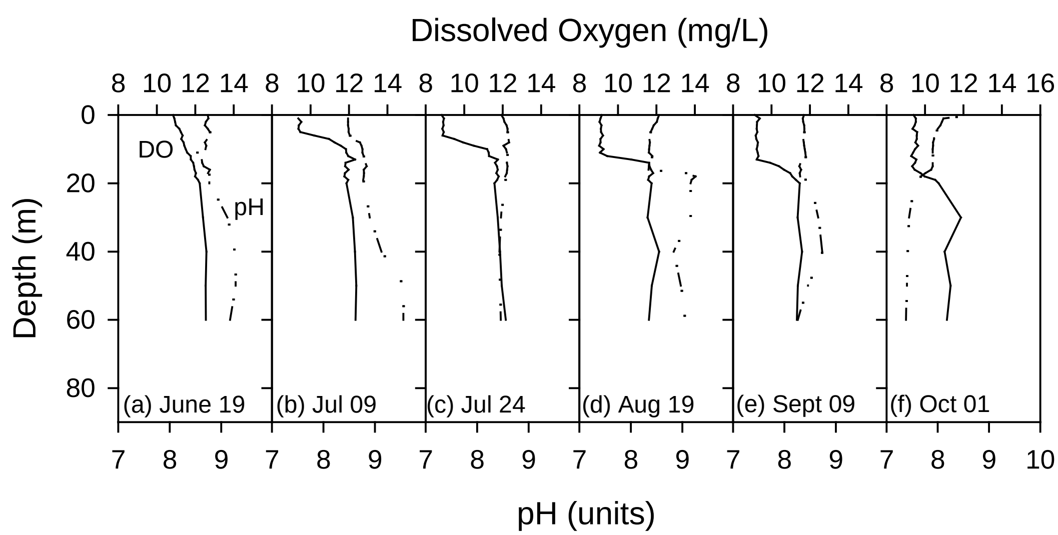


Figure 6. Vertical profiles of dissolved oxygen (mg/L, solid line) and pH (dashed line) during 2019 at TOS 2 site: (a) June 19, (b) July 9, (c) July 24, (d) August 19, (e) September 9, (f) October 1. Profiles made using YSI measurements.

3.2.3. Comparison to previous studies

Average epilimnetic (0-10 m) DO concentrations were slightly greater from June to July than concentrations observed during these months in previous studies (Figure 7a). Concentrations decreased from June (11.2 mg/L) to August (9.1 mg/L), and then slightly increased until the end of the monitoring period, mirroring water temperature. Dissolved oxygen was slightly oversaturated (100 – 115%) in the upper waters throughout the monitoring period, indicating substantial amounts of photosynthetic activity. Hypolimnetic DO concentrations remained relatively constant throughout the monitoring period, and were similar to concentrations observed in previous years (Figure 7b). Seasonal epilimnetic and hypolimnetic DO patterns in 2019 were consistent with trends observed in previous years.

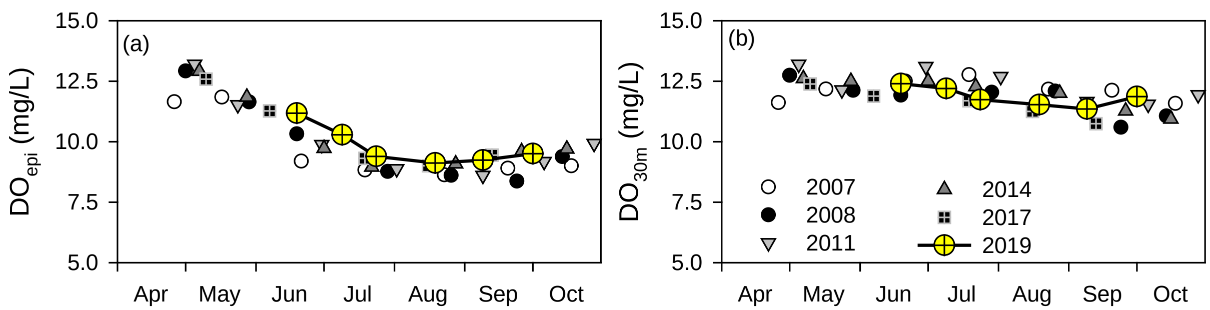


Figure 7. Time series plots of previous studies (2007, 2008, 2011, 2014, and 2019) and 2019 study for TOS 2/Site 2: (a) epilimnetic (0-10 m) dissolved oxygen (DO; mg/L), (b) hypolimnetic (30 m) dissolved oxygen.

3.3. Water quality

3.3.1. Background

Often from a stakeholder standpoint, water quality can be considered "good", "bad", or "healthy"; these terms are subjective based on how the stakeholder wishes to use the waterbody (e.g. Canter et al. 1992, Smith et al. 1995). Water quality from a scientific or natural resources management perspective, on the other hand, is the combination of chemical and biological properties of a waterbody that direct proper usage of the resource. Skaneateles Lake is used as a public water supply, so it is important to monitor the various aspects of water quality to in order to know how to best maintain drinking water standards.

One main component of water quality is the amount of primary productivity, which is typically quantified by measuring the photosynthetic pigment chlorophyll a (Chl-*a*). Masses of phytoplankton can accumulate to form "blooms", and alter limnological characteristics within a waterbody. The phytoplankton community is comprised of several taxonomic groups with varying characteristics including chlorophyll content, toxin production, and physical forms. One such group that is a concern to human health is "blue green algae" or cyanobacteria. Members of this group are actually photosynthesizing bacteria, and are capable of producing toxins and forming HABs. Although cyanobacterial toxin production is not completely understood, high temperatures, calm water, and excess nutrient availability have been correlated to HABs. Reducing the frequency of HABs and limiting primary productivity are usually top management priorities.

Phytoplankton stocks are influenced by the availability of dissolved nutrients (including phosphorus, nitrogen, carbon species), environmental conditions (i.e. light and temperature), and grazing pressure (Kalff 2002). Controlling the amount and type of nutrients available to phytoplankton is a common method used to manage phytoplankton. Although nutrients can be naturally found within the waterbody or watershed, anthropogenic activities within the watershed increase the concentration or frequency of input of the key nutrients that increase primary productivity. In most freshwater systems, phosphorus is the most limiting nutrient of algal growth (Wetzel 2001); reducing the amount of phosphorus inputs to a system can reduce phytoplankton stocks.

Phosphorus can be present in multiple forms, and some forms are more bioavailable than others. Most phosphorus found in a waterbody is bound in organic matter, such as cellular constituents, or adsorbed to inorganic and dead organic particulates (Wetzel 2001). Total phosphorus (TP) is the summation of both inorganic/organic and dissolved/particulate phosphorus present; this concentration is related to primary productivity, but a large percentage of the concentration present cannot be readily used by algae. Total phosphorus concentration is often used as an indicator to characterize trophic state (Section 3.5). Total dissolved phosphorus (TDP) and soluble reactive phosphorus (SRP) are not bound to particulates, and are more bioavailable to primary producers. Another key nutrient needed by all living beings is carbon. Particulate organic carbon (POC) is a fraction of total carbon present, and can be related to primary productivity and limnological characteristics (Wetzel 2001).

3.3.2. Phosphorus

3.3.2.a. 2019 results

In general, TP concentrations were low, and a majority of all samples collected (at 0, 20 and 75 m) were below 6 µg/L (Table 6). The maximum TP of all samples was observed at 75 m on October 1st (8.2 µg/L). The greatest TP value measured at the surface occurred on August 19th (5.7 µg/L). The TP concentration at 20 m was often greater than the values at 75 m and the surface (Figure 9). Total dissolved phosphorus concentrations varied slightly between depths during the middle of the monitoring period (late July – August; Figure 9h, k), and most concentrations were below 6 µg/L. Soluble reactive phosphorus at all depths was low (< 4 µg/L) with a maximum of 3.0 µg/L at 75 m on September 9th. Generally, SRP concentrations increased with depth; however, on August 19th and September 9th SRP initially declined at 20 m then increased (Figure 9l,o).

Phosphorus concentrations were low in 2019, with some observations below the method detection and/or quantification limits; these values are still presented here to show relative concentrations at various depths (Figure 8). If phosphorus was released from the sediments, we would expect to observe elevated phosphorus (TP, TDP, and SRP) consistently near the bottom of the lake. Overall, there was little evidence of phosphorus release from the sediments (Figure 9). Additionally, there was little evidence of sediment resuspension (i.e. Figure 12). The metalimnion and hypolimnion are likely not large contributors of phosphorus to the epilimnion.

Table 6. Mean concentrations of measured phosphorus fractions (TP, TDP, SRP) and derived constituents (PP, DOP) in Skaneateles Lake during the 2019 monitoring period. Standard deviation shown in parentheses.

Depth (m)	TP (µg/L)	TDP (µg/L)	SRP (µg/L)	PP (µg/L)	DOP (µg/L)
0	3.2 (1.3)	2.8 (1.5)	1.2 (0.8)	0.4 (2.4)	0.8 (1.0)
20	5.1 (1.6)	3.1 (2.7)	1.7 (0.7)	2.0 (2.9)	1.4 (2.4)
50	--	--	1.6 (0.7)	--	--
75	3.7 (2.3)	3.4 (1.8)	1.7 (0.7)	0.3 (2.4)	1.7 (2.0)

3.3.2.b. Comparison to previous studies

Total phosphorus concentrations measured at the surface were similar to the average concentrations observed in the epilimnion in previous studies (Figure 8). The current monitoring program differed from those conducted in the past because samples at multiple depths were collected and additional phosphorus fractions were analyzed in each sample. The concentrations of phosphorus below the epilimnion are important to measure in order to better understand nutrient cycling within the water column.

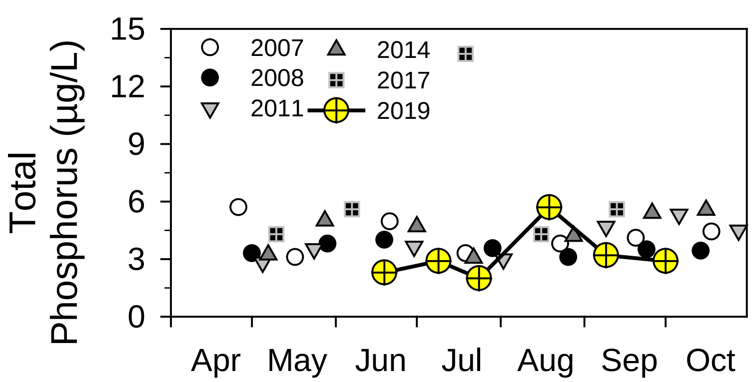


Figure 8. Time series plots of total phosphorus concentrations of the epilimnion from contemporary studies (2007, 2008, 2011, 2014, 2017, and 2019).

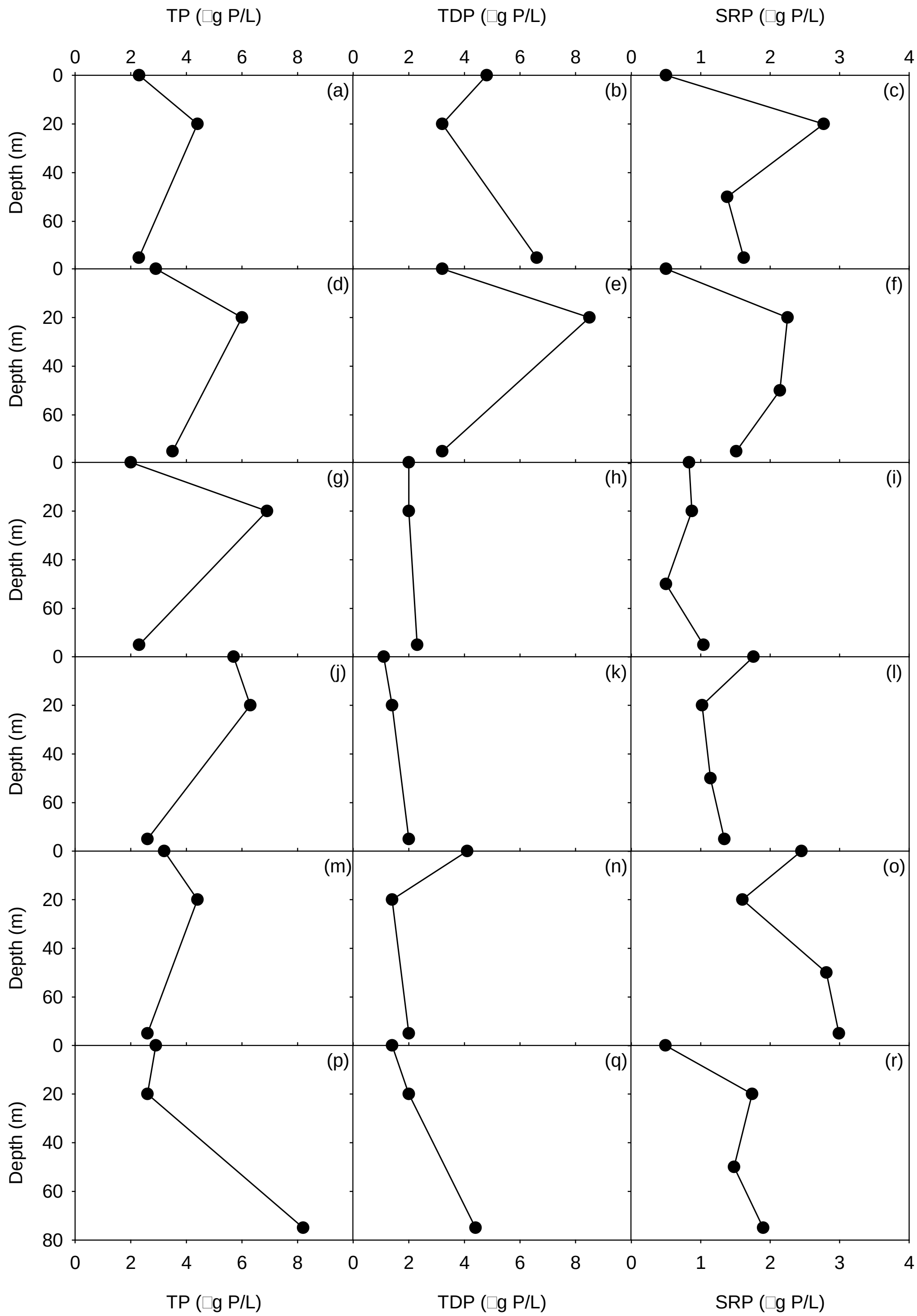


Figure 9. Vertical concentrations of TP (a, d, g, j, m, p), TDP (b, e ,h, k, n, q), and SRP (c, f, i, l, o, r) on June 19 (a-c), July 9 (d-f), July 24 (g-i), August 19 (j-l), September 9 (m-o), and October 1 (p-r).

3.3.3. Carbon

The average POC concentration at the surface was 0.26 mg/L and the average concentration at 20 m was 0.33 mg/L; the highest concentration for both the surface (0.52 mg/L) and at 20 m (0.82 mg/L) were observed in mid-June. Throughout the monitoring period, POC concentrations at both depths generally had a decreasing trend (Figure 10). Notably, in early July POC concentrations at 0 and 20 m fell below 0.2 mg/L then increased to approximately 0.35 mg/L in late July. Concentrations of POC in oligotrophic lakes typically are related to phytoplankton biomass and distribution, and the maximum POC is observed after periods of high productivity due to the sedimentation of plankton (Wetzel 2001). The amount of POC does not usually fluctuate greatly from year to year because it is derived from autochthonous production; however, human activities within the watershed can influence POC levels through increases in nutrient loading and algal growth (Wetzel 2001).

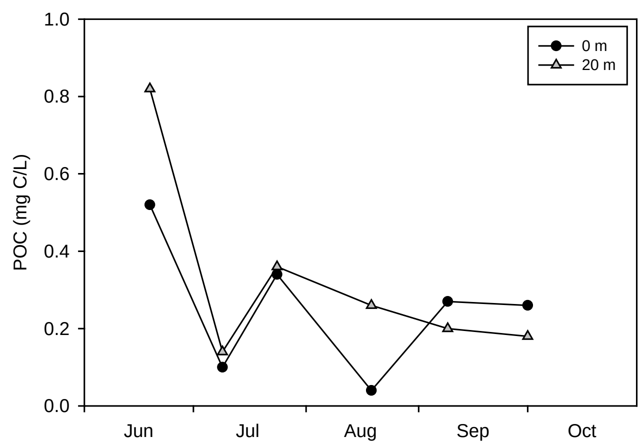


Figure 10. Particulate organic carbon (POC) concentrations in Skaneateles Lake during 2019 monitoring, 0 and 20 m depths.

3.3.4. Algae community and chlorophyll-*a*

3.3.4.a. 2019 chlorophyll-a results and comparison to previous studies

The average surface Chl-*a* concentration was 1.6 µg/L with the highest concentration (2.1 µg/L) observed in both early July and October. Surface Chl-*a* concentrations were consistent with trends in epilimnetic (0-10 m) concentrations measured in previous studies (Figure 11); however, the average surface Chl-*a* was the highest concentration observed over the last decade (Table A.1.) All Chl-*a* measurements were below the upper bounds of oligotrophy (Table 5).The average Chl-*a* concentration at 20 m was slightly greater than at the surface (1.8 µg/L) with the greatest concentration (3.0 µg/L) observed in early July. The chlorophyll measured at this depth is related to the deep chlorophyll maximum (DCM). This phenomenon is indicated by higher photosynthetic rates (higher Chl-*a*) at depths greater than rates in the epilimnion (Wetzel 2001). The DCM can be related to optical properties including light penetration (See section 3.4 for more optical information). The DCM was very pronounced in August and September with concentrations of approximately 2.5 µg/L near 20 m (Figure 12d-e). The peak laboratory and *in-situ* Chl-*a* concentrations on July 9 coincide with a sharp peak of c660 (Figure 12b). The DCMs observed were at or below the thermocline, and occurred in the lower bounds of the photic zone (~ 10% incident light).

In-situ fluorometric Chl-*a* values were typically higher than laboratory (extraction) values at 20 m. This is the typical outcome when comparing the two measurements, because while both provide valuable insight, the methods are looking at different aspects of the Chl-*a* present. Laboratory measurement of Chl-*a* are a more exact measurement of the magnitude of the concentration of Chl-*a* whereas the *in-situ* fluorometric measurements provide relative concentrations and patterns of Chl-*a* distribution in the water column.

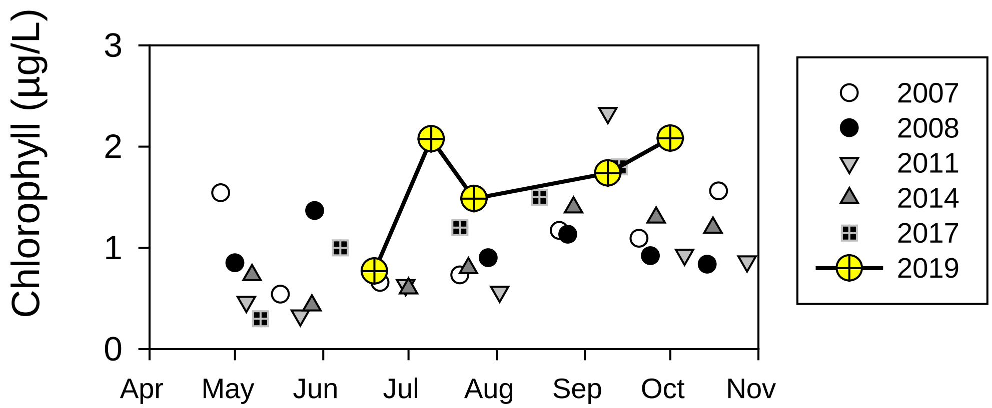


Figure 11. Epilimnetic (0-10 m average) chlorophyll-*a* concentrations of contemporary studies.

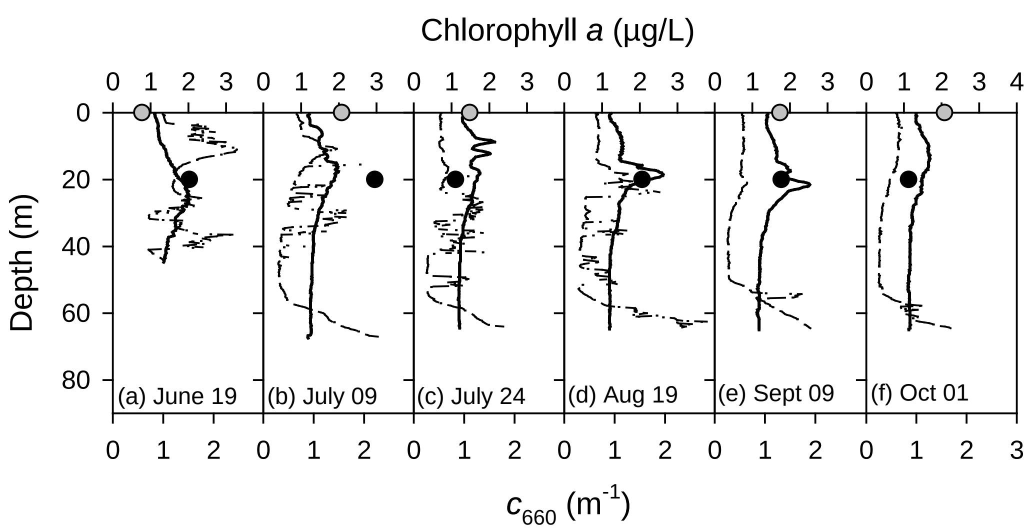


Figure 12. Vertical profiles of Chl-*a* (solid line) and c660 (dashed line) with laboratory Chl-*a* measurements at 0 m (gray point) and 20 m (black point) in 2019: (a) June 19, (b) July 9, (c) July 24, (d) August 19, (e) September 9, and (f) October 1.

3.3.4.b. 2019 algal community composition and comparison to previous studies

FluoroProbe measurements were made at 0 m throughout the monitoring period, and additional measurements at 9 m were made for the last two dates in the monitoring period. Cyanobacteria (blue green algae) concentrations were low to non-detectable throughout most of the monitoring period (Figure 13), which is consistent with observations made at this site in 2017 (UFI 2017). A majority of the samples were dominated by green algae (Chlorophyta) and diatoms (Bacillariophytoa). Green algae were more dominant during the early portion of the monitoring period (June-July), and then diatoms became dominant towards the end of the monitoring period (September-October). Cyanobacteria comprised 8 and 11% of the total chlorophyll-*a* at the surface in September and October, respectively. Although the contribution of cyanobacteria to total chlorophyll was small at this pelagic location, shoreline blooms can form from accumulations of cyanobacteria (at low levels) from the pelagic zone. . Microcystin concentrations were measured on two of the last three monitoring dates; all concentrations were low and well-below drinking water guidance values (1 µg/L; WHO 2011). All samples collected at 0 and 9 m were below reporting limit (reporting limit = 0.3 µg/L).

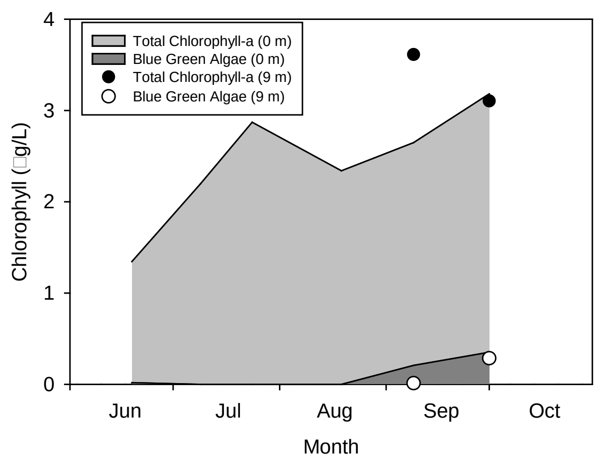


Figure 13. Contribution of cyanobacteria (blue green algae) to total chlorophyll-*a* concentration in the pelagic zone of Skaneateles Lake.

3.4. Optics

3.4.1. Background

Optical characteristics are important ecological and water quality features of surface waters. Visual clarity, as measured with a Secchi disk (SD), has the longest record of use in optical characterization (Tyler 1968, Preisendorfer 1986), and it remains the most commonly measured optical attribute. Moreover, it remains closely coupled to the public's perception of water quality (Effler 1985, Smith and Davies-Colley 1993). Visual clarity is not only the sighting distance of a submerged target such as a SD, but is also the penetration of diffuse irradiance (light) into the water; both aspects of clarity are of interest in limnology (Davies-Colley et al. 1993). Penetration of light in water is often represented by the diffuse light attenuation coefficient for downwelling irradiance (E_d), k_d (m^{-1}; slope of ln E_d versus depth). This attribute is important for determining the vertical limits of primary production when measured over the photosynthetically available radiation (PAR) wavelength interval (400-700 nm; Davies-Colley et al. 1993, Wetzel 2001).

Both SD and k_d describe characteristics of the ambient light underwater and are regulated by the two light attenuating processes of absorption (a, m^{-1}) and scattering (b, m^{-1}). The beam attention coefficient, c $(= a + b)$, is a third optical property that can be used to describe the light field. The value of c at 660 nm (c_{660}) is accepted as a reliable surrogate of the scattering coefficient (b; Babin et al. 2003). Although SD and k_d are related, there are fundamental differences and relationships between these measurements of clarity.

An inverse dependency of SD on k_d, manifested as a uniform $k_d \times SD$ product, has been widely assumed (Idso and Gilbert 1974); however, $k_d \times SD$ has been observed to differ substantially amongst surface waters and temporally within individual systems. This may be in part due to the fundamental differences in the response of k_d and SD to the relative magnitudes of a and b. Secchi disk measurements are more sensitive to changes in b (scattering), whereas k_d is more sensitive to changes in a (absorption; Davies-Colley et al. 1993). The variations in the $k_d \times SD$ product may have diagnostic utility in identifying and characterizing differences and dynamics in light attenuating conditions (Effler 1985).

Light absorbing and scattering constituents, such as colored dissolved organic matter (CDOM), phytoplankton, and tripton (inanimate organic and inorganic particles) are commonly found in waterbodies, and alter properties of visual clarity. Regulating the magnitudes and dynamics of these constituents is fundamental to optical water quality management initiatives (Cooke et al. 2005). Phytoplankton biomass has been believed to be a primary regulator of SD when algal concentrations are high (Lorenzen 1980); however, a growing number of lakes and reservoirs have been identified where tripton is considered as important to regulating visual clarity (Davies-Colley et al. 1993, Effler and Perkins 1996, Jassby et al. 1999, Swift et al. 2006). Tripton may have internal (e.g. chemical precipitation; Weidemann et al. 1985, Effler et al. 1987) or external (e.g. watershed; Kirk 1985, Effler et al. 2006) origins.

3.4.2. 2019 results and comparison to previous studies

As expected, exponential decreases in irradiance were observed with increasing depth (Figure 14; Wetzel 2001). There was interference within the first few meters due to the shadow of the boat (Figure 14). The mean Secchi depth was 7.8 (standard deviation = 1.5); the greatest SD was observed in June (10.5 m) and the least in August (6.5 m). The k_d values ranged from 0.13 to 0.21 m^{-1}, inversely corresponding to the largest and smallest SD. The 1% light depth ranged between 34 and 22 m, similar to values observed in previous studies (2007, 2008, 2011, and 2014; Figure 16). Seasonal variation in k_d was less than SD; the coefficient of variation of the 6 monitoring dates for k_d was 0.15 compared to 0.20 for SD. This suggests that there are slightly greater variations in scattering (*b*) than absorption (*a*) properties. The average $k_d \times SD$ product was 1.35 (coefficient of variation = 0.08); the low value was consistent with values calculated in previous studies, and indicates that light scattering is relatively important to light penetration characteristics (high *b*:*a* ratio). Additionally, the dependence of SD on light scattering levels is consistently supported by the significant (p = 0.06) relationship between SD (as SD^{-1}) and c_{660} (Figure 15).

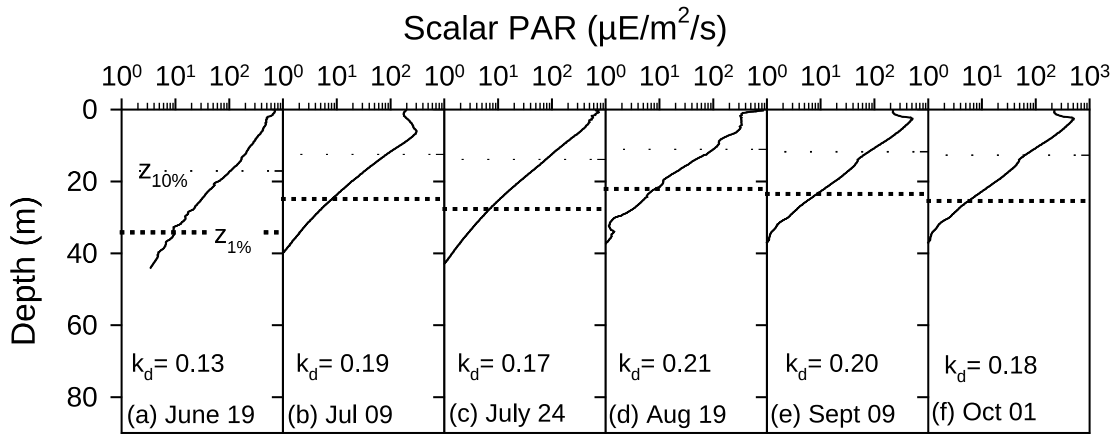


Figure 14. Vertical profiles of photosynthetically active radiation (PAR) during 2019: (a) June 19, (b) July 09, (c) July 24, (d) August 19, (e) September 09, and (f) October 01. Dotted lines indicate the depth to 1 % of incident light ($z_{1\%}$) and dashed lines indicate the depth to 10 % of incident light ($z_{10\%}$). The light extinction coefficient (k_d) is reported. Interference within the upper waters due to the boat shadow can be seen in (b), (d), (e), and (f).

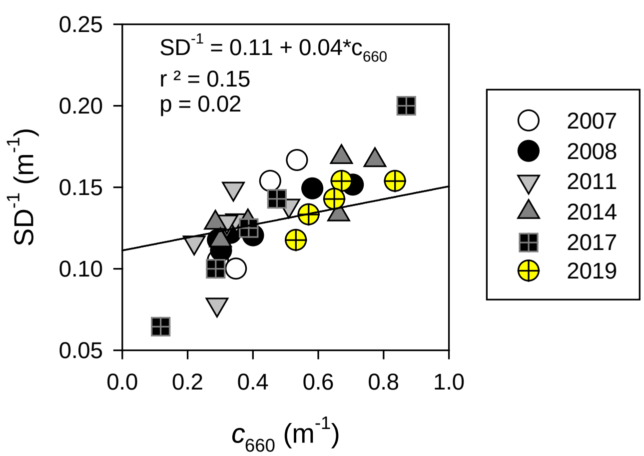


Figure 15. Evaluation of the relationship between the inverse of Secchi disk depth (SD^{-1}) and c_{660} for contemporary monitoring studies.

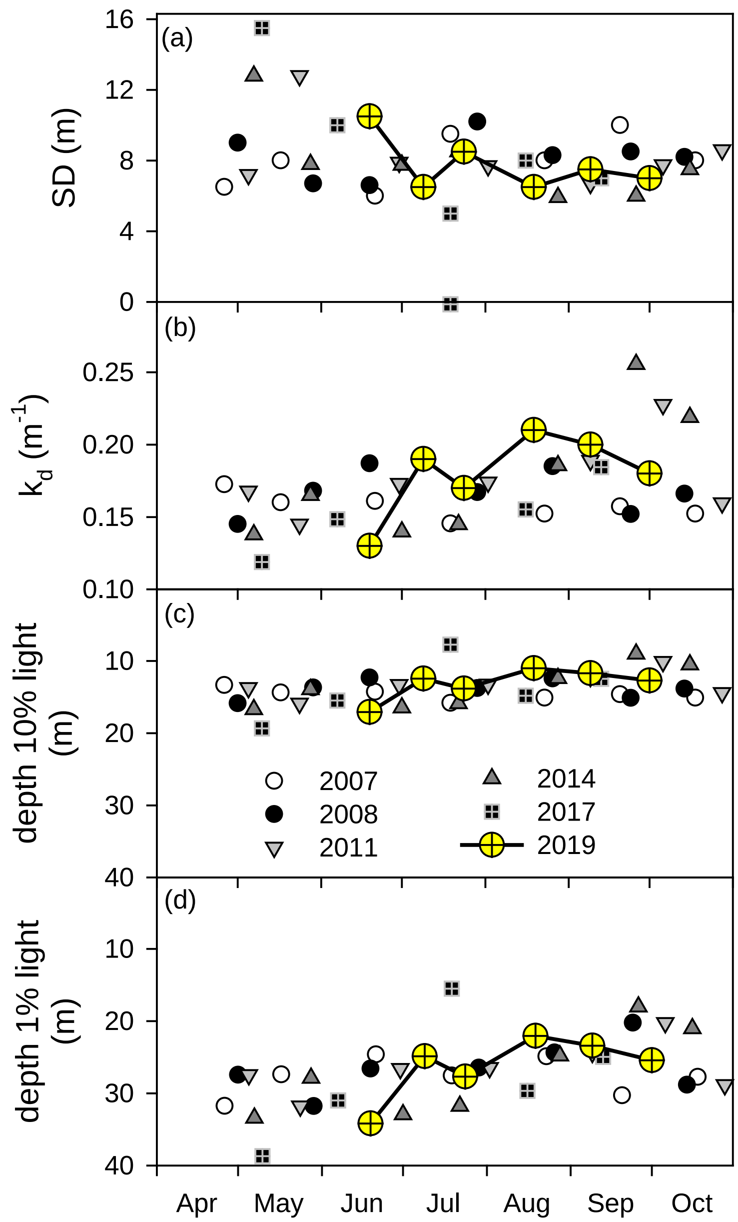


Figure 16. Time series of optical properties from contemporary studies: (a) Secchi disk (SD) depth, (b) light extinction coefficient (k_d), (c) depth to 10% of incident light, and (d) depth to 1% of incident light.

3.5. Trophic state

3.5.1. Background

Trophic state refers to the level of primary production within an aquatic ecosystem. The three classic trophic state classifications are oligotrophy, mesotrophy, and eutrophy, which correspond to low, intermediate, and high levels of productivity, respectively. Often these classifications are interpreted subjectively (i.e. eutrophy is “bad” or “unhealthy”), but these categories allow one to broadly know what limnological characteristics to expect in that waterbody such as dissolved oxygen depletion, optical properties, and biological productivity. Comprehensive measurements of primary production and related constituents throughout an entire year are the most desired by scientists to measure trophic state (Wetzel 2001); however, such measurements are laborious, costly, and rare. The most commonly applied surrogate metrics of trophic state include: chlorophyll *a* (Chl-*a*) concentrations, total phosphorus (TP) concentrations, and Secchi disk transparency (SD). These metrics are included in Carlson’s (1977) trophic state index and are related to one another (See Section 2.3). For example, low concentrations of Chl-*a* and TP and high SD typically indicate low levels of primary production (oligotrophy).

Phytoplankton biomass is itself an imperfect measure of primary production (Wetzel 2001), and there are potential short-comings in each of these trophic state indicators because they all depend on assumptions of relationships coupled to phytoplankton biomass. For example, Chl-*a* content of phytoplankton can vary depending on community composition and ambient environmental conditions (e.g. light and nutrient availability, see Section 3.3; Wetzel 2001). High concentrations of inanimate mineral particles (tripton) can alter usage of TP and SD as indicators of phytoplankton biomass because these particles can contain phosphorus and contribute to light attenuation (See Sections 3.3 and 3.4; Effler et al. 2002). Oftentimes Chl-*a* is the most utilized of these three metrics because it is the most direct measurement of primary production.

3.5.2. 2019 results

Skaneateles Lake is currently oligotrophic according to Carlson's TSI (Table 7). Total phosphorus and chlorophyll-*a* concentrations at the surface were all below the oligotrophic threshold (Table 5). Secchi depth varied throughout the monitoring period, but never approached the lower limit for mesotrophic lakes (2 m).

Table 7. Carlson's (1977) Trophic State Index (TSI) values and classifications for Skaneateles Lake in 2019.

Trophic State Indicator	2019 TSI	Classification
Chlorophyll *a* (µg/L)	35	Oligotrophic
Total phosphorus (µg/L)	20	Oligotrophic
Secchi depth (m)	30	Oligotrophic

Table 8. TSI values calculated during the routine monitoring program in the past decade at Skaneateles Lake.

	TSI value				
Trophic State Indicator	2008	2011	2014	2017	2019
Chlorophyll *a* (µg/L)	31	29	30	32	35
Total phosphorus (µg/L)	24	24	26	32	20
Secchi depth (m)	30	29	30	28	30

3.5.3. Comparison to previous studies

The average Chl-*a* in 2019 was greater than epilimnetic Chl-*a* values observed in the past, and SD and TP both decreased in 2019 (Table A.1). The TSI values in 2019 are similar to those observed in the past decade, though. The Chl-*a* TSI is the highest since the 1970s (Table 8, Table A.1.). Relationships between TSI variables can indicate other limnological conditions that are related to algal biomass. For example, when TSI(Chl) is greater than TSI(SD), large particulates or algal colonies (e.g., *Aphanizomenon*) may dominate (Carlson 1991). It is likely that particulates within Skaneateles Lake affect trophic indicator relationships and overall phytoplankton biomass. The Chl-*a* – TP and Chl-*a* – SD relationships were not strong for the contemporary studies (Figure 17). The Chl-*a* – SD relationship is statistically significant, though, with Chl-*a* explaining 23% of the variation in SD (Figure 17). Contributions from tripton may explain a portion of the remaining variation in SD. These particles also may contribute to the poor relationship between TP and Chl-*a* due to phosphorus sorption to inorganic particles.

In 2019, approximately 50 inches of precipitation fell at the Syracuse Airport, which is the third greatest amount measured in a year with comprehensive monitoring data for Skaneateles Lake (Table A.1). This study was completed before the year concluded so precipitation was estimated for November and December of 2019 by calculating the average rainfall during these months from 2010 to 2018. The epilimnetic Chl-*a* concentration in Skaneateles Lake was found to be significantly related to annual precipitation (p=0.001; Figure 19a) using data from available studies (Table A.1). The addition of 2019 data strengthened the relationship observed through 2017 ($r^2 = 0.59$; UFI 2017). There were no significant relationships between either TP or SD and annual precipitation (Figure 19b, c). This continues to support the notion that hydrologic inputs (i.e. precipitation and associated stream runoff) may be important in the variations in annual Chl-*a* values and that TP is not directly related to Chl-*a* concentration (UFI 2017). The small range of TP, Chl-a, and SD values observed in Skaneateles Lake contributes to the weak relationships between these metrics of trophic state.

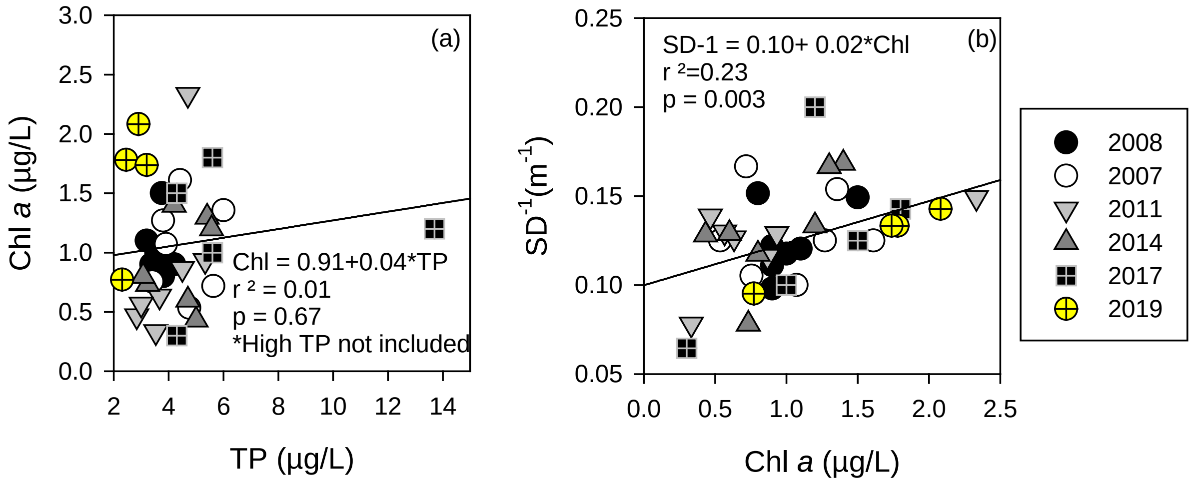


Figure 17. Trophic relationships between chlorophyll *a* and total phosphorus (a), and Secchi depth and chlorophyll *a* (b). The high TP point in 2017 was not included in the regression.

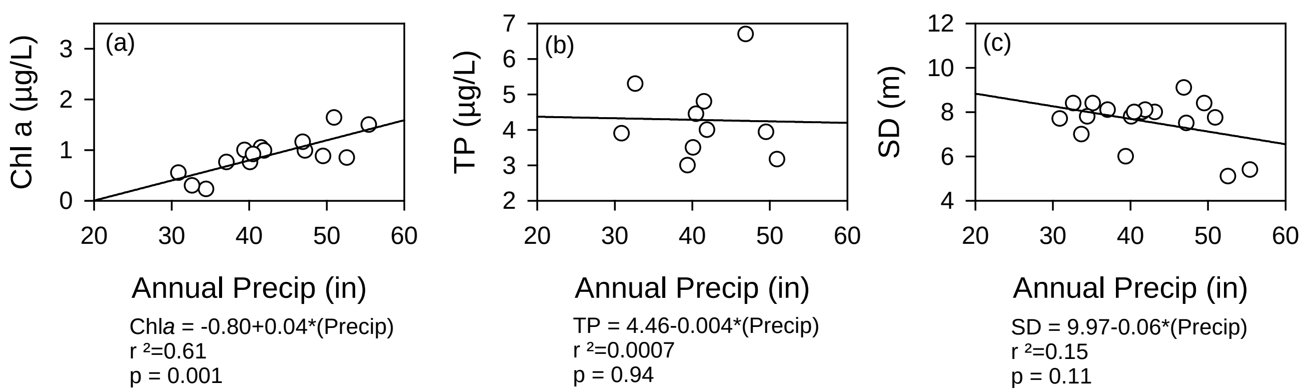


Figure 18. Relationships between annual precipitation and trophic indicators observations at TOS 2 (See Appendix Table A.1). Precipitation data from Hancock International Airport in Syracuse, NY.

4. Summary

4.1. Conclusions

Specific objectives of this monitoring program included reporting the current limnological conditions and comparing these conditions to those examined in previous years. Although there were some differences between certain metrics, there has generally been little change in the overall water quality of the lake. Summer average concentrations of chlorophyll *a* were higher than concentrations measured in previous years, and Secchi disk depth and total phosphorus were lower (Table A.1.). However, these common metrics of trophic state continued to remain within the accepted ranges for oligotrophic lakes. Inter-annual differences in water quality are expected; however, it is important to note these differences in case of a systematic trend. Low concentrations of dissolved phosphorus fractions (i.e., TDP and SRP) and the lack of systematic vertical gradients suggest that release from the sediments is not a major source of phosphorus to Skaneateles Lake. The phytoplankton community in the upper waters of the pelagic zone was dominated by green algae and diatoms, with only modest contribution from cyanobacteria in September. Microcystin toxins concentrations measured at this location were below the reporting limit for the test and well below guidance values for health effects. However, it is important to note that elevated cyanobacteria and microcystin concentrations as the reported shoreline blooms may be the result of accumulations from small concentrations originating in the pelagic portions of the lake. The data collected in this study will be useful for the development of a 9E management plan and water quality model. Long term monitoring efforts, such as those supported by the Town of Skaneateles, are important for the continued protection of Skaneateles Lake and its watershed.

4.2. Recommendations for future monitoring

The Upstate Freshwater Institute has several recommendations related to future monitoring of the lake, guided by the findings of the 2019 monitoring program, previous monitoring programs, and anticipated needs for the development of a 9E plan or water quality model.

1) Due to the condition and value of the lake, a water quality monitoring program should be continued on Skaneateles Lake in order to track changes in trophic state and water quality.
2) Monitoring multiple locations, such as near shore locations, tributary inflows and macrophyte beds, may be beneficial to understanding nutrient cycling and inputs.
3) Adding and continuing a broad range of water quality measurements (e.g. phosphorus, nitrogen, carbon fractions, and silica) in both the epilimnion and hypolimnion of the lake at a high frequency. Although a wide sampling interval is often appropriate for oligotrophic systems, temporal variations associated with runoff or wind events can be important to understanding phytoplankton community dynamics.
4) The addition of a monitoring buoy equipped with temperature, chlorophyll *a*, turbidity, and dissolved oxygen sensors to provide high frequency data about in-lake hydrodynamics and water quality (e.g., seiches and stratification).
5) Measurements of phosphorus flux from the lake bottom at various depths and in areas with and without macrophytes/Dreissenid mussels.
6) Continued monitoring of major and minor tributaries to Skaneateles Lake in order to quantify nutrient/sediment loading.
7) Conducting a whole-lake Dreissenid mussel survey. Dreissenids, including both quagga (*Dreissena rostriformis*) and zebra mussels (*D. polymorpha*), can alter the phytoplankton community via: 1) removal of particles resulting in clearer water, 2) increased recycling of available phosphorus, and 3) selective rejection of certain cyanobacteria (Fishman et al. 2009).
8) Conducting a macrophyte survey to evaluate its contribution to phosphorus cycling within the lake.

5. References

Babin M, A Morel, V Fournier-Sier, F Fell, D Stramski. 2003. Light scattering properties of marine particles in coastal and open waters as related to the particle mass concentration. Limnol Oceanogr. 48:843-859.

bbe Moldaenke. 2017. bbe FluoroProbe User Manual, version 2.6 E2. 125 pp.

Canter LW, DI Nelson, JW Everett. 1992. Public perception of water quality risks-Influencing factors and enhancement opportunities. J Environ Sys. 22(2):163-187.

Carlson RE. 1977. A trophic state index for lakes. Limnol Oceanogr. 22:361-369.

Carlson. 1991. Expanding the trophic state concept to identifiy non-nutrient limited lakes and reservoirs. Enhancing the States' Lake Management Programs. 59-71. North American Lake Management Society.

Chapra SC. 1997. Surface water-quality modeling. McGraw-Hill, New York. 844 pp.

Cooke GD, EB Welch, SA Peterson, SA Nichols. 2005. Restoration and management of lakes and reservoirs. Taylor and Francis, CRC Press, Boca Raton, FL.591 pp.

Davies-Colley RJ, WN Vant, DG Smith. 1993. Colour and clarity of natural waters. Ellis Horwood, New York, New York. 310 pp.

Effler SW. 1985. Attenuation versus transparency. J Environ Engrg Div ASCE. 111:448-459.

Effler SW, SD Field. 1983. Vertical diffusivity in the stratified layers of the mixolimnion of Green Lake, Jamesville, NY. J Freshwat Ecol. 2:273-286.

Effler SW, EM Owens. 1985. Impact of lake acidification on stratification. J Environ Engrg Div ASCE. 111:822-832.

Effler SW, EM Owens, KA Schimel. 1986. Density stratification in ionically enriched Onondaga Lake, USA. Water Air Soil Pollut. 27:247-258.

Effler SW, CM Brooks, MG Perkins, MA Meyer, SD Field. 1987. Aspects of the underwater light field of eight Central New York lakes. Wat Resour Bull. 23:1193-1201.

Effler SW, MG Perkins. 1996. An optics model for Onondaga Lake. Lake and Reserv Manage. 12:115-125.

Effler SW, DA Matthews, MG Perkins, DL Johnson, F Peng, MR Penn, MT Auer. 2002. Patterns and impacts of inorganic tripton in Cayuga Lake. Hydrobiologia. 482:137-150.

Effler SW, AR Prestigiacomo, F Peng, KB Bulygina, DG Smith. 2006. Resolution of turbidity patterns from runoff events in a water supply reservoir, and the advantages of in situ beam attentuation measurements. Lake and Reserv Manage. 22:79-93.

Effler SW, AR Prestigiacomo, DM O'Donnell. 2008. Water quality and limnological monitoring for Skaneateles Lake: Field Year 2007. Report prepared for the Town of Skaneateles. Prepared by Upstate Freshwater Institute. 57 pp.

Effler SW, AR Prestigiacomo, DM O'Donnell. 2009. Water quality and limnological monitoring for Skaneateles Lake: Field Year 2008. Report prepared for the Town of Skaneateles. Prepared by Upstate Freshwater Institute. 57 pp.

Effler SW, AR Prestigiacomo, DM O'Donnell. 2012. Water quality and limnological monitoring for Skaneateles Lake: Field Year 2011. Report prepared for the Town of Skaneateles. Prepared by Upstate Freshwater Institute. 47 pp.

Effler SW, AR Prestigiacomo, DM O'Donnell. 2015. Water quality and limnological monitoring for Skaneateles Lake: Field Year 2014. Report prepared for the Town of Skaneateles. Prepared by Upstate Freshwater Institute. 44 pp.

[EPA] Environmental Protection Agency, Division of Environmental Sciences. 2015. Ohio EPA Total (Extracellular and Intracellular) Microcystins – ADDA by ELISA Analytical Methodology; Method 701.0 Version 2.2 (and previous versions); Ohio EPA: Reynoldsburg, OH, November 2015.

Fishman DB, SA Adlerstein, HA Vanderploeg, GL Fahnenstiel, D Scavia. 2009. Causes of phytoplankton changes in Saginaw Bay, Lake Huron, during the zebra mussel invasion. Journal of Great Lakes Research. 35:482-495.

Ford DE, HG Stefan. 1980. Thermal predictions using integral energy model. J Hydraul Eng. 106:39-55.

Harleman DR. 1982. Hydrothermal analysis of lakes and reservoirs. J Hydraul Eng. 108:302-325.

Hutchinson GE. 1938. On the relation between oxygen deficit and the productivity and typology of lakes. Int Revue ges Hydrobiol Hydrogr. 36:336-355.

Idso SB, RG Gilbert. 1974. On the universality of the Poole and Atkins Secchi disk-light extinction equation. The Journal of Applied Ecology. 11:399-401.

Jassby, AD, CR Goldman, JE Reuter, RC Richards. 1999. Origins and scale dependence of temporal variability in the transparency of Lake Tahoe, California-Nevada. Limnol Oceanogr. 44:282-294.

Kalff J. 2002. Limnology. Upper Saddle River, NJ. Prentice-Hall, Inc. 592 pp.

Kaushal SS, S Duan, TR Doody, S Haq, RM Smith, TA Newcomer Johnson, KD Newcomb, J Gorman, N Bowman, PM Mayer, KL Wood, KT Belt, WP Stack. 2017. Human-accelerated weathering increases salinization, major ions, and alkalinization in fresh water across land use. Applied Geochemistry. 83:121-135.

Kaushal SS, GE Likens, ML Pace, RM Utz, S Haq, J Gorman, M Grese. 2018. Freshwater salinization syndrome on a continental scale. PNAS. 115(4):574-583.

Kirk JTO. 1985. Effects of suspensoids (tubidity) on penetration of solar radiation in aquatic ecosystems. Hydrobiologia. 125:195-209.

Lorenzen MW. 1980. The use of chlorophyll-Secchi disk relationships. Limnol Oceanogr. 25:373-377

Mortimer CH. 1941. The exchange of dissolved substances between mud and water in lakes. Parts I and III. J Ecology. 29:280-329.

[NLCD] Yang L, S Jin, P Danielson, C Homer, L Gass, A Case, C Costello, J Dewitz, J Fry, B Grannemann, M Rigge, G Xian. 2018. A new generation of the United States national land cover database: Requirements, research priorities, design, and implementation strategies. pp.108-123.

[NYSDEC] 2017. Harmful Algal Bloom Action Plan Skaneateles Lake. 95 pp.

[NYSDEC] New York State Department of Environmental Conservation. 2019a. Skaneateles Lake. Accessed 21 October 2019. Retrieved from https://www.dec.ny.gov/outdoor/36556.html.

[NYSDEC] New York State Department of Environmental Conservation. 2019b. HAB Archive 2018. Accessed 24 October 2019. Retrieved from https://www.dec.ny.gov/chemical/83332.html.

Oglesby RT, WR Shaffner. 1978. Phosphorus loadings o lakes and some of their responses. Part 2. Regression models of summer phytoplankton standing crops, winter total P, and transparency of New York lakes with known phosphorus loadings. Limnol Oceanogr. 23(1):135-145.

Perkins MG, SW Effler, CM Strait, L Zhang. 2009. Light absorbing components in the Finger Lakes of New York. Fundamental and Applied Limnology. 173/4:305-320.

Powell TA, A Jassby. 1974. The estimation of vertical eddy diffusivities below the thermocline in lakes. Wat Resour Res. 10:191-198.

Preisendorfer RW. 1986. Secchi disc science: Visual optics of natural waters. Limnol Oceanogr. 31:909-926.

Rice EW, RB Baird, AD Eaton, LS Clesceri. 2012. Standard methods for the examination of water and wastewater, 22 ed. American Public Health Association, American Water Works Association, Water Environmental Federation, Washington, DC. 1220 pp.

Schaffner WR, RT Oglesby. 1978. Phosphorus loadings to lake and some of their responses. Part 1. A new calculation of phosphorus loadings and its applications to 13 New York lakes. Limnol and Oceanogr. 23:120-134.

[SLA]. Skaneateles Lake Association. 2018a. Milfoil Project. Accessed 31 October 2019. Retrieved from https://skaneateleslake.org/milfoil-project/control-effort/.

SLA. 2018b. Stewardship. Accessed 31 October 2019. Retrieved from https://skaneateleslake.org/stewardship/.

Smith DG, RJ Davies-Colley. 1993. Perception of water clarity and colour in terms of suitability for recreational use. J Environ Manage. 36:225-235.

Smith DG, GF Croker, K McFarlane. 1995. Human perception of water appearance. New Zealand Journal of Marine and Freshwater Research. 29:29-43.

Stefan HG, DE Ford. 1975. Temperature dynamics in dimictic lakes. J Hydraul Eng. 101:97-114.

StreamStats Version 4.3.8. Web application by United States Geological Survey, AngularJS, Leaflet, and Angular Leaflet Directive. Accessed October 2019. Retrieved from https://streamstats.usgs.gov/ss/.

Swift T, J Perex-Losada, S Schladow, J Reuter, A Jassby, C Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquatic Sciences-Research Across Boundaries.68:1-15.

Tyler JE. 1968. The Secchi disc. Limnol Oceanogr. 13:1-6.

[UFI] Upstate Freshwater Institute. 2017. Water quality and limnological monitoring for Skaneateles Lake: Field Year 2017. Report prepared for the Village of Skaneateles, December 2017. 48 pp.

[USEPA] United States Environmental Protection Agency. 1997. In Vitro Determination of chlorophyll a and pheophytin a in marine and freshwater algae by fluorescence. Method 445.0 Rev. 1.2. National Exposure Research Laboratory Office of Research and Development, Cincinnati, OH. Pages 445.0-1 -445.0-22.

Weidemann AD, TP Bannister, SW Effler, DL Johnson. 1985. Particulate and optical properties during CaCO3 precipitation in Otisco Lake. Limnol Oceanogr. 30:1078-1083.

Wetzel RG. 2001. Limnology: Lake and reservoir ecosystems. Academic Press, New York.

[WHO] World Health Organization. 2011. Guidelines for drinking-water quality. 4th Ed. World Health Organization, Malta. 564 pp.

[YSI] Yellow Springs Incorporated. 2011. 6-Series multiparameter water quality sondes user manual: Revision H. YSI, Yellow Springs, OH.

6. Appendices

6.1. Appendix A: Additional information

Table A.1. Comparisons of summer average measures of trophic state to historic observations at long-term monitoring site (TOS 2/Site2).

Year	Chl (µg/L)	Secchi disk (m)	TP (µg/L)	Source	Apr.-Oct. Rainfall[(a)] (in)	Annual Rainfall[(a)] (in)
1910	-	10.3[(b)]	-	Birge and Juday, 1914	-	-
early 1970s	1.95	6.6	6.1	Bloomfield 1978	-	-
1972	1.5	5.4	-	Mills, 1975	38.2	38.2
1973	0.9	5.1	-	Mills, 1975	34.5	55.4
1982	-	8.4	-	Effler et al., 1987	20.6	52.6
1987	-	7.0	-	Cole, 1987	23.2	35.1
1988	0.2	7.8	-	Effler et al., 1988	23.2	33.7
1996	1.0	6.0	3.0	UFI	22.8	34.4
1997	0.3	8.4	5.3	NYSDEC	16.9	39.4
1998	0.8	8.1	-	NYSDEC	22.4	32.6
1999	0.6	7.7	3.9	NYSDEC	16.0	37.1
2004	-	8.0	-	UFI	31.5	30.9
2005	0.8	7.8	3.5	UFI	27.0	43.1
2006	1.0	7.5	-	UFI	34.3	40.1
2007	1.1	8.0	4.8	UFI	21.5	47.2
2008	1.0	8.1	4.0	UFI	23.8	41.5
2011	0.9	8.4[(c)]	3.9	UFI	35.3	37.8
2014	0.9	8.0	4.45	UFI	26.2	49.5
2017	1.2	9.1	6.7	UFI	29.6	45.7
2018	0.9	8.5	3.9	CSLAP[(d)]	21.8	41.3
2019	1.6	7.8	3.17	UFI	34.1	49.9[(e)]

[(a)] Hancock International Airport
[(b)] single observation
[(c)] 7.6m without inclusion of 5/24/11
[(d)] Average of data collected through the Citizen Statewide Lake Assessment Program at Sites 1 & 2
[(e)] December 2019 component of annual precipitation based on overall November and December precipitation (2010-2018) because study completed before end of the year

Table A.2. Instrument specification for 2019 Skaneateles Lake monitoring.

Instrument	Parameters (units)	Manufacturer	Range of Detection
SeaBird	T (°C)	SeaBird	-5 – 35 °C
	SC (µS/cm)	SeaBird	0 – 70,000 µS/cm
	$\mathbf{c}_{660}$ (1/m)	WET Labs	~ 0.003 to 138.15 1/m
	Turbidity, Tn (NTU)	D & A Instruments	0 – 250 NTU
	Chl-*a* (µg/L)	WET Labs	0.01 – 50 µg/L
	Depth (m)	SeaBird	0 – 100 m
	Scalar PAR (µE/m^2/s)	LiCor	> +/- 10 % quantum response
YSI 6600	T (°C)	YSI	-5 to 45 °C
	SC (µS/cm)	YSI	0 to 100 mS/cm
	Dissolved Oxygen, DO (mg/L)	YSI	0 to 50 mg/L
	pH (units)	YSI	0 to 14 units
	Depth (m)	YSI	0 to 200 m
FluoroProbe	Depth (m)	bbe moldaenke	0 – 100 m
	Green algae class	bbe moldaenke	0 – 200 ug Chl-*a*/L
	Bluegreen class	bbe moldaenke	0 – 200 ug Chl-*a*/L
	Diatom class	bbe moldaenke	0 – 200 ug Chl-*a*/L
	Cryptophyte class	bbe moldaenke	0 – 200 ug Chl-*a*/L

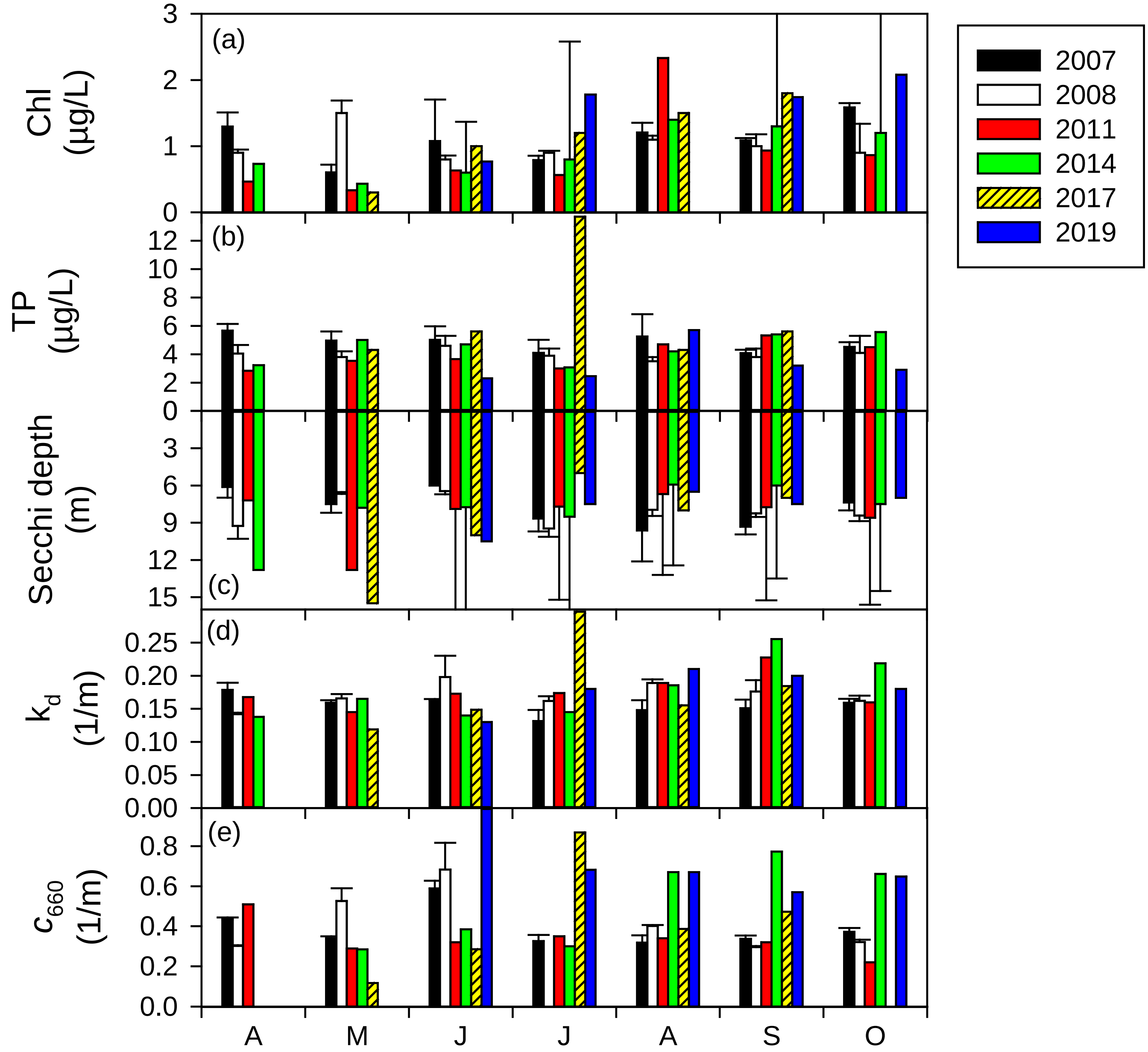


Figure A.1. Averaged epilimnetic (0-10) water quality parameters for Skaneateles Lake of contemporary studies (2007, 2008, 2011, 2014, 2017, 2019): (a) Chl-a, (b) TP, (c) Secchi depth, (d) kd, and (e) c660. Vertical bars represent one standard deviation, based on longitudinal observations in 2007 and 2008 only.

6.2. Appendix B: Glossary

absorption	a process responsible for the diminishment of penetrating light in a water column
alkaline	solution with great number of carbonate forms, and great buffering capacity to neutralize strong acids
anoxic	absence of oxygen
attenuation coefficient	value that quantifies the diminishment of light as a function of depth
autochthonous	formed in present position, e.g. nutrients from non-terrestrial/human sources
bioavailable	substance or portion of substance that is accessible to an organism for uptake or adsorption, typically across cellular membrane
biomass	mass of living material per unit area, or volume, at an instant in time
chlorophyll a	the primary photosynthetic pigment of oxygen producing organism; commonly used as a surrogate metric of phytoplankton biomass
cyanobacteria	commonly known as "blue green algae"; not actually algae, but is a prokaryotic, bacteria; most are capable of producing toxins and contribute to HABs
dimictic	(adj) lakes that circulate (turnover) twice per year, generally separated in time by summer stratification and ice cover
ecology	the study of natural systems, including the living and nonliving components
epilimnion	the upper, well-mixed region (layer) of a stratified lake
eutrophic/eutrophy	the condition of a lake having a high level of primary production; e.g. high levels of nutrients
hydrology	study of the water cycle
hypolimnion	lower, colder region (layer) of a stratified lake, below the metalimnion
hypoxic	deficiency of oxygen
irradiance	radiant flux incident on an infinitesimal element of a surface; a metric of the amount of "light"
limnology	study of freshwater systems
mesotrophic/mesotrophy	the condition of a lake having a moderate level of primary production; e.g. moderately rich in nutrients
metalimnion	the central stratum in a thermally stratified lake, between the epilimnion and hypolimnion; characterized by a strong thermal gradient
monomictic	lakes that circulate (turnover) or mix once per year
morphometry	specifications of the physical dimensions of a lake
oligotrophic/oligotrophy	the condition of a lake having a low level of primary production; e.g. low levels of nutrients
orthograde	refers to vertical pattern of dissolved oxygen in which concentrations increase with depth below the epilimnion
photoadaption	adjustments of phytoplankton to low light levels, commonly accompanied by increases in photosynthetic pigments
photosynthesis	production of plant biomass and oxygen, from carbon dioxide,

	water, and light by pigmented plants
phytoplankton	the portion of the plankton (free floating organisms) community composed of photosynthetic, oxygen-producing, microbes
primary production/productivity	rate of energy content or mass of photosynthetic organisms
respiration	oxygen-demanding metabolic processes
salinization	accumulation of water-soluble salts
Secchi disk	black and white quadrant disk that is lowered in the water to the point of detection as a measure of clarity
seiche	an oscillation, or internal wave, of water reestablishing equilibrium after having been disturbed
scattering	a process responsible for the diminishment of penetrating light in a water column
thermal stratification	vertical layering of water in a lake according to temperature, and therefore density; e.g. summer stratification has warmer waters in the surface layers and cooler waters below
tripton	inanimate particles
trophic state	the level of primary productivity in a lake; generally classified as oligotrophic, mesotrophic, or eutrophic
turnover	intervals when temperature (and density) of water column is vertically uniform (isothermal); commonly accompanied by active mixing throughout the water column
watershed	the area surrounding a lake where runoff contributes to water inputs via tributaries, surface water, or ground water
whiting	periods of calcium carbonate precipitation; common during summer in hardwater lakes

6.3. Appendix C: Acronyms and symbols

9E	nine element
a	light absorption coefficient (m^{-1})
AHOD	areal hypolimnetic oxygen deficit
b	light scattering coefficient (m^{-1})
c_{660}	beam attenuation coefficient at 660 nm wavelength (m^{-1})
c	beam attenuation coefficient
Chl-*a*	chlorophyll a concentration, also noted as “Chl”
CSLAP	Citizens Statewide Lakes Assessment Program
DCM	deep chlorophyll maximum
DO	dissolved oxygen
DOP	dissolved organic phosphorus ($= TDP - SRP$)
HAB(s)	harmful algal bloom(s)
k_d	attenuation coefficient (m^{-1})
NYSDEC	New York State Department of Environmental Conservation
PAR	photosynthetically available radiation
POC	particulate organic carbon
PP	particulate phosphorus ($= TP - TDP$)
SC	specific conductance
SD	Secchi disk depth (m)
SLA	Skaneateles Lake Association
SRP	soluble reactive phosphorus
TDP	total dissolved phosphorus
TP	total phosphorus concentration
TSI	trophic state index
UFI	Upstate Freshwater Institute