Lakes Environmental Association

2021 Water Testing Report

Chapter 2 — Automated Monitoring Buoys

LEA's Automated Buoys

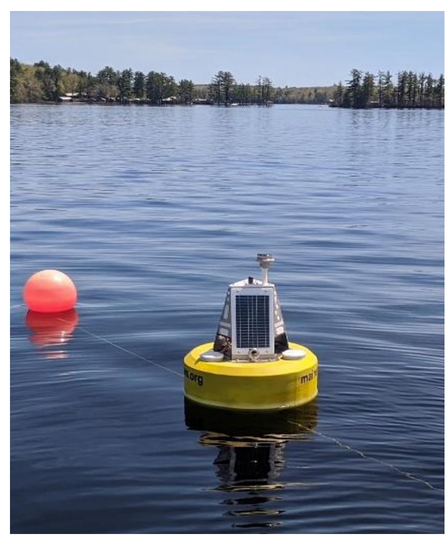
Highland Lake buoy

Each year, LEA deploys two fully automated monitoring buoys – one on Highland Lake and one on Long Lake in the north basin (see map next page). These buoys collect water quality information at 15-minute intervals throughout the spring, summer, and fall. This data is transmitted to us in real time, so we can see conditions change on the lake as they happen. The goals of LEA's monitoring buoy program are to better understand the condition of our lakes, to raise awareness of water quality issues locally, and to contribute to worldwide research and knowledge on lakes.

The Highland Lake buoy was first deployed in 2014 and has seven temperature and oxygen sensors mounted at 2-meter (6.6-ft) intervals from the surface of the lake to near the bottom. Also mounted on the buoy are two solar radiation sensors and a single chlorophyll sensor, as well as a small weather station for measuring precipitation, barometric pressure, relative humidity, wind speed and direction, and air temperature. The Long Lake buoy was first deployed in August 2016. Like the Highland Lake buoy, it has oxygen and temperature sensors at 2-meter intervals (total of eight) and a single chlorophyll sensor. Both buoys use three 10-watt solar panels and a rechargeable battery as their power supply (see schematic next page).

The advantages of these buoys are that they automate and enhance the water quality monitoring process. Our traditional (boat-based) water testing program collects data once every two weeks from each lake, usually around the same time of day. In contrast, the buoys automatically record readings from each sensor every 15 minutes, or 96 times per day and can be left in the water longer than the traditional monitoring season. Even though the buoys measure fewer water quality parameters than the testing program does (for instance phosphorus is not measured), the wealth of additional data gives us an incredibly detailed picture of what is happening in the lake at any given time throughout the open-water growing season. The simultaneous measurements of water temperature, dissolved oxygen, algae (chlorophyll), water clarity, and weather conditions lets us see the effects of air temperature, wind, and precipitation events in real time, thus allowing us to better interpret how these factors affect lake conditions.

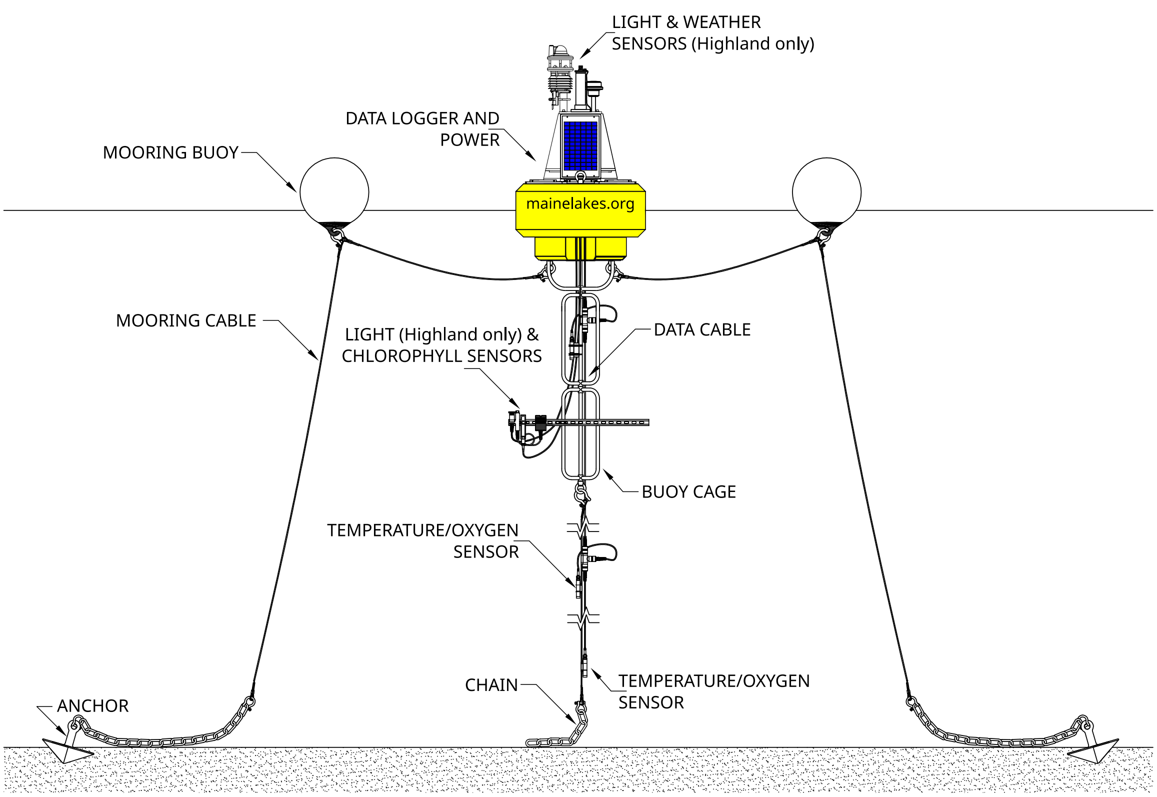
Another aspect of the buoy program is our ability to collaborate with researchers on a larger scale by sharing ideas and methods and contributing to research. Buoys similar to LEA's can be seen in lakes throughout New England and the world. An international organization called GLEON (Global Lake Ecological Observatory Network) helps to connect researchers that collect and use lake data, particularly from automated monitoring buoys, for a variety of projects. GLEON's mission is "to understand, predict, and communicate the impact of natural and anthropogenic influences on lake and reservoir ecosystems".



Long Lake buoy

LEA could not have acquired either buoy without a great deal of support from several sources. The Highland buoy was funded by a grant from an anonymous foundation and contributions from landowners around Highland Lake. The Long Lake buoy was funded by a very generous donation from a resident of Long Lake, foundation funding, and contributions from lakefront landowners. LEA worked closely with Colby College professor Dr. Whitney King and Fondriest Environmental to design and set up the buoys.

Map of buoy locations

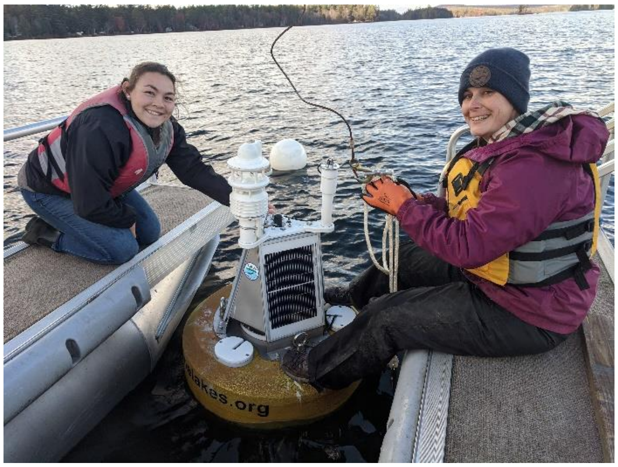


Automated Buoy Schematic

2021 Buoy Deployment

We present the latest buoy findings in three sections beginning with a general summary of the deployment and data followed by a summary of weather conditions that helped drive the patterns of temperature, oxygen, and algae in each lake in 2021. Those patterns are then presented for each lake in the remaining two sections.

Deployment and Results Summary



The 2021 deployment of the automated buoys began on May 24 for Highland Lake and on May 28 for Long Lake. The buoys were in place recording data until November 10 (Highland) and 11 (Long), when they were removed from the lakes. Thermal stratification had already occurred prior to the start of deployment, but we did capture the time point of complete lake mixing (fall turnover) before we retrieved the buoys. During deployment, we performed two to three onsite cleaning and calibration checks for the sensors on each buoy. One oxygen sensor on the Long Lake buoy failed and had to be replaced with a backup sensor. Combined, the buoys collected 32,300 sets of sensor readings during their time (168 to 171 days) on the water. Much of this data was available in real time on our website.

The water temperature patterns in both lakes showed the same basic response to the warmer and drier-than-average conditions of 2021. Stratification and mixing events occurred about the same time; wind events in July and late September led both lakes to mix deeply followed by restratification during the warm August and October that followed. Still, the water temperature patterns did vary between the two lakes due in large part to contrasting size and shape. For example, the thermocline depth (location in the water column where temperature changes most rapidly) was generally deeper and the temperatures were slightly warmer at the deeper Long Lake site. Complete mixing (lake turnover) occurred in Long Lake three days later than in Highland Lake.

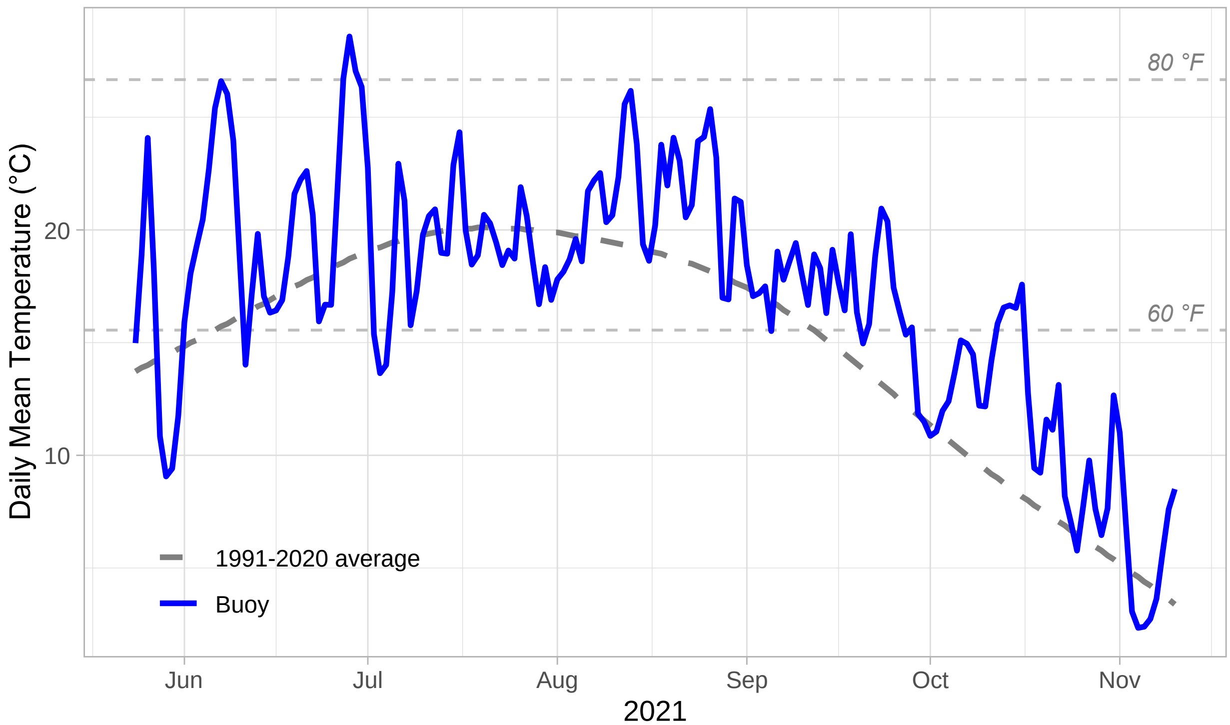
In both lakes, dissolved oxygen declined as temperature increased and as stratification strengthened. Anoxia (absence of dissolved oxygen) occurred in each system in 2021, but as in previous years, Highland Lake's greater oxygen consumption rate meant that it developed anoxia sooner (early July as opposed to late August) and lasted longer than Long Lake.

Chlorophyll fluorescence, which is an estimate of algae concentration, was slightly lower in Highland Lake than Long Lake, though differences could be related to the deeper location of the sensor. Fluorescence on the Highland buoy increased in between visits apparently due to the growth of algae near the sensor. Less biofouling and less impact on the fluorescence signal was noticed on the Long Lake buoy, again possibly related to the greater depth of the sensor.

Overall, the 2021 season was a success for the automated buoys. Staff members Ben Peierls, Maggie Welch, Lauren Pickford, and Alyson Smith and interns Shannon Nelligan and Hanna Holden provided technical support in the field. Former intern Garrett Higgins volunteered to help deploy the Highland Lake buoy. Thanks goes to all who were involved.

Weather Conditions (Highland Lake)

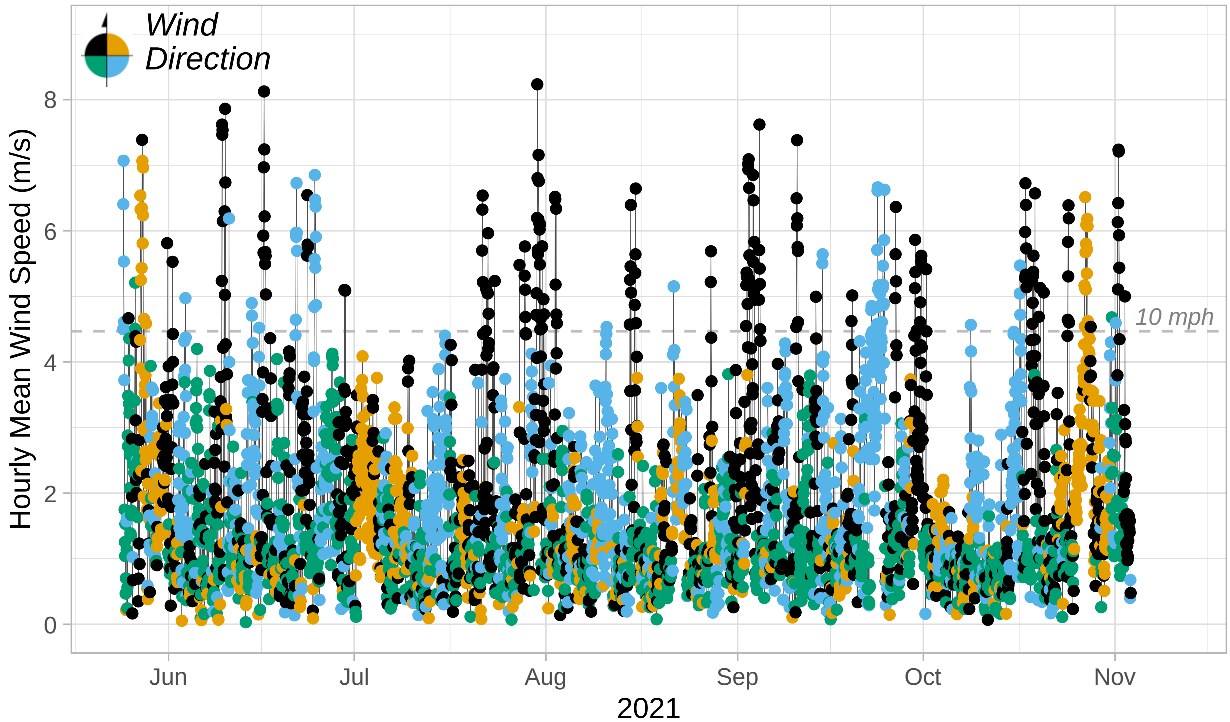
Air Temperature



Local weather conditions (air temperature, wind, rain) play a major role in controlling lake water quality. Sensors on the Highland Lake buoy collect weather and water data simultaneously, and in this section we summarize the weather results. Because the two lakes are geographically close together, the Highland Lake weather data are applicable to Long Lake as well, though the surrounding topography does affect local conditions at each site. Air temperature is important for understanding the heating, cooling, stability, and evaporation of lakes because it plays a strong role in the heat balance of surface water. Instantaneous air temperature measured on the buoy ranged from -2.3 to 33.4 °C (27.9 to 92.1 °F). The daily mean values (blue line, above) followed a typical seasonal pattern albeit warmer than normal for this area (1991-2020, gray dashed line, above; source: Global Historical Climatology Network, Station USC00170844 Bridgton) throughout much of the deployment. June, August, late September, and the first half of October were good examples of this, while July temperatures were mostly at or below normal temperature. Warm weather favors stable, stratified lake conditions, while cooler temperatures reduce the energy needed to mix water layers. In previous years we have compared our buoy data to a nearby land-based weather station, but information from that location was unavailable this year. Those past comparisons have shown almost identical readings except for more extreme values over land, which shows how lake water can have a moderating influence on the overlying air temperature.

Weather Conditions (Highland Lake)

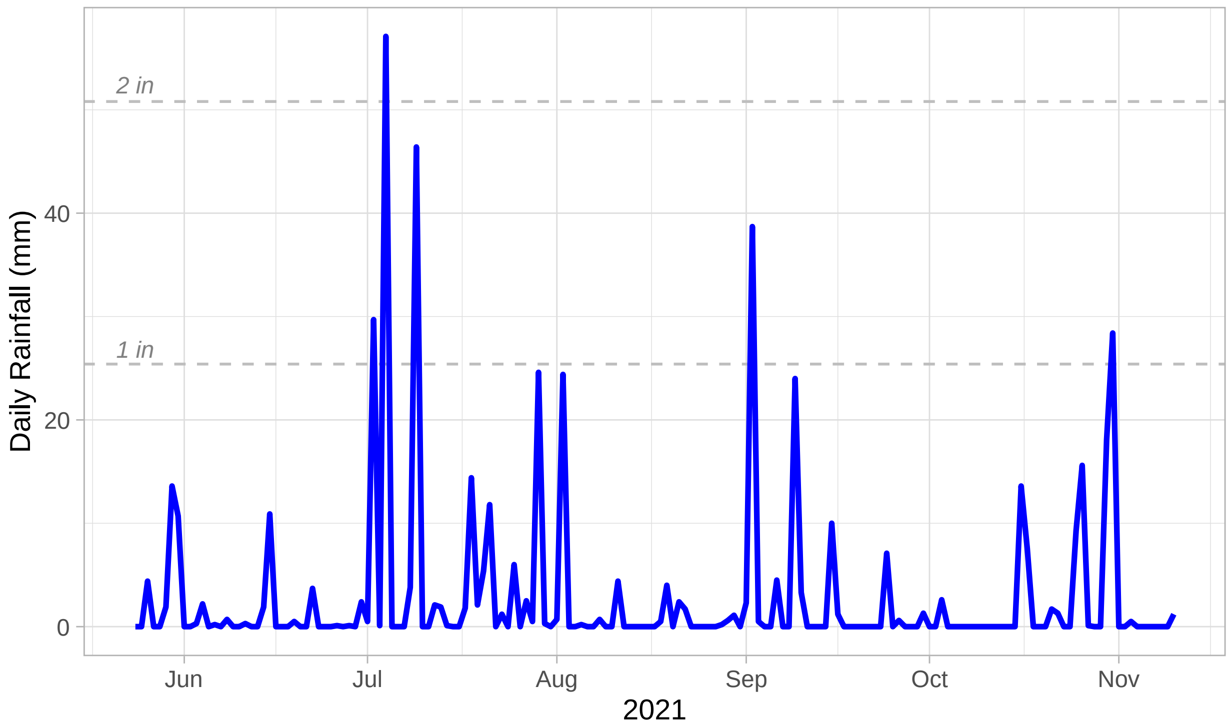
Wind



Wind also has a significant impact on conditions within a lake. Together with temperature, wind controls the physical structure of a lake, like the change from being stratified to being fully mixed. Wind speed and direction measurements recorded by the buoy were quite variable at the 15-minute scale, so broader scale patterns were examined using hourly mean values. In the figure above, the height of the point denotes the mean wind speed and the color indicates the direction from which the wind is blowing (like a weather vane); black means the wind was blowing from anywhere in the north to west (N-W) quadrant, for example. Hourly mean wind speed ranged from 0.030 to 8.2 m/s (0.067 to 18 mph), and the buoy recorded a maximum wind speed of 14.4 m/s (32.2 mph) on November 1. Other notable strong winds occurred in late May, throughout June, late July, early and late September, and middle to late October. Wind direction was highly variable, though stronger winds tended to come out of the N-W and S-E quadrants, the prevailing winds for this area. Since the longest lake axis is aligned in those directions, wind measurements at the buoy may be stronger for prevailing winds than other directions because they are unimpeded by local topography. An exception to this was when the passage of a nor'easter on October 27 produced strong northeasterly winds; this event may have been the final push to fully mix Long Lake.

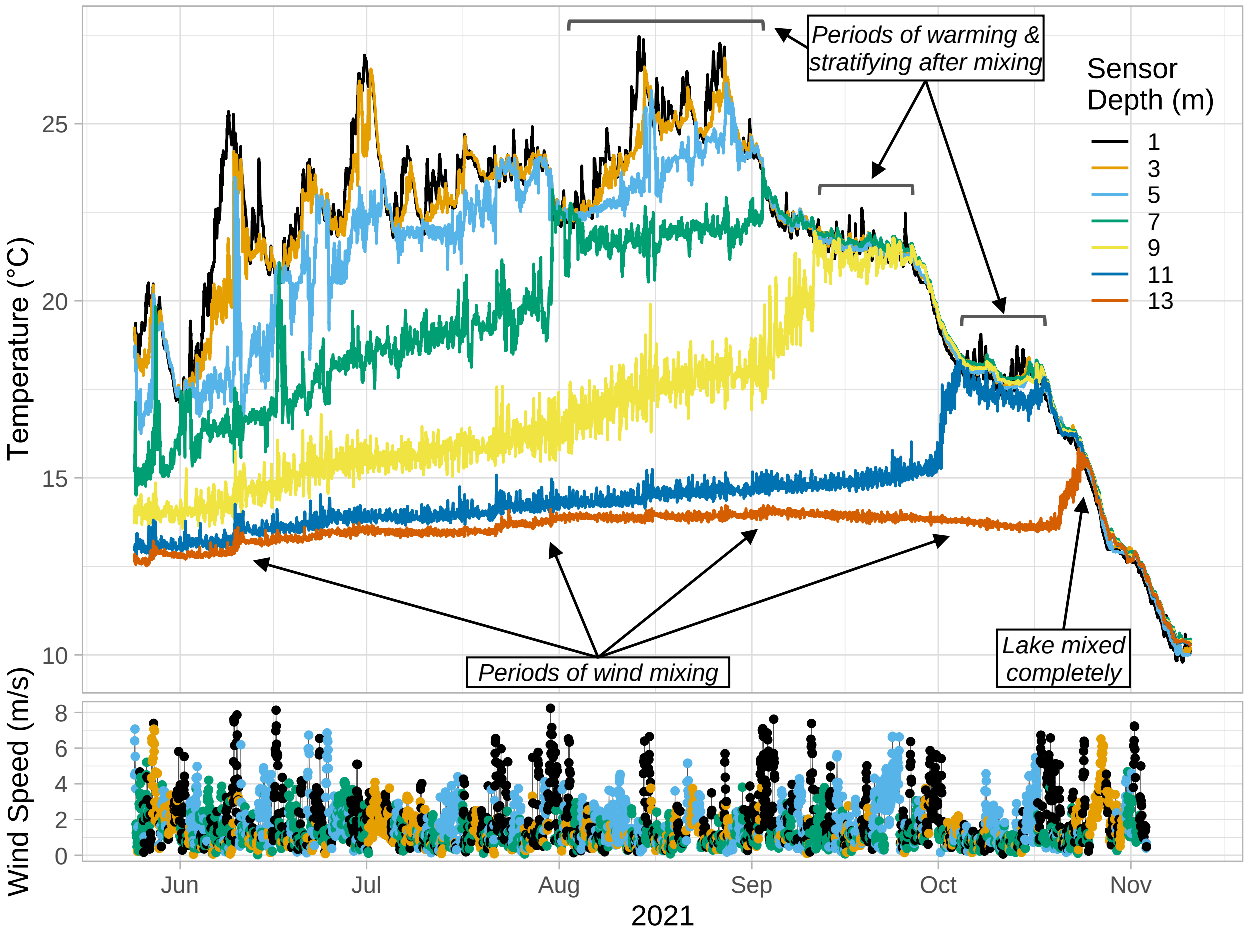
Weather Conditions (Highland Lake)

Rain



Rain adds water directly to a lake and also indirectly through watershed runoff. Rain is important in maintaining lake levels, but sediment and nutrients can be delivered along with it, depending on rain amount and intensity. Total rain recorded by the buoy during the 2021 deployment was about 501 mm (19.7 in), which was more than last year, but quite a bit less than the 30-year normal rainfall of 668 mm (26.3 in) for May through October. This came following another lower-than-normal winter snowfall and a return to drought conditions in April. Significant rainfall in early July, including the highest single day total of 57.1 mm (2.24 in) from the remnants of Tropical Storm Elsa, ended the drought conditions. Drier conditions returned in August followed by more wet weather in September. The remnants of Hurricane Ida brought 41 mm (1.6 in) of rain at the beginning of the month. More post-tropical storms impacted the area in the second half of October to close out the season's rainfall. High intensity storm events have the most impact on water quality because of the erosion and pollution potential. Most of the time when rain fell, rain intensity was about 2 mm per hour (0.08 in/hr), but the buoy recorded a maximum of 57.1 mm per hour (2.25 in/hr) on July 4; this was the highest rainfall rate yet recorded by the buoy. Climate change models predict that along with warming air and water temperature, Maine will experience more precipitation and more periods of high intensity rainfall.

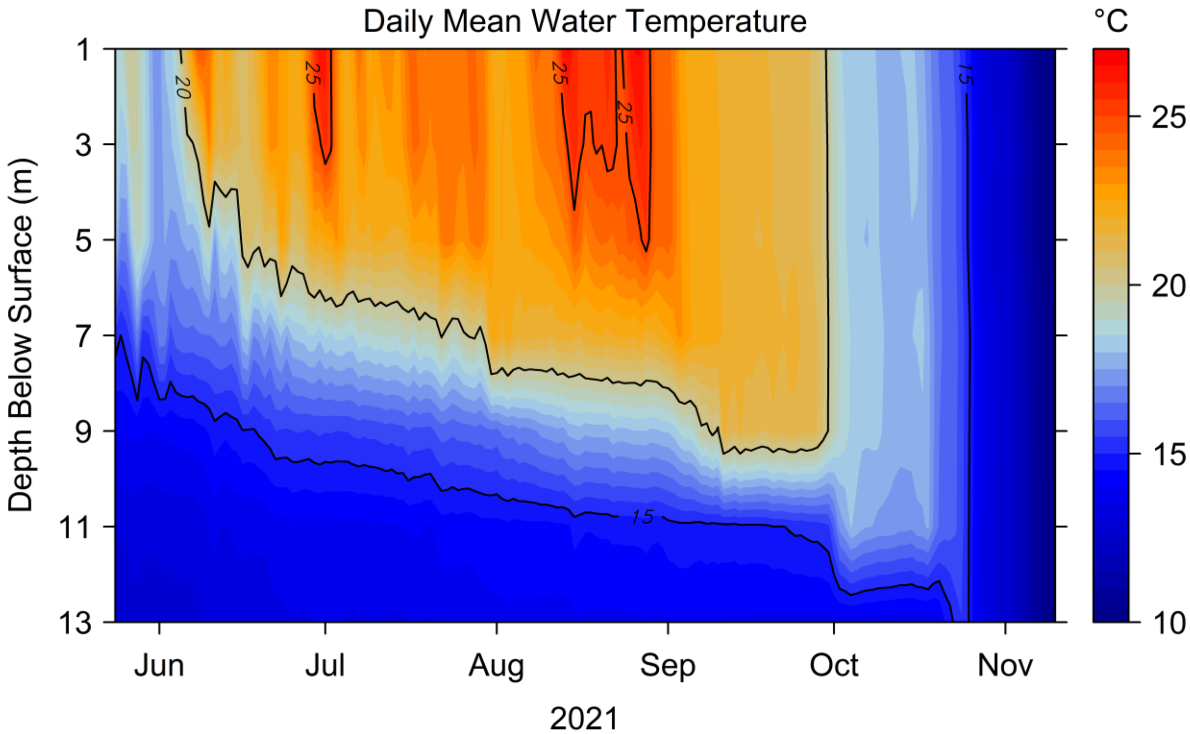
Water Temperature



Water temperature data forms the foundation for most water quality measures and is essential for understanding lake physical dynamics, nutrient cycling, metabolic rates, and habitat availability for fish and other aquatic organisms. Data from the individual temperature sensors, along with hourly mean winds, are shown in the above figure. Each colored line represents water temperature at a specific depth below the surface recorded at 15-minute intervals. The maximum recorded temperature on Highland Lake was 27.5 °C (81.5 °F) on August 13, and the minimum temperature was 9.79 °C (49.6 °F) on November 6. Daily heating and cooling of the surface water can be seen in the saw-tooth pattern of the 1-m sensor data (black line). That daily cycle dissipates with depth, and the temperature variation gradually gets more rapid and irregular from the "sloshing" of internal waves (or seiches) caused by wind energy. Stratification (indicated by wide spaces between lines) had already occurred before the buoy was deployed, and partial mixing (lines overlapping at the same temperature) happened throughout the season, especially at times of high winds. Good examples of this can be seen in early June, late July, early September, and the beginning of October. Calm, warm periods after mixing can cause lake water to stratify again as seen in early August and more subtly in mid-September and the first half of October. Aside from those periods, surface waters started cooling in September, which gradually reduced the resistance to mixing in the water column. Complete mixing occurred on October 24 following significant wind events that continued through the fall. This turnover date is one of the latest yet recorded by the automated buoy or previous temperature sensor arrays (see table on next page). By comparison, Long Lake mixed three days later on October 27.

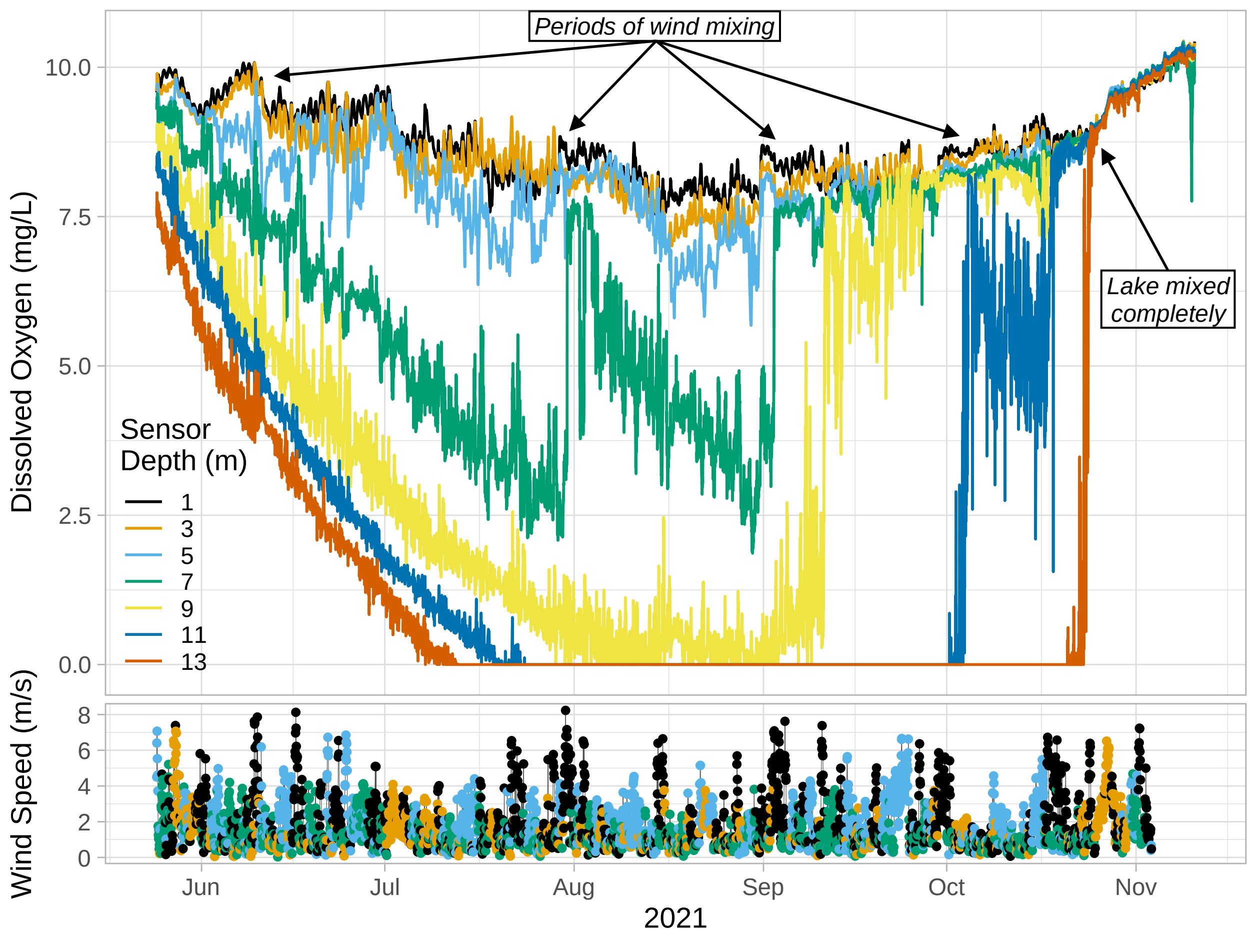
Date of Fall Turnover (Complete Mixing) by Year

YEAR	2013	2014	2015	2016	2017	2018	2019	2020	2021
Turnover Date	after 10/11	10/12	10/11	10/10	11/4?	10/16	10/9	10/8	10/24



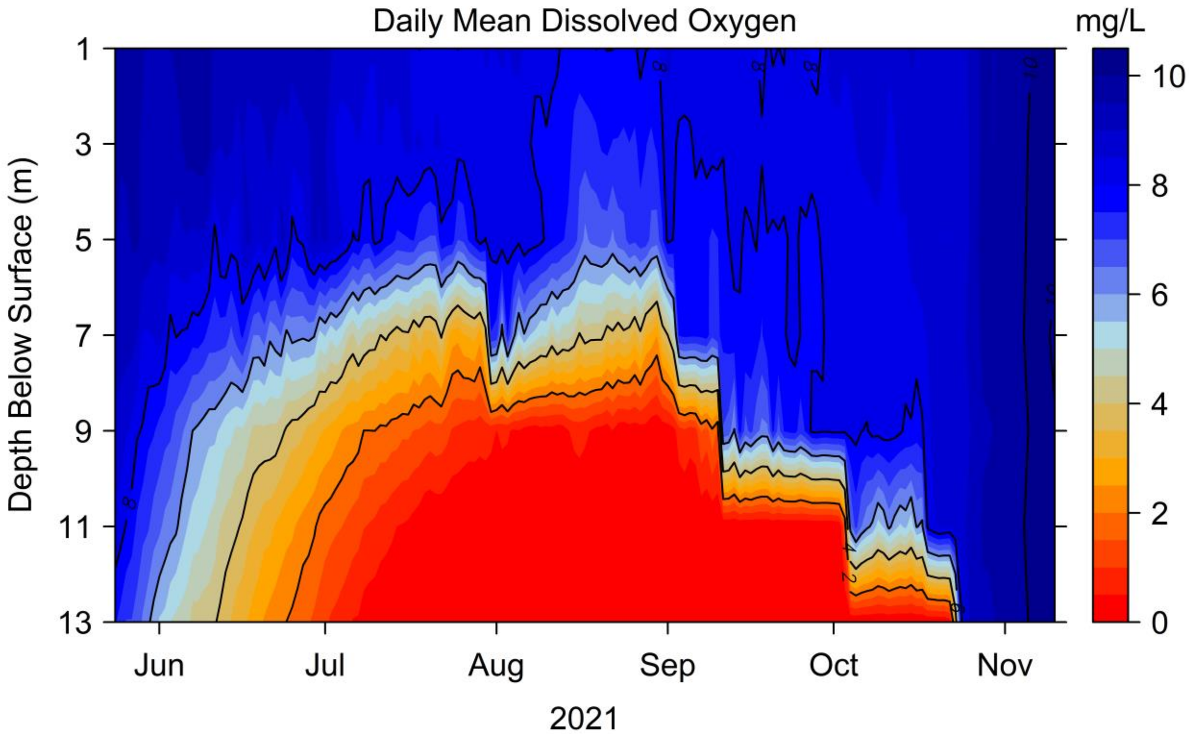
Another, perhaps easier, way to visualize the temperature data is with contour plots (or heat maps) shown in the figure above, which uses daily mean values for smoother lines. Temperature variation across depth and time is represented by colored contours, where the blue to red color range corresponds to a low to high temperature range. Temperature stratification shows up as areas of the plot where colors change in the vertical direction and contour lines are tilted more towards horizontal (from June through early October). The area where contours come closest together (i.e., temperature changes most rapidly with depth) is often referred to as the thermocline. Vertical contour lines indicate mixed conditions, and areas of a single color from top to bottom (such as late-October into November) indicate completely mixed conditions. The effect of wind, like the events previously discussed, can be seen as dips in the contour lines. Warm, stratified conditions stand out as darker red and orange areas during July through August. The downward sloping contours show that the upper layer (epilimnion) and thermocline deepened throughout the summer; thermocline depths ranged from 3 m in June to 12 m before lake turnover.

Dissolved Oxygen



The same types of plots used for temperature can be used to examine the dissolved oxygen (DO) time series collected at each buoy. The data shown above has been corrected for sensor drift and biofouling using independent, discrete DO measurements at the same location. The data exhibit a pattern of generally decreasing DO from the start of the record through August. Some of that is simply due to warming water, since cold water can contain more DO than warm water, all else being equal. Oxygen in the deeper waters, however, decreased more rapidly; deep DO readings reached zero (anoxia) by early July. This is due to biological consumption (animals and bacteria using oxygen) and the reduced aeration (wind mixing) during stratified conditions. With strong enough winds, however, deeper waters were able to be mixed as evidenced by the rapid and large DO concentration swings from late July through October. The daily warming-cooling cycle of the air, the daily cycle of photosynthesis and respiration, and the back and forth rocking of internal waves are responsible for the smaller variations in DO concentration seen in the figure. By late October, the water column was completely saturated with oxygen after temperatures dropped and winds fully mixed the lake.

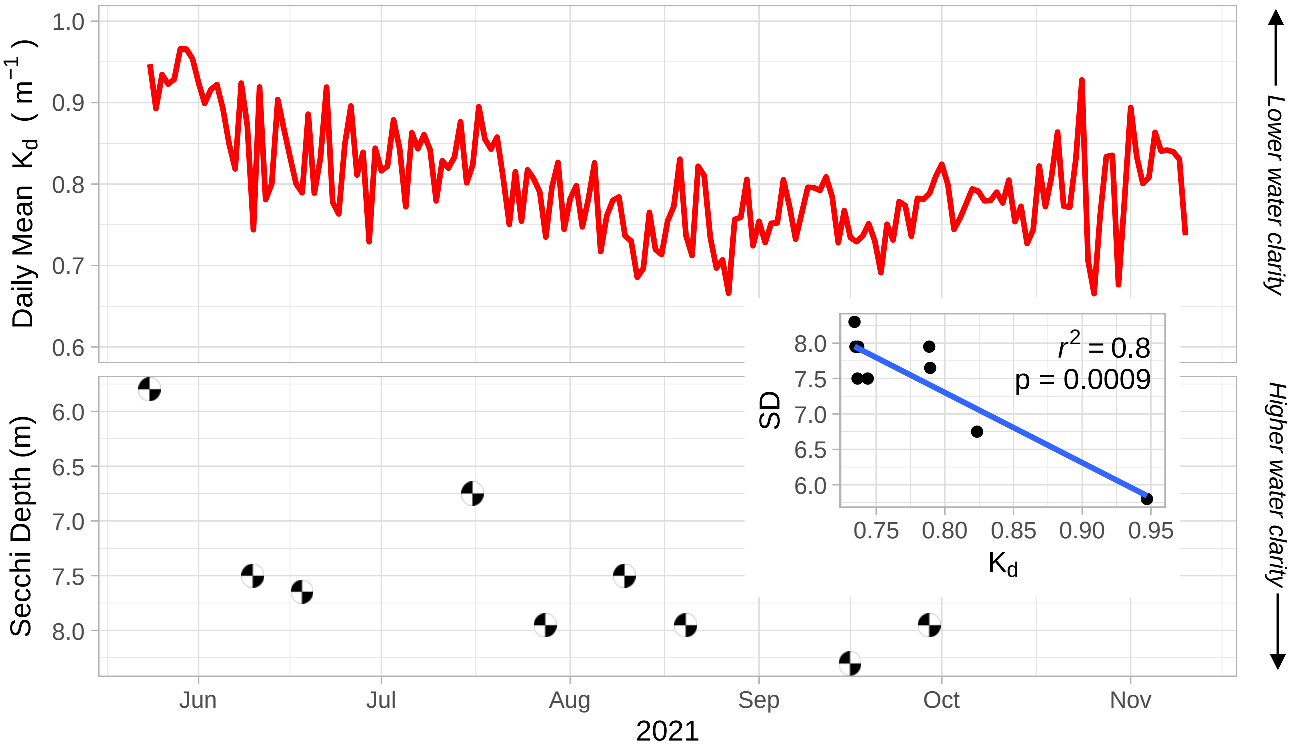
Highland Lake Conditions 2021



We can also illustrate the buoy dissolved oxygen (DO) data using depth-date contour plots as was done for temperature, though here we have reversed the color scheme so that red and blue signify low and high DO, respectively. The contour plot highlights nicely the pattern of lower DO concentrations in summertime deep waters and provides a quick visual gauge of where and when hypoxic (DO < 2 mg/L) conditions occur. As was seen in the previous line plot, Highland Lake bottom water became anoxic (DO = 0 mg/L) starting in early July and remained so until late October, when the water column mixed completely. Anoxia reached into waters as shallow as 9 m (ca. 30 ft) during the summer. Prior to lake turnover, more minor wind mixing events can be seen in the downward dips in the DO contours, such as the late July, September, and early October events.

Besides wind and water temperature, the major control of lake water DO concentrations is biological activity (i.e., respiration and photosynthesis). Oxygen is a byproduct of photosynthesis, so actively growing algae can be an additional source of oxygen in shallow, aerated, well-lit waters. In contrast, deep water DO is reduced when microbes, fish, and plants respire or “breathe” and oxygen cannot be replenished due to thermal stratification. This oxygen consumption eventually leads to hypoxia and anoxia. Fish tend to avoid and are stressed when moving through areas that have DO concentrations below about 4 mg/L, while anoxic bottom waters allow phosphorus trapped in sediments to be released for use by algae; these phenomena highlight the importance of collecting oxygen data.

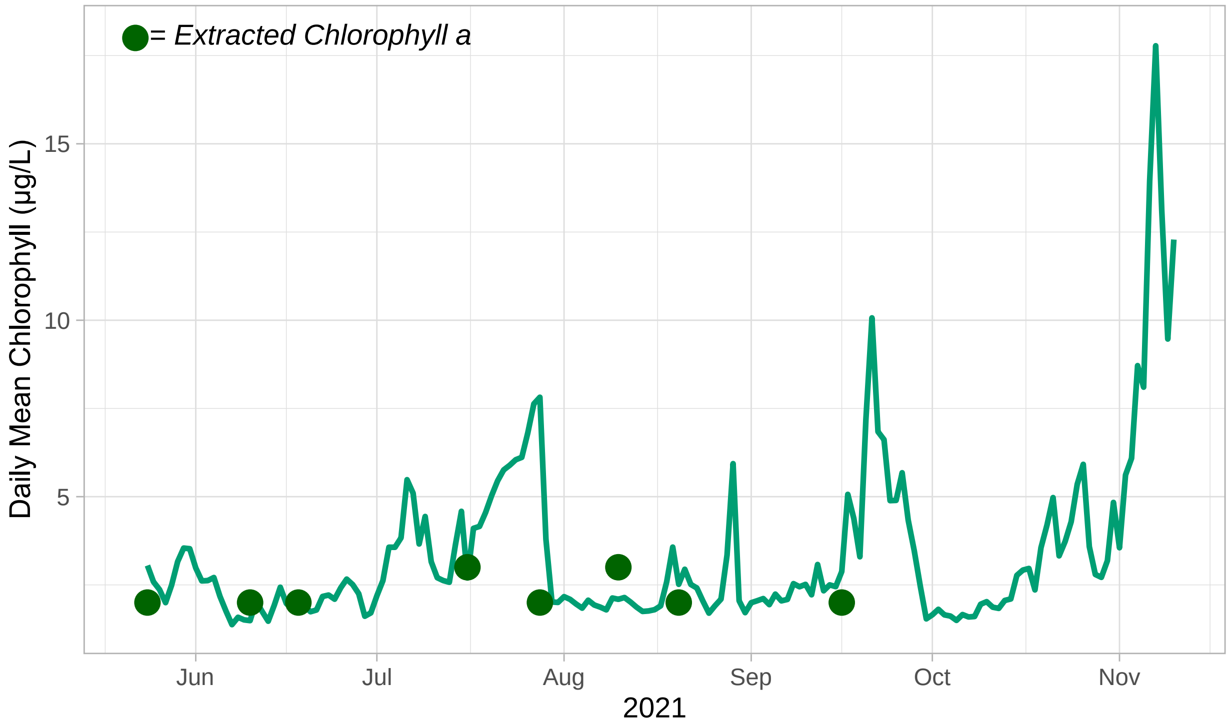
Light Attenuation (Water Clarity)



The Highland buoy has two light sensors, one mounted on top of the buoy and one mounted at 1.5 m depth below the water surface. Both sensors measure the amount of light at visible wavelengths (400-700 nm) reaching them, but the underwater sensor receives less light because the water and the matter it contains reduces or attenuates the solar energy. This decrease in light with depth is quantified using the light attenuation coefficient (or K_d), which is calculated from the above- and below-water sensor readings. K_d is a measure of water transparency or clarity like Secchi depth, only smaller K_d values indicate clearer water. When K_d equals 1, the photic zone (where there is enough light for algae to grow) is about 4.6 m deep and a K_d of 0.6 means the photic zone is about 7.8 m deep. At the buoy, daily mean K_d varied from 0.67 to about 1 m^{-1} with an overall mean of 0.8 m^{-1}. Higher K_d values (lower clarity) occurred in May, June, July, and October, while lower K_d values (higher clarity) were measured from late July through early October.

Light attenuation is a function of material that absorbs or reflects light like humic and tannic acids, soils and sediments, algae, and even water itself. These same factors influence Secchi depth measurements, so we expect these two water clarity indicators to be correlated. The lower panel shows Secchi depths measured near the buoy during regular monitoring trips; note that the depth scale is reversed. The two parameters have the same temporal pattern and were strongly related (see inset plot). Since water clarity can be controlled by wind-driven sediment resuspension, we examined the buoy data for any connection. We did find that wind speed was weakly correlated to K_d, but water clarity is likely controlled by a combination of factors like the ones previously mentioned. The buoy light data is essential to better understand and monitor changes in water clarity.

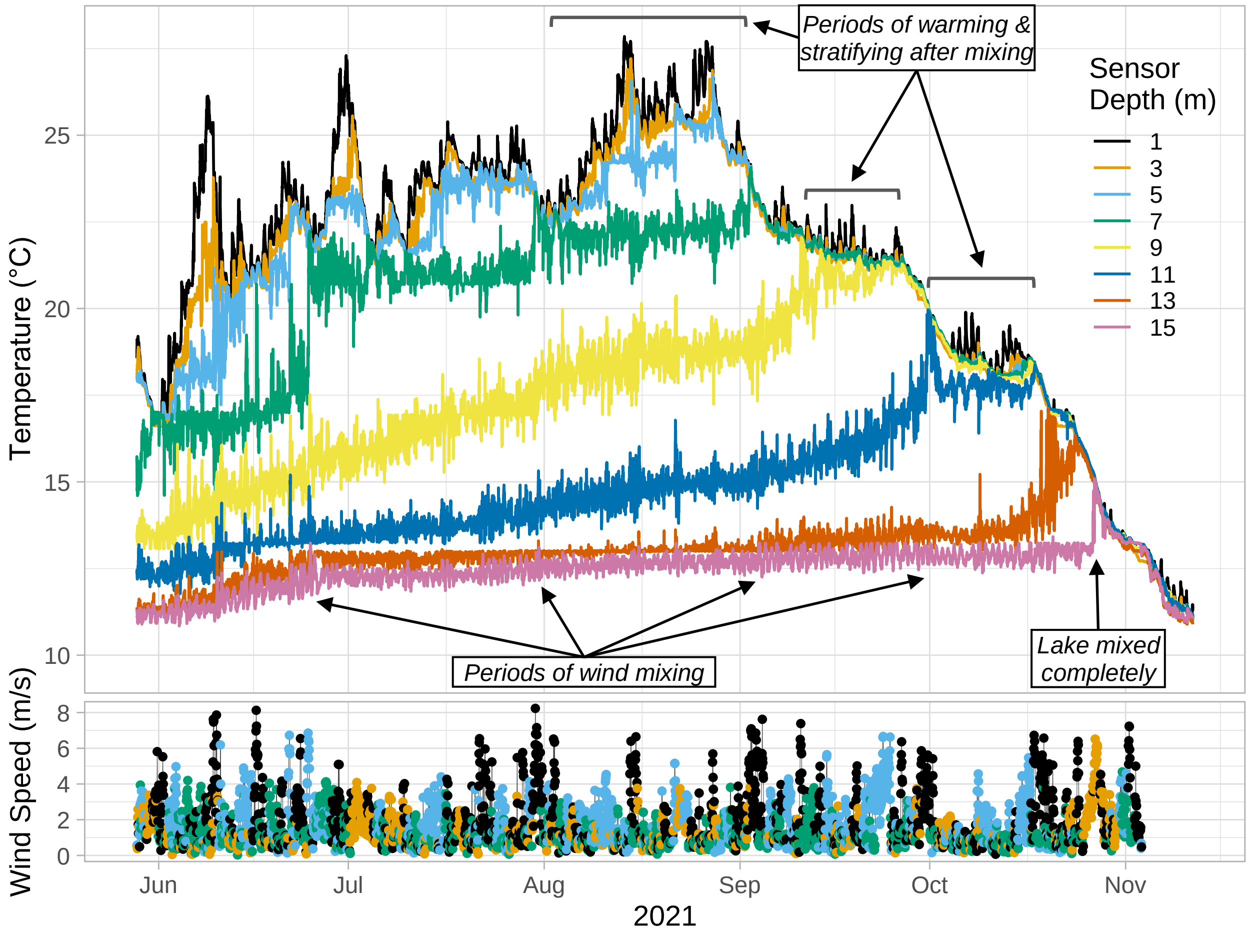
Chlorophyll or Algae Biomass



The Highland buoy has one sensor mounted 1.5 m below the lake surface that measures chlorophyll concentrations using fluorescence (same as the field fluorometer used on regular testing trips and discussed in Chapter 4 of the Water Testing Report). The amount of this pigment (found in all plants and algae) can be used as a proxy for algae biomass and as a measure for the productivity of a lake. It is important to note that field fluorescence is a relative measure and is not as accurate as lab-based chlorophyll *a* measurements. Also, chlorophyll fluorescence often shows variation with depth and the buoy can only measure at a single discrete depth. Still, buoy chlorophyll and extracted chlorophyll *a* concentrations in the epilimnion (upper mixed layer) from our regular testing trips (points in the figure above) were quite similar. Daily mean chlorophyll fluorescence, after filtering out extreme outliers, ranged from about 1 to 18 µg/L, with a mean of 3.4 µg/L (or parts per billion).

We found heavy filamentous algae growth near the sensor when we pulled the buoy for cleaning at the end of July and September. Since chlorophyll declined rapidly after the visits, the increased chlorophyll in July and September was likely due to biofouling and not algae in the water. Chlorophyll (algae) can increase if nutrients (phosphorus) and light are available. Therefore the increase in chlorophyll at the end of October could be a function of nutrients introduced into surface waters by mixing from deep layers, but biofouling was more likely the cause of the extreme values. Runoff from rain events add nutrients that fuel algae production, but the uncertainty in the buoy chlorophyll record limits our ability to correlate it with rainfall. There are, of course, other factors that control algae populations, like competition between different species and zooplankton grazing, but those are beyond the monitoring capabilities of the buoy.

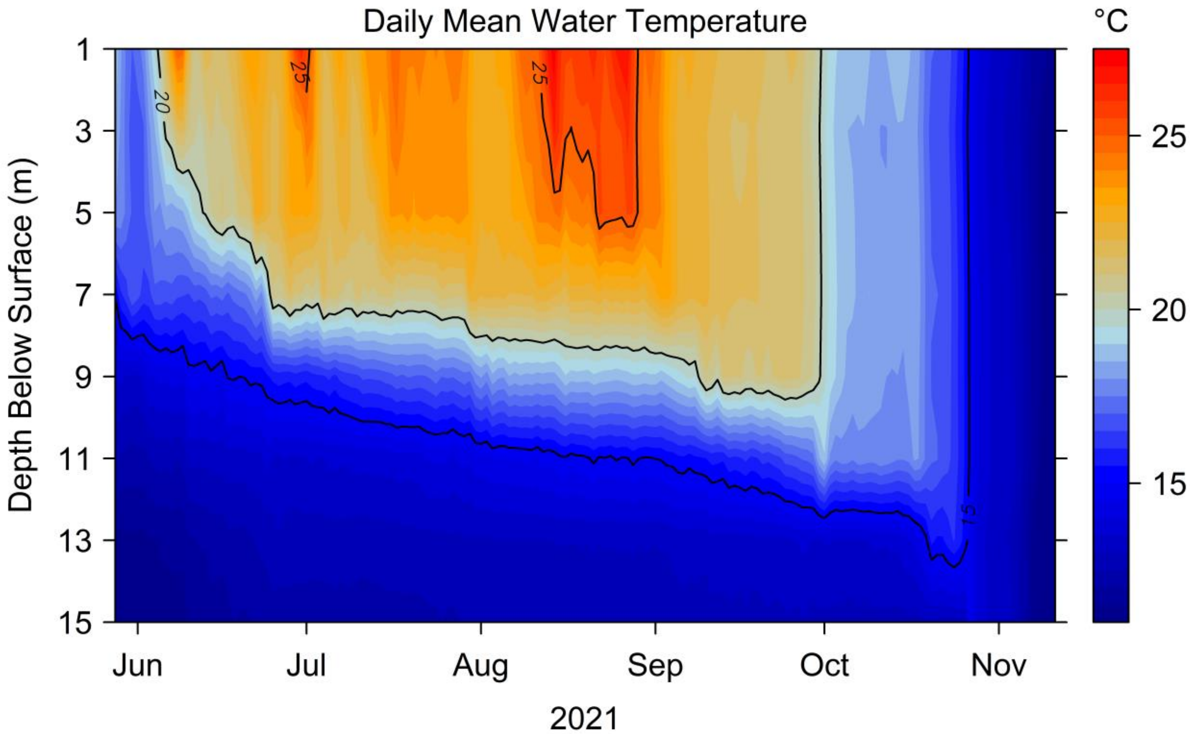
Water Temperature



Water temperature data forms the foundation for most water quality measures and is essential for understanding lake physical dynamics, nutrient cycling, and habitat availability for fish and other aquatic organisms. Data from the individual temperature sensors, along with hourly mean winds, are shown in the above figure. Each colored line represents water temperature at a specific depth below the surface recorded at 15-minute intervals. The maximum recorded temperature on Long Lake was 28.9 °C (84.0°F) on August 1, and the minimum temperature was 9.0 °C (48.2 °F) right before the buoy was removed for the season. Daily heating and cooling of the surface water can be seen by the saw-tooth pattern of the 1 m sensor data (black line). Temperature variation was more irregular and sometimes greater in the middle of the water column due to the "sloshing" of internal waves (or seiches) caused by wind energy. Stratification (indicated by wide spaces between lines) had already occurred before the buoy was deployed and partial mixing (lines getting closer together) happened throughout the season, especially at times of high winds. Good examples of this can be seen in late June, late July, early September, and at the beginning of October. Calm, warm periods after mixing can cause lake water to stratify again as seen in early August and more subtly in in mid-September and the first half of October. Aside from those periods, surface waters started cooling in September, which gradually reduced the resistance to mixing in the water column. Complete mixing first occurred on October 27 following significant wind from passing nor'easters. This turnover date is one of the latest yet recorded by the automated buoy or previous temperature sensor arrays (see table on next page). By comparison, Highland Lake mixed three days earlier on the October 24.

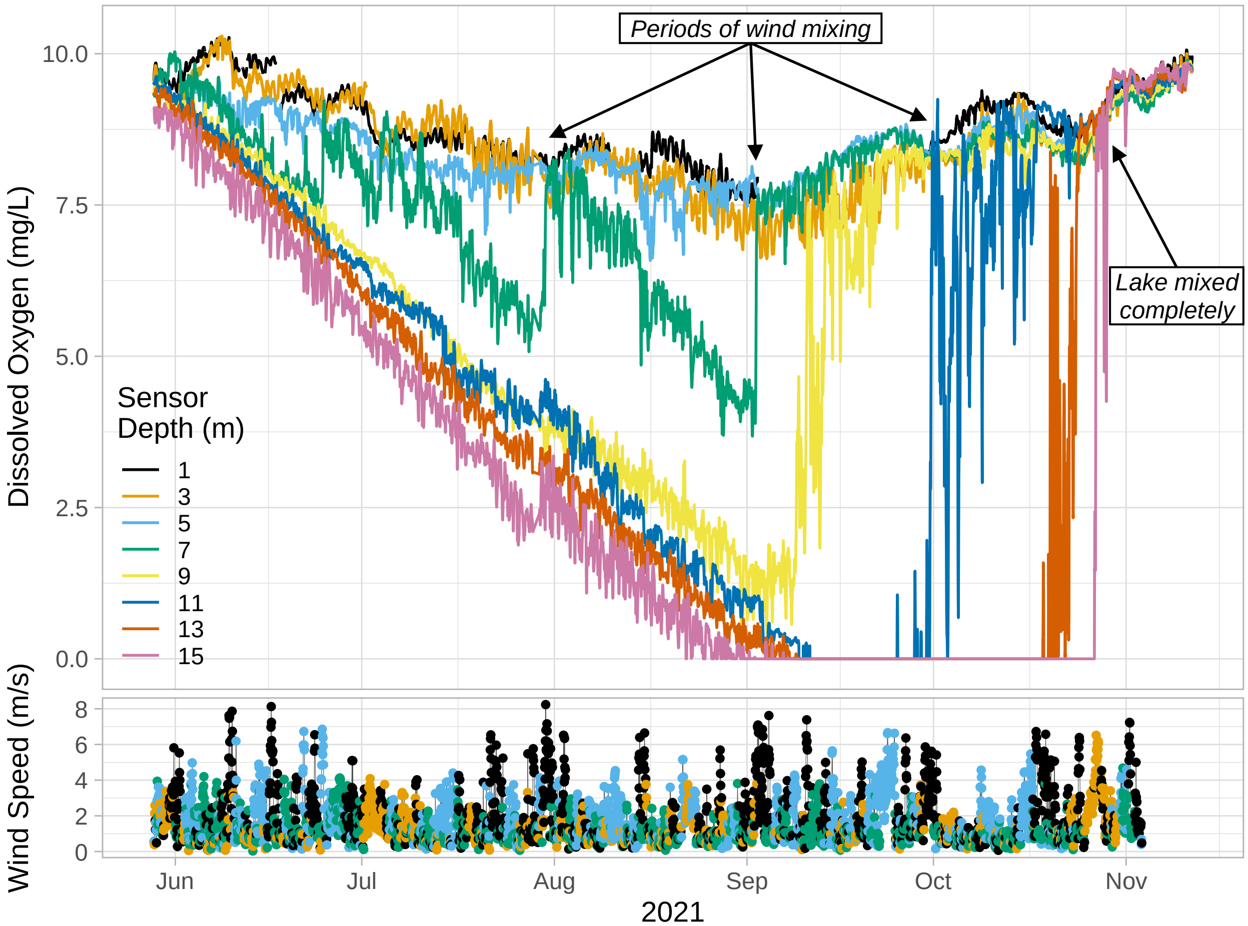
Date of Fall Turnover (Complete Mixing) by Year

YEAR	2013	2014	2015	2016	2017	2018	2019	2020	2021
Turnover Date	10/25	10/23	N/A	N/A	11/4	10/18	10/18	10/8	10/27

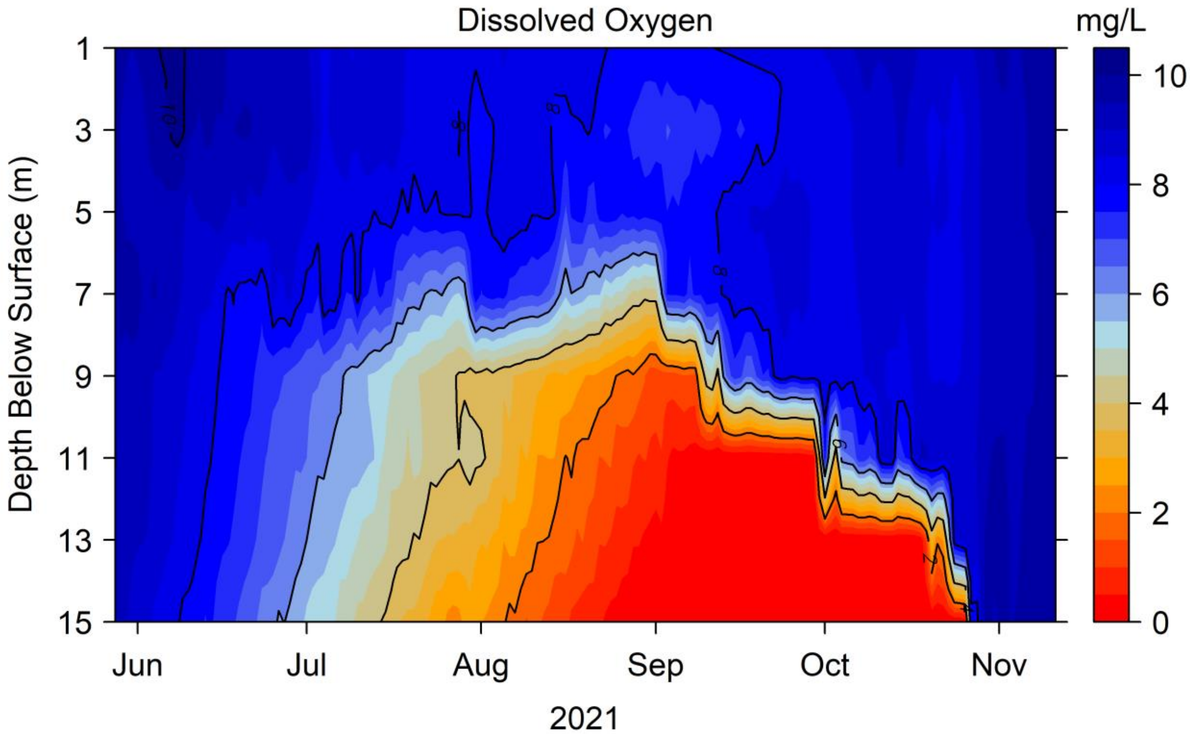


Another, perhaps easier, way to visualize the temperature data is with contour plots (or heat maps) shown in the figure above, which uses daily mean values for smoother lines. Temperature variation across depth and time is represented by colored contours, where the blue to red color range corresponds to a low to high temperature range. Temperature stratification shows up as areas of the plot where colors change in the vertical direction and contour lines are tilted more towards horizontal (from June through early October). The area where contours come closest together (i.e., temperature changes most rapidly with depth) is often referred to as the thermocline. Vertical contour lines indicate mixed conditions, and areas of a single color from top to bottom (such as late October into November) indicate completely mixed conditions. The effect of wind, like the events previously discussed, can be seen as dips in the contour lines. Warm, stratified conditions stand out as darker red and orange areas during July through August. The downward sloping contours show that the upper layer (epilimnion) and thermocline deepened throughout the summer; thermocline depths ranged from about 5 m in June to 14 m before lake turnover.

Dissolved Oxygen



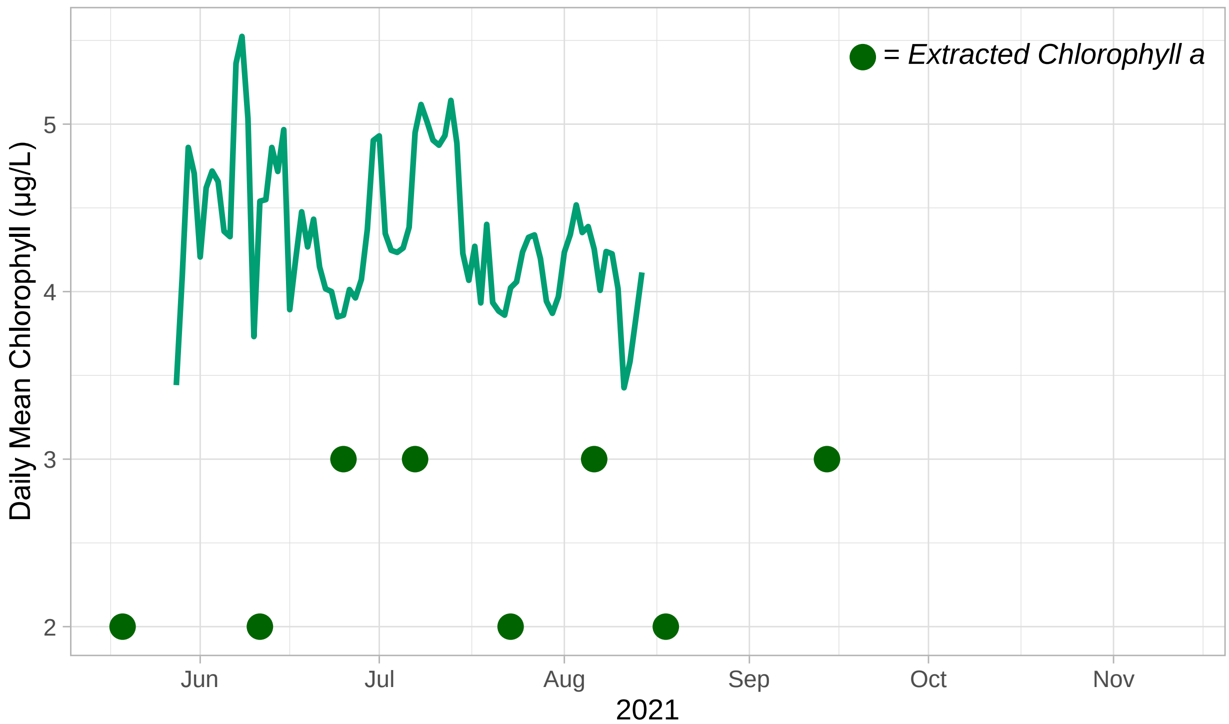
The same types of plots used for temperature can be used to examine the dissolved oxygen (DO) time series collected at each buoy. The data shown above has been corrected for sensor drift and biofouling using independent, discrete DO measurements at the same location. The 1-meter sensor had periods of bad readings and eventually failed altogether, which led to some gaps in the record. DO generally decreased from the start of the deployment through August. Some of that is simply due to warming water, since cold water can contain more DO than warm water, all else being equal. Oxygen in the deeper waters, however, decreased more rapidly; deep DO readings reached zero (anoxia) by late August. This is due to biological consumption (animals and bacteria using oxygen) and the reduced aeration (wind mixing) during stratified conditions. With strong enough winds, however, deeper waters were able to be mixed as evidenced by the rapid and large DO concentration swings from late July through October. The daily warming-cooling cycle of the air, the daily cycle of photosynthesis and respiration, and the back and forth rocking of internal waves are responsible for the smaller variations in DO concentration seen in the figure. By late October, the water column was completely saturated with oxygen after temperatures dropped and winds fully mixed the lake.



We can also illustrate the buoy dissolved oxygen (DO) data using depth-date contour plots as was done for temperature, though here we have reversed the color scheme so that red and blue signify low and high DO, respectively. The data has been interpolated to fill in the gaps due to missing readings from the surface sensor. The contour plot highlights nicely the pattern of lower DO concentrations in summertime deep waters and provides a quick visual gauge of where and when hypoxic (< 2 mg/L) conditions occur. As was seen in the previous line plot, Long Lake bottom water became anoxic (DO = 0) by late August and remained so until late October, when the water column mixed completely. Anoxia reached into waters as shallow as 11 m (ca. 36 ft) during the summer. Prior to lake turnover, more minor wind mixing events can be seen in the downward dips in the DO contours. The extent of hypoxia and anoxia was smaller in Long Lake compared to Highland Lake, shown clearly by comparing the individual contour plots.

Besides wind and water temperature, the major control of lake water DO concentrations is biological activity (i.e., respiration and photosynthesis). Oxygen is a byproduct of photosynthesis, so actively growing algae can be an additional source of oxygen in shallow, well-lit, aerated waters. In contrast, deep water DO is reduced when microbes, fish, and plants respire or “breathe” and oxygen cannot be replenished due to thermal stratification. This oxygen consumption eventually leads to hypoxia and anoxia. Fish tend to avoid and are stressed when moving through areas that have DO concentrations below about 4 mg/L, while anoxic bottom waters allow phosphorus trapped in sediments to be released for use by algae; these phenomena highlight the importance of collecting oxygen data.

Chlorophyll or Algae Biomass



The Long Lake buoy has a single sensor at 5 m below the lake surface that measures chlorophyll concentrations using fluorescence (same as the field fluorometer used on regular testing trips and discussed in chapter 4). This buoy used to have chlorophyll sensors at 1 and 3 m, but those failed and have yet to be replaced. The concentration of chlorophyll (a pigment found in all plants and algae) can be used as a proxy for algae biomass and as a measure for the productivity of a lake. It is important to note that field fluorescence is a relative measure and is not as accurate as lab-based chlorophyll *a* measurements. Also, chlorophyll fluorescence often shows variation with depth and the buoy can only measure at a single depth. Still, buoy chlorophyll and extracted chlorophyll *a* concentrations in the epilimnion (upper mixed layer) from our regular testing trips (points in the figure) were within about two to three µg/L (or two to three parts per billion) of each other during the period. The depth of the sensor might explain why the buoy values were higher than the extracted chlorophyll *a*.

Daily mean chlorophyll ranged from near 3.4 to 5.5 µg/L, with a mean of 4.3 µg/L. The sensor readings became extremely noisy and then dropped to and stayed near zero in the latter half of August; we filtered the time series to remove those readings. The chlorophyll time series varied within a limited range, so explaining the variability is challenging. Chlorophyll (algae) can increase if nutrients (phosphorus) and light are available. Runoff from rain events or wind-driven mixing can add nutrients that fuel algae production. The limited range and variation of the buoy chlorophyll meant that rain and wind could not be used to explain the pattern. There are, of course, other factors that control algae populations, like competition between different species and zooplankton grazing, but those are beyond the monitoring capabilities of the buoy