UC DAVIS

TAHOE: STATE OF THE LAKE REPORT 2023

Tahoe Environmental Research Center

The UC Davis Tahoe Environmental Research Center is dedicated to interdisciplinary research and education to advance the knowledge of aquatic and terrestrial ecosystems and their interactions within natural and developed Earth systems, and to communicate science-informed solutions worldwide.

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INTRODUCTION

The University of California, Davis has conducted continuous monitoring of Lake Tahoe and its watershed since 1968, amassing a unique record of change for one of the world's most beautiful and vulnerable lakes.

In the UC Davis Tahoe: State of the Lake Report, we summarize how natural processes and human activity in the watershed and beyond are affecting the lake's clarity, physics, chemistry, and biology. We also present a portion of the data collected in 2022 — presenting all of it would be overwhelming. While Lake Tahoe is unique, the forces and processes that shape it are similar to those acting in most natural ecosystems. As such, Lake Tahoe is an indicator for other systems both in the western United States and worldwide.

Our goal is to understand the lake's complexity and to use that knowledge to provide the scientific underpinnings for ecosystem restoration and management actions. Choosing among those options and implementing them is the role of management agencies that also need to account for and balance a host of other considerations.

This annual report is intended to inform non-scientists about the factors that affect lake health. One indicator of Lake Tahoe's health status, the annual clarity, is reported earlier each year. In this report, we publish many other environmental and water quality factors that serve as other indicators of the lake's condition and help explain the lake's changing clarity. This report sets the context for understanding the year-to-year changes as well as those that are observed over many decades.

Part of this report describes research and education taking place independently of the long-term monitoring. These updates highlight some of the most exciting and promising findings of work that is still in progress. The insights being gained through this research will help keep Lake Tahoe at the cutting edge of science for years to come. Many of the sections explore new ideas and approaches to address the ever-evolving challenges at Lake Tahoe.

The data we present are the result of efforts by a great many scientists, engineers, students, technicians, and educators who have worked at Lake Tahoe throughout the decades since monitoring commenced. I would, however, like to acknowledge (in alphabetical order) the contributions to this year's report by Brant Allen, Carmen Bedke, Brandon Berry, Fabian Bombardelli, Mike Bruno, Tom Burt, Luciana Cardoso, Bob Coats, Troy Corliss, Alicia Cortés, Randy Dahlgren, MJ Farruggia, Helen Fillmore, Alex Forrest, Drew Friedrichs, Fatima Garcia, Jenessa Gjeltema, Wyatt Grognet, Scott Hackley, Tina Hammell, Simon Hook, Camille Jensen, Jessica Landesman, Jackelyn Lang, Kenneth Larrieu, Anne Liston, Patricia Maloney, Keeley Martinez, Claire McHenry, Jasmin McInerney, Antonina Myshyakova, Holly Oldroyd, Kanarat (Job) Pinkanjananavee, Gerardo Rivera, Steven Sadro, Heather Segale, Katie Senft, Oscar Sepulveda, Steven Sesma, Noah Shapiro, Samantha Sharp, Roland Shaw, David Smith, Adrianne Smits, Micah Swann, Lidia Tanaka, Misa Terrell, Ruth Thirkill, Raph Townsend, Alison Toy, Sean Trommer, Sergio Valbuena, Aaron Vanderpool, Lindsay Vaughan, Shohei Watanabe, and Erik Young to this year's report. In particular, Shohei Watanabe was responsible for the majority of the data analysis and Alison Toy led the compilation and layout of the final report.

Funding for the actual data collection and analysis has come from many sources over the decades. While many additional water quality variables could be tracked, funding ultimately limits what we measure and report on. Current funding for the long-term monitoring and analysis is provided by the Lahontan Regional Water Quality Control Board, Tahoe Regional Planning Agency, U.S. Geological Survey, and UC Davis.

Funders for current projects include the following: CalFire, California Delta Stewardship Council, California Natural Resources Agency, California Tahoe Conservancy, Incline Village General Improvement District, NASA Jet Propulsion Laboratory, the National Science Foundation, Nevada Department of Tourism and Cultural Affairs, Nevada Division of Environmental Protection, Nevada Division of State Lands, Parasol Tahoe Community Foundation, Santa Clara Valley Water District, the Tahoe Resource Conservation District, the Tahoe Truckee Community Foundation, the Tahoe Water Suppliers Association, the U.S. Bureau of Reclamation, and the U.S. Embassy, Chile.

Our monitoring is frequently done in collaboration with other research institutions and agencies. In particular, we would like to acknowledge our collaborators at UC Davis, the Desert Research Institute (DRI), the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), the Tahoe Resource Conservation District (TRCD), the U.S. Forest Service, (USFS), the U.S. Geological Survey, the University of Miami at Ohio, and the University of Nevada, Reno (UNR).

We are very proud to recognize the funding support for actual production of this annual report from the following organizations: California Tahoe Conservancy, Incline Village Waste Not Program, Lahontan Regional Water Quality Control Board, Lake Tahoe Marina Association, Mountain Workspace, Parasol Tahoe Community Foundation, Tahoe Fund, Tahoe Lakefront Owners' Association, Tahoe Regional Planning Agency, Tahoe Truckee Airport Community Partner, Tahoe Water Suppliers Association, and True Point Solutions. We sincerely thank these organizations for their dedication in supporting science to save the lake.

Sincerelv.

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EXECUTIVE SUMMARY

The long-term data set collected on the Lake Tahoe ecosystem by the University of California, Davis and its research collaborators provides a unique tool for understanding ecosystem function and change. It has become an important resource for decision-making by elected officials and public agencies tasked with restoring and managing the Tahoe ecosystem and other lake ecosystems. This is, in part, because it provides an independent basis for assessing the progress toward attaining Tahoe's restoration goals and desired conditions, while at the same time building our understanding of the natural processes that drive the ecosystem.

The UC Davis Tahoe Environmental Research Center (TERC) is innovating with new approaches to enrich the long-term data record for Lake Tahoe and to address emerging questions. These approaches include real-time measurements at over 25 stations around the basin and remote sensing from autonomous underwater vehicles, satellites, aerial drones, helicopters, and computer modeling tools. These efforts are all focused on quantifying the changes that are happening and, at the same time, understanding what actions and measures will be most effective for control, mitigation, and management in the future. Our newest nearshore station was installed in July 2023. This real-time water quality station at Cedar Point on the west shore will provide new data on the behavior of the lake's nearshore region. In June 2023, an Acoustic Doppler Current Profiler was installed at a depth of 300 feet on the west side of the lake to provide continuous water velocity measurements and to track the expected resurgence of the *Mysis* shrimp in the coming years.

This Tahoe: State of the Lake Report 2023 presents data from 2022 in the context of the long-term record. While we report on the data collected as part of our ongoing measurement programs, we also include sections summarizing some of the current research that is being driven by the important questions of the day and concerns for the future. These include:

- The impacts of food web change on lake clarity. Data showing the change in multiple lake biological variables that followed the collapse of the *Mysis* shrimp population are presented.

- The extremes in conditions experienced over this last 2022/2023 winter including the freezing of the entirety of Emerald Bay and the very extended period of complete vertical lake mixing in February 2023.

- The Secchi disk, a simple

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"Previous year" for some parameters means data collated in terms of the water year, which runs from October 1 throught September 30; for other parameters, it means data for the calendar year, January 1 through December 31. Therefore, for this 2022 report, Water Year data are from October 1, 2020 through September 30, 2021. Calendar year data are from January 1, 2021 through December 31, 2021.

EXECUTIVE SUMMARY

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and widely used tool for measuring lake clarity is shown to provide highly repeatable data with three independent field researchers.

- Microplastic pollution, a growing global issue is also an issue at all depths of Lake Tahoe. The values found at Tahoe approach those measured in San Francisco Bay.

- New machine-learning approaches used to monitor the beaches and nearshore of Lake Tahoe are described, along with the motivation of why they are needed to better describe the growing severity and extent of metaphyton and periphyton growth.

- The power of modeling tools that increase our understanding of complex lake motions, better track where contaminants are transported in the lake, and even inform how future monitoring should be conducted.

- No-wake zones are in place around the periphery of Lake Tahoe. Are they scientifically meaningful?

- The heavy coating of pollen across the basin this summer has people concerned about its effect on lake health. The question was actually answered over 50 years ago.

- A new undergraduate student summer internship program launched in June provides opportunities for the next generation of environmental scholars and leaders to work at Lake Tahoe on some of the most pressing issues.

Meteorologically, the persistent, long-term trends have not changed from year-to-year. However, a changing climate is evident in almost all the long-term meteorological trends, including rising air temperature and the declining fraction of precipitation as snow. The weather experienced each year can be far more variable. For most of 2022, the monthly average temperatures were similar to the previous two years and the long-term average. The monthly average air temperatures for November and December, however, were much colder than the long-term average, with November being the third coldest on record since 1910. At 32.7 inches, 2022 precipitation was just 1.2 inches above the long-term average. Snow, measured at Tahoe City, has declined as a fraction of total precipitation from an average of 52 percent in 1910 to 33 percent in 2022.

The water level in Lake Tahoe varies throughout the year due to inflows, outflows, precipitation, and evaporation. In 2022, the highest lake level was 6,224.52

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feet on June 13, and the lowest was 6,222.58 feet on November 30, 2022. The natural rim of the lake is at an elevation of 6,223 feet. The subsequent wet winter of 2022/2023 has brought the lake back to almost maximum capacity.

Despite year-to-year variability, the annual average surface water temperatures show an increasing trend. For 2022, the average surface water temperature was 52.5 °F slightly below the long-term trend line. The overall rate of warming of the lake surface is 0.39 °F (0.22 °C) per decade since 1970. In 2022, July surface water temperature was relatively cool. It averaged 63.8 °F (17.7 °C). This was a decline of over 4.8 °F from the record-setting value of the previous year. Lake Tahoe mixes vertically each winter as surface waters cool and sink downward. Mixing depth has profound impacts on lake ecology and water quality. Deep mixing brings nutrients to the surface, where they promote algal growth. It also carries oxygen downward to deep waters, promoting aquatic life throughout the water column. On February 18, 2022, Lake Tahoe was observed to have mixed to a maximum depth of 328 feet (100 m), the second lowest value on record.

The stability of the lake is an important concept that expresses its resistance to vertical mixing and determines its length of stratification. High stability can mean that oxygen is not transferred to deep portions of the lake, pollutant-bearing inflows enter the lake closer to the surface, and the types and vertical distribution of phytoplankton change. The length of time that Lake Tahoe is stratified has generally increased each year, another consequence of climate change. Since 1968, the length of the stratification season has increased by 29 days, albeit with considerable year-to-year variation. In 2022, the length of the stratified season was only 181 days, the lowest value in over ten years.

The reduction of nutrient and fine particle loads to the lake is a fundamental part of the restoration efforts driven largely by the Total Maximum Daily Load (TMDL) program. The stream-borne nitrogen and phosphorus loads from the Upper Truckee River were again low in 2022, which was in line with the average precipitation for the year. Total nitrogen load from the Upper Truckee River, the largest inflowing stream, was 11.1 MT/yr, compared to the long-term mean annual load of 17.3 MT/yr. Total phosphorus inputs decreased to 1.68 MT, the lowest annual load on record. In-lake nitrate and total hydrolyzable phosphorus concentrations increased slightly, partly due to the absence of deep mixing in 2021 and 2022 and possibly the influence of wildfire smoke. Surface nitrate

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EXECUTIVE SUMMARY

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levels were moderate in the first few months of the year but declined to near-zero for most of 2022. The concentration of fine particles in the surface of the lake was markedly lower in 2022, particularly from August onwards. The levels have been elevated since the record inflows of 2017 but have now fallen below those levels.

The lake saw the greatest areas of change in 2022 related to its biology. Biologically, the primary productivity of the lake has increased dramatically since 1959. In 2021 and 2022, primary productivity reached the highest values ever. This coincided with high algal biovolume, at levels similar to observations from the 1980s and earlier. The Deep Chlorophyll Maximum (DCM) of the lake formed in spring, but in early fall it disappeared. Cyanobacteria were the most abundant phytoplankton (by number) in Lake Tahoe for a second successive year, but their biovolume was low. The data indicates that the occurrence of the cyanobacteria started in late 2021 and continued in the first few months of 2022. Diatoms were still the dominant group by volume. Of these, *Synedra* formed the largest percentage of the biomass. Biovolume was significantly higher than previous years. The collapse of the *Mysis* population was probably the largest singular change in Lake Tahoe in 2022. Changes in phytoplankton and zooplankton regimes continued throughout 2022 and also coincided with the large improvement in lake clarity. These food web changes have continued to evolve since that time.

The attached algae (periphyton) on the rocks around the lake were elevated in 2022, based on a synoptic survey. As usual, the California side of the lake continued to display higher concentrations of periphyton. 2022 was the last year in which the traditional fixed- point measurements of attached algae will be collected. In 2023, a remotely sensed approach using helicopters and drones will be used to focus on the aerial extent of nearshore algae.

ABOUT LAKE TAHOE AND THE TAHOE BASIN

- Maximum depth: 1,645 feet (501 meters), making it one of the deepest lakes in the world and second deepest lake in the United States
- Average depth: 1,000 feet (305 meters)
- Lake surface area: 191 square miles (495 square kilometers)
- Watershed area: 312 square miles (800 square kilometers)
- Length: 22 miles (35 kilometers)
- Width: 12 miles (19 kilometers)
- Length of shoreline: approximately 75 miles (120 kilometers)
- Volume of water: 40 trillion gallons, plus or minus
- The daily evaporation from Lake Tahoe (half a billion gallons) would meet the daily water needs of 5 million Americans
- The number of algal cells in Lake Tahoe is approximately 30 million trillion, within a few trillion or so
- A single *Daphnia* can consume 100,000 fine particles every hour
- In 2022, there were less than three billion *Mysis* shrimp, potentially setting the stage for the rebound of the cladoceran population and the continuation of clarity improvement in 2023
- Number of inflowing streams: 63, the largest being the Upper Truckee River
- Number of large lakes worldwide with annual clarity exceeding Tahoe's: 0
- Number of outflowing streams: one, the Truckee River, which exits at Tahoe City, flows through Truckee and Reno, and terminates in Pyramid Lake, Nevada
- Number of monitoring stations TERC utilizes in the Tahoe Basin: 225
- Length of time it would take to refill the lake: about 600 years
- Average elevation of lake surface: 6,225 feet (1,897 meters)
- Highest peak in basin: Freel Peak, 10,891 feet (3,320 meters)
- Latitude: 39 degrees North
- Longitude: 120 degrees West

ABOUT THE UC DAVIS TAHOE ENVIRONMENTAL RESEARCH CENTER (TERC)

The UC Davis Tahoe Environmental Research Center (TERC) is a world leader in research, education, and public outreach on lakes and watersheds, providing critical scientific information to help understand, restore, and sustain the Lake Tahoe Basin and other systems worldwide. Since 1968, UC Davis has conducted continuous, year-round scientific monitoring of Lake Tahoe, creating the foundation on which restoration and stewardship efforts can be based.

TERC's activities are conducted out of permanent research facilities in the Tahoe Basin and at the University's main campus in Davis, California, about 90 miles west of the lake.

Our main laboratories and offices are in Incline Village, Nevada, on the third floor of the Tahoe Center for Environmental Sciences building. On the first floor, we operate the Tahoe Science Center™, an educational resource for K-12 students and learners of all ages, that is open to the public.

In Tahoe City, California, we operate a field station (housed in a fully renovated, former state fish hatchery) and the Eriksson Education Center. The field station also houses the CITRIS Autonomous Underwater Vehicle testing facility. Tahoe City is the mooring site for our research vessels, the R/V John LeConte and the R/V Bob Richards. The R/V Ted Frantz operates out of Clear Lake, California and the R/V Tom and the R/V Martini are currently based in Davis, California. Malyj Manor, a 4-bedroom house in Tahoe City, provides short term housing for students and visiting researchers.

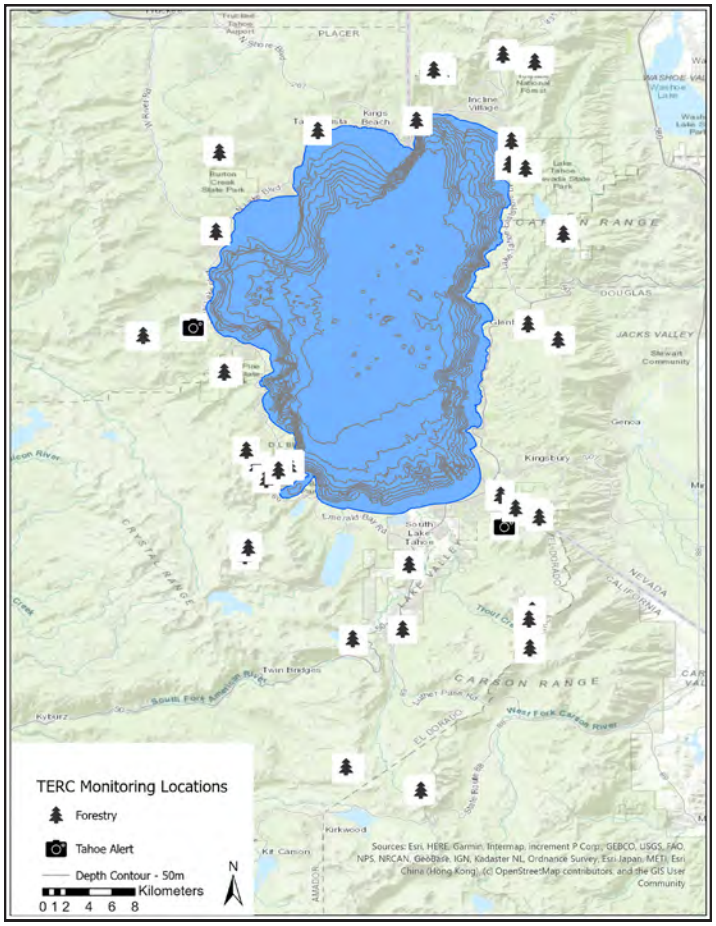
Additional laboratories and offices are located on the UC Davis campus at the Center for Watershed Sciences, Ghausi Hall and in Wickson Hall.

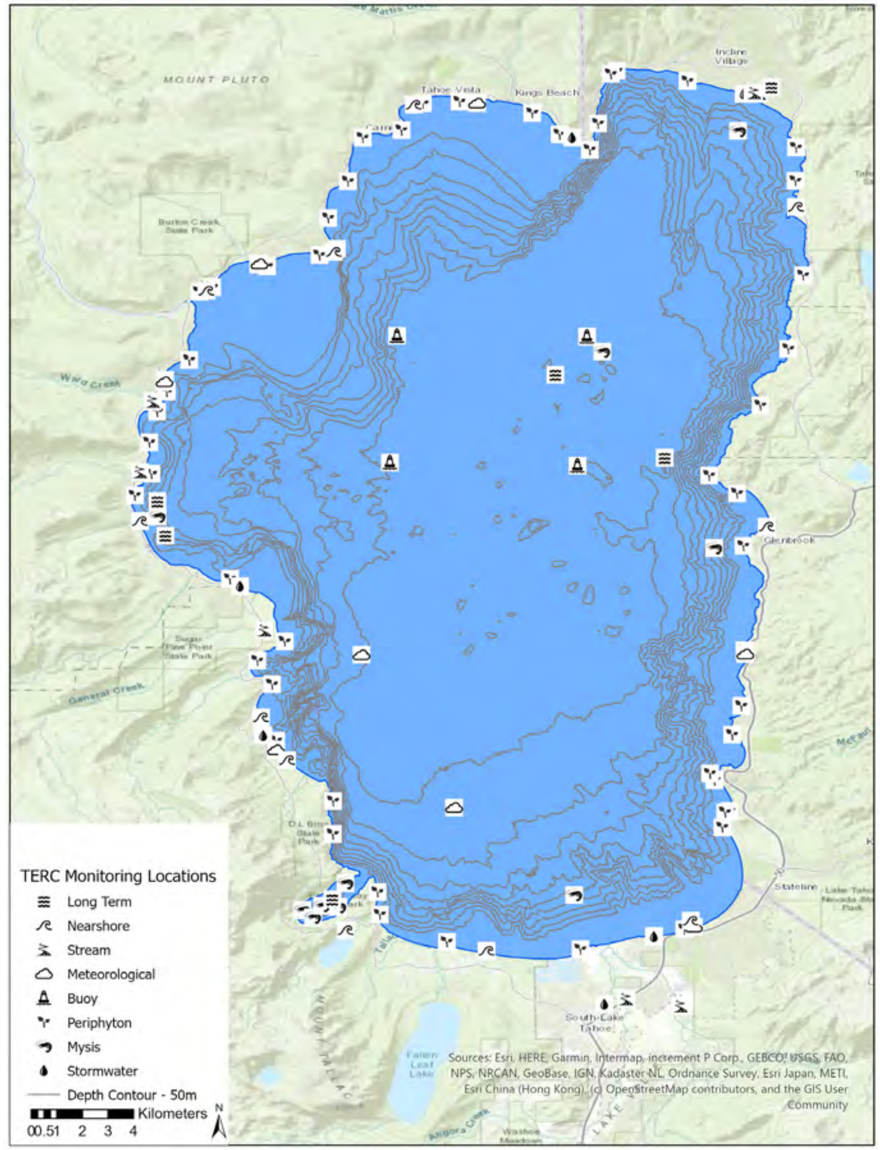
At locations throughout the basin, we have sensors continuously reporting on the health and well-being of the lake and its environs, all contributing to making Lake Tahoe the smartest lake in the world.

Our website (https://tahoe.ucdavis.edu) has more information about our programs, including:

- Information for potential students, staff, faculty, research collaborators, and visitors;
- Access to near-real-time data sensors;
- TERC research publications;
- Exhibits and events at the education centers; and
- Information about supporting our research and learning programs.

TAHOE BASIN DATA COLLECTION SITES





TAHOE: STATE OF THE LAKE REPORT 2023

CURRENT RESEARCH

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Current research

This section of the State of the Lake Report describes some ongoing research that is above and beyond the monitoring described in the subsequent sections, although in many cases it is predicated on that monitoring.

The changes to Lake Tahoe that were observed in late 2021 and in 2022 are among the largest and most significant that have been observed in the 55-year data record. These changes are documented in this section, and relate to major shifts in the lake's zooplankton and phytoplankton. The extent to which these shifts are inter-related is a focus of our current research. Being able to understand what is driving these changes and what these circumstances may mean for issues like restoring lake clarity, makes them all high-priority research questions.

Left to right: Long periods of freezing cold temperatures had quite an impact on the Lake's clarity. Extreme snow levels mean extreme stream conditions.
(Photos: A. Toy and A. Vanderpool)

The changes in Lake Tahoe's deepwater biology and implications for clarity

The last two years have seen some major changes in the lake's deepwater, or pelagic, biology related to the base of the food web. There are also major changes happening in the shallow water regions, but that is a different topic.

What is driving these pelagic changes and what their consequences will be are part of our ongoing research. But with researchers out on the lake most days of the week year-round, and with over 55 years of a long record to draw upon, TERC is uniquely positioned to detect these changes. The first inklings of the changes were from our lake sampling team noticing changes in the color of the filters that were used to separate algae from the water, changes in algae on the zooplankton nets, and observing species that had never previously been recorded in the sampling history.

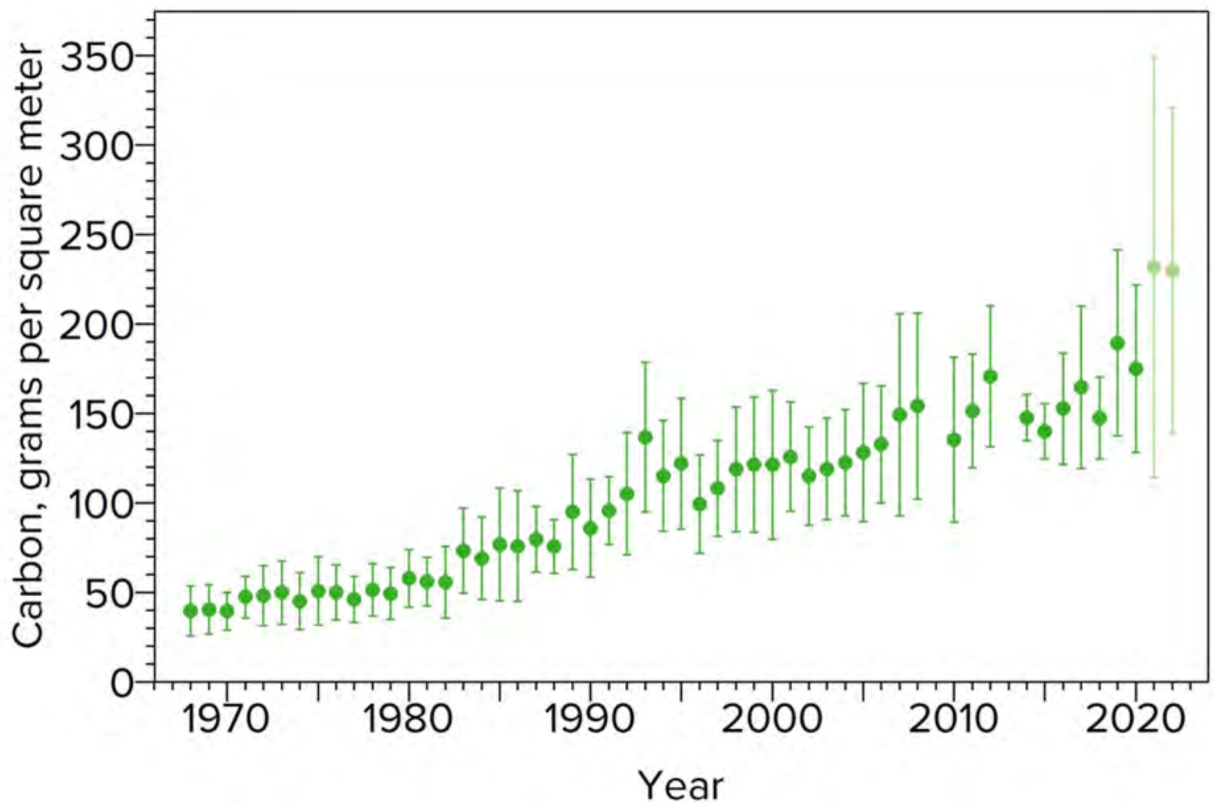
In the last two year, cold temperatures at Lake Tahoe have had major implications on lake clarity. Photo: B. Allen

Changes in the zooplankton regime has also contributed to the changes in lake clarity. Photo: A. Toy

The changes in Lake Tahoe's deepwater biology and implications for clarity

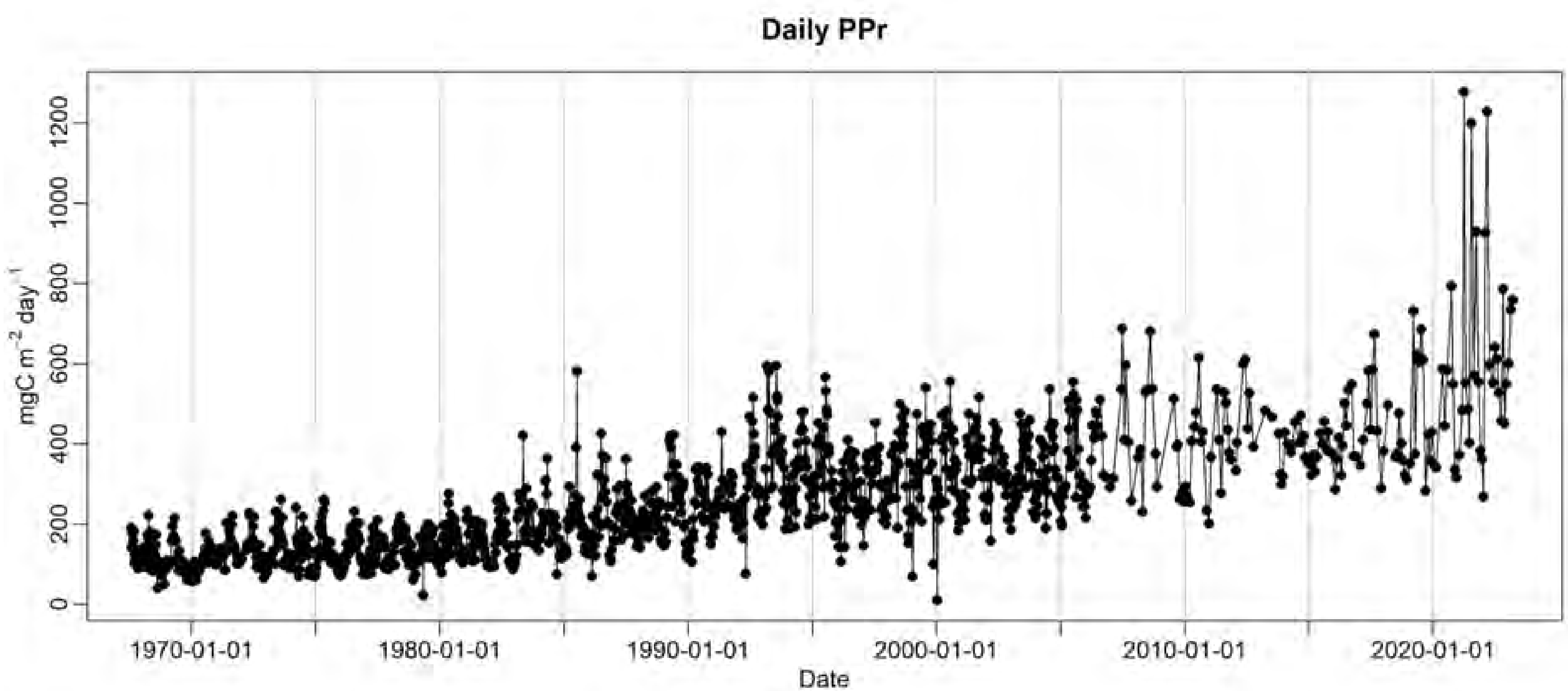
Phytoplankton

The algae, or phytoplankton, are the base of the aquatic food web. In 2021 and 2022, the primary productivity (PPr), the annual rate at which phytoplankton take in carbon carbon, rose to rates higher than experienced for the last 55 years.



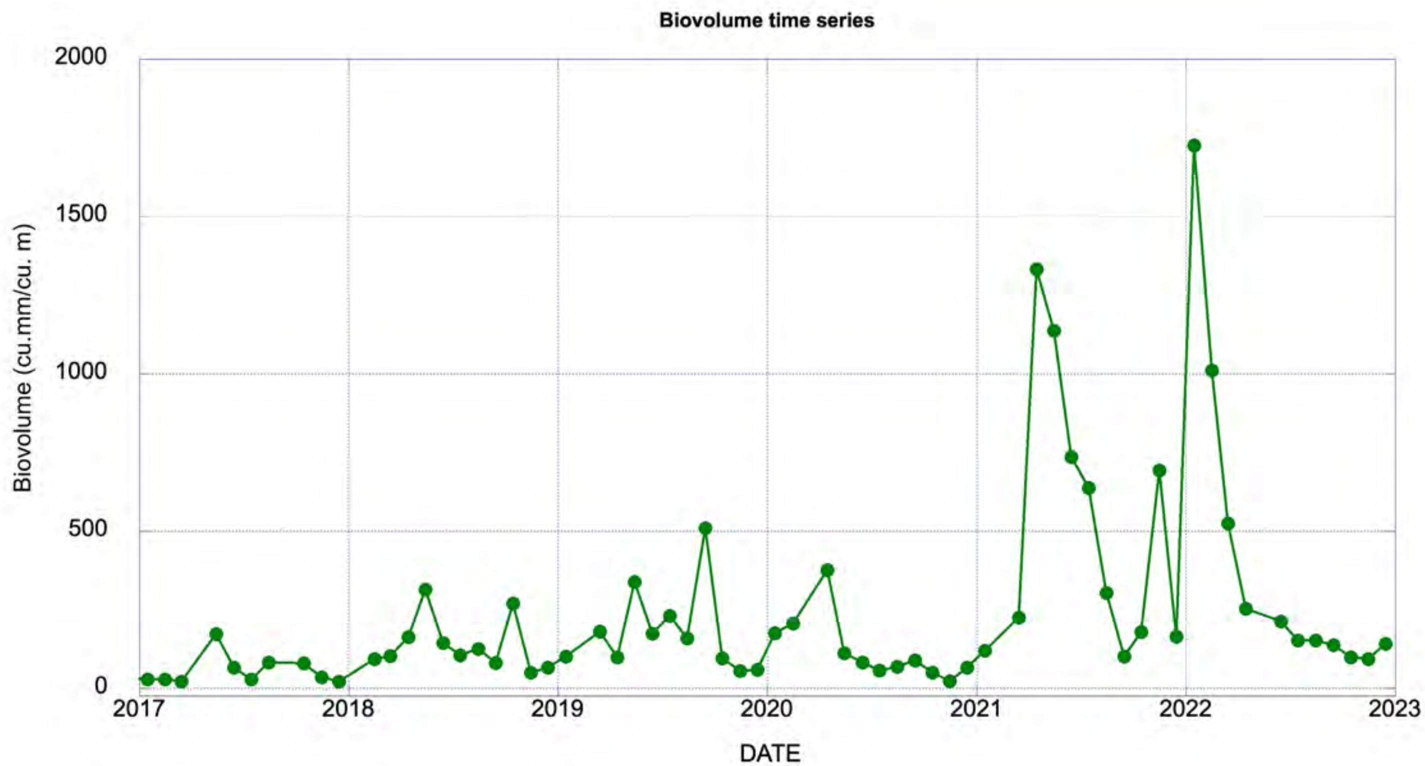
The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

The individual PPr readings that are averaged over 12 depths in the upper 350 ft of the lake, showed an extremely high level of variability, as shown in the monthly values for the entire 55 year record. In the context of the entire record, the last two years stood out as different. Could this change be real? Or are the measurements erroneous?



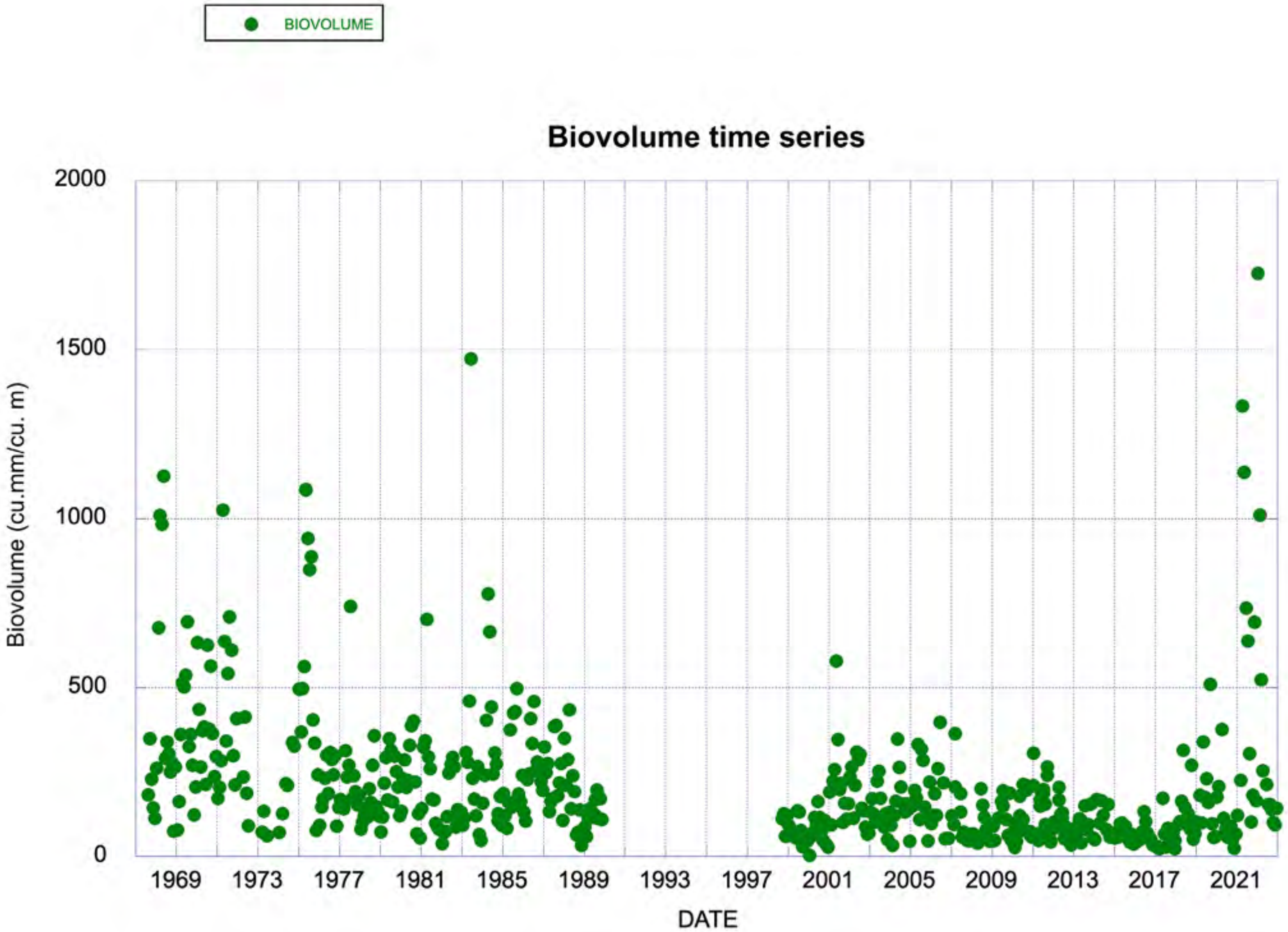
The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

To answer that question we reviewed other, independent measures related to algal growth. The first of these is the biovolume. The biovolume (or cell volume) of phytoplankton is an estimate of the concentration of algal biomass in the upper part of the lake. It is based on a time-intensive process in which biovolume is estimated for individual taxa from formulae for solid geometric shapes that closely match the cell shape. Samples for biomass estimates are taken from depths of 5, 20, 40, 60, 75 and 90 meters, and an integrated estimate is produced. The biovolume data since 2017 show that it too has "anomalous" peaks in 2021 and 2022. The biovolume peaks and the PPr peaks do not align as they represent different things. The PPr is a growth rate and tends to be low when the biovolume is high.



The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

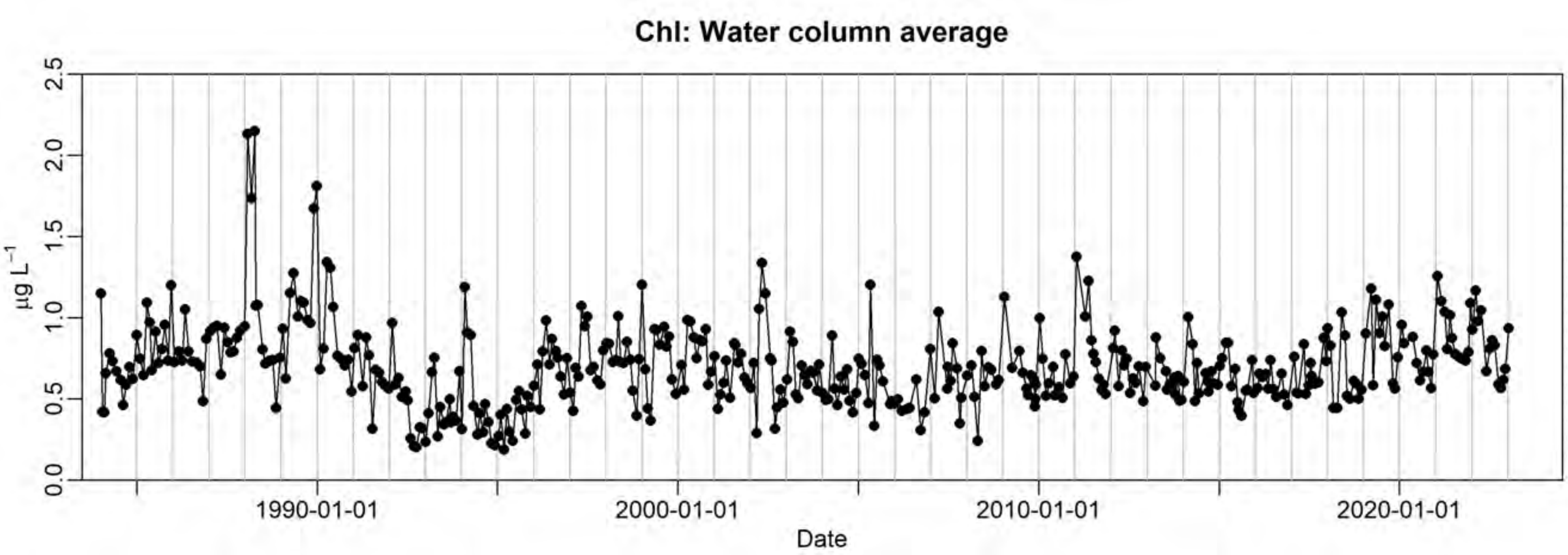
The picture gets interesting when we look at the entire record of biovolume estimates from 1968 to the present. Although there were little data from the 1990s, what is apparent is that high values of biovolumes are not new. Through the 1980s, there were numerous occasions when biovolume was at similar levels to what was observed in 2021 and 2022, suggesting that the high peaks of the last few years are not anomalous, but rather a return to conditions similar to earlier conditions.



The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

A third measure related to phytoplankton is their chlorophyll-*a* concentration, the photosynthetic pigment that they contain. The long-term data (back to 1984) show that chlorophyll-*a* concentration has remained relatively more stable, at least since the mid-1990s, although peaks in the last two years are higher than many years.

Both the PPr and the biovolume data, and possibly the chlorophyll-*a* data suggest that there was a significant change in 2021 and 2022. Did the taxa of the phytoplankton change?

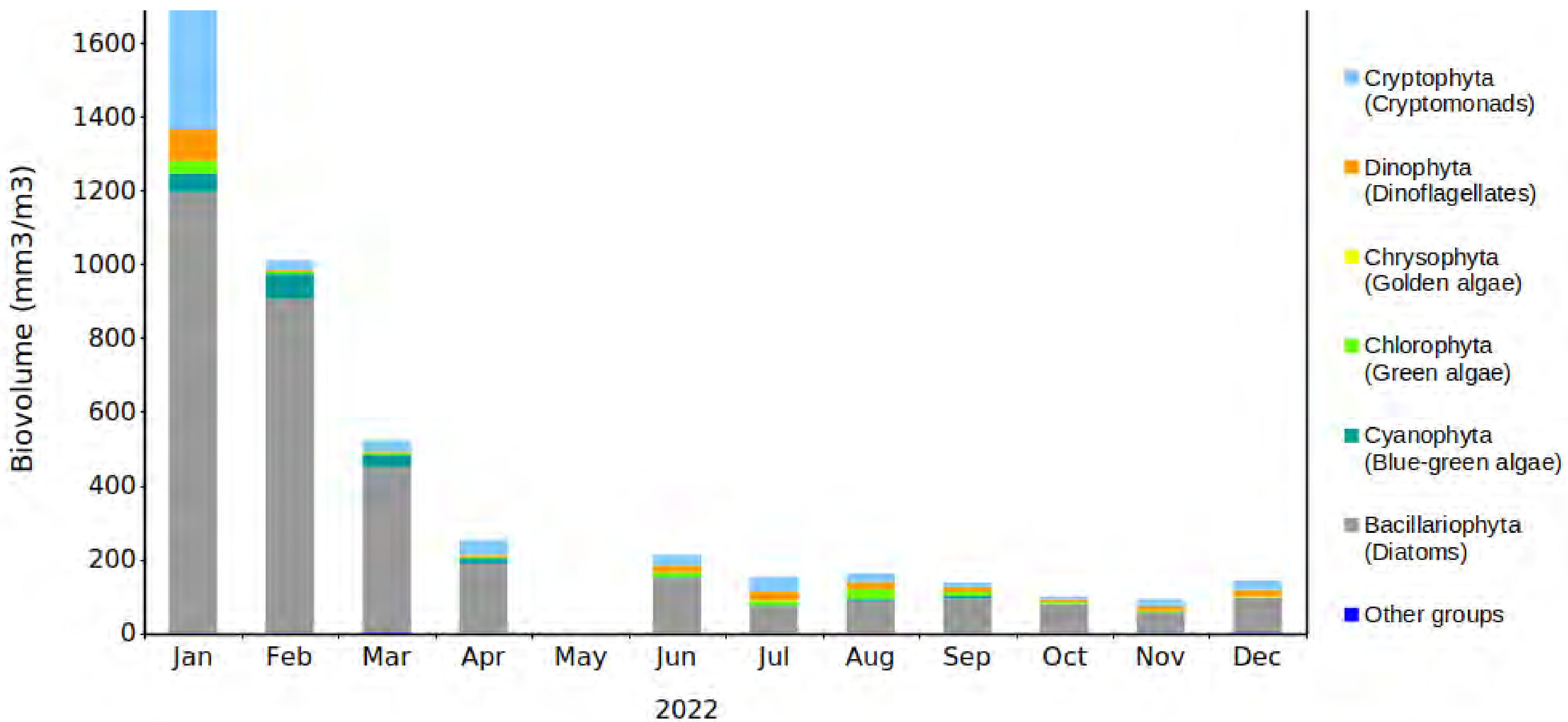


The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

Looking in detail at which algal taxa comprised the biovolume by month in 2022, we can start to understand what may be happening. The high values of biomass in the first three months of 2022 were dominated by the diatom *Synedra*. While *Synedra* often dominates in Lake Tahoe, it rarely reaches the biovolumes levels it reached 2021 and 2022, and is typically below 100 mm^3/m^3 for most of the year.

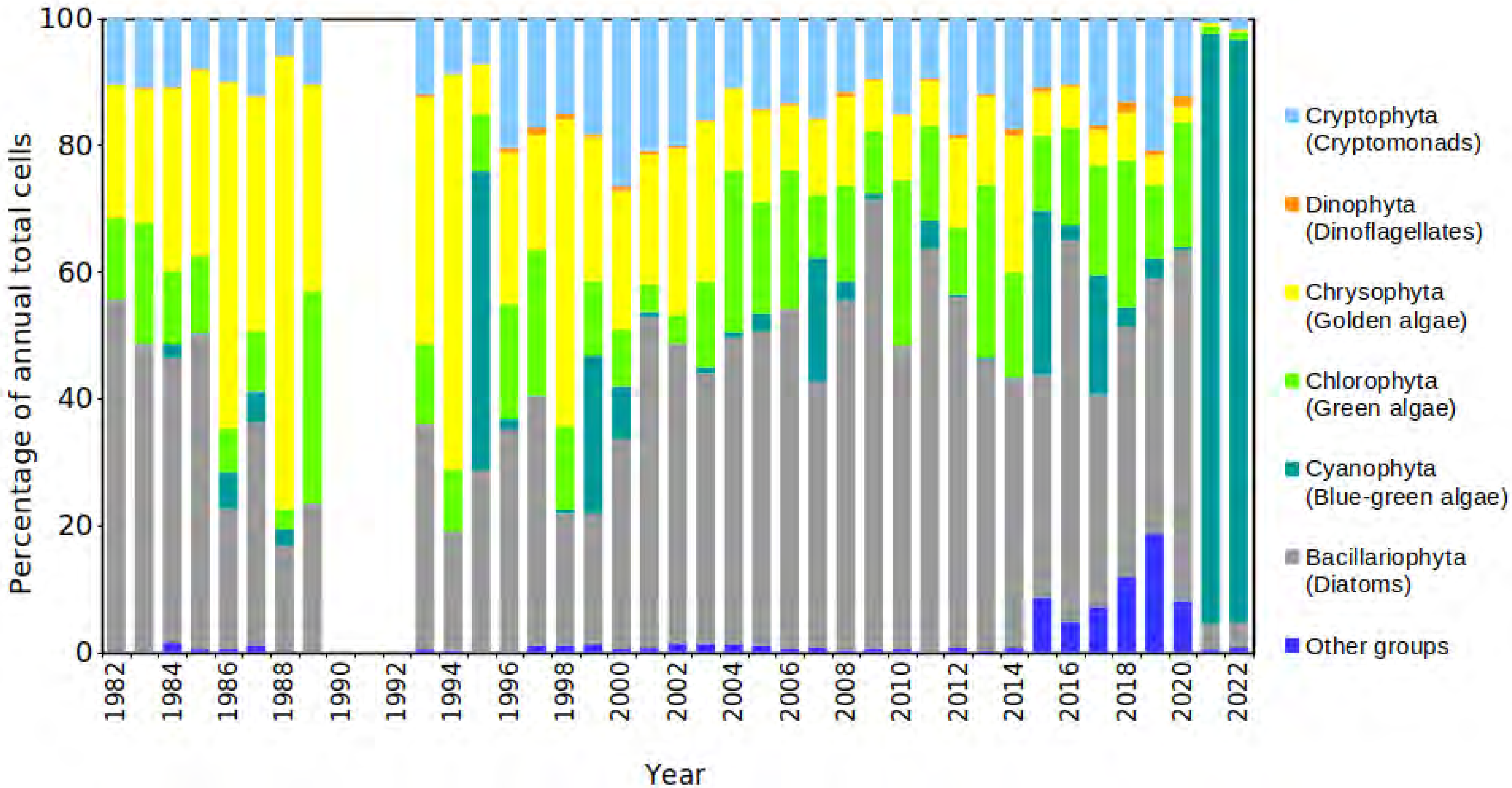
It is noteworthy that larger algae have higher biovolumes, while smaller algae, though far more numerous, have smaller biovolumes. Comparing a 2 micron and a 200 micron spherical algal cell, it would require one million of the smaller algae to have the same biovolume of a single large alga.

So we now have in the first part of 2022, exceptionally high PPr, exceptionally high biovolumes, elevated chlorophyll and the occurrence of large diatoms. The idea that the PPr measurements are not an "error", but an indicator of real change now seems far more plausible.



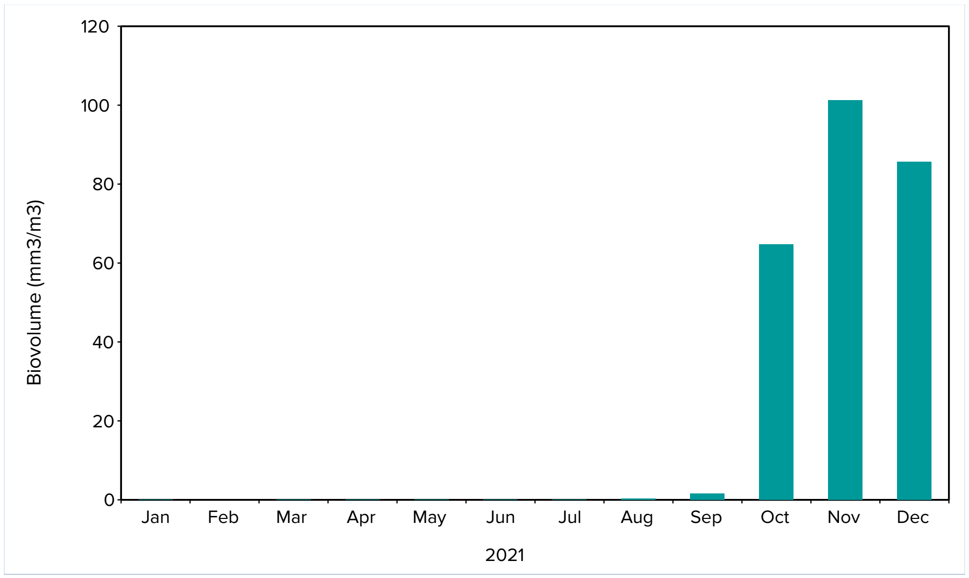
The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

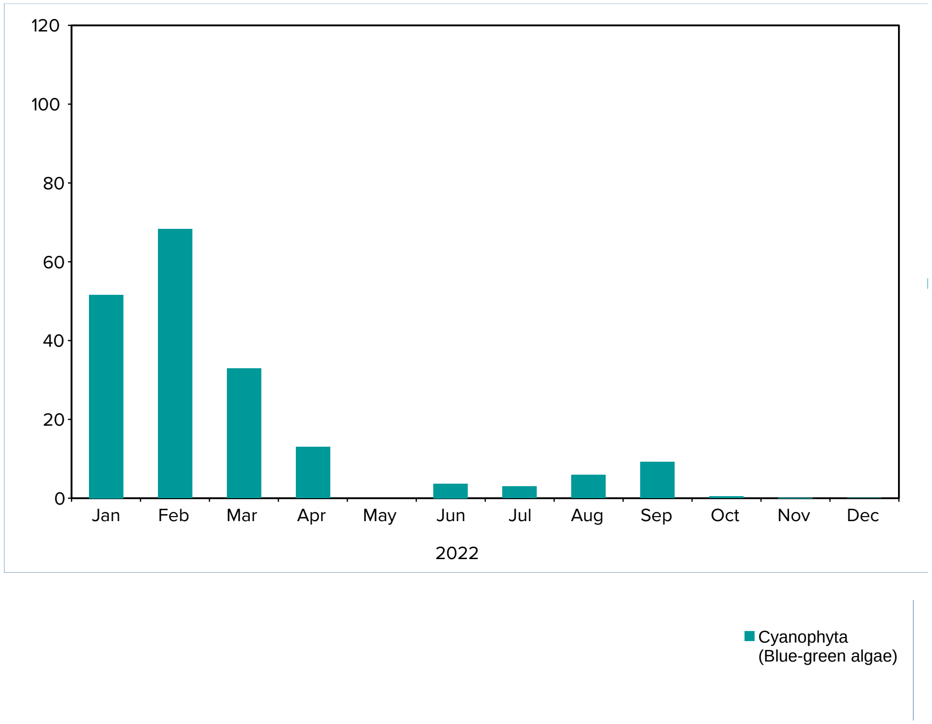
But the story is actually more complex. At the same time that the *Synedra* was dominating the biovolume, the actual number of individual algal cells was dominated by a very small algal cell, the cyanobacteria, *Leptolyngbya*. Looking at the annual percentage of total algal cells in the lake, it is dominated in 2021 and 2022 by *Leptolyngbya*, even though they comprise a small part of the biovolume.



The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

Leptolyngbya was first reported in late 2021, as being suddenly present as a likely consequence of nutrient inputs from wildfire smoke. This is actually reinforced by looking at the *Leptolyngbya* data from 2021 and 2022 side-by-side.



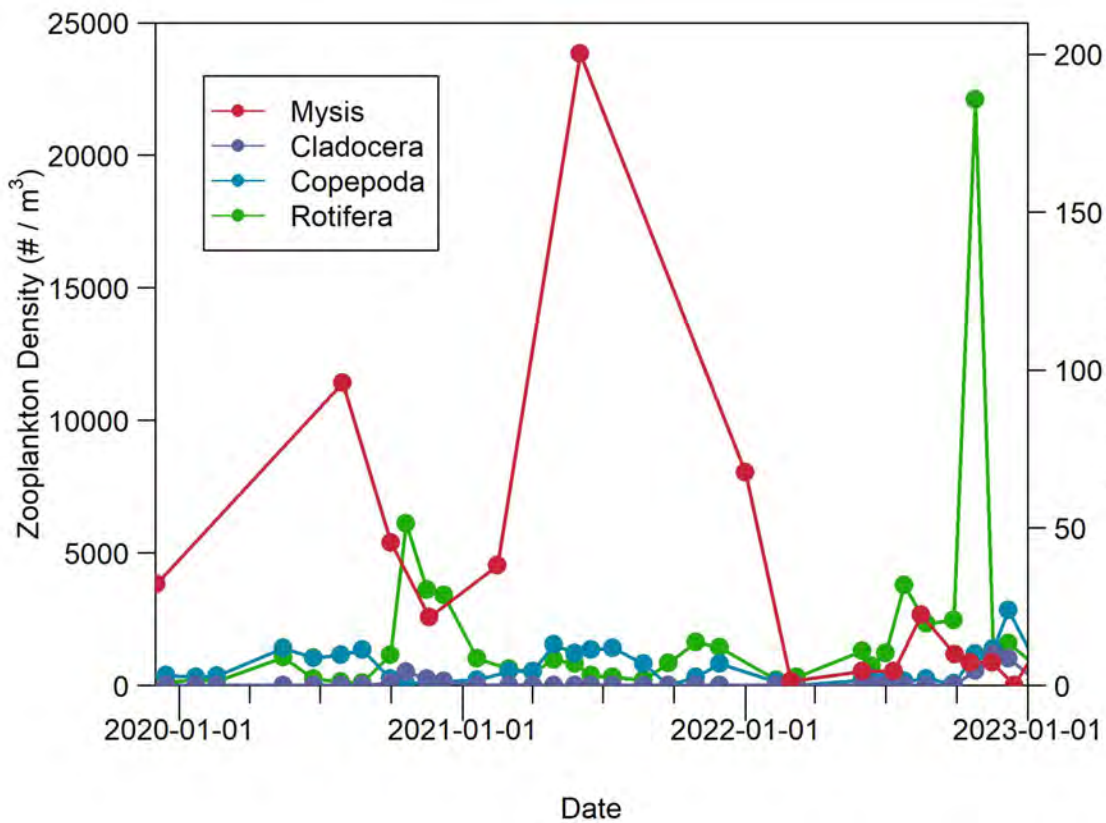


The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

Mysis and zooplankton

In early 2022 the population density of *Mysis* shrimp suddenly collapsed. Since their introduction in the 1960s their numbers have varied and generally been in excess of 100 individuals/sq. m, but now they were present in single digits.

Immediately prior to their collapse the populations of copepods also collapsed. The reason for this collapse is believed to be a fungal infection, and as they are a primary source of *Mysis* sustenance this may well have contributed the *Mysis* collapse by starvation.



Two dead copepods covered by fungus.
Photo: K. Senft

The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

With *Mysis* and copepods reduced, there was the opportunity for other species to become established. One such group was cladocerans, that prior to the introduction of *Mysis* were the dominant zooplankton group and known to be able to clear water of fine particles at a high rate. However, cladocerans did not immediately re-establish and instead rotifers increased by April 2022 and it took a further four months for cladocerans to start increasing.

The two cladocerans species at Lake Tahoe, Bosmina (left), Daphnia (middle), and the rotifer (right) which quickly reestablished itself following the mysterious die-off of the Mysis shrimp.

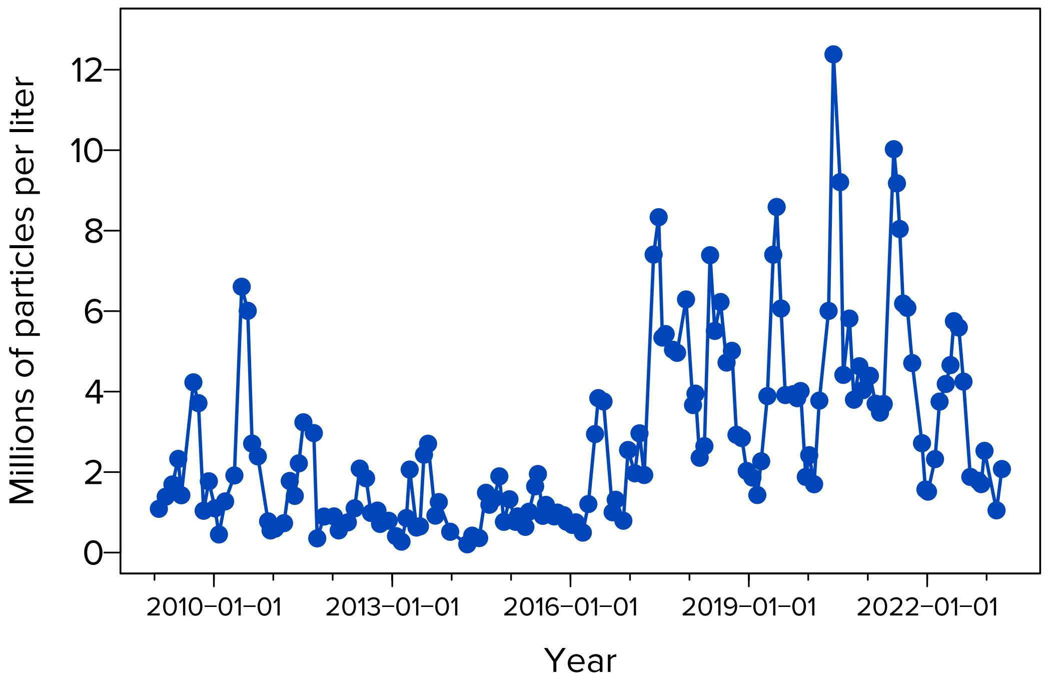
The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

Clarity

Do these biological changes have any bearing on lake clarity? We believe they do. It is known that the very smallest phytoplankton and inorganic particles have a very large impact on reducing clarity. The number of fine particles in Lake Tahoe had been elevated since the very wet winter of 2017. The figure below shows the concentration of fine particles (1–6 microns) in the upper 165 feet of the water column. The annual peaks from 2017 through 2021 are evident, and account for the poor clarity in those years.

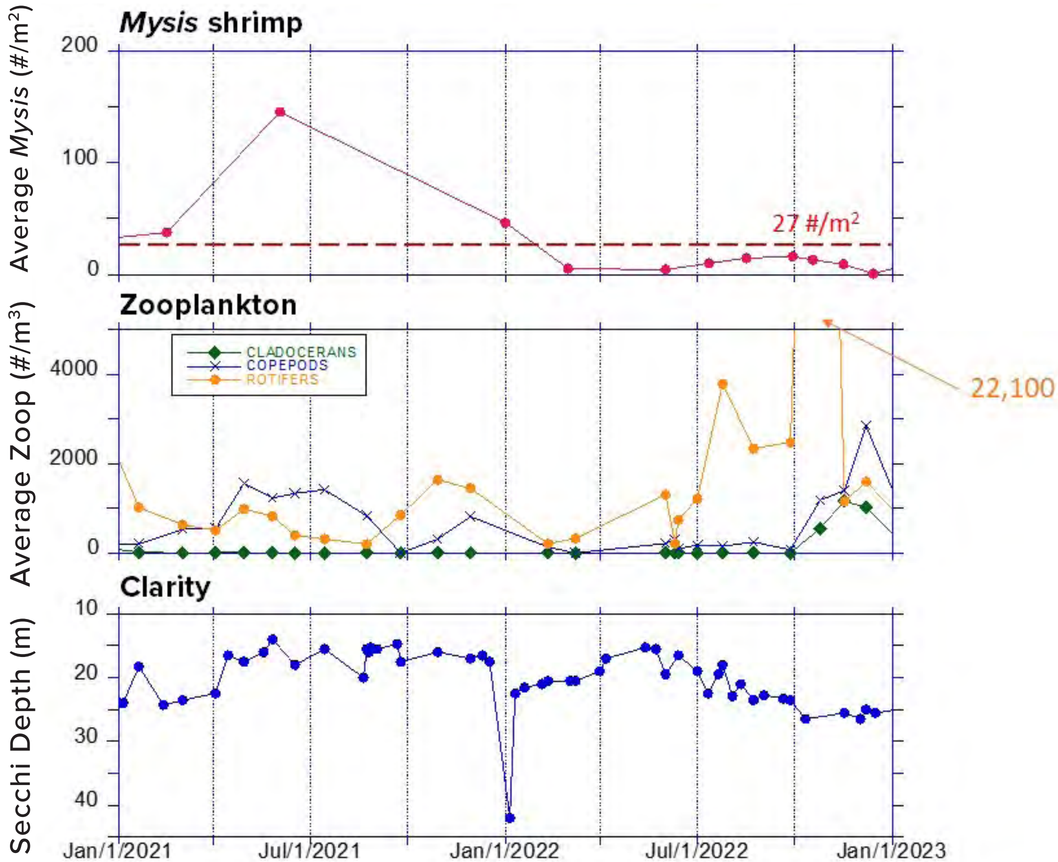
At the beginning of 2022, the concentration of particles is low, but that is possibly due to the impact of the extreme upwelling event described elsewhere in this report. But it is only after June, that the concentration of particles commences to decrease to low values.

That is the period, August–December 2022, when clarity at Lake Tahoe attained values that had not been observed consistently since the 1980s.



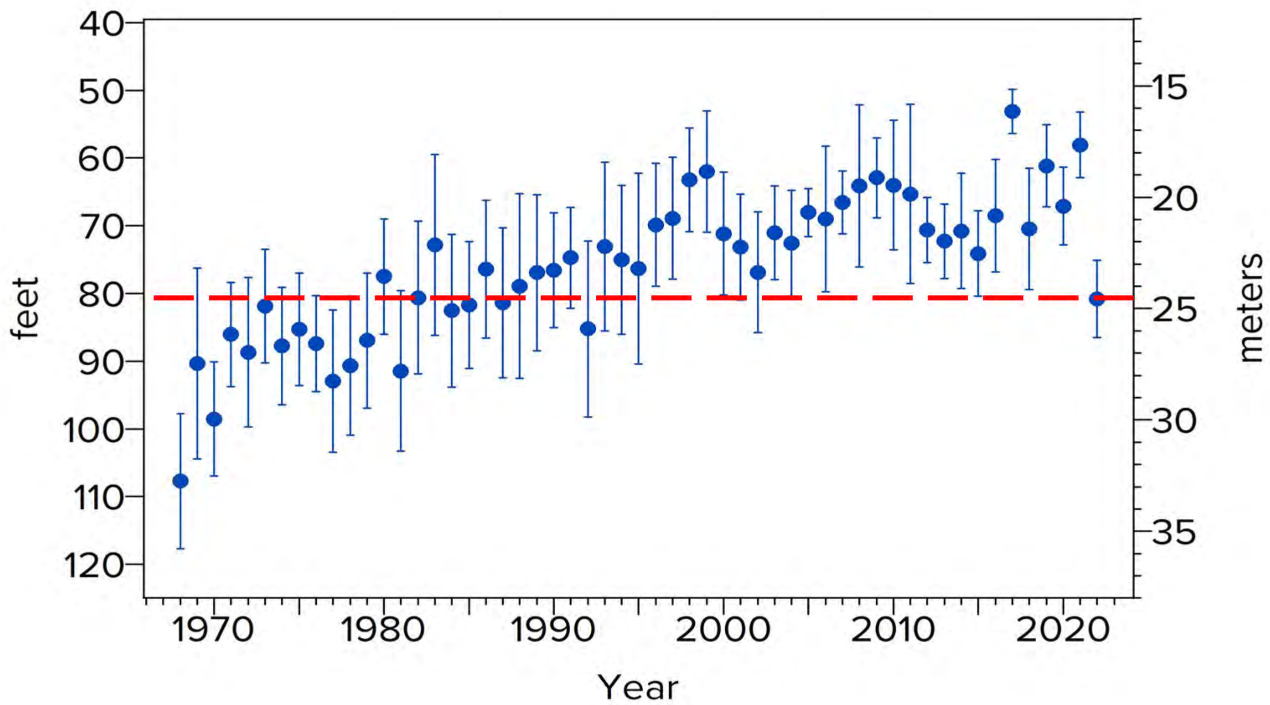
The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

This figure provides a chronology of events that unfolded in 2021 and 2022. The decline of *Mysis* below a level of 27 individuals/m^2 has been shown in research in the 1980s to be a level at which *Mysis* and cladocerans can co-exist. Within less than 6 months of *Mysis* populations falling below this value, changes started manifesting themselves in the zooplankton community. Initially this was observed in a large increase in the rotifer population, followed by increases in copepods and finally cladocerans. Throughout this succession of events the lake clarity improved to levels not experienced in over 40 years.



The changes in Lake Tahoe's deepwater biology and implications for clarity, continued

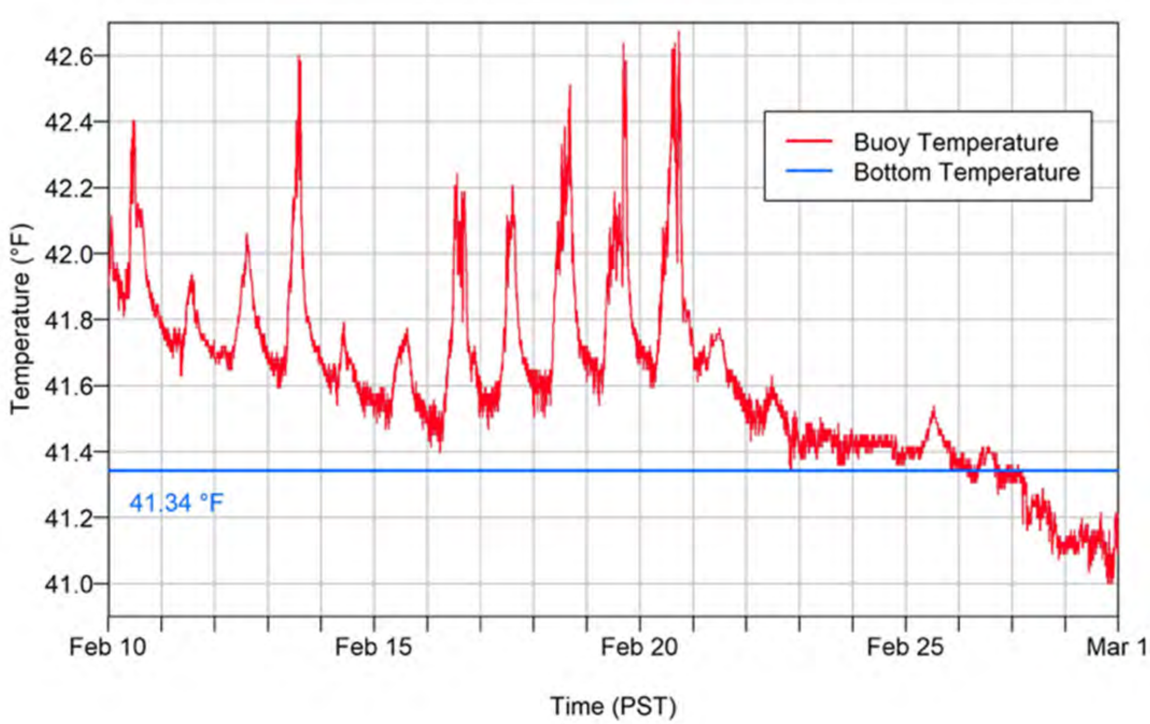
2023 promises to be an interesting year. The record winter has brought large concentrations of fine particles into the lake. At the same time, the conditions still exist where *Mysis* are largely absent and cladocerans are increasing. With the continued monitoring of the lake, we are likely to learn a lot about the controllers of lake clarity.



Extreme ice and extreme mixing

One of the most extreme periods on record at Lake Tahoe was the year 2022 and the first part of 2023. The basin and surround areas experienced the intensity of the 2022-2023 winter, and in particular, very low air temperatures. For example, in November and December 2022, averaged temperatures were well-below the 112-year average temperature (see Fig. 7.4).

The first direct consequence of these extremely cold air temperatures was the complete mixing or "flipping" of Lake Tahoe from top to bottom. Every winter, the surface waters of Lake Tahoe cool and become denser and start to descend. The falling of the water leads to vertical mixing. Most years the mixing might only reach a depth of 600–700 feet. Possibly in every 4-5 years the mixing will extend all the way to the bottom, and that is what happened commencing on February 27, 2023. By continuously measuring the water temperature from a buoy, we can determine when the water temperature fell below the bottom water temperature, an indicator of complete mixing.

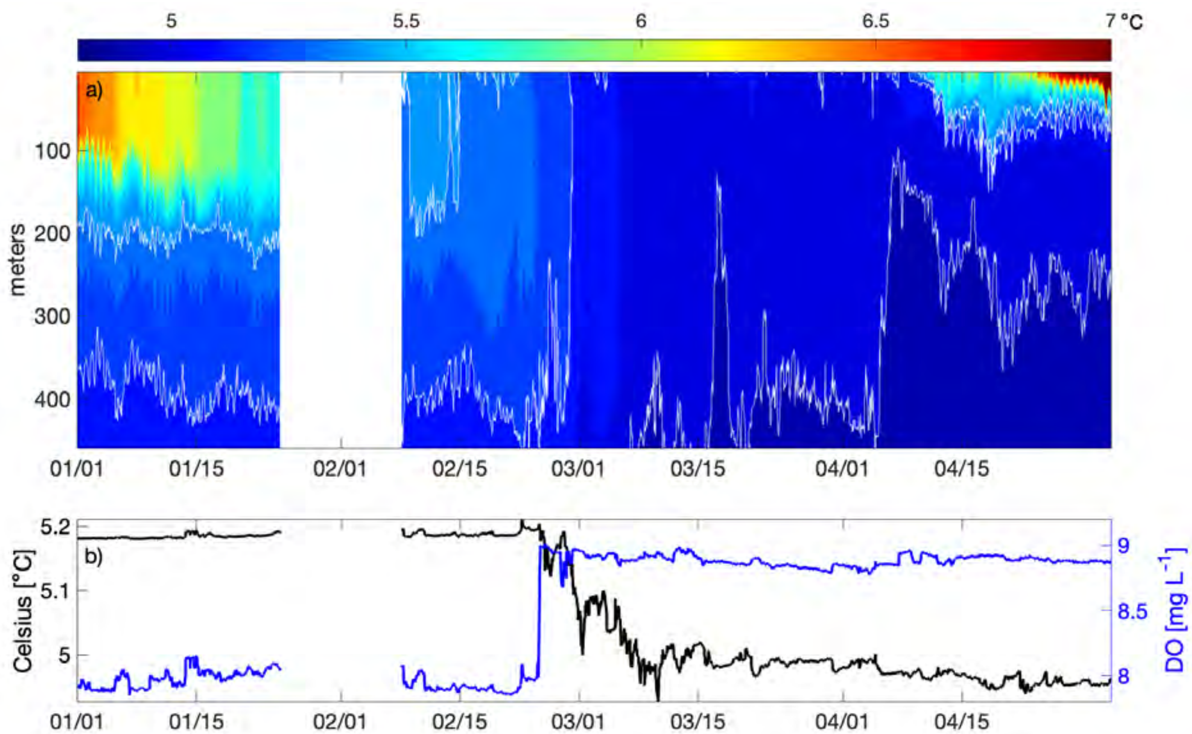


Freezing temperature

Extreme ice and extreme mixing, continued

What are the consequences of "flipping"? First, it is a major controller of the water temperature at the bottom of the lake. Second, and more importantly, it is one of the ways that oxygen reaches the bottom of the lake. The upper panel shows the vertical temperature structure measured at our permanent station near Glenbrook, Nevada, from January to April 2023. The white lines indicate 0.2 °C isotherms. The plot illustrates the loss of thermal stratification on around February 27, and the ensuing cooling of the lake bottom.

The lower panel shows the temperature (black) and dissolved oxygen (blue) as measured at a depth of 460 meters. As deep mixing proceeds, the temperature rapidly declines over a two-week period, then continues to slowly cool over the next seven weeks. The change in dissolved oxygen is far more rapid, with an almost instantaneous jump in dissolved oxygen just as the deep mixing process commences. Figures courtesy of Micah Swann.



Extreme ice and extreme mixing, continued

The second direct consequence of this winter's low air temperatures was the freezing of the entire surface of Emerald Bay. As early as February 1, large parts of the lake started developing a thin crust of ice, but it was not until March that the entire surface froze and snow started accumulating on top of the ice. This is believed to be the first time this has happened in at least 40 years.

Lake Tahoe did not completely freeze over, although many marinas and parts of the shoreline experienced ice during this last winter. There are no data to show that Lake Tahoe has ever been ice-covered since the time of John Fremont's first sighting of the lake in 1844. Why? Quite simply it is too deep given its latitude and altitude. For the lake to freeze, the surface water would have to fall to 39.2 oF across its entirety, which would require losing a lot of stored heat. Winter is not long enough for that to occur.

Emerald Bay Feb 1, 2023, before freezing over. Photo: Brant Allen, TERC

Emerald Bay March 15, 2023, after freezing over. Photo: Cal. State Parks

The passing of the disk

The management of Lake Tahoe has to a large degree been predicated on the clarity of the lake, as defined by how far down a highly trained observer could see a 10" white disk, known as a Secchi disk. From 1968 to 2004, responsibility for reading the depth of the Secchi disk rested on one person, TERC boat captain Bob Richards. After he retired, that responsibility fell on the new boat captain Brant Allen, who for many years had been trained under the watchful "eyes" of Bob Richards. Alas, after 35 years of studying Lake Tahoe (19 years of which included responsibility for the Secchi disk readings), Brant Allen has also decided to retire.

For many years, TERC received a great many questions about the health of the lake, the complex motions of the water, the algae accumulating in the nearshore, and other important topics. However, the most frequently asked question is, "how do you know that the clarity of the lake is declining, rather than the eyesight of the reader?" The question was usually answered by providing evidence of the 20/20 vision of our two long time readers, describing the highly prescribed methodology that is followed for an "official" Secchi disk reading, and citing the scientific literature that confirms the robustness of this measure.

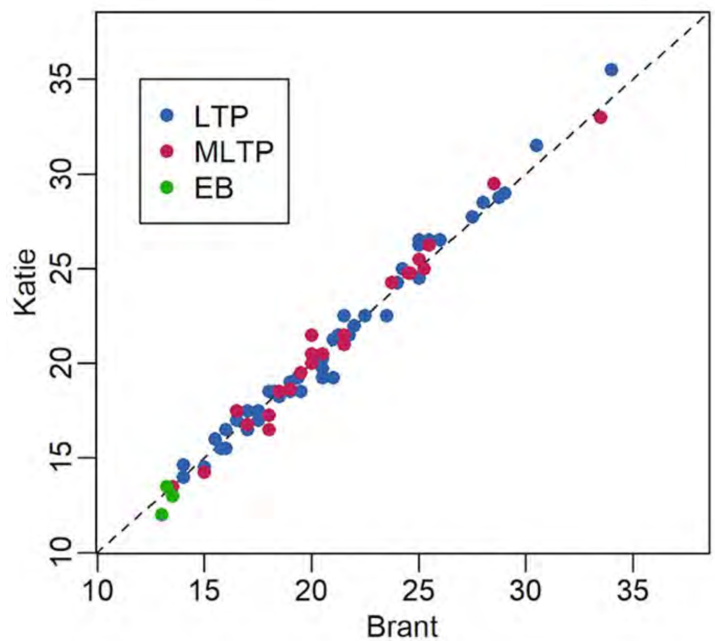
After over 30 years as TERC's boat captain dedicated to research and conservation efforts at Lake Tahoe, Brant Allen sets his eyes on new things. Photo: M. Okimoto

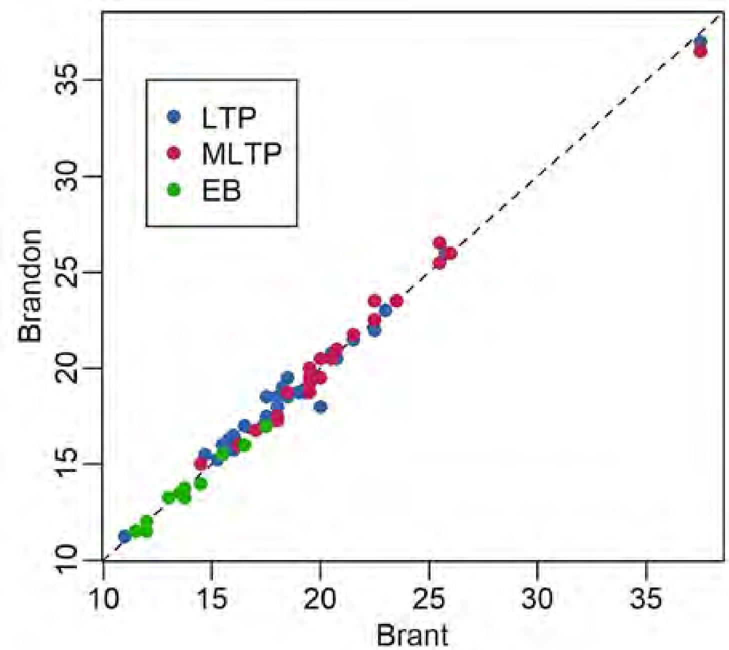
The passing of the disk, continued

As we prepared to enter this post-Brant era, let us settle the question once and for all. Since 2016, our two "back up" Secchi disk readers, Katie Senft and Brandon Berry, have independently read the Secchi depth within a few minutes of Brant completing his "official" reading. None of the readers were aware of the others reading and the results were passed off under the highest security to our data manager, Dr. Shohei Watanabe. For the first time, the results from this first-of-its-kind Secchi disk comparison is being revealed publicly.

The figures indicate the comparisons between observations from Katie and Brant (left) and observations from Brandon and Brant (right). The tests were conducted at the mid-lake MLTP site, the western LTP site, and in the center of Emerald Bay. As the results show, the correlation is remarkable. Statistically, both Katie and Brandon are within 0.2% of Brant's reading. In other words, if Brant reads 23 m (75.5 ft), then the other readings coincide to within 5 cm (2 inches).

Hopefully, understanding this rigorous comparison of Secchi depth readings will allay fears of accuracy. In the same way that we test the veracity of clarity measurements, we also go to great lengths to double check the tens of thousands of measurements we take annually at Lake Tahoe.



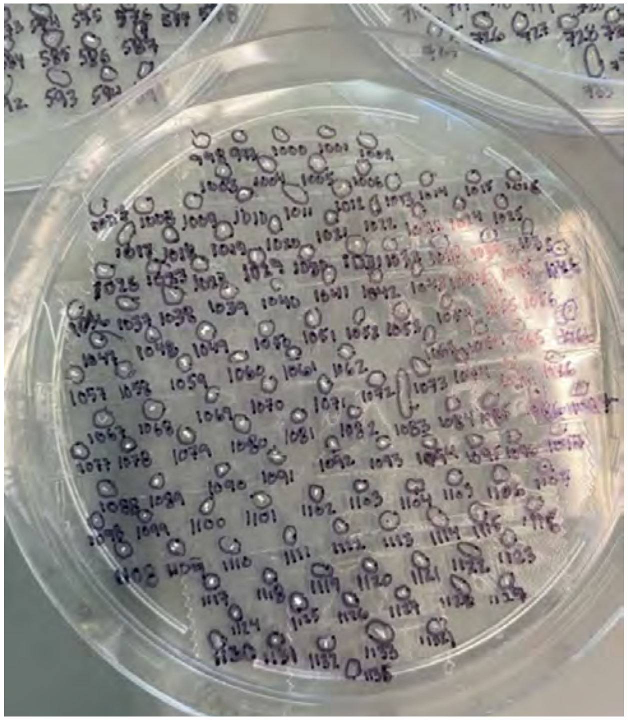


The microplastics of Lake Tahoe

A research team comprised of TERC researchers and the UC Davis One Health Institute completed the most comprehensive evaluation of microplastics in Lake Tahoe to date. The study was funded by the Nevada Division of Environmental Protection and the Tahoe Water Suppliers Association.

Using a Manta Trawl, water samples were collected from the lake surface and from 6 depths within the lake, down to 1,500 ft. Additionally, lake sediments and biota (Asian clams and kokanee salmon) were sampled. Following collection, processing, and isolation of particles suspected to be plastic, the particle composition was determined using Raman spectroscopy. Based on chemical identity determined by Raman spectroscopy, particles were classified into different types of plastics.

Manta trawl skims the water, collecting microplastics from Lake Tahoe's surface. Photo: K. Senft



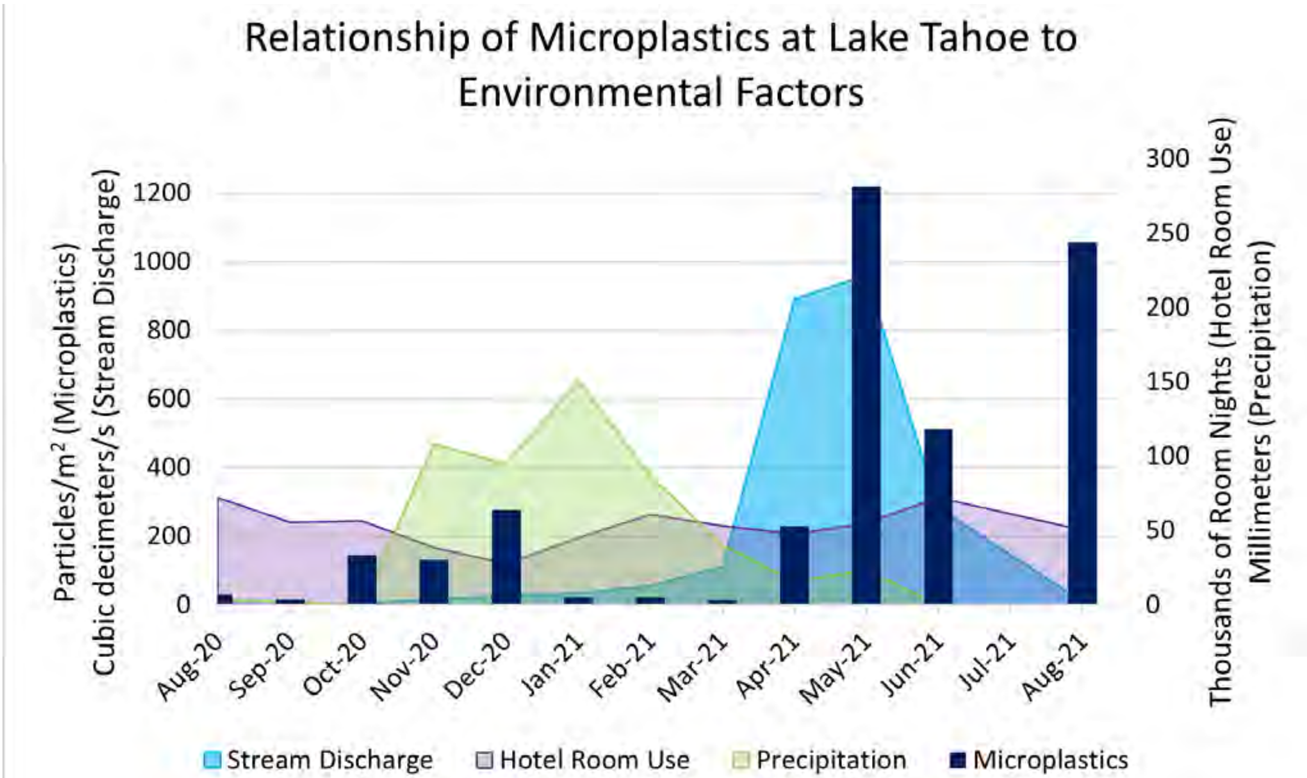
A meticulous count microplastics pulled from lake samples. Photo: S. Sesma

The microplastics of Lake Tahoe, continued

The microplastic abundance on the surface waters of Lake Tahoe are some of the highest reported amongst North American lakes (range: 13,000 – 1,220,000 particles/km2). However, higher values have been reported in other systems such as Lake Taihu, China (range: 10,000 – 6,800,000 particles/km2) and the San Francisco Bay (range: 34,000 – 1,800,000 particles/km2).

This study was limited by the mesh size of the traditional methodology of a Manta trawl, which allowed the escape of microplastics less than 335 microns or 1/64 of an inch. It is believed that smaller microplastics are far more abundant and are more likely to have human health and wildlife health impacts. A current pilot study, titled “The Ones that Got Away”, is examining particles down to 1 micron (4 hundred thousandths of an inch) in size.

Our full report is available at https://tahoe.ucdavis.edu/sites/g/files/dgvnsk4286/files/inline-files/LakeTahoe%20Microplastics%20Report_Final_20230302.pdf



The state of Lake Tahoe beaches

The nearshore of Lake Tahoe is where the public most often interacts with the lake and where public opinion regarding the lake's aesthetic character is primarily formed. Beyond aesthetics, the condition of the shore is a symptom of the overall health of the entire lake ecosystem and the presence of periphyton (attached algae) and metaphyton (unattached algae) are strong indicators.

In 2022, Lake Tahoe's nearshore regions and beaches experienced some of the most extreme conditions ever observed. Whether it was the broad expanses of attached algae (periphyton) around Tahoe City or the acres of washed-up filamentous algae (metaphyton) on the southern shoreline, these were not conditions that anybody wanted to continue.

Metaphyton and iron-rich pools at Conservancy Beach, September 29, 2022. Photo: S. Hackley

Metaphyton washing up on Kiva Beach, August 2022. Photo K Senft

The state of Lake Tahoe beaches, continued

The apparent increase in both the intensity and spatial extent of nearshore nuisance algae has a range of contributing factors, including climate warming of the nearshore waters and low lake levels during droughts. For the case of metaphyton, which have become a particular nuisance for the beaches, it is clear that the presence of Asian clams is a major driver. Laboratory experiments have shown that the Asian clam excretion contains 10–100x the level of nutrient concentrations of ambient lake water, sufficient to meet the nutrient needs of metaphyton species. Warming temperatures also allow Asian clams to be active for longer each summer.

What is being done? First, with Agency support, TERC has improved the ability to quantify the actual location of both periphyton and metaphyton. TERC researchers are currently implementing and evaluating a new monitoring program for nearshore algae that combines remotely sensed (drone and helicopter) imagery data with in-situ data collected by divers. Estimates of algal coverage and biomass will be generated from aerial images using machine learning and compared with coverage and biomass measurements at fixed stations around the lake. The new monitoring plan is designed to track both spatial differences in algal coverage as well as seasonal and interannual change in nearshore periphyton and metaphyton biomass.

A helicopter raw image showing the banded nature of the periphyton north of Ward Creek on April 28, near the peak of periphyton growth. Photo: M. Bruno

Periphyton near the mouth of the Truckee River, June, 2022. Photo: S. Hackley

The state of Lake Tahoe beaches, continued

Second, we are working on solutions for metaphyton control. One of the solutions entails the suction removal of metaphyton while it is still located above the Asian clam beds and before it is washed up on the beaches. The second, approach deals with the root cause of the problem, the Asian clams themselves. A laboratory experiment in summer 2023 will explore the efficacy of using hydrogen peroxide to oxidize Asian clams. Although hydrogen peroxide is a chemical, something that many at Tahoe are concerned about, it has the advantage that as it works it breaks down to form pure water.

Collected metaphyton, Regan Beach, August 2022. Photo K. Senft

Asian clams in a solution of hydrogen peroxide and water. Photo: O. Nole

Where does the flow go?

Lake Tahoe has 63 inflowing streams. Depending on the temperature and flow rate of each stream, as well as the temperature stratification of the lake, inflows can either flow in horizontally at the surface or they can plunge down vertically below the surface. In spring, when the stream flows are highest, they typically plunge below the surface, but most of the water stays in the upper 100 feet of the lake.

Where does the stream water flow to? That is a more complex question to answer, as it depends on the lake's currents, which are constantly changing in response to wind and other factors. But it is an important question as the stream water is loaded with nutrients, fine particles, microplastics, and a range of other pollutants of concern. To answer the question, it is necessary to use a complex, three-dimensional hydrodynamic model that can represent the flows that will carry the inflows.

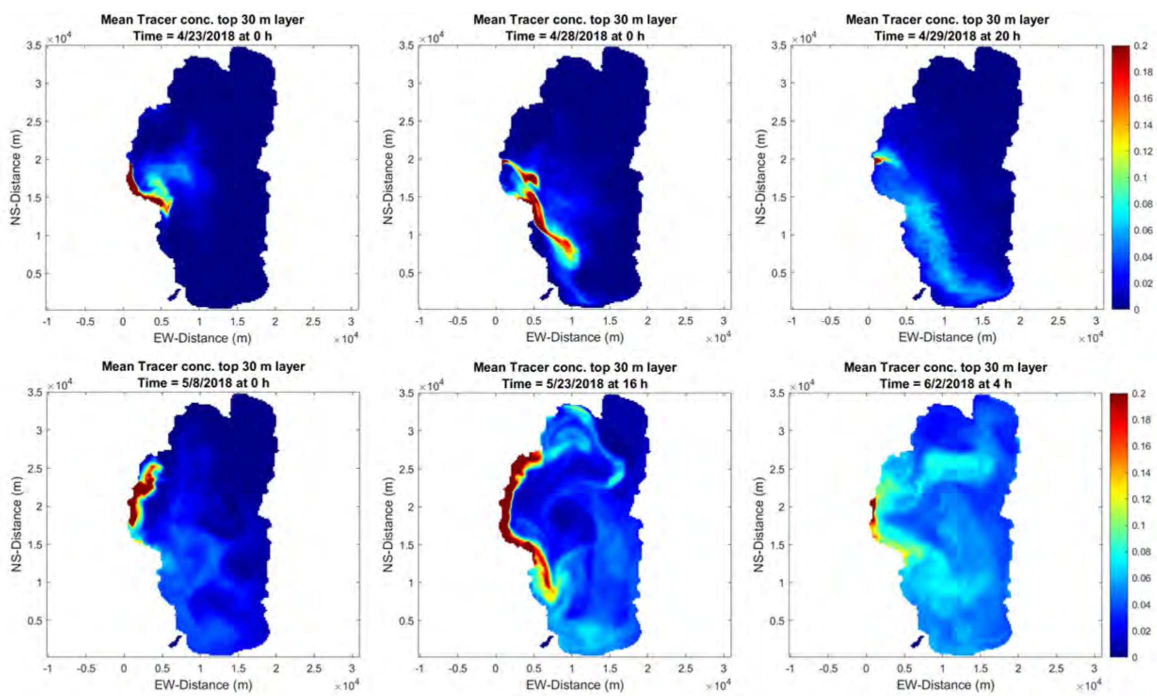
To illustrate the complexity of the fate of the stream water, the model depicts where a "tracer" would be carried in the upper 100 feet of Lake Tahoe. For illustration purposes, a continuous injection of a tracer added to Blackwood Creek was modeled commencing in April 2018. The tracer was just added to the model, not to the actual creek.

Streamflow can vary from year to year and based on flow rates and temperature stratification can have various effects on Lake Tahoe. Photo: A. Toy

Where does the flow go?, continued

The results are displayed as a series of the tracer distribution images in the upper 100 feet of the lake. They show multiple changes in the inflow fate during spring 2018. The tracer injection commenced on April 20, 2018 and continued through June 2, 2018. During late April, the inflow tended to flow south hugging the shoreline, but at the same time part of the inflow can be seen in the center of the lake. By early May, the flow pattern changed, and while the water inflow was observed moving north, the entire southern part of the lake showed some tracer concentration. By May 23, there are high concentrations along most of the west shore, but nearly the entire lake was impacted. By June 2, inflows are low, so relatively little tracer is being added, but the existing tracer was being spread and diluted throughout the lake.

Running scenarios with hydrodynamic models provide great insight into the workings of the lake, both physically and ecologically. It allows us to better understand the fate of contaminants that enter Lake Tahoe and in so doing allows for the more strategic planning of future monitoring. This is an important tool for helping to protect the long-term health of Lake Tahoe. Model results provided courtesy of Alicia Cortés.



The scientific underpinnings of no-wake zones

No-wake zones are common in most lakes, including Lake Tahoe. Near the shore, where the water is shallow and boating activity is high, the flows and waves generated by boats have the potential to resuspend sediment and nutrients from the lakebed.

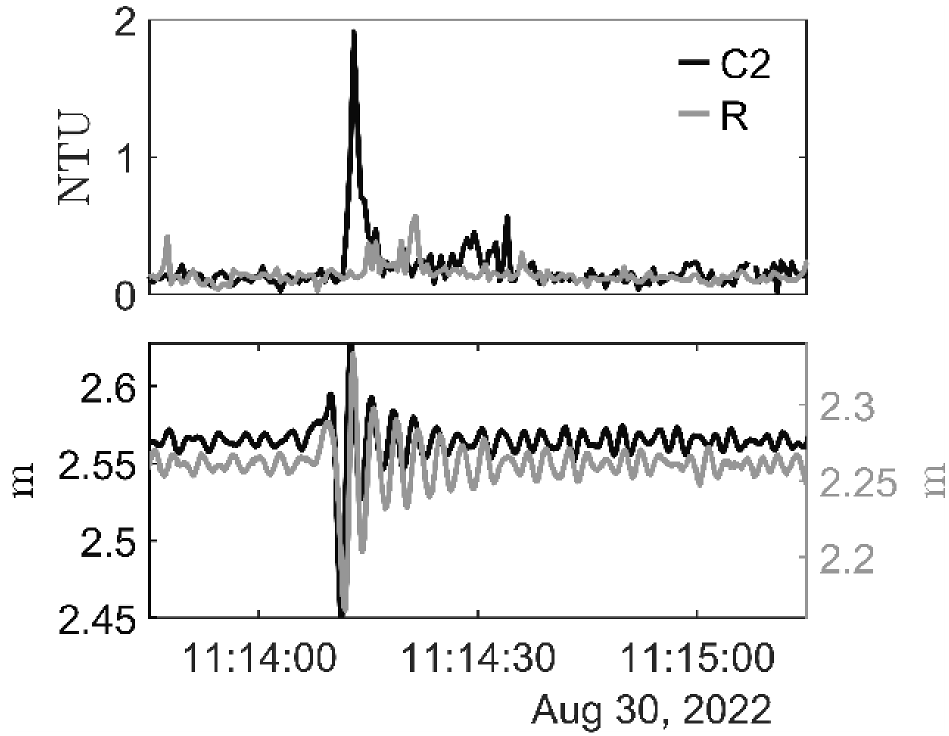
Field campaigns in 2019 and 2022, funded by the Tahoe Regional Planning Agency, revealed that boat-induced waves accounted for up to 45% of the total wave activity registered on the south shore of Lake Tahoe during the summer. The boat-induced waves generally at a maximum between 10:00 am and 12:00 pm, gradually declining in the afternoon to about 10% of the total wave activity. As the summer transitioned into fall, the contribution of boat wake to overall wave activity decreased.

The instruments at Site C2 measuring water clarity (turbidity), pressure (depth), and water velocity induced by a boat travelling at 10mph over the site. Site R is out of the frame as it is 20 ft to the left of Site C. An in situ video camera was used for this image.

The scientific underpinnings of no-wake zones, continued

In 2022, turbidity and wave measurement instruments were installed at a water depth of 8 feet, and boats driven over the site at a range of speeds. When boat speeds exceeded 5 mph, sediment resuspension occurred, and resulted in turbidity increases of up to 6 NTU. This value is well above the desired turbidity level. The highest impacts were for speeds of 10 mph. The boat-induced sediment resuspension was characterized by an instantaneous increase in turbidity (decrease in water clarity).

The study found that the existing no-wake zones were protective of most, but not all, of Lake Tahoe's nearshore. Where they were found to be lacking were on the south shore and on the northwest shore, where shallow shelfs are present. We are working with Agencies to determine if modifications to the policy are needed to provide more complete protection. Plots courtesy of Sergio Valbuena.



Turbidity (upper) and wave amplitude induced by boat passage of recreational watercraft at speed of 10 mph. The instruments at C2 are located immediately below the boat passage, whereas the instruments at R are 20 feet off the boat's trajectory.

What is yellow and floating in the middle of Lake Tahoe?

In late June 2023, Tahoe visitors bore witness to the very large release of pine pollen at Lake Tahoe. The pollen coated cars with a yellow hue, infiltrated homes, and caused allergies to flare up, but much of it seemed to end up on the lake itself. Being lighter than water, pollen floats for a long time, before either being washed up on the shore or becoming coated with other particles and sinking to the lake bottom.

A pine pollen grain from 20 m depth at Lake Tahoe. Photo: L. Tanaka

Pollen forming intricate patterns at Crystal Bay, NV. Photo: M. Bruno

What is yellow and floating in the middle of Lake Tahoe?, continued

Does the pollen impact lake water quality? In a 1970 study performed by Dr. Pete Richerson of UC Davis, five plastic tubs were placed around the lake to collect the pollen. Based on the results, an estimated 12.5 kg of nitrogen and 16.6 kg of phosphorus were added across the entire lake via pollen. By comparison, in 2022, the Upper Truckee River alone contributed 11,100 kg and 1,680 kg of nitrogen and phosphorus respectively. Therefore the nutrient contribution from pollen is negligible.

Does the pollen impact clarity? Probably not. Most pollen grains are about 20–100 microns in diameter, about 10 times larger than the particle sizes that reduce clarity.

In conclusion, it seems that the largest negative impact of the pollen is the annual cleaning of decks, garden furniture,

Pollen in the nearshore at Tahoe Vista, CA. Photo: K. Larrieu

Dense collection of pollen at Moon Dunes beach. Photo: A. Toy

A new opportunity for tomorrow's scientists and educators

This year TERC has launched a new summer internship program to help train and inspire the future generations of scientists. While we have always had summer interns, they were focused on a single area of TERC research and generally were unpaid positions. As a consequence, only students who did not need a paying position or already had housing in the Tahoe area would apply.

This year is different. Each intern is paid a "living stipend" and works under the guidance of a research mentor. The group convenes weekly to share their progress and updates. They participate in a weekly lecture from outside experts from Tahoe's agencies, non-profits, or other community experts. On the first day of the 2023 program, the group had a unique opportunity to hear from Herman Fillmore, the Washoe Tribe's Culture and Language Resources Director, speaking on the history and significance of his tribe at Lake Tahoe. Through this new innovative program, interns are gaining exposure to all of TERC research and learn about science guided policy and advocacy from local experts.

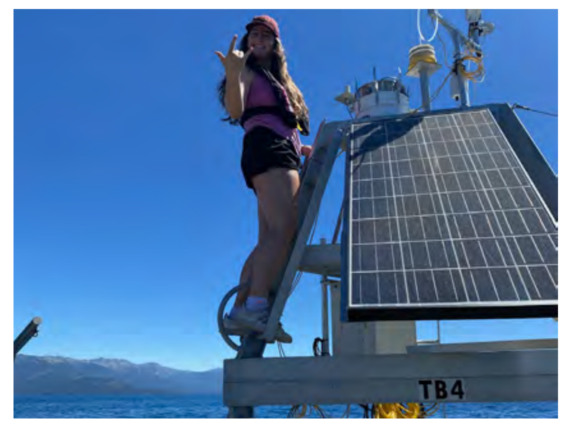
Following the launch of the TERC Internships for Scholars program, we had over 30 applicants and were able to offer positions to seven scholars whose interests and level of scholarship best matched our research needs. The group represents students from UC Davis, Cal Poly San Luis Obispo, University of Nevada Reno, Drake University, University of Washington, and University of Denver.

The culmination of the summer internships will take place on August 10, 2023, at Granlibakken in Tahoe City, and the whole community is invited to meet them and learn the results of their research.

The funding for the TERC Internships for Scholars program has come exclusively from philanthropic support and we thank the donors who gave so generously. If you are interested in supporting this annual program, please visit https://give.ucdavis.edu/TERC/TERCG56

Olivia Nole sets up bins of hydrogen peroxide for an Asian clam experiment. Photo: O. Nole

Sydney Mendelson and Sidney Barbier teach visitors and residents all about TERC. Photo: K. Wilson



Katie Fielder checking out the TERC research equipment aboard buoy TB4. Photo: K. Senft

TAHOE: STATE OF THE LAKE REPORT 2023

METEOROLOGY

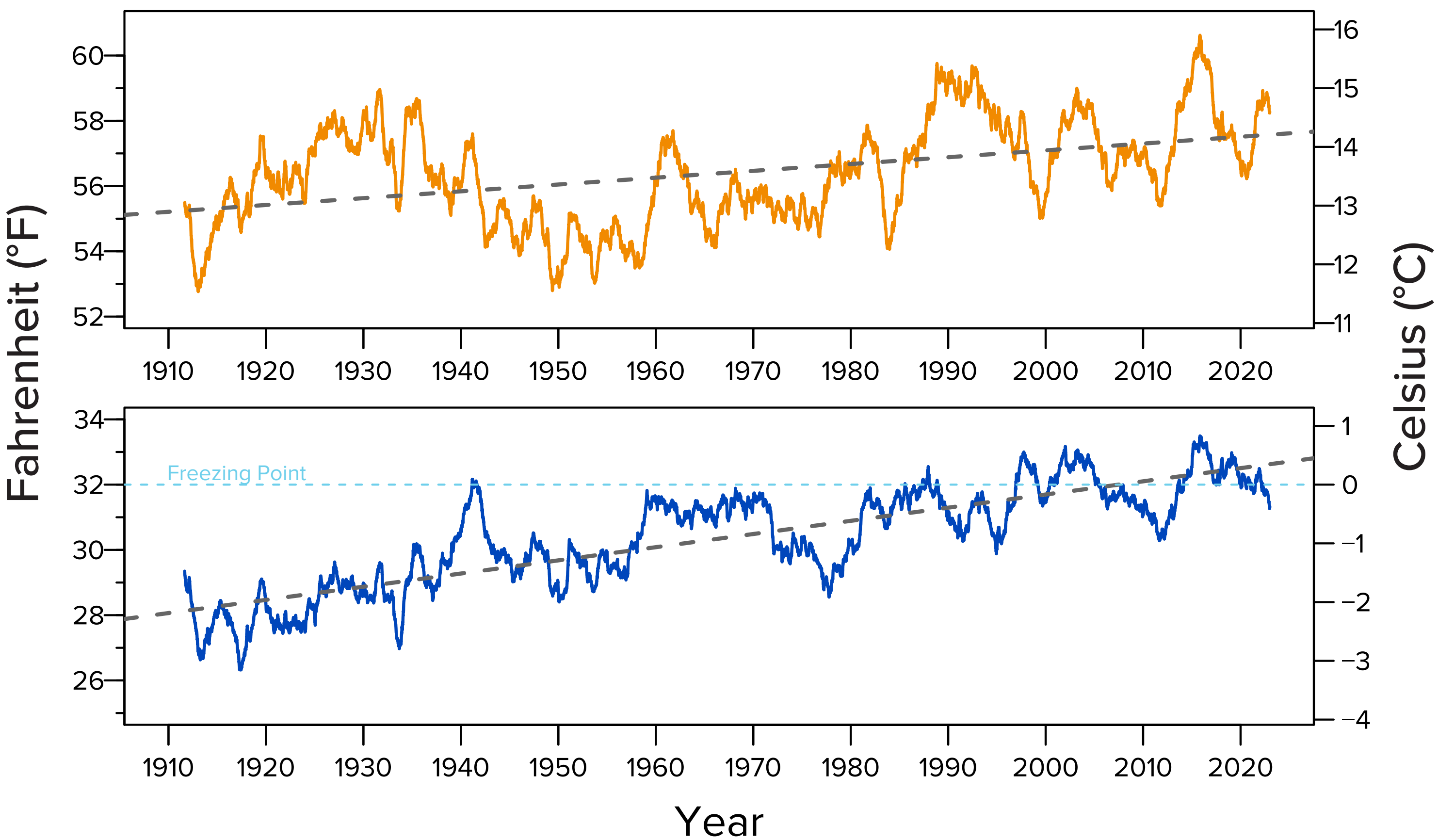
UCDAVIS
Tahoe Environmental
Research Center

Air temperature - smoothed daily maximum and minimum

Daily since 1911

Over the last 111 years, daily air temperatures measured at Tahoe City have increased. The long-term trend in average daily minimum temperature (bottom figure) has increased by 4.50 °F (2.50 °C) and the long-term trend in average daily maximum temperature (upper figure) has risen by 2.33 °F (1.29 °C). The trend line for the minimum air temperature has exceeded the freezing temperature of water for the last 17 years, contributing to generally more rain and less snow as well as earlier snowmelt at Lake Tahoe. These data are smoothed using a two-year running average to remove daily and seasonal fluctuations. The minimum temperature dropped back below the freezing point in 2022.

Data source: Long-term NOAA daily maximum and minimum temperatures data set.

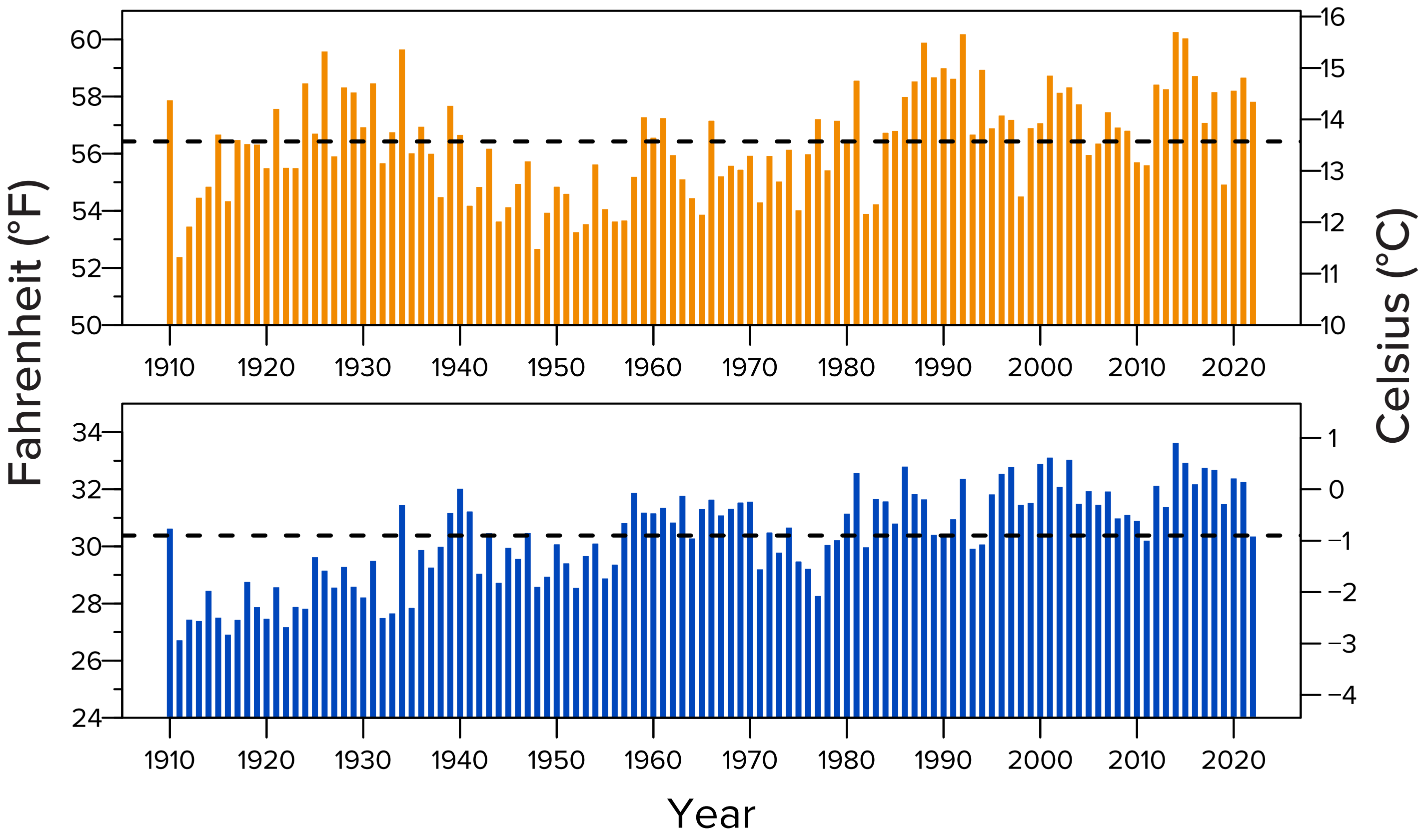


Air temperature - annual average maximum and minimum

Since 1910

Annual average maximum (upper figure) air temperatures in 2022 was similar to the previous year and above the long-term average (dashed line) air temperature. Annual average minimum (lower figure) air temperatures in 2022 was distinctly lower than the previous year and coincided with the long-term average (dashed line) air temperature. The annual average maximum temperature was 57.9 °F (14.4 °C), which was 0.7 °F cooler than the previous year. The 2022 annual average minimum was 30.4 °F (-0.9 °C), which was 1.9 °F cooler than the previous year. The long-term averages for the maximum and the minimum are 56.4 °F (13.6 °C) and 30.4 °F (-0.9 °C), respectively.

Data source: Long-term NOAA daily maximum and minimum temperatures data set measured at Tahoe City.



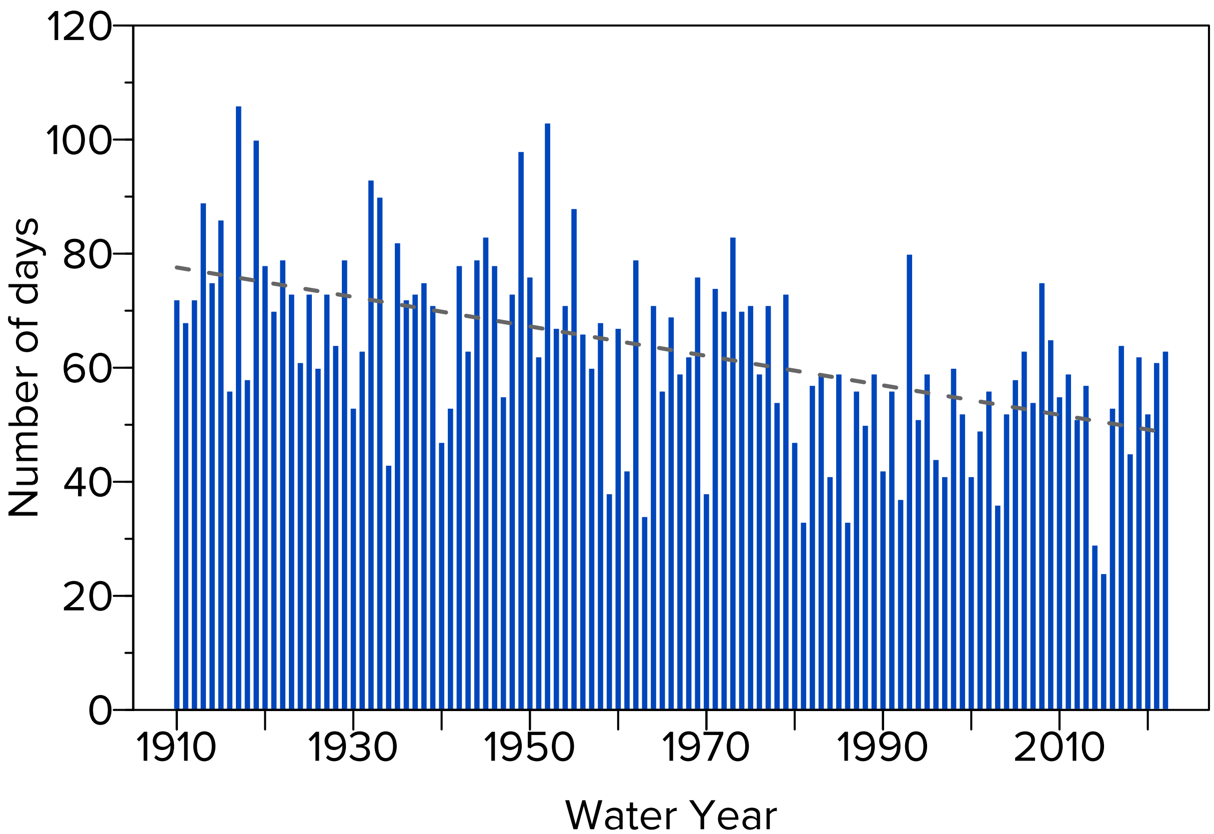
Below-freezing air temperatures

Yearly since 1910

The method used for this analysis sums the number of days with daily average temperatures below freezing between December 1 and March 31 for each Water Year (WY). Although year-to-year variability is high, the number of days when air temperatures averaged below-freezing has declined by over 29 days since 1911. In WY 2022, the number of freezing days was 63, above the declining long-term trend line. This is consistent with the measured air temperatures in 2022.

Data source: Long-term NOAA daily maximum and minimum temperatures data set measured at Tahoe City.

Note: The Water Year extends from October 1 through September 30.



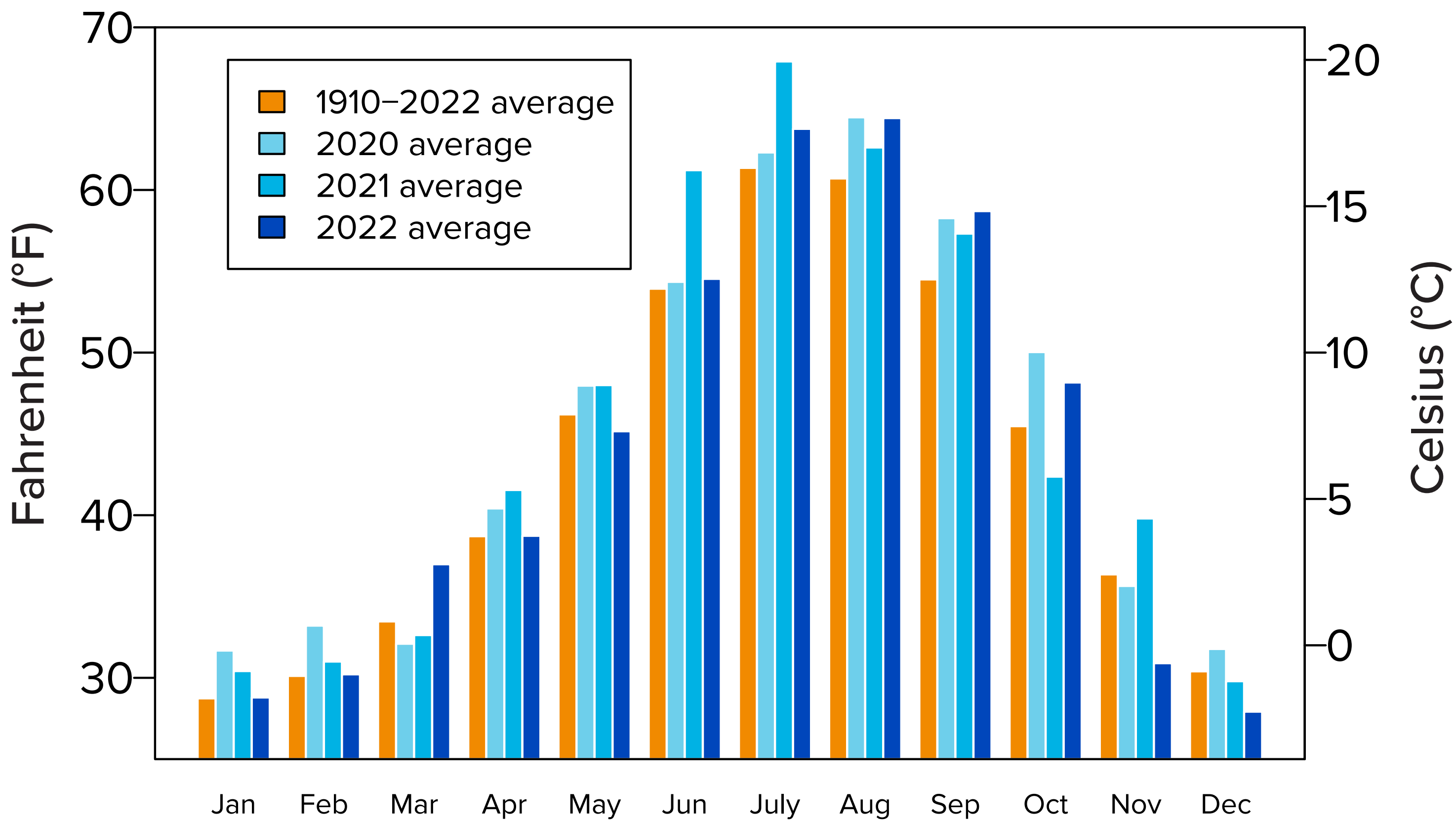
Monthly air temperature

2020, 2021, 2022 and 1910 to 2022

In 2022, monthly air temperatures were similar to 2020 and 2021. However, for the months of November and December, temperatures were distinctly colder than the previous two years and the long-term average. The November mean temperatures were the third coldest on record after 1994 and 1931, while in December temperatures were the 22nd coldest.

For nine months of the year, monthly air temperatures were equal to or greater than the long-term average air temperature (since 2010). Most of this was due to an increase in daytime maxima.

Data source: Long-term NOAA daily maximum and minimum temperatures data set.

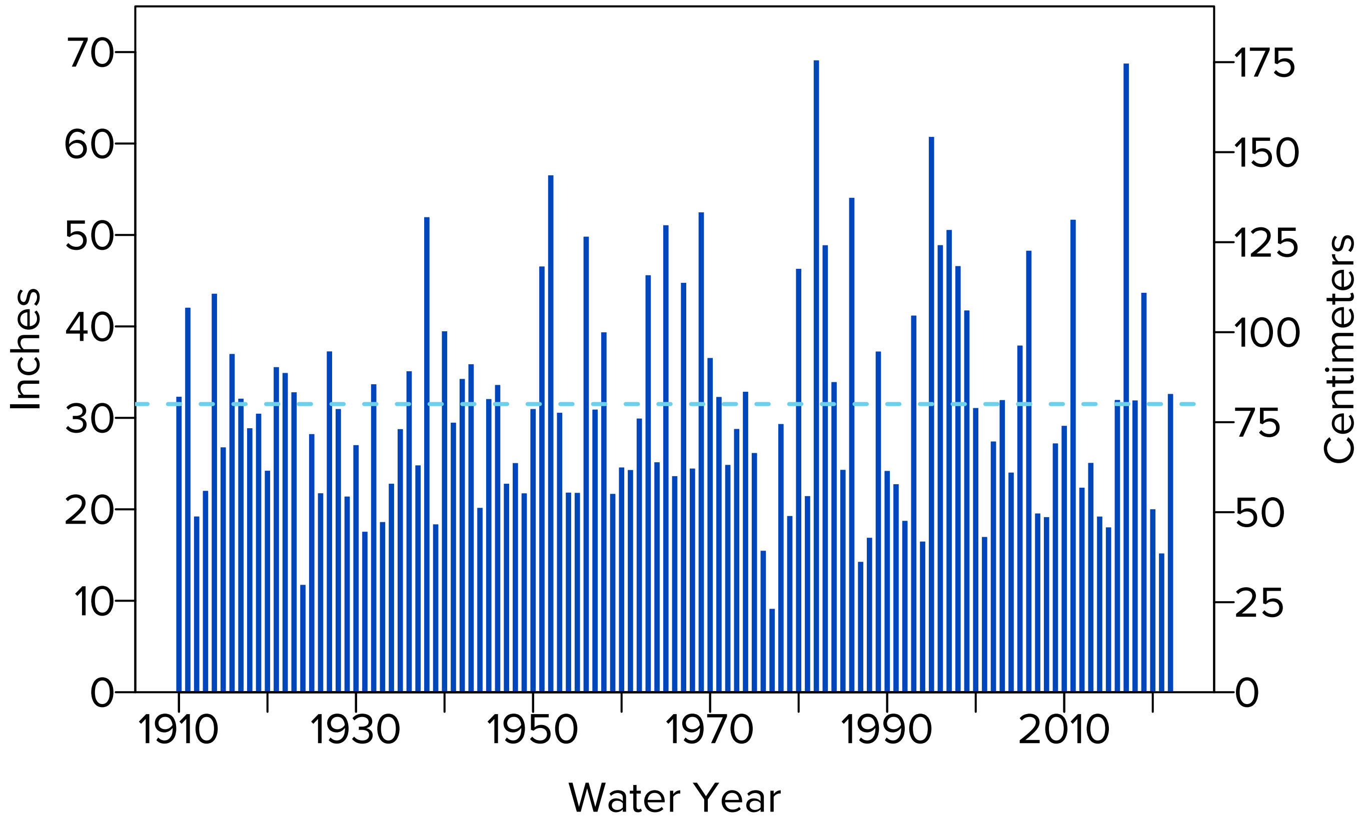


Annual precipitation

Yearly since 1910

From 1910 to 2022, average annual precipitation (water equivalent of rain and snow) measured at Tahoe City was 31.5 inches. The maximum recorded was 69.2 inches in 1982. The minimum recorded was 9.2 inches in 1977. At 32.7 inches, 2022 was 1.2 inches above the long-term average (shown by the dashed line). Generally, there is a gradient in precipitation from west to east across Lake Tahoe, with almost twice as much precipitation falling on the west side of the lake. There is also an increase in precipitation with elevation in the Tahoe basin. Precipitation is summed over the Water Year, which extends from October 1 through September 30.

Data source: Long-term NOAA daily precipitation data set.

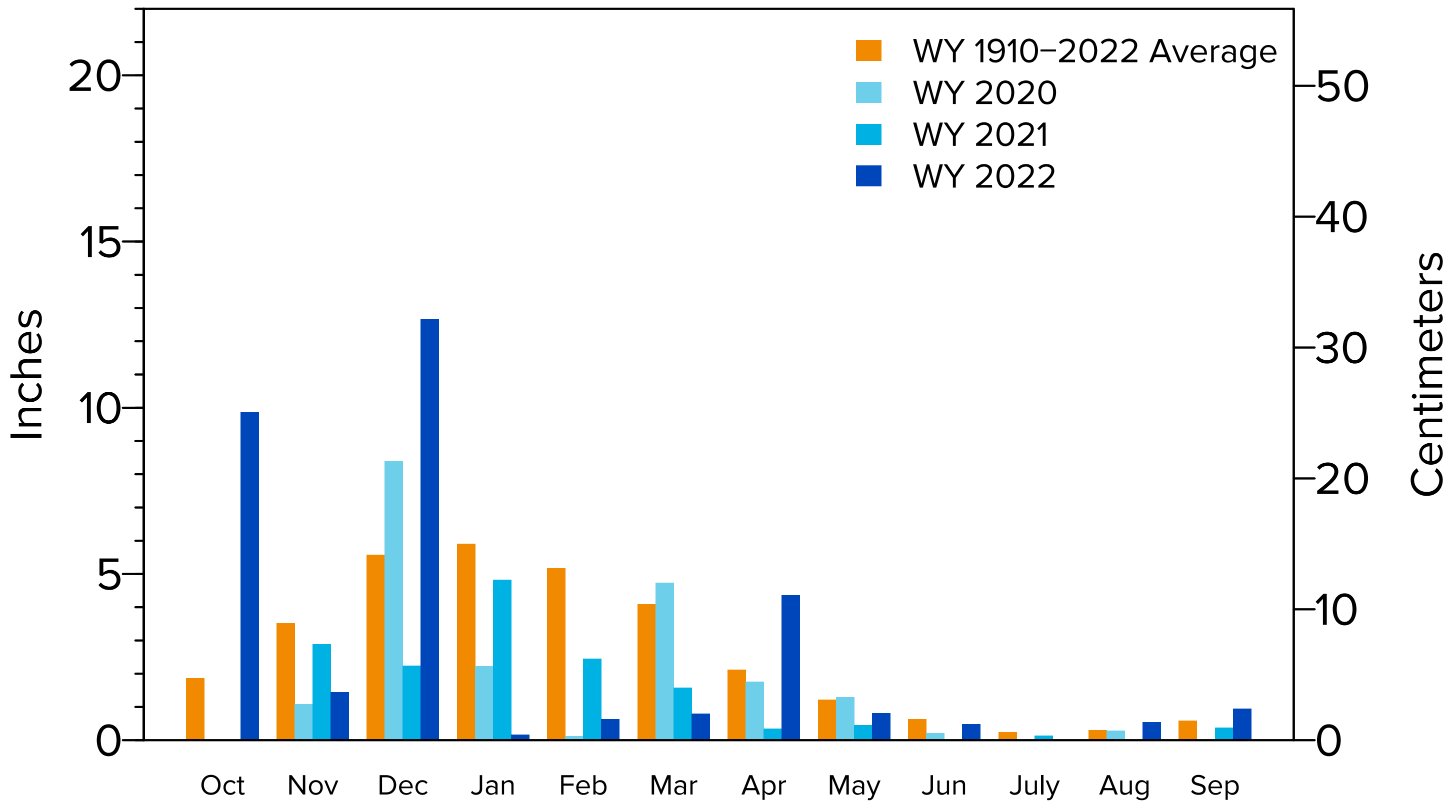


Monthly precipitation

2020, 2021, 2022 and 1910 to 2022

The 2022 Water Year had an annual average of 32.7 inches of precipitation, slightly above the long-term average of annual precipitation of 31.5 inches at Tahoe City. Precipitation in October, December and April for the 2022 Water Year was well-above the long-term average for those months. In all other months it was generally lower than the long-term average. The 2022 Water Year extends from October 1, 2021 through September 30, 2022.

Data source: Long-term NOAA daily precipitation data set.

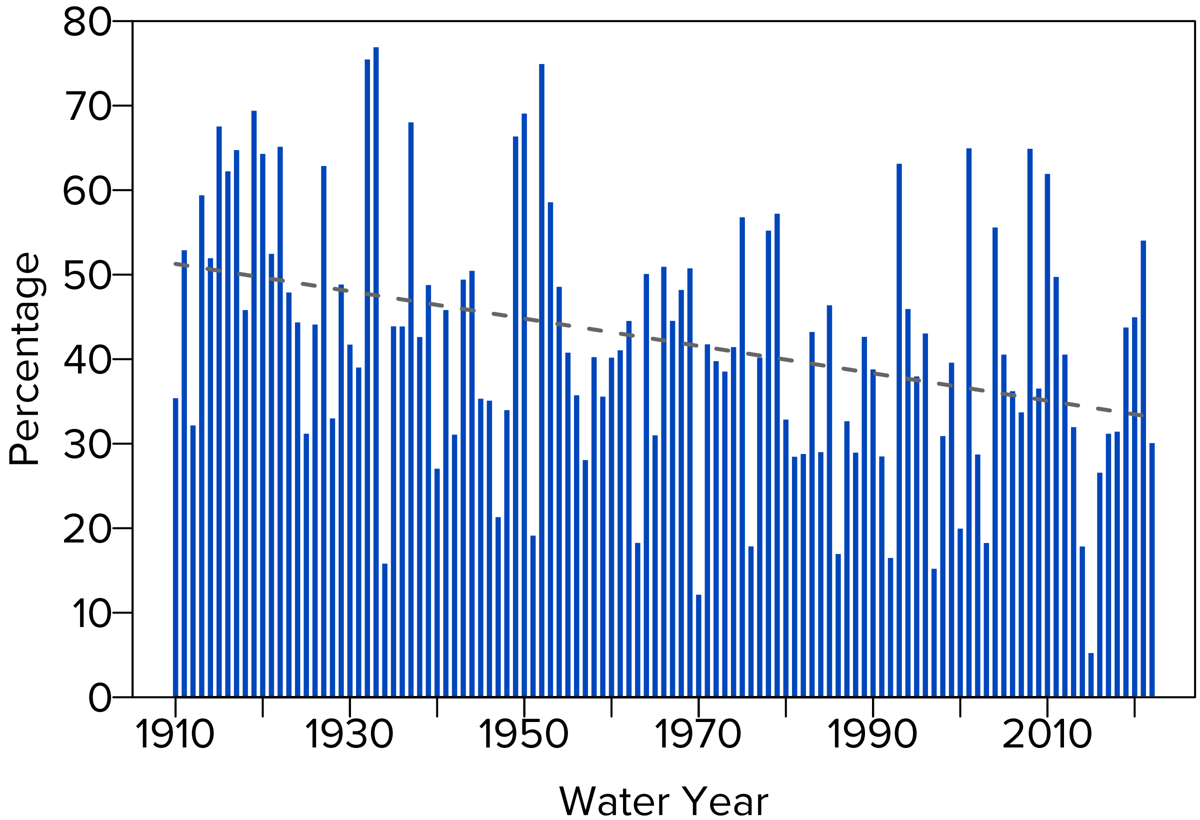


Snow as a fraction of annual precipitation

Yearly since 1910

Snow has declined as a fraction of total precipitation from an average of 52 percent in 1910 to 33 percent in 2022. In Tahoe City, snow represented 30.2 percent of the 2022 total precipitation. These data are calculated based on the assumption that precipitation falls as snow whenever the average daily temperature (the average of the daily maximum and minimum temperatures) is below-freezing. Precipitation is summed over the Water Year, which extends from October 1 through September 30.

Data source: Long-term NOAA daily air temperature and precipitation data sets.



April snowpack

Since 1916

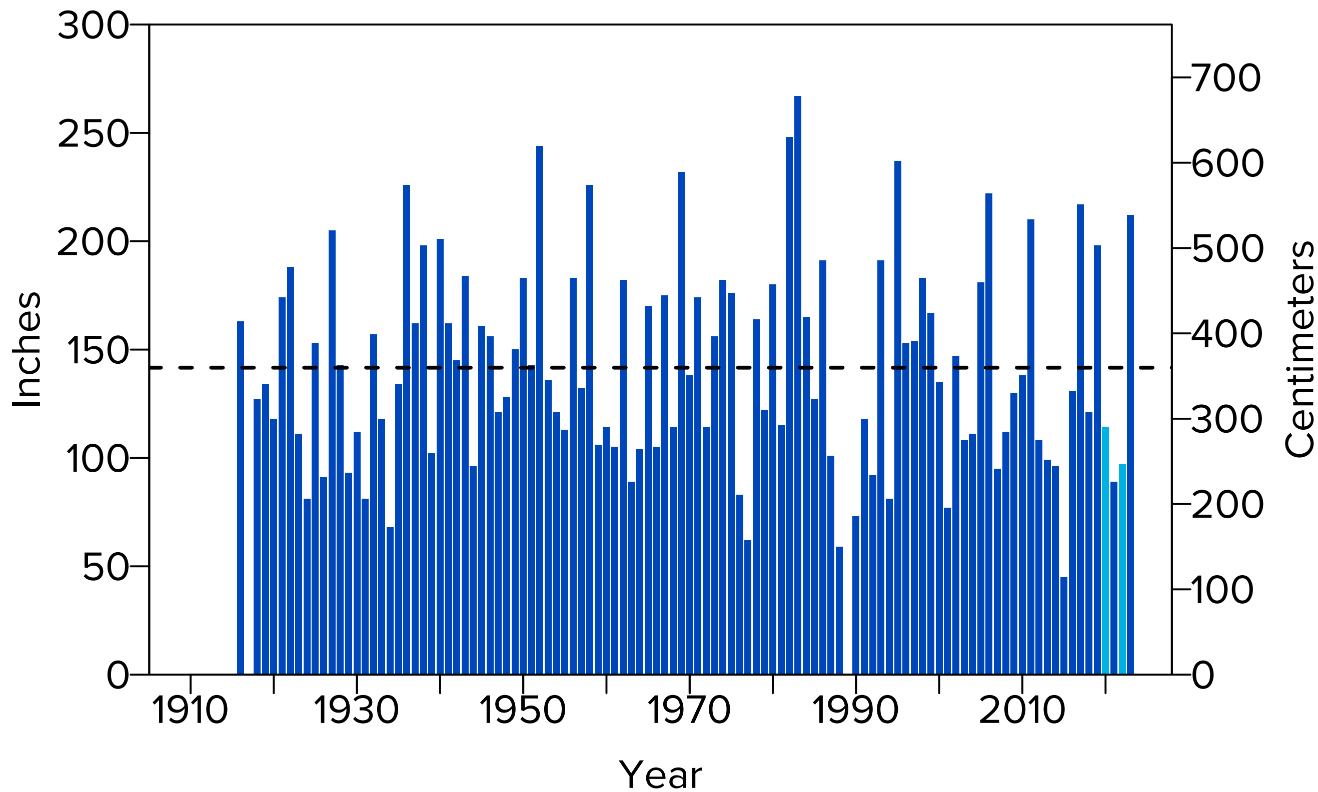
The depth of the snowpack is measured over the year at multiple locations throughout the Sierra. Shown here are the readings taken on approximately April 1 since 1916 at the Lake Lucille Snow Course Station (located in Desolation Wilderness, elevation 8,188 feet (Lat. 38.86 deg. Long. -120.11 deg.).

In 2020 and in 2022, the April snowpack readings at Lake Lucille were not made due to storm conditions. Instead, the values were estimated by correlation with values made at the Rubicon #1 snow course. The correlation estimates are shown with the lighter blue columns.

For April 13, 2023, the value was 212 inches, well-above the long-term average. The largest amount on record was 267 inches on April 5, 1983. The average snow depth (shown by the dotted line) over the period 1916-2023 was 142.3 inches.

Note: April snow depth data are not available for 1917 and 1989.

Data source: USDA Natural Resources Conservation Service, California Monthly Snow Data.

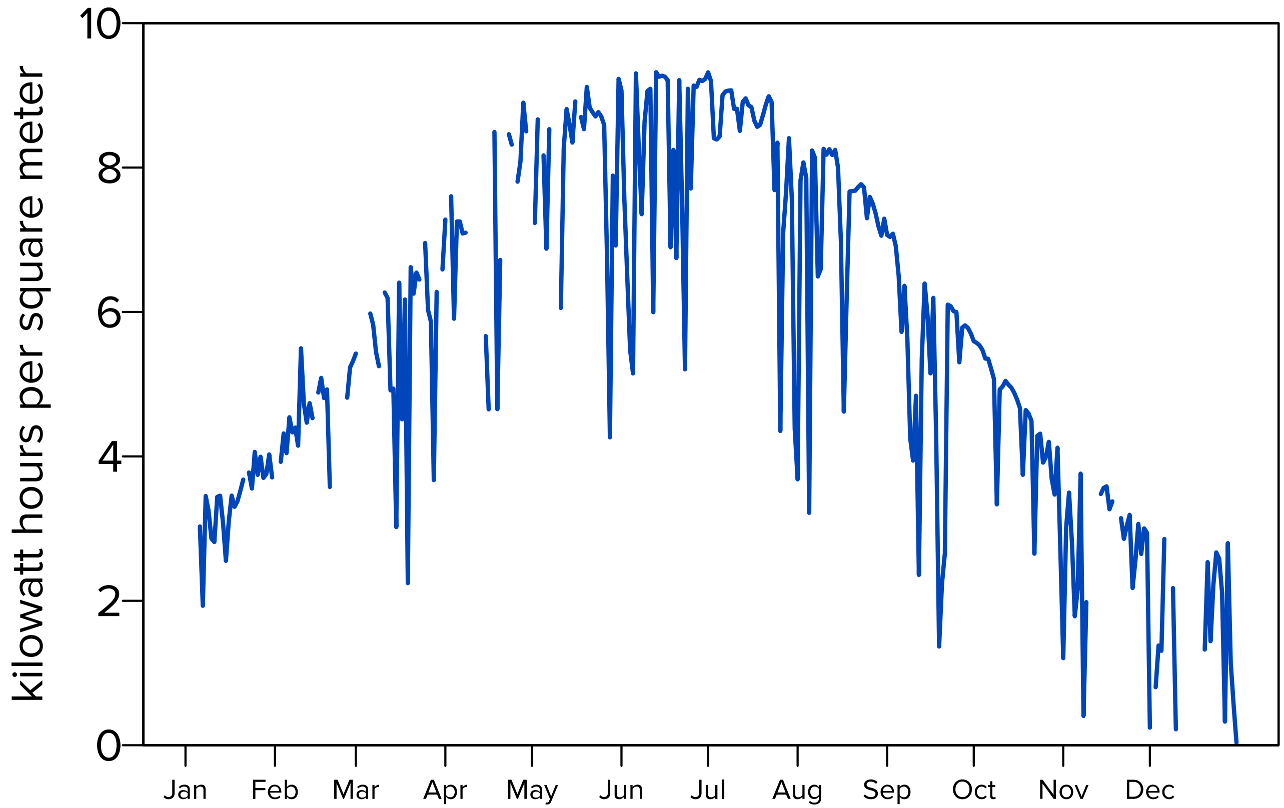


Daily solar radiation

In 2022

Solar radiation showed the typical annual pattern of sunlight, peaking at the summer solstice on June 21 or 22. Dips in daily solar radiation are primarily due to cloud coverage. Smoke and other atmospheric constituents play a smaller role. It is worth noting that solar radiation on a clear day in mid-winter can exceed that of a cloudy or smokey day in mid-summer.

The TERC meteorological station where these data are collected is located on the U.S. Coast Guard dock at Tahoe City.



TAHOE: STATE OF THE LAKE REPORT 2023

PHYSICAL PROPERTIES

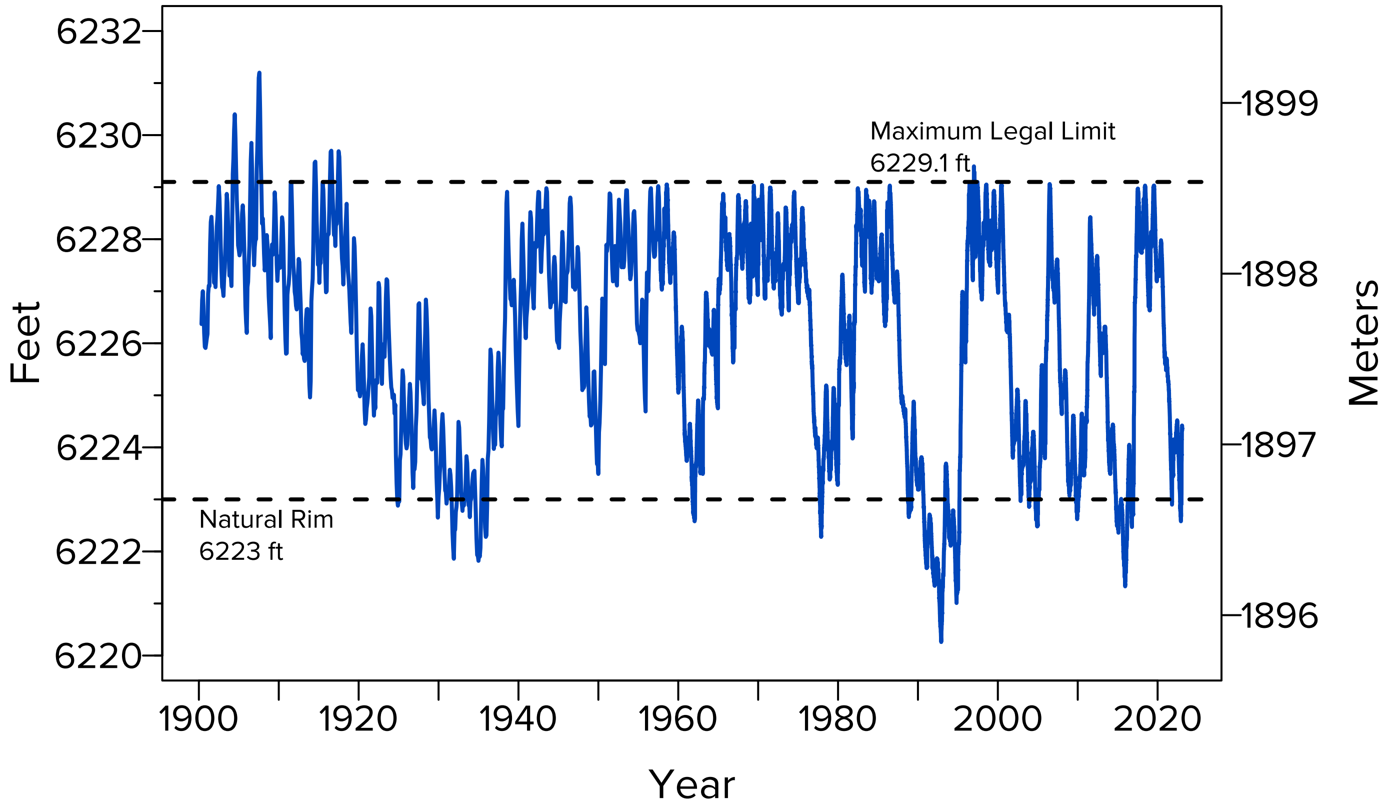
UC DAVIS Tahoe Environmental Research Center

Lake surface level

Daily since 1900

Lake surface level varies throughout the year. Lake levels rise due to high stream inflow, groundwater inflow, and precipitation of rain and snow directly onto the lake surface. It falls due to evaporation, in-basin water withdrawals, groundwater outflows, and outflows via the Truckee River at Tahoe City. In 2022, the highest lake level was 6,224.52 feet on June 13, and the lowest was 6,222.58 feet on November 30, 2022. The natural rim of the lake is at an elevation of 6,223 feet. Lake Tahoe fell below its rim on October 24 but rose back above it on December 27. When the lake was below its rim, outflows via the Truckee River ceased. Several episodes of lake level falling below the natural rim are evident since 1920. The frequency of low water episodes appears to be increasing. The lowest lake level on record is 6,220.26 feet on November 30, 1992 when the lake was 2.74 feet below the natural rim.

Data source: U.S. Geological Survey level recorder in Tahoe City.



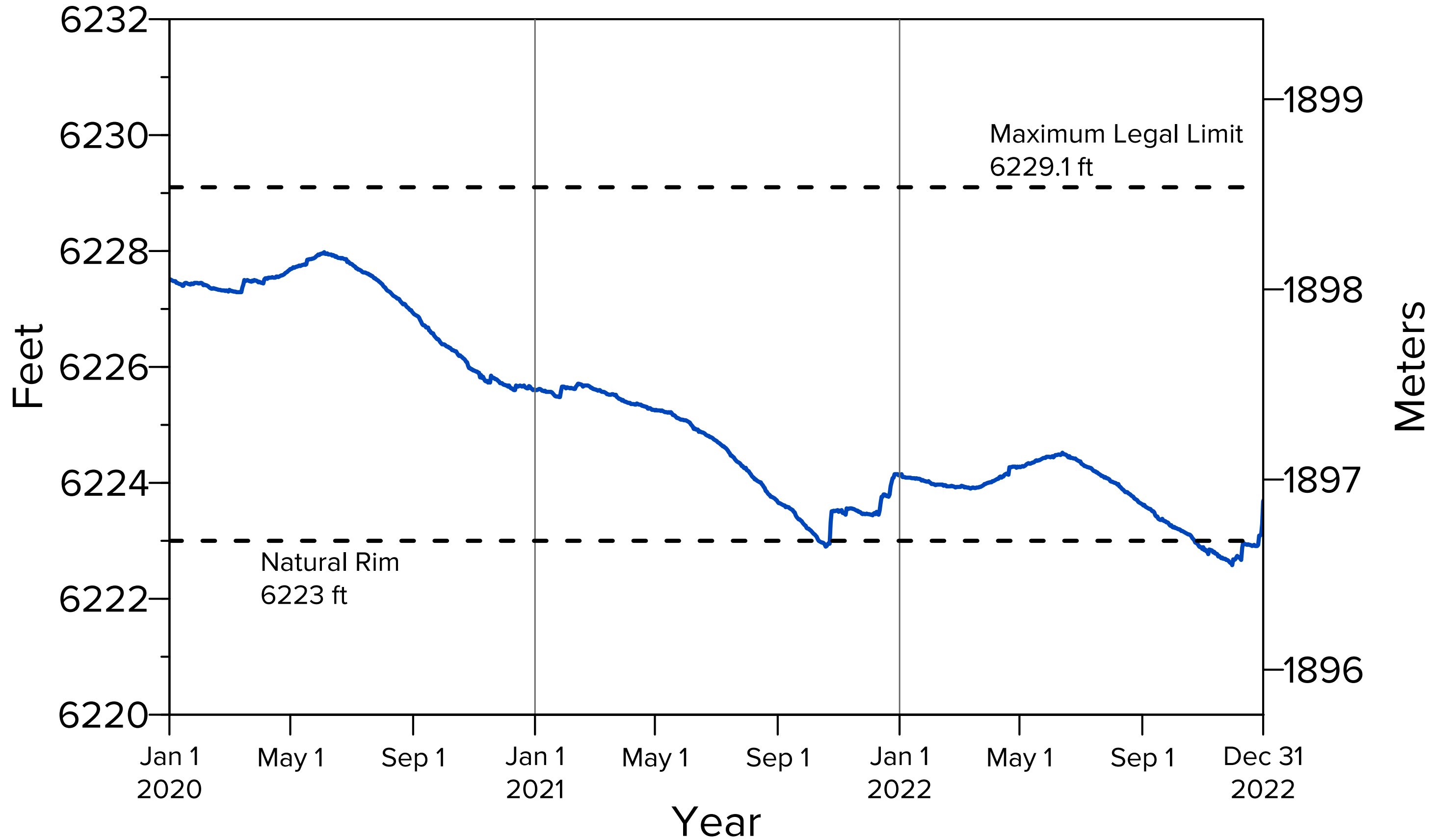
Lake surface level

Daily in 2020, 2021, and 2022

The subset of lake surface data is extracted from the same data as in Figure 8.1 for the most recent three years from 2020–2022. This more time-restricted presentation of recent lake level data better displays the annual patterns of rising and falling lake level in greater detail.

In 2022, on account of the average precipitation, the winter and spring rises in lake level are evident. Precipitation in October and December 2021 produced sudden jumps in lake level. Snowmelt in spring continued the rise in lake level, but after June 13 the water level slowly fell until winter precipitation again caused lake level to rise.

Data source: U.S. Geological Survey level recorder in Tahoe City.

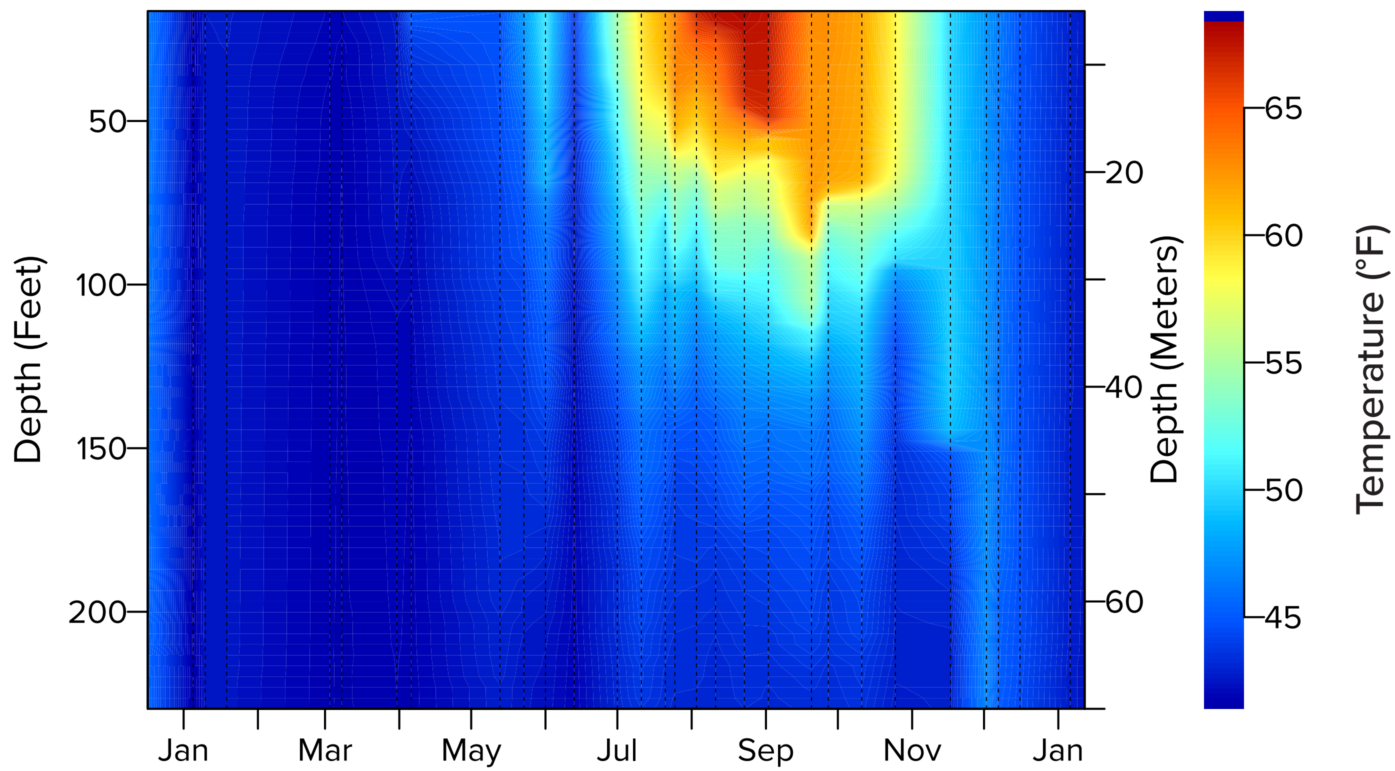


Water temperature profile

In 2022

Water temperature profiles are measured in the lake using a CTD (conductivity, temperature, depth) profiler on the days indicated by the dashed vertical lines. The measured temperature is accurate to within 0.005 °F. The vertical distribution of water temperature is a very important lake attribute as it represents lake density. During the summer months, the warmer, lighter water remains suspended at the lake surface. The temperature in the upper 230 feet (70 m) of Lake Tahoe is displayed as a color contour plot. In the early part of 2022, the lake temperature followed the typical seasonal pattern. In February and March, the lake surface was at its coldest, while it was at its warmest in August.

Data source: TERC lake monitoring.

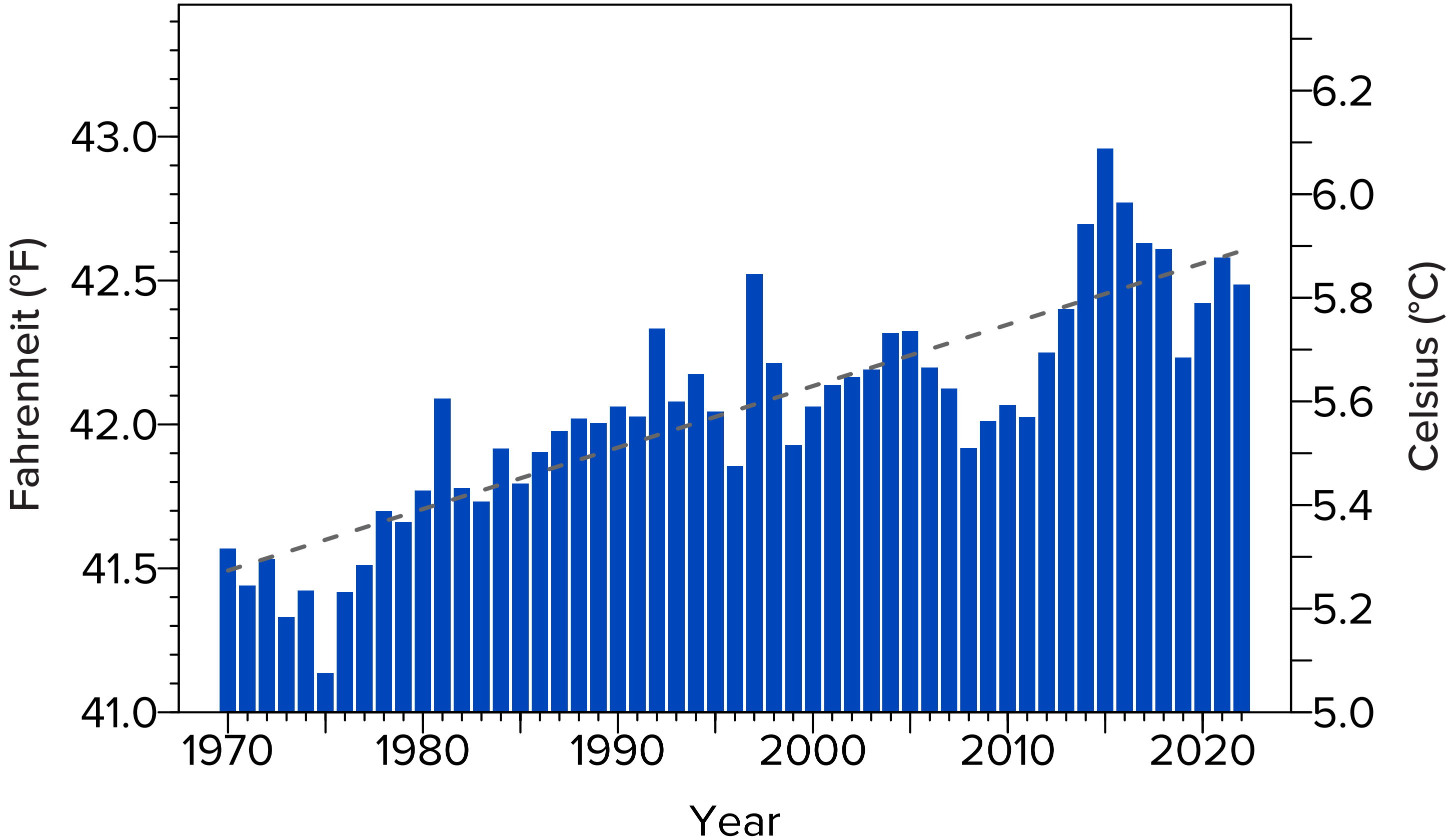


Annual average water temperature

Since 1970

The volume-averaged temperature of the lake for each year since 1970 is shown. The trend line indicates that water temperature has increased by approximately 1.1 °F (0.62°C) since 1970. The annual rate of warming is 0.21 °F/decade (0.12 °C/decade). The monthly temperature profile data from the top to the bottom of the lake has been smoothed, and any seasonal influences were removed to best show the long-term trend.

Data source: TERC lake monitoring.

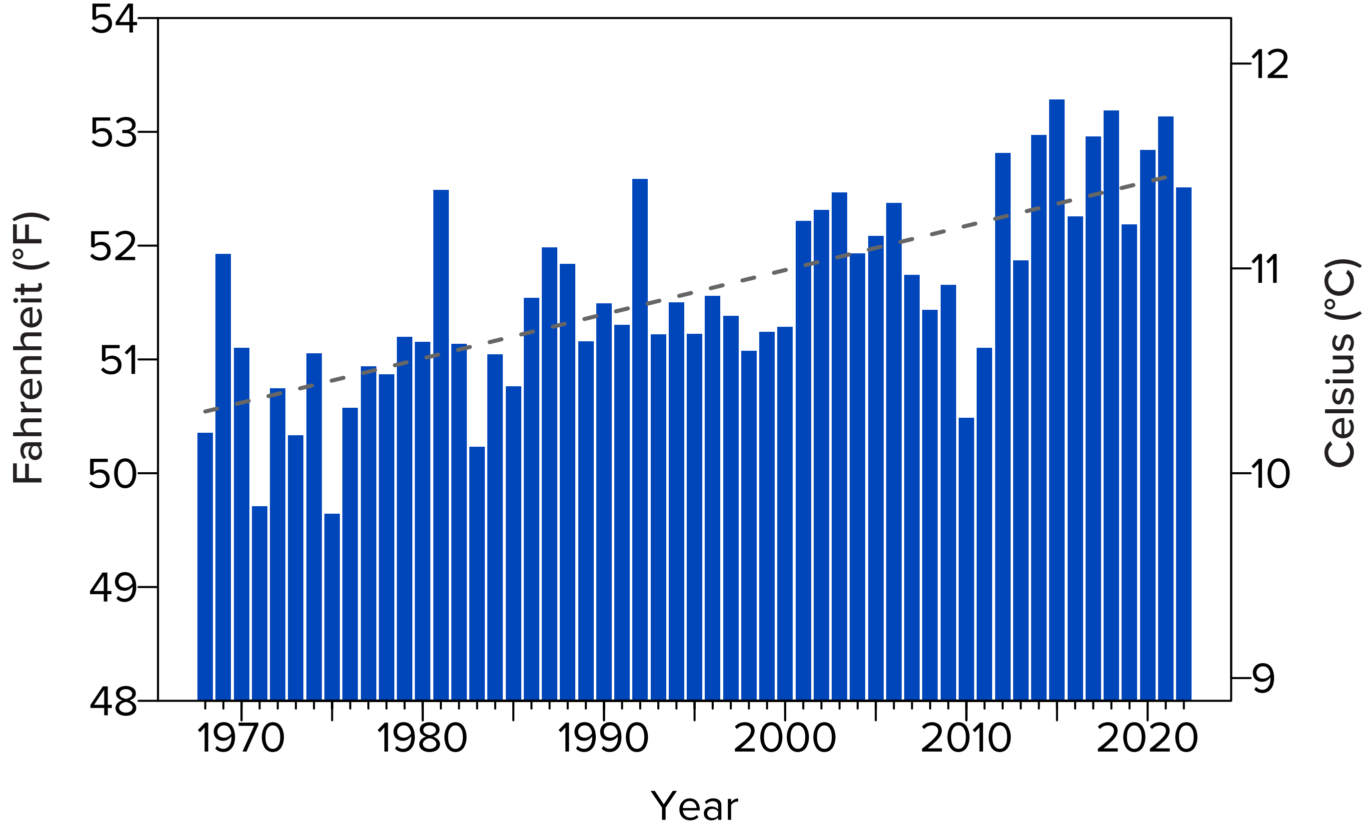


Annual surface water temperature

Yearly since 1968

Surface water temperatures (measured at a depth of 5 feet) have been recorded monthly at the Mid-lake and Index stations from TERC's research vessels since 1968 and from four research buoys since 2007. Despite year-to-year and longer cyclical variability, the annual average surface water temperatures show an increasing trend. The average temperature in 1968 was 50.4 °F (10.2 °C). For 2022, the average surface water temperature was 52.5 °F (11.4 °C), slightly below the long-term trend line. The overall rate of warming of the lake surface is 0.39 °F (0.22 °C) per decade.

Data source: TERC lake monitoring.

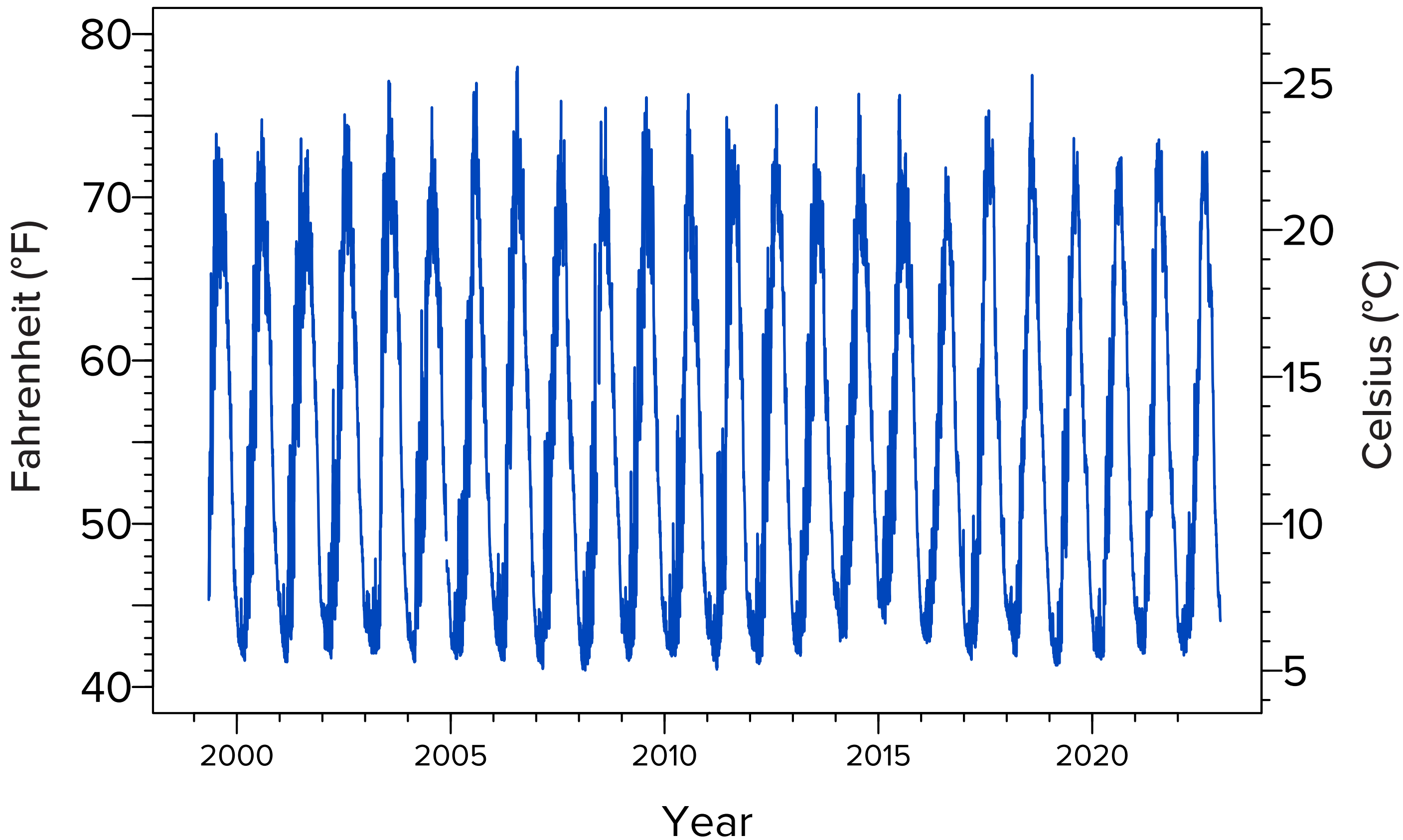


Maximum daily surface water temperature

Surface temperature measured since 1999 every 2 minutes

The maximum daily surface water temperature follows a sinusoidal pattern, with the temperature being in equilibrium with the air temperature and other meteorological variables. In 2022, the highest maximum daily surface water temperature (summer) was 72.8 °F (22.7 °C), recorded on July 30, 2022. The lowest maximum daily surface water temperature (winter) was 41.9 °F (5.5 °C), which was recorded on February 22. This was relatively warm, due in part to the absence of deep mixing.

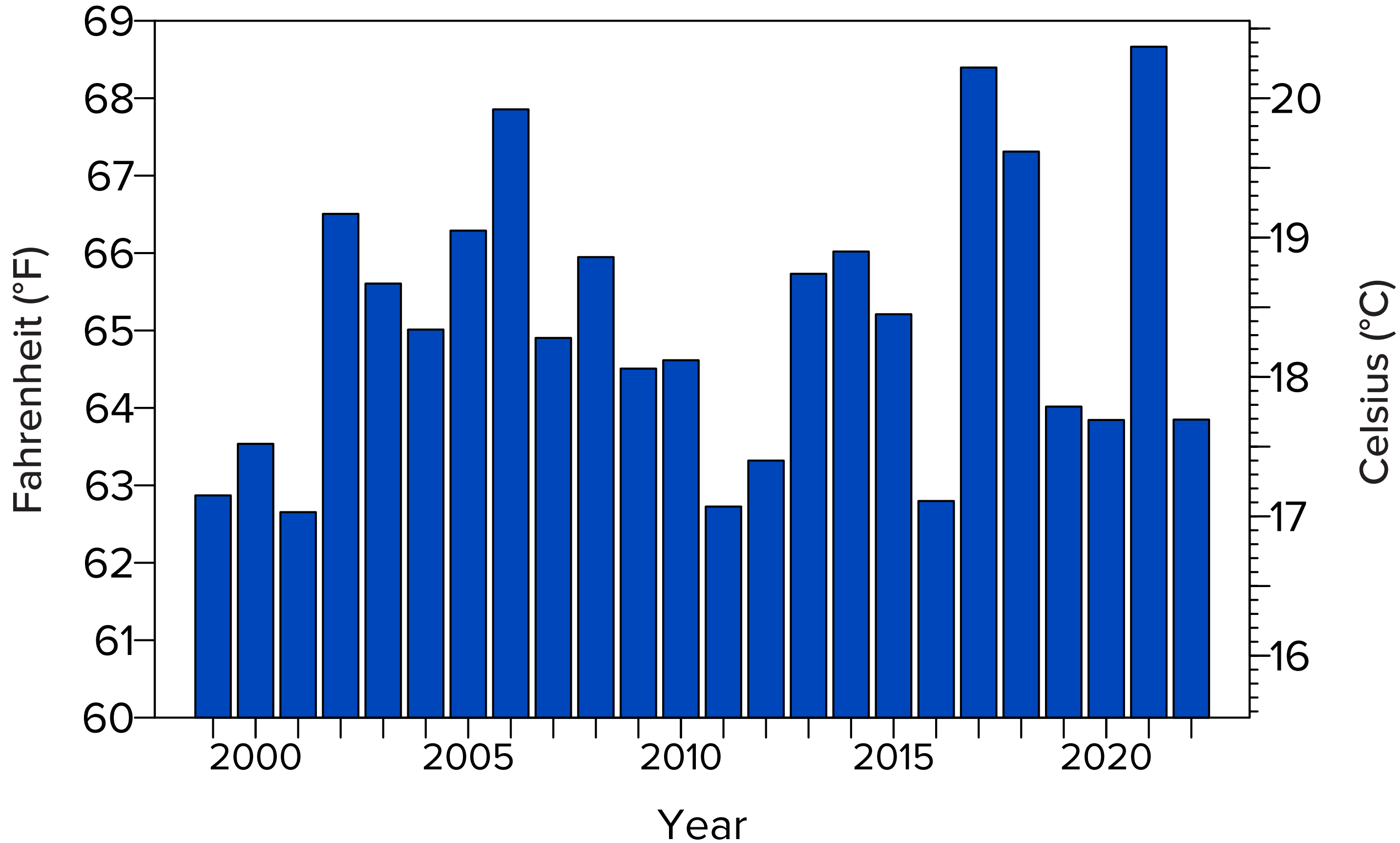
These data are collected from thermistors at a depth of 5 feet (1.5 m) that are attached to four research buoys located over the deepest parts of the lake. The highest daily value from among the four buoys is considered as the daily maximum.



July average surface water temperature

Measured since 1999 every 2 minutes

Surface water temperature has been continuously recorded since 1999 from four NASA/UC Davis buoys in the center of the lake. Shown here are 24 years of average surface water temperatures in the month of July when water temperatures are typically at their warmest and the greatest number of people are recreating on the lake. In 2022, July surface water temperature was relatively cool. It averaged 63.8 °F (17.7 °C). This was a decline of over 4.8 °F from the record setting value of the previous year. The long-term average is 65.1°F (18.4°C) for the 24-year period of record. These data are collected from thermistors at a depth of 5 feet (1.5 m) that are attached to four buoys located over the deepest portions of the lake.



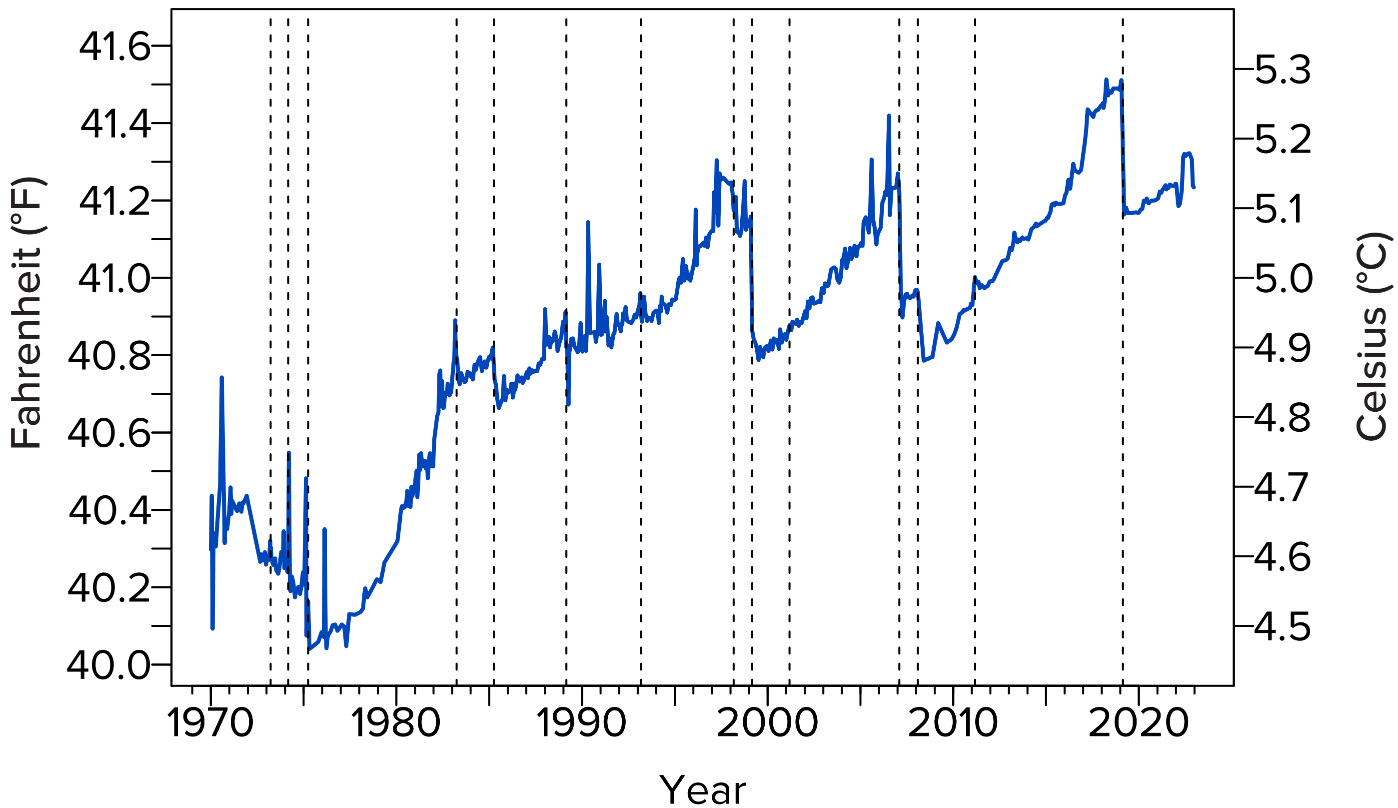
Deep water temperature

Monthly since 1970

The water temperature at a depth of 1,320 feet (400 m) is indicative of conditions in the deeper waters (hypolimnion) of Lake Tahoe. The deep-water temperatures show a complex pattern of warming and sudden cooling. During deep mixing events (the dashed vertical lines), the temperature can drop "precipitously" over a short period of time, although these drops are generally less than 0.3 °F. The heating of the bottom water along with the fluctuations when deep mixing does not occur is an area of current research.

In general, bottom temperatures are warming. In 2022, there was no deep mixing (see Fig. 8.9) and water temperatures rose slightly. Between the last two deep mixing events in 2011 and 2019, the rate of water warming was 0.07 °F/yr. During the deep mixing of 2019, the water temperature fell over 0.3 °F in just a few weeks. Complete vertical mixing is an event that allows a huge amount of heat to escape from the lake.

Data source: TERC lake monitoring.



Depth of mixing

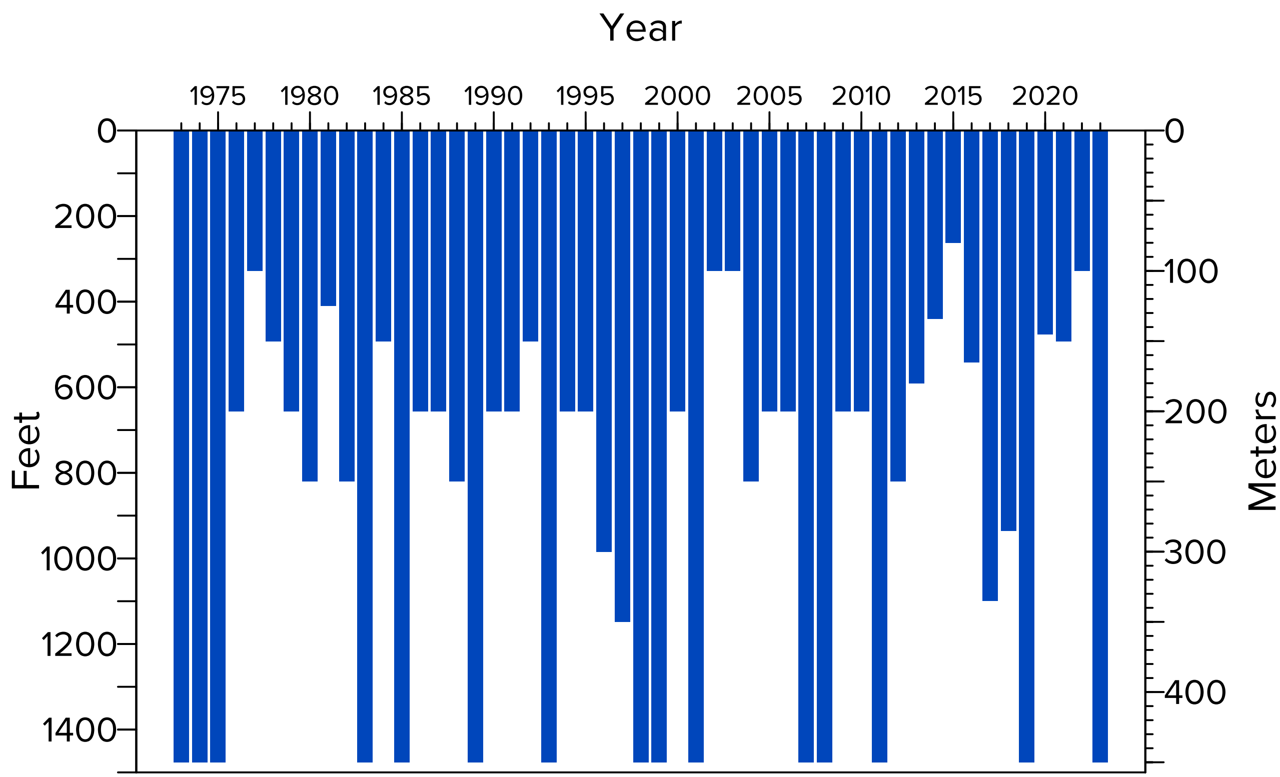
Yearly since 1973

The water of Lake Tahoe vertically mixes each winter as surface waters cool and sink downward. In a lake as deep as Tahoe, the intensity of cooling in winter determines how deep the lake mixes vertically. Mixing depth has profound impacts on lake ecology and water quality. Deep mixing brings nutrients that promote algal growth to the surface. It also carries oxygen downward to deep waters, promoting aquatic life throughout the water column.

The deepest mixing typically occurs between February and March. On February 18, 2022, Lake Tahoe was observed to have mixed to a maximum depth of 330 feet (100 m), the second lowest value on record. On March 3, 2023, Lake Tahoe mixed fully to a depth of 1476 feet (450 m). The duration of the 2023 mixing period is one of the longest recorded.

Since 2013, the depth of mixing has been determined with high-resolution temperature profiles rather than nitrate concentration sampled at discrete depths. Continuous temperature measurements off Glenbrook provided additional confirmation data.

Data source: TERC lake monitoring.

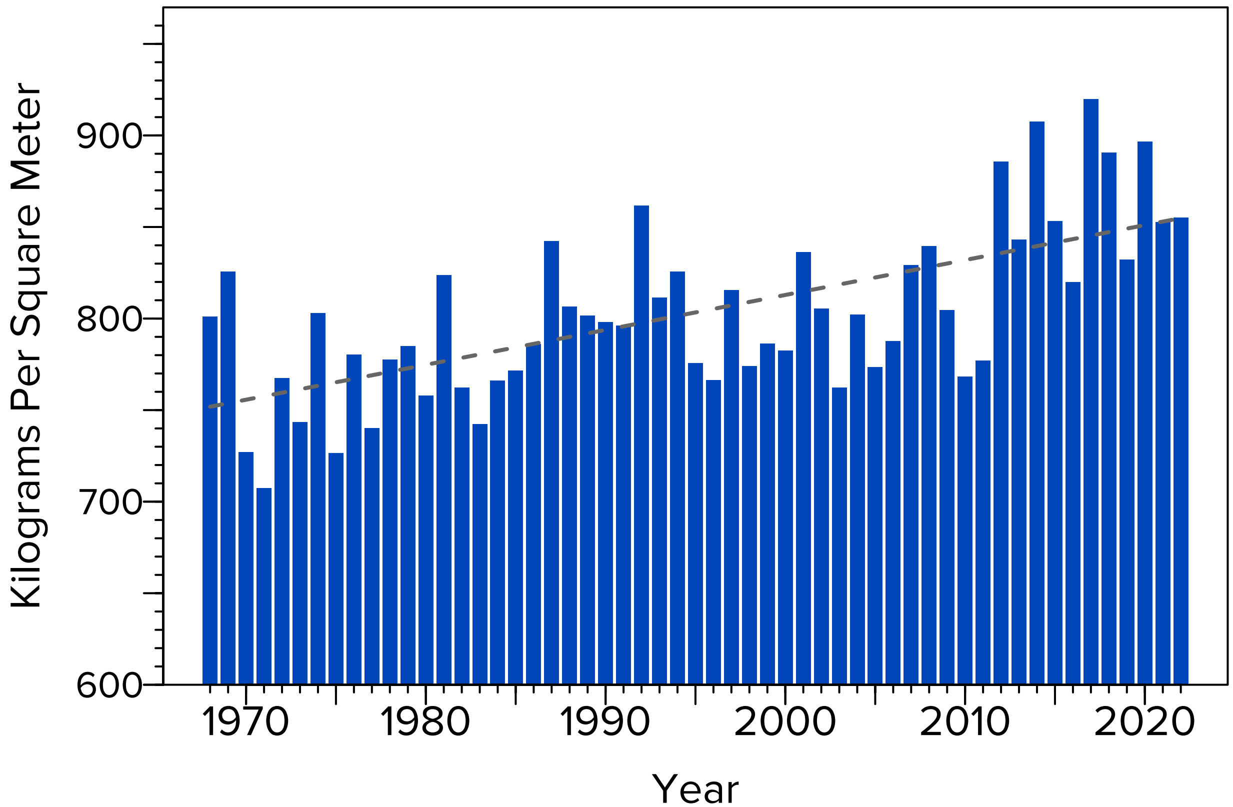


Lake stability index

Since 1968

When the lake has a vertical distribution of temperature, it has a corresponding distribution of density. Warmer and lighter water remains at the surface above the colder and denser water below. As the temperature difference between top and bottom increases, the lake is said to become more stable. Increasing stability poses a potential threat to all lakes. The stability index is a measure of the energy required to vertically mix the lake when it is density stratified. The average stability index for the upper 330 feet (100 m) of Lake Tahoe is plotted for the period of May through October each year. The values are derived from temperature profiles taken at the Index Station at approximately 10- to 20-day intervals. There has been an overall increase in lake stability by 13.4 percent in the last 55 years.

Data source: TERC lake monitoring.



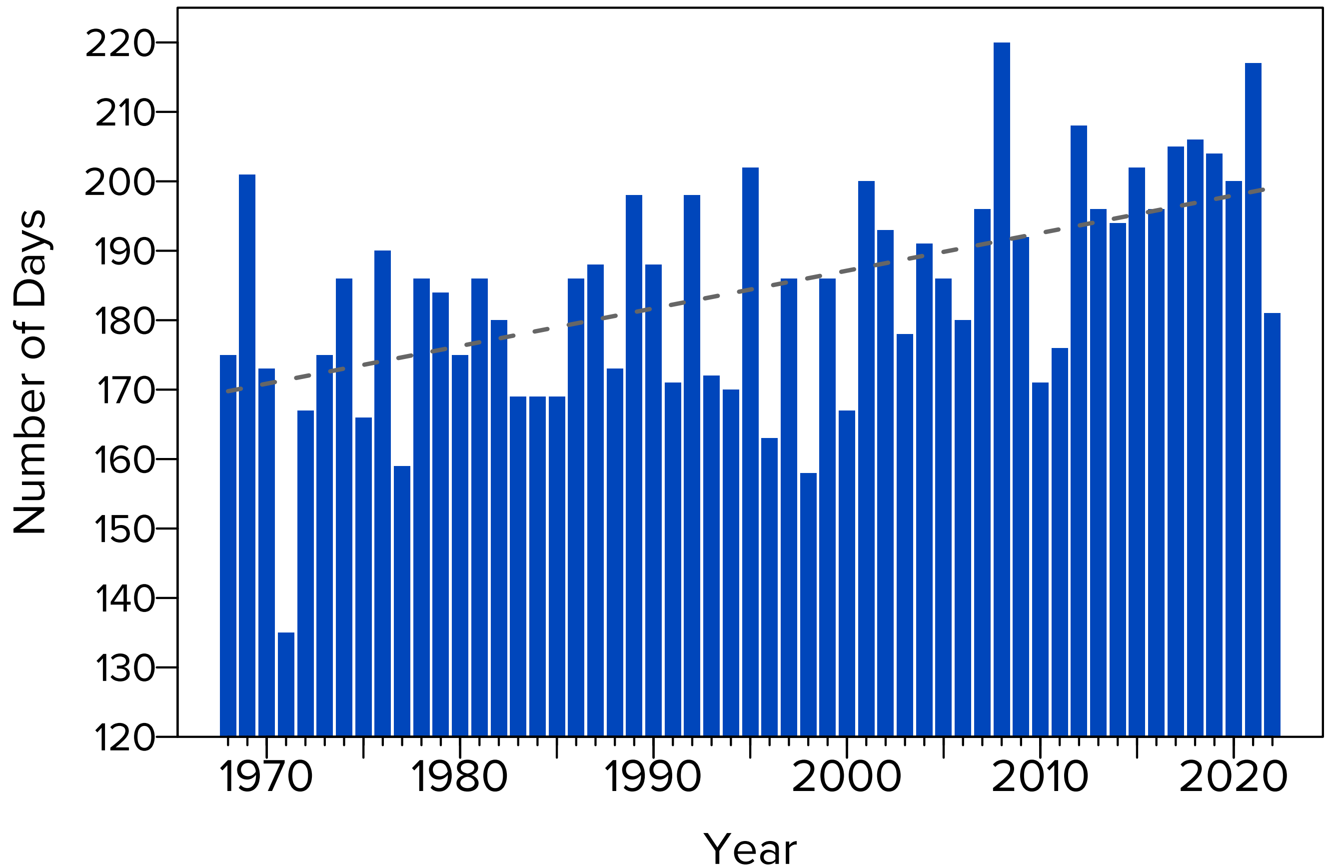
Stratified season length

Since 1968

The stability index is a measure of the energy required to vertically mix the lake that can be evaluated for every day of the year. We define the stratification season as the number of days when the stratification index exceeds a value of 600 kilograms per square meter. Since 1968, the length of the stratification season has increased by 29 days, albeit with considerable year-to-year variation.

In 2022, the length of the stratified season was only 181 days, the lowest value in over ten years.

Data source: TERC lake monitoring.



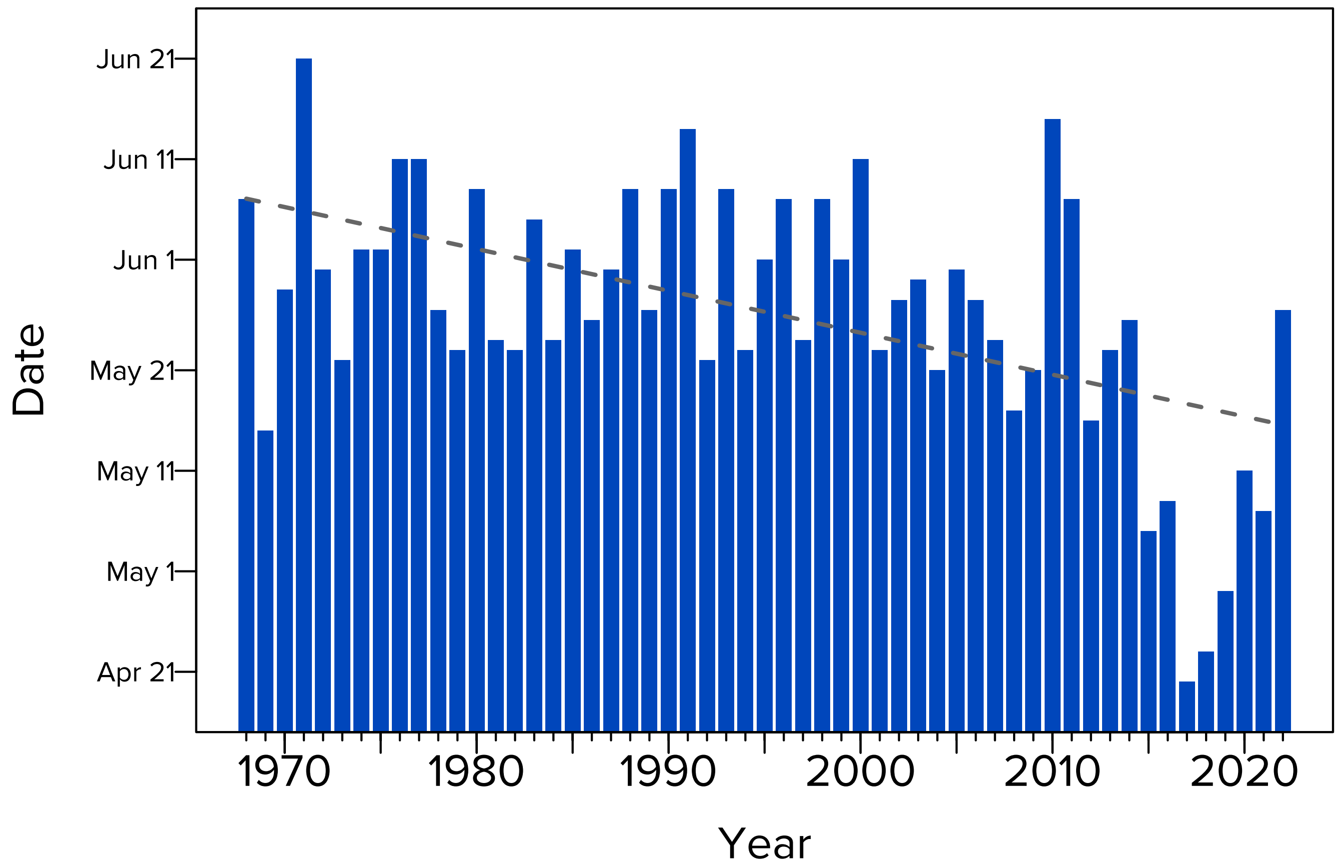
Beginning of the stratification season

Since 1968

The amount of time that Lake Tahoe is stratified has been increasing since 1968. One reason for this is the increasingly early arrival of spring as evidenced by the earlier commencement of stratification.

In 2022, the stratification commenced relatively late, on May 27 (Day 147). This was almost two weeks later than the long-term trend line would have suggested.

Data source: TERC lake monitoring.

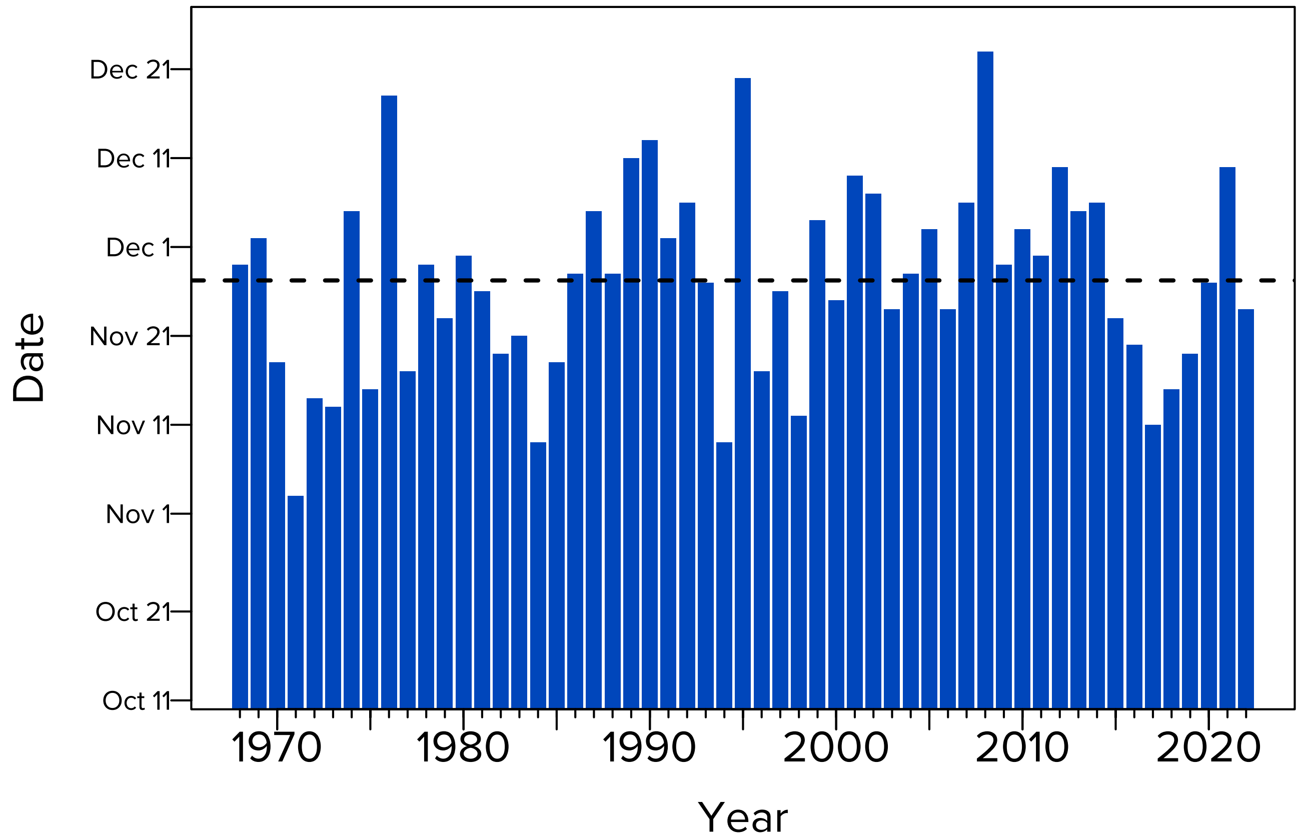


End of stratification season

Since 1968

The amount of time that Lake Tahoe is stratified appears to have increased by almost a month since 1968. The end of the stratification season has been extended, but not as much as the onset of stratification (See Fig. 8.12). Over the 55-year record, the end of stratification appears to have been extended by approximately one week. Although the trend is not statistically significant, extended duration of stratification can have important implications for lake mixing and water quality, such as the buildup of nitrate at the bottom of the lake. The dashed black line indicates the long-term mean for the end of stratification date. In 2022, the end of stratification was seven days earlier than the long-term mean.

Data source: TERC lake monitoring.

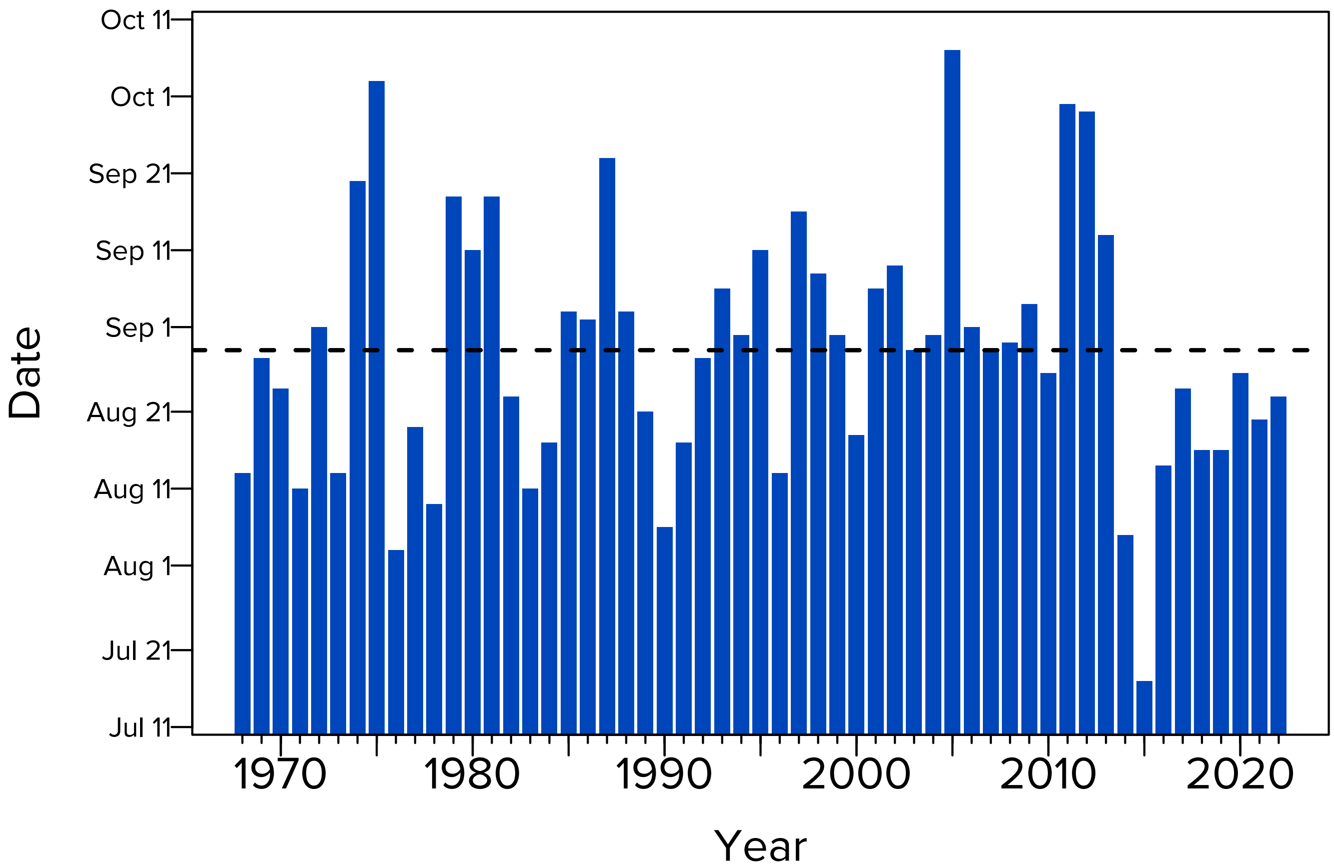


Peak of stratification season

Since 1968

The day of the year when lake stratification reaches its maximum value is the peak of the stratification season. There is considerable year-to-year variation, but over time there has been no statistically significant change in when the peak occurs. The dashed line shows the long-term mean. In 2022, the peak occurred on August 29. Over the last nine years the occurrence of the peak of stratification has been earlier than the long-term mean date.

Data source: TERC lake monitoring.

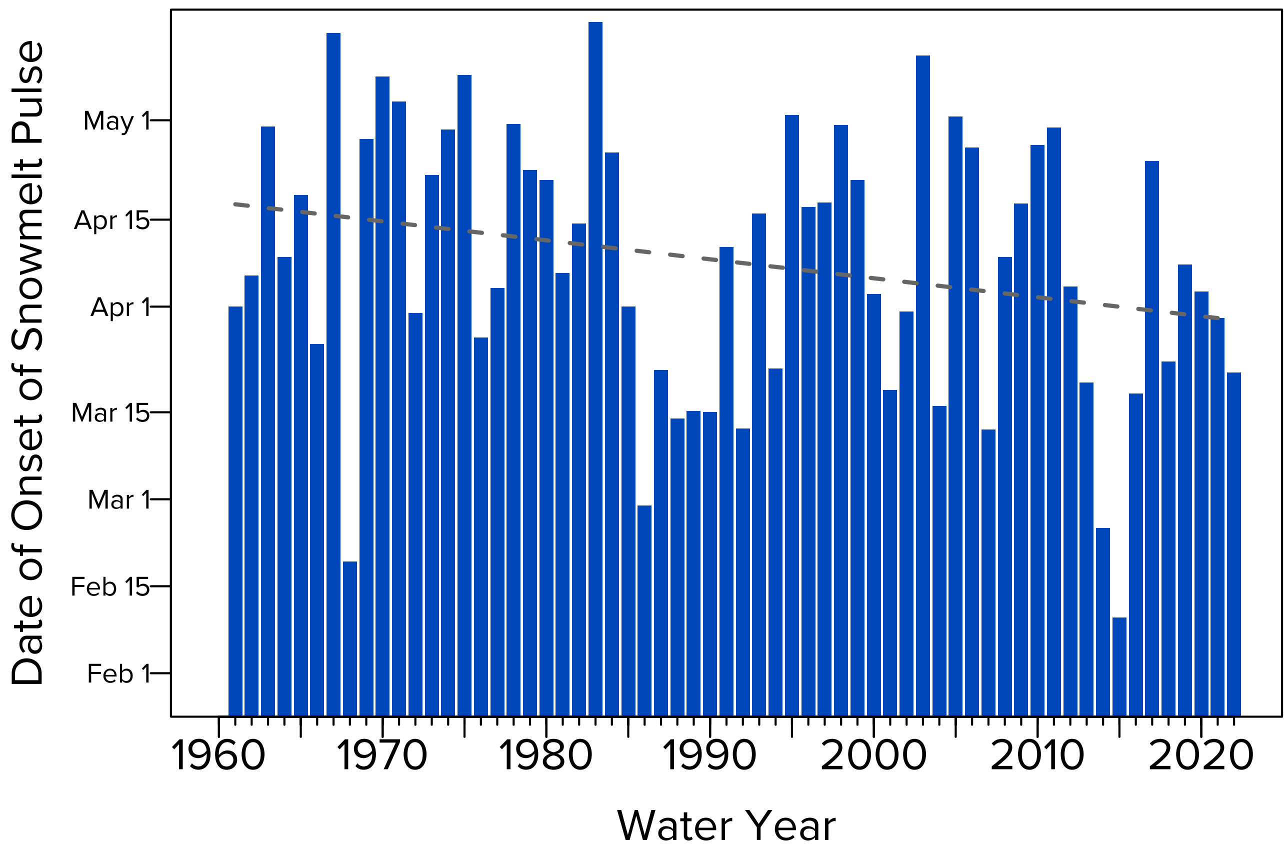


Onset of snowmelt pulse

Yearly since 1961

Although the date on which the onset of snowmelt commences varies from year to year, since 1961 it has shifted earlier by an average of over 16 days. The snowmelt pulse is calculated and averaged for five streams—the Upper Truckee River, Trout Creek, Ward Creek, Blackwood Creek, and Third Creek. This shift is statistically significant and is one effect of climate change at Lake Tahoe. In 2022, the onset occurred on March 21, nine days earlier than the previous year. According to the regression line, since 1961, the onset of the snowmelt pulse has occurred earlier by 19 days than it did in 1961. The onset of the pulse is calculated as the day when flow exceeds the mean flow for the period January 1 to July 15. In the past, the peak of the stream hydrograph was used to estimate this metric.

Data source: U.S. Geological Survey stream monitoring.

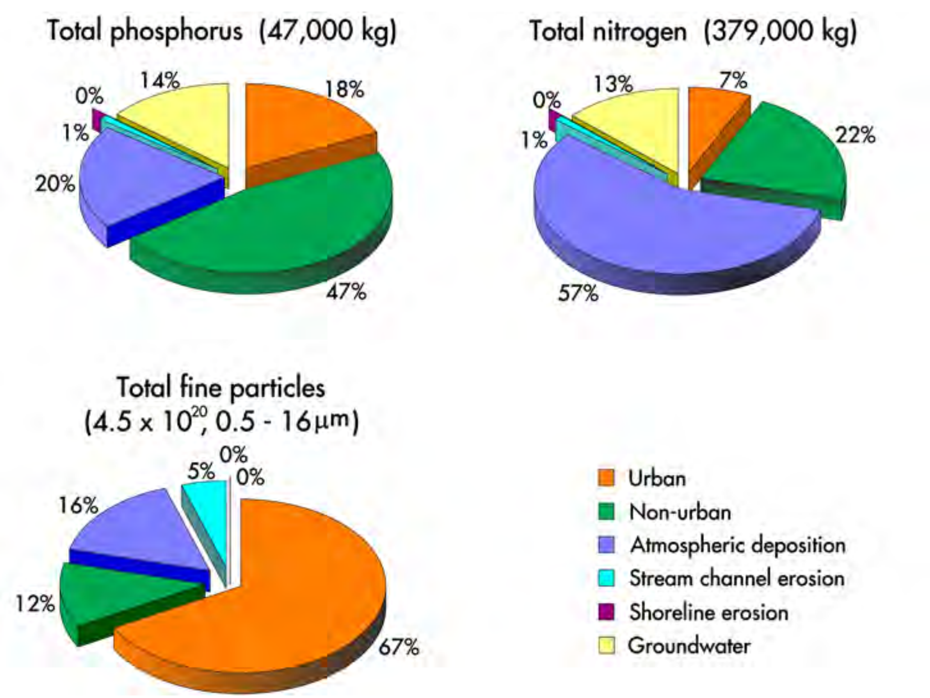


TAHOE: **STATE OF THE LAKE** REPORT **2023**

NUTRIENTS AND PARTICLES

Sources of clarity-reducing and blueness-reducing pollutants

Research has quantified the primary sources of nutrients (nitrogen and phosphorus) and fine particulate material that are causing Lake Tahoe to lose clarity and blueness in its upper waters. One of the primary contributors to clarity decline is extremely fine particles (in the size range of approximately 1–6 microns) in stormwater that originate from the urbanized watersheds, the streams that drain the majority of the basin's land area, and atmospheric deposition. For nitrogen, atmospheric deposition is the major source (57 percent). Phosphorus is primarily introduced by the urban (18 percent) and non-urban (47 percent) watersheds. These categories of pollutant sources form the basis of a strategy to restore Lake Tahoe's open-water clarity by management agencies, known as the Lake Tahoe Total Maximum Daily Load (TMDL) Program.



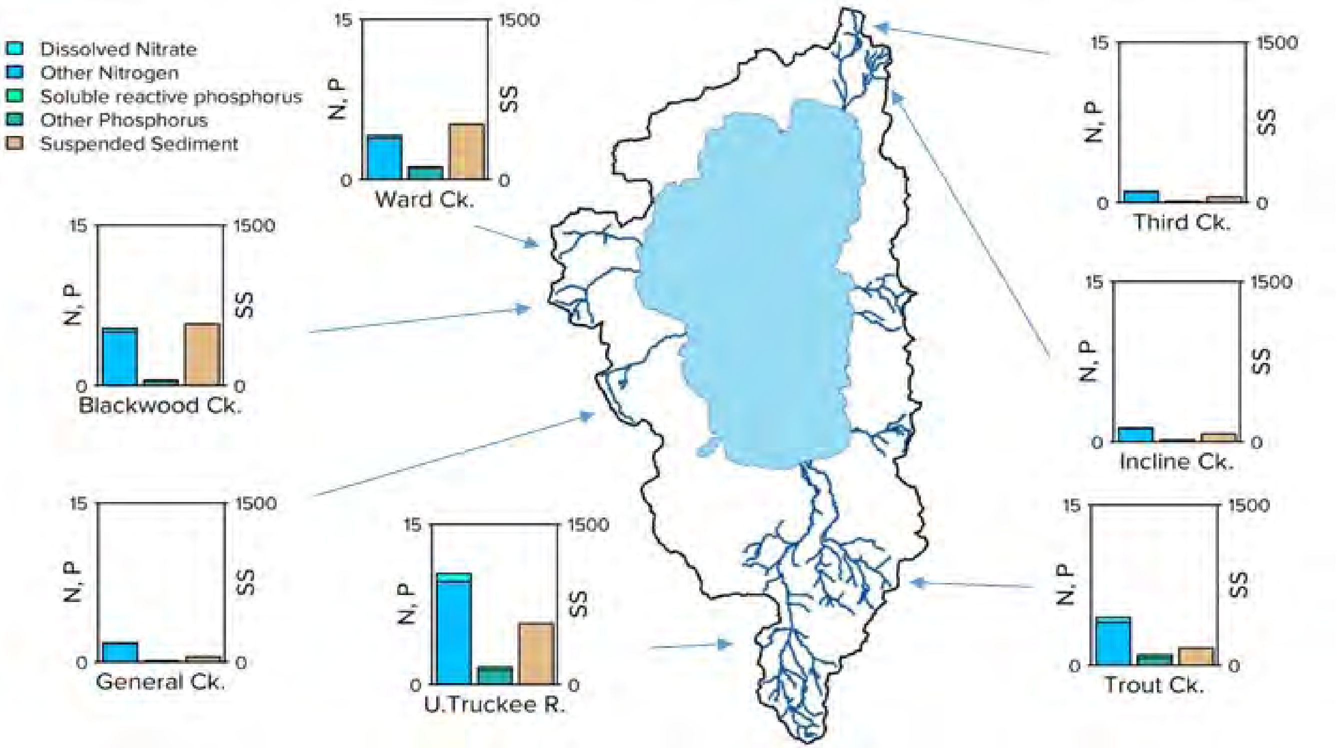
Pollutant loads from seven watersheds

In 2022

The Lake Tahoe Interagency Monitoring Program (LTIMP) measures nutrient and sediment input from seven of the 63 watershed streams. The streams are the Upper Truckee River, Trout Creek, Incline Creek, Third Creek, Ward Creek, Blackwood Creek, and General Creek. In 2022, the majority of stream phosphorus and nitrogen, as well as suspended sediments, came from the Upper Truckee River. This is often the case, but in some years, smaller streams, such as Ward Creek and Blackwood Creek, can also be significant contributors.

It should be noted that suspended sediments as represented in these data include all sediment sizes and is measured by weight. For clarity, it is the number of fine particles (in the range of 1–6 microns) that is important. These particles make up a very small fraction of the suspended sediment, but largely control lake clarity.

The LTIMP stream water quality program is supported by the Lahontan Regional Water Quality Control Board, the Tahoe Regional Planning Agency, the U.S. Geological Survey, and UC Davis TERC. TERC and the U.S. Geological Survey jointly collect and analyze the stream data.



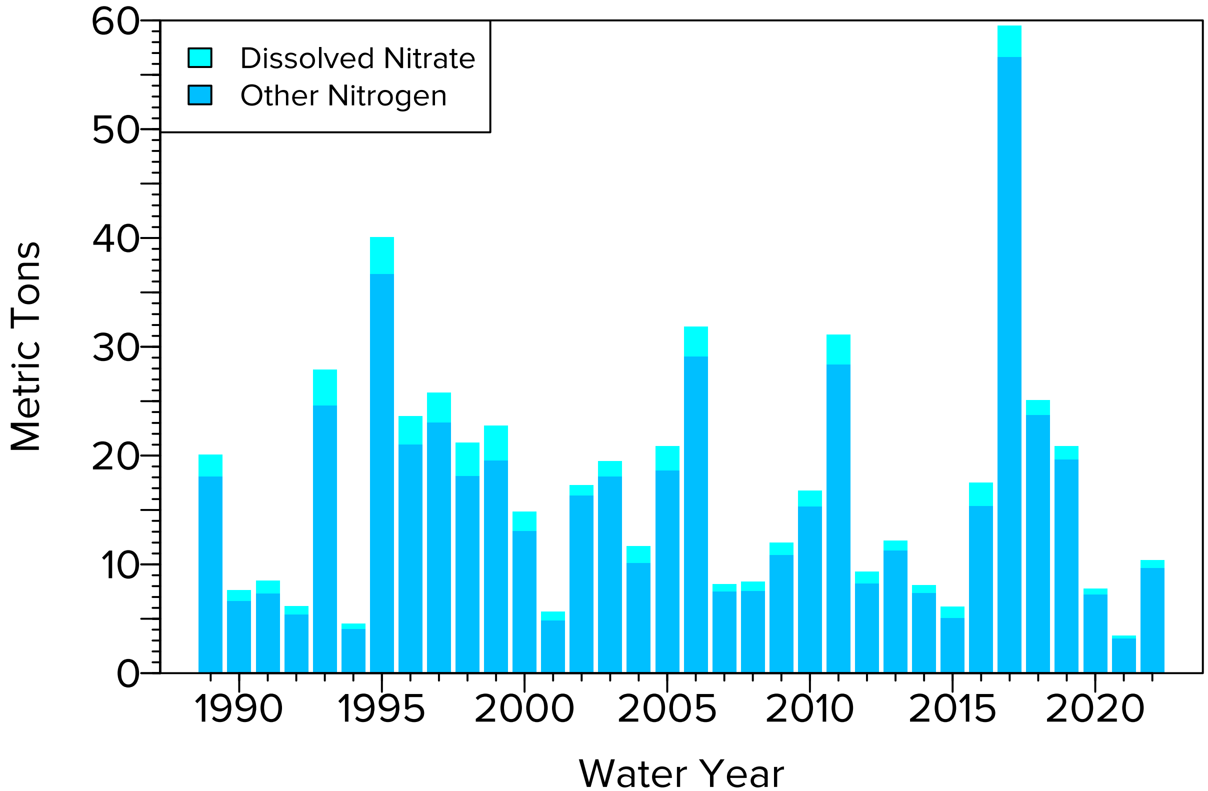
Nitrogen contribution by Upper Truckee River

Yearly since 1989

Nitrogen (N) is important because it, along with phosphorus (P), stimulates algal growth. The Upper Truckee River is the largest of 63 streams that flow into Lake Tahoe, contributing about 25 percent of the inflowing water. The river's estimated contribution of dissolved nitrate and the remainder of the total nitrogen load are shown here. Over the 34 years of record, the percentage of nitrate to total nitrogen has been in the range of 5–14 percent. The year-to-year variations primarily reflect changes in precipitation. For example, 1994 had 16.6 inches of precipitation and a low total nitrogen load of 4.6 MT, while 2017 had 68.9 inches of precipitation and a record high total nitrogen load of 59.5 MT.

In 2022, there were 32.7 inches of precipitation and the total nitrogen load from the Upper Truckee River of 11.1 MT. Nitrate load was 0.71 MT. The long-term mean annual total nitrogen load is 17.3 MT/yr while for nitrate it is 1.6 MT. (One metric ton (MT) = 2,205 pounds.)

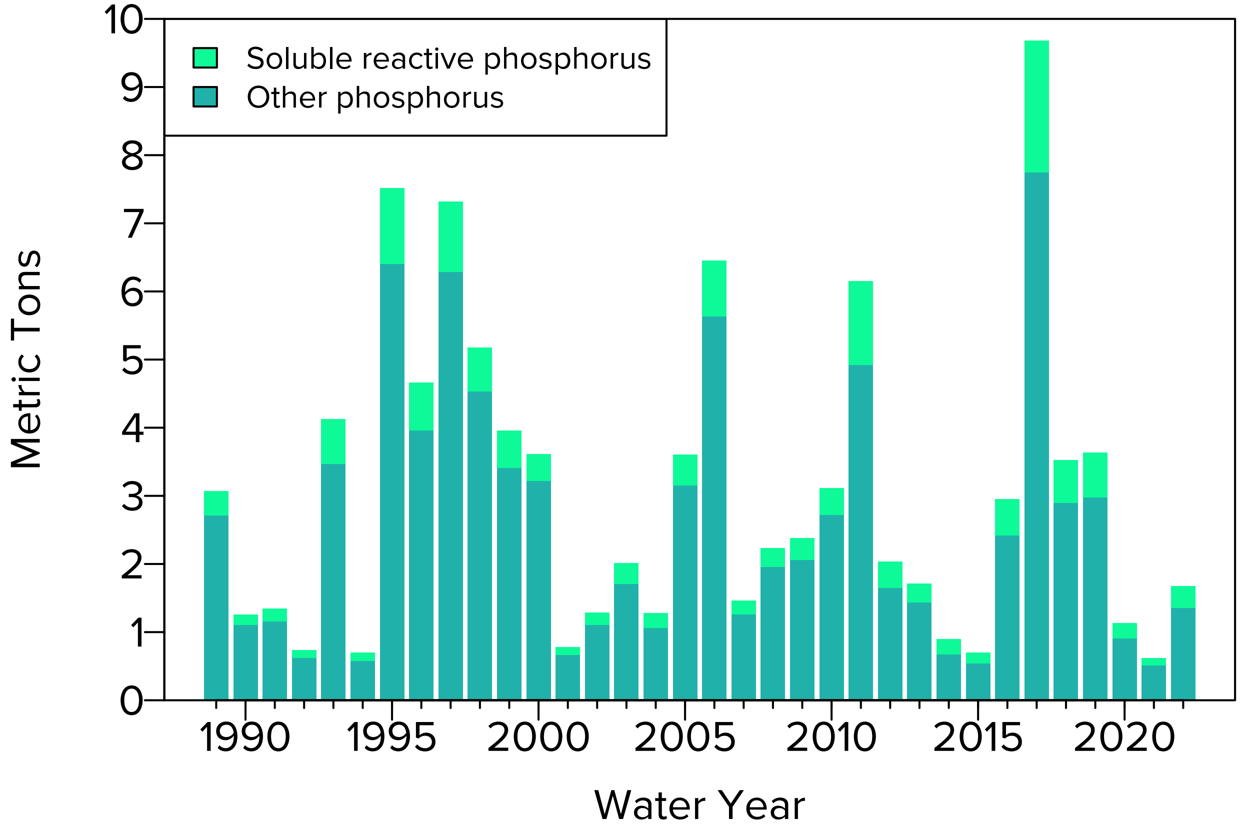
Data source: TERC and U.S. Geological Survey stream monitoring.



Phosphorus contribution by Upper Truckee River

Yearly since 1989

Soluble reactive phosphorus (SRP) is the fraction of total phosphorus immediately available for algal growth. As with nitrogen (Fig. 9.3), the year-to-year variation in estimated loads largely reflects the changes in precipitation. Near-average precipitation in 2022 resulted in a total phosphorus load of 1.68 MT and SRP load of 0.32 MT, the lowest values on record, likely due to the record low stream flows. These compare with the long-term averages of 3.02 and 0.47 MT respectively. Over the 34 years of record, the percentage of SRP to total phosphorus load has been in the range of 11–25 percent. Decreasing nutrient inputs are fundamental to restoring Lake Tahoe's iconic blueness. Total phosphorus is the sum of SRP and other phosphorus, which includes organic phosphorus and phosphorus associated with particles. (One metric ton (MT) = 2,205 pounds.) Data source: TERC and U.S. Geological Survey stream monitoring.

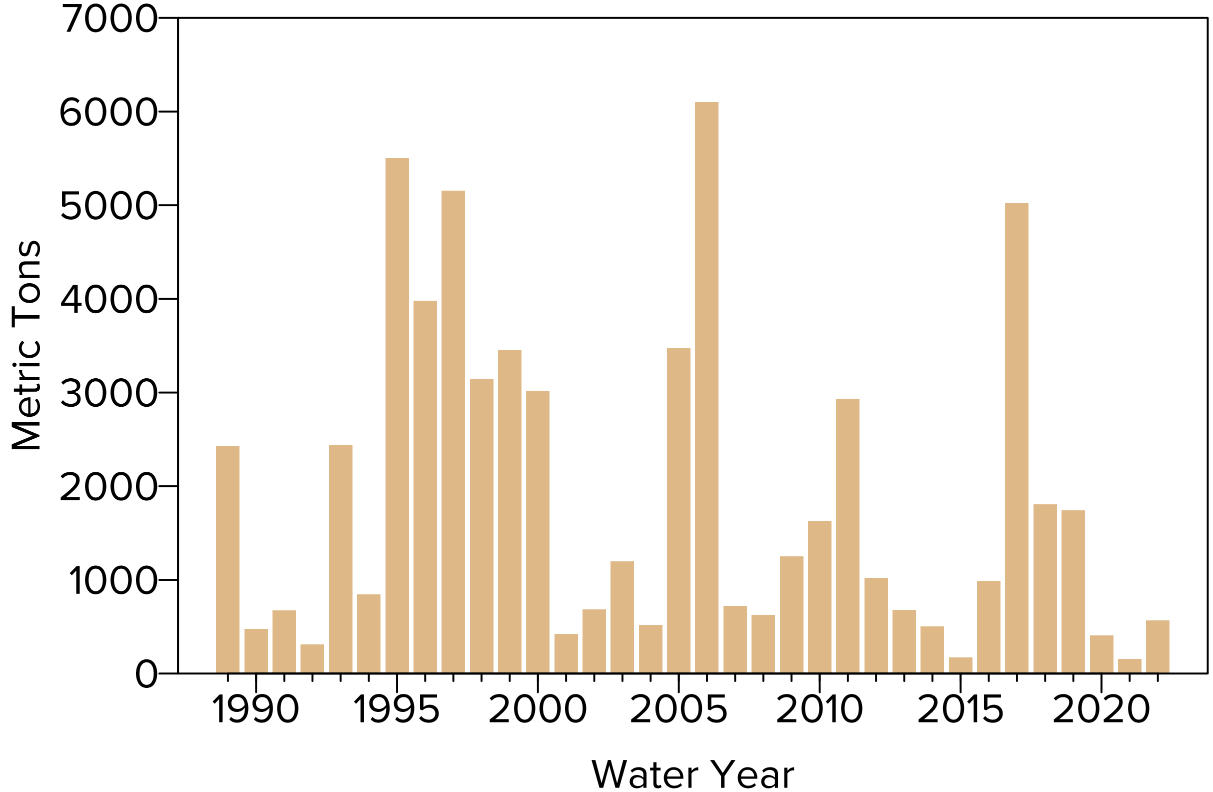


Suspended sediment contribution by Upper Truckee River

Yearly since 1989

The load of total suspended sediment delivered to the lake by the Upper Truckee River is related to landscape condition and erosion as well as to precipitation and stream flow. Inter-annual variation in sediment load over shorter time scales is more related to the latter. Plans to restore lake clarity emphasize reducing loads of very fine suspended sediment (in the size range of 1–6 microns in diameter) from urbanized areas. By contrast, efforts to restore natural stream function, watershed condition, and restoration of habitat for plants and wildlife, focus on reducing loads of total sediment regardless of size. In 2022, the estimated suspended sediment load from the Upper Truckee River was 569 MT. The highest load ever recorded was 6,100 MT in 2006. The average annual load is 1,882 MT. (One metric ton (MT) = 2,205 pounds.)

Data source: TERC and U.S. Geological survey stream monitoring.

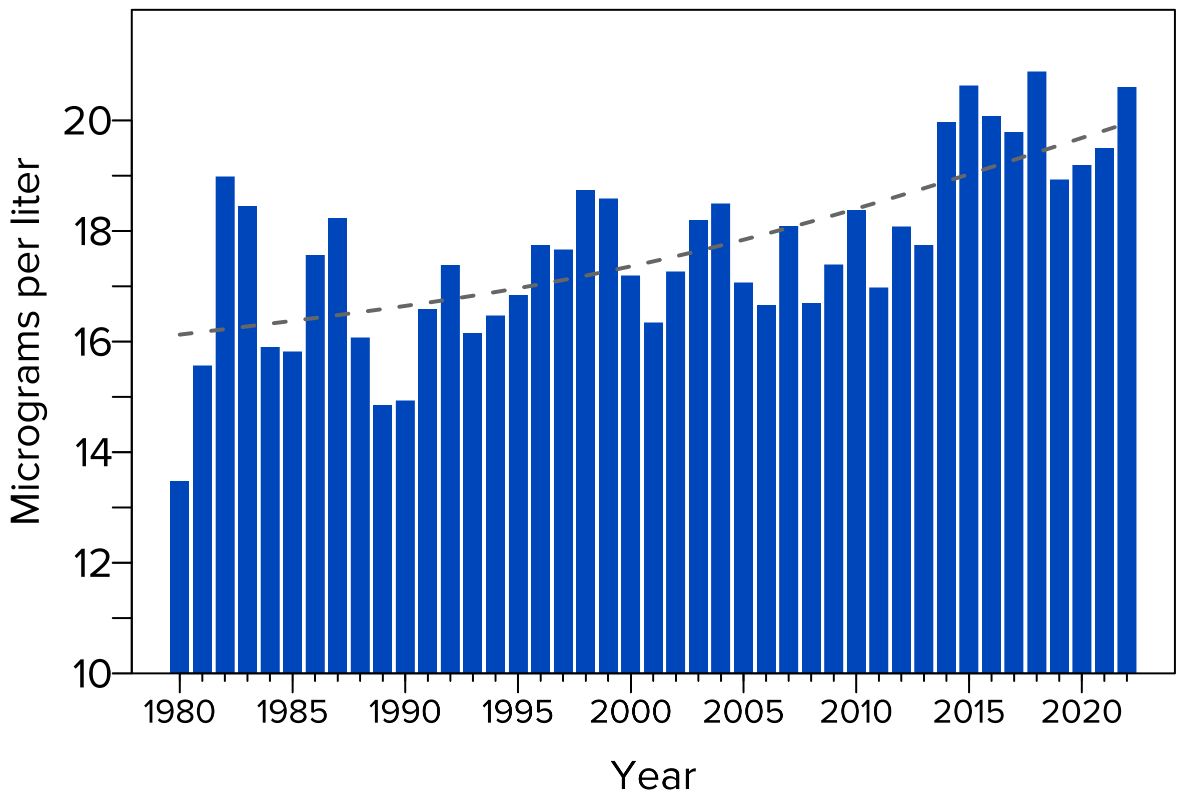


Lake nitrate concentration

Yearly since 1980

Until 2012, the volume-weighted annual average concentration of nitrate-nitrogen had remained relatively constant year-to-year, ranging between 13–19 micrograms per liter. Since that time, however, the lake's nitrate concentration has been increasing, as evident in the trend line produced with a Generalized Additive Model. In 2022, the volume-weighted annual average concentration of nitrate-nitrogen was 20.6 micrograms per liter. In 2019, lake nitrate concentration declined due to the deep mixing that redistributed the nitrate built up at the bottom of lake for the previous eight years and made it available for algal uptake. In 2021 and 2022, with only shallow mixing, nitrate has recommenced accumulating, resulting in the increasing in-lake nitrate concentration. Another factor in the last several years is the additional atmospheric nutrient loading due to wildfire smoke engulfing the region. The impact of the 2021 wildfires is the subject of a continuing analysis.

Data source: TERC lake monitoring.



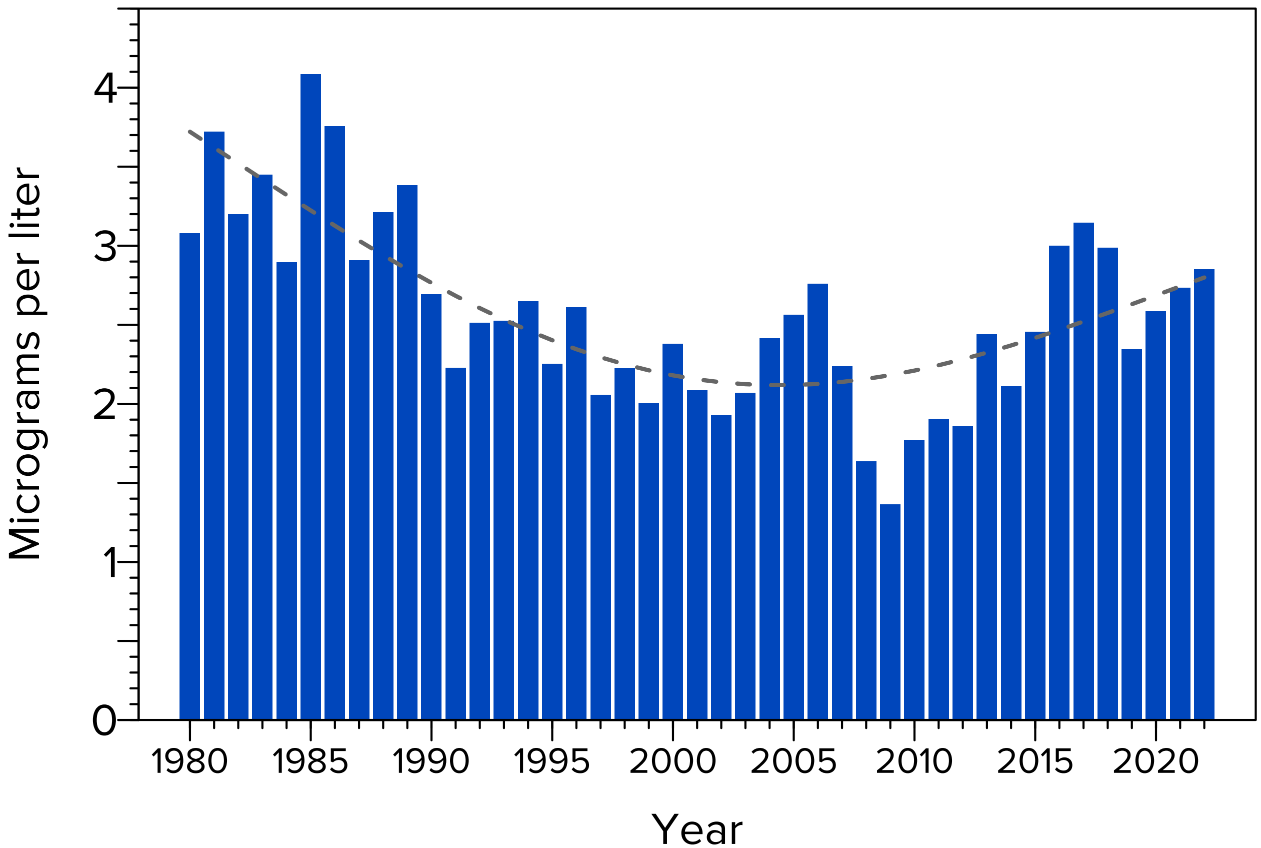
Lake total hydrolyzable phosphorus concentration

Yearly since 1980

Phosphorus naturally occurs in Tahoe Basin soils and enters the lake from soil disturbance and erosion. Total hydrolysable phosphorus (THP) is a measure of the fraction of phosphorus that algae can use to grow. It is similar to the SRP that is measured in the streams. Since 1980, THP has declined, although in the last 17 years the values have been increasing.

In 2022, the volume-weighted annual average concentration of THP was 2.85 micrograms per liter. Another factor in the last several years is the additional atmospheric nutrient loading due to wildfire smoke engulfing the region. The impact of the 2021 wildfires is the subject of a continuing analysis.

Data source: TERC lake monitoring.



Lake fine particle concentration

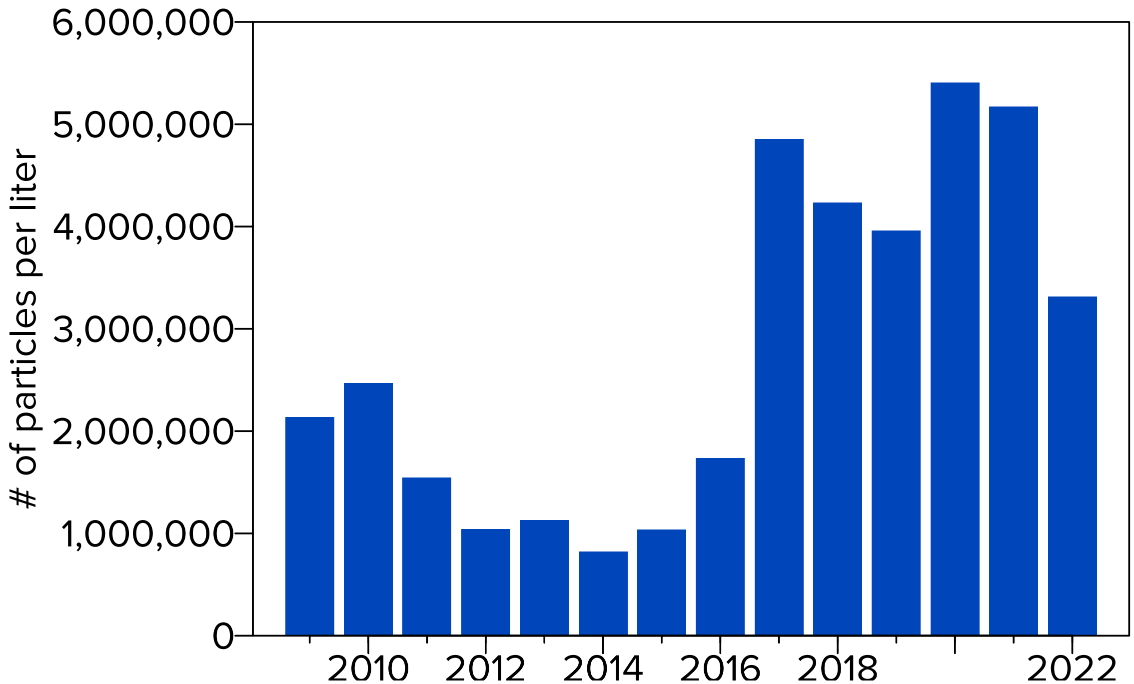
Yearly since 2009

Fine particles in the size range of approximately 1–6 microns in the upper 50 meters are principally responsible for the attenuation of visible light and the consequent loss of lake clarity. These particles can be inorganic (clay and silt) or organic (phytoplankton). As particles in this size range settle slowly, their removal from the lake depends, in large part, on their aggregation into larger particles. The settling rate of a particle depends on the square of its diameter. Larger, aggregated particles will settle disproportionately faster.

2017 was an extremely wet year and there was a large increase in fine particles delivered to Lake Tahoe from the streams in the watershed. This would account for the step change in concentration evident between 2016 and 2017. The continued high average concentration since that time is difficult to explain. In 2020 and 2021, both of which were low precipitation years, displayed an increase in particle concentration beyond the 2017 level.

In 2022, the annual fine particle concentration fell to their lowest concentration since 2017 but are still higher than earlier years. Loading of particles from wildfires and streams were lower in 2022. A preliminary analysis comparing rates of aggregation of lake particles, suggests that aggregation rates have not changed significantly over the period of the record. Water samples are taken monthly at the MLTP (mid-lake) station at 13 depths from the surface to 1,480 feet.

Data source: TERC lake monitoring.



Lake fine particle concentration

Monthly since 2015

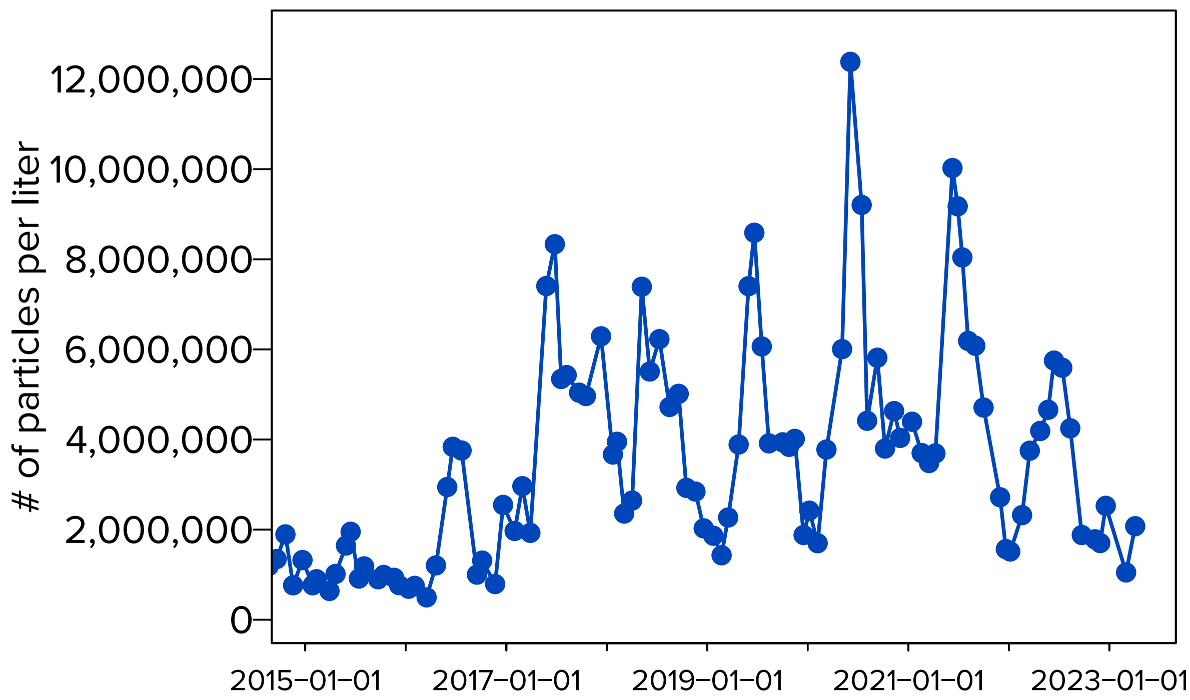
Fine particles in the size range of approximately 1–6 microns in the upper 50 meters are principally responsible for the attenuation of visible light and the consequent loss of lake clarity. These particles can be inorganic (clay and silt) or organic (phytoplankton).

The data indicate the annual increase of fine particles at mid-year were due to a combination of particle influx from to spring snowmelt and a consequent algal bloom. In 2017, a historically wet year, there was a large increase in fine particles delivered to Lake Tahoe from the streams in the watershed. This would account for the step change in concentration evident between 2016 and 2017. The continued high average concentration since that time is difficult to explain. 2020 and 2021, both of which were low precipitation years, displayed an increase in particle concentration beyond the 2017 level.

In 2022, the annual fine particle concentration fell to their lowest concentration since 2017 but are still higher than earlier years. Loading of particles from wildfires and streams were lower in 2022. A preliminary analysis comparing rates of aggregation of lake particles, suggests that aggregation rates have not changed significantly over the period of the record.

Water samples are taken monthly at the MLTP (mid-lake) station at 13 depths from the surface to 1,480 feet. Here, data from 0 m, 10 m, and 50 m were utilized.

Data source: TERC lake monitoring.



Nitrate distribution

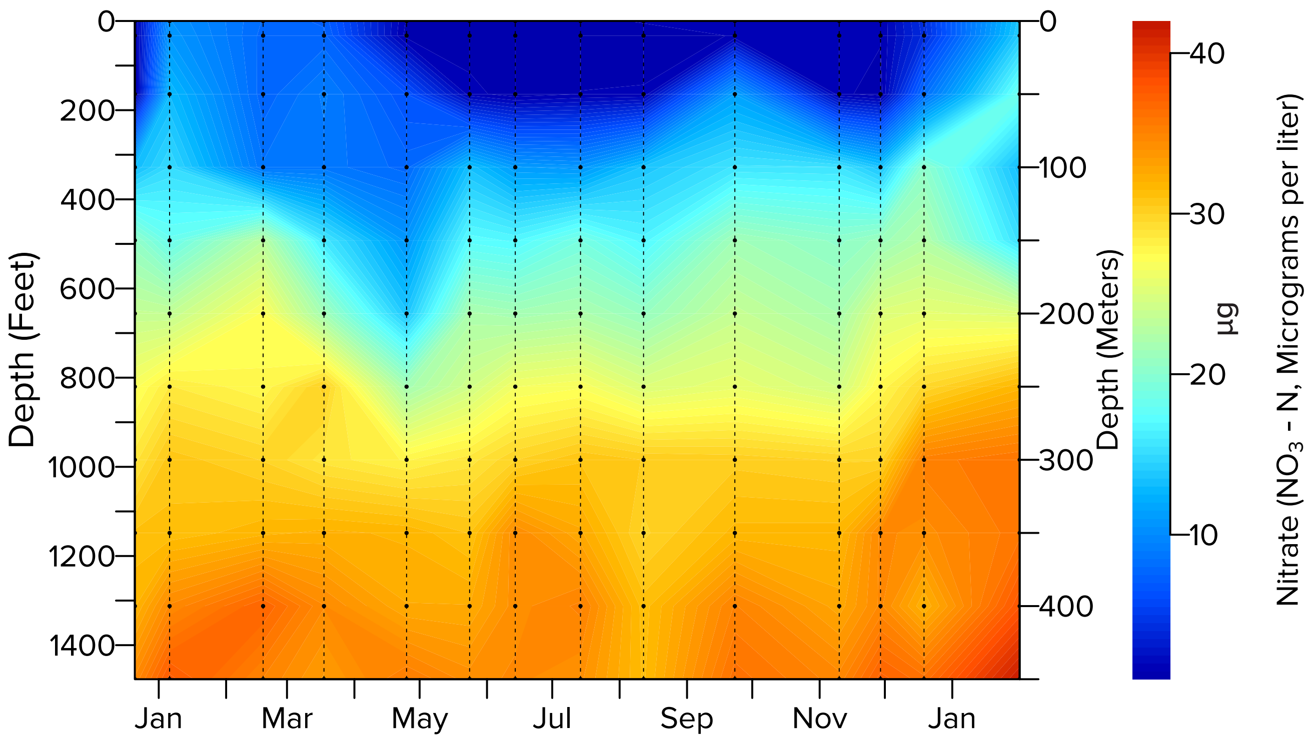
In 2022

Water samples are collected approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) at the MLTP station in the middle of the lake. These samples are the processed and analyzed in the TERC laboratory for nutrient concentrations. Here the nitrate concentration is shown in the form of color contours.

Most evident is the persistence of the high nitrate region in the lower part of the lake. It is evident that the limited extent of deep mixing in 2022 did not homogenize the nitrate distribution. Instead, a "nitricline" is evident between depths of 400 and 800 feet through much of the year.

Although most of the introduced nitrate enters at the surface through atmospheric deposition, it is rapidly taken up by the algae and surface concentrations remain generally low. As algae sink and decompose, the nitrate they consumed reappears deep in the lake. At these depths, however, there is insufficient light for algae to grow and to use these nutrients.

Data source: TERC lake monitoring.



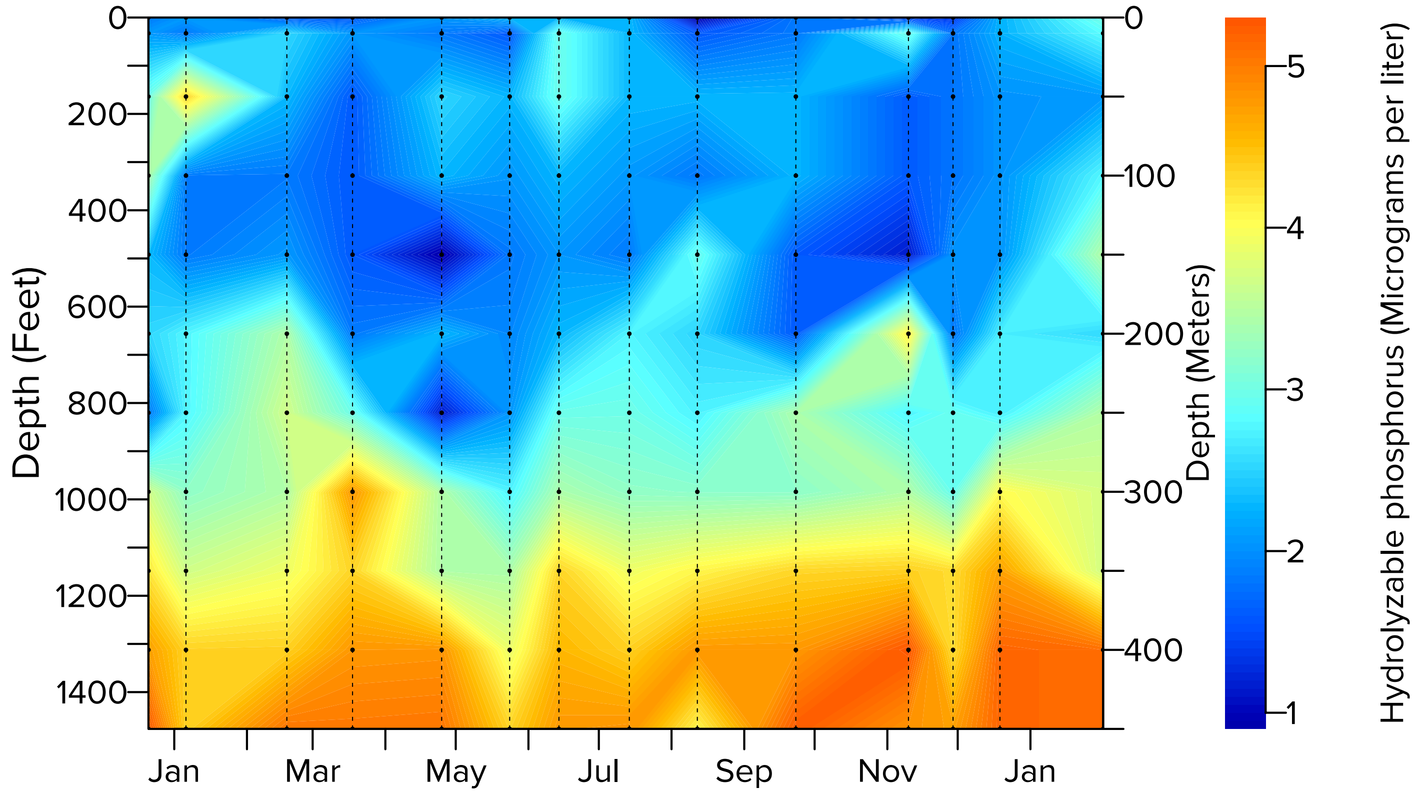
Total hydrolyzable phosphorus distribution

In 2022

Water samples are collected approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) at the MLTP station in the middle of the lake and analyzed in the TERC laboratory for nutrient concentrations. Here the total hydrolysable phosphorus (THP) concentration, the fraction of phosphorus that can be readily used by algae, is shown in the form of color contours.

Phosphorus mainly entered the lake in association with fine particles during runoff events in May through June. The relatively elevated values near the surface in June suggest that in 2022, nitrogen was the nutrient that limited algal growth, rather than phosphorus early in the summer. The elevated concentrations of phosphorus deep in the lake throughout the year were the result of the absence of deep mixing in 2022.

Data source: TERC lake monitoring.



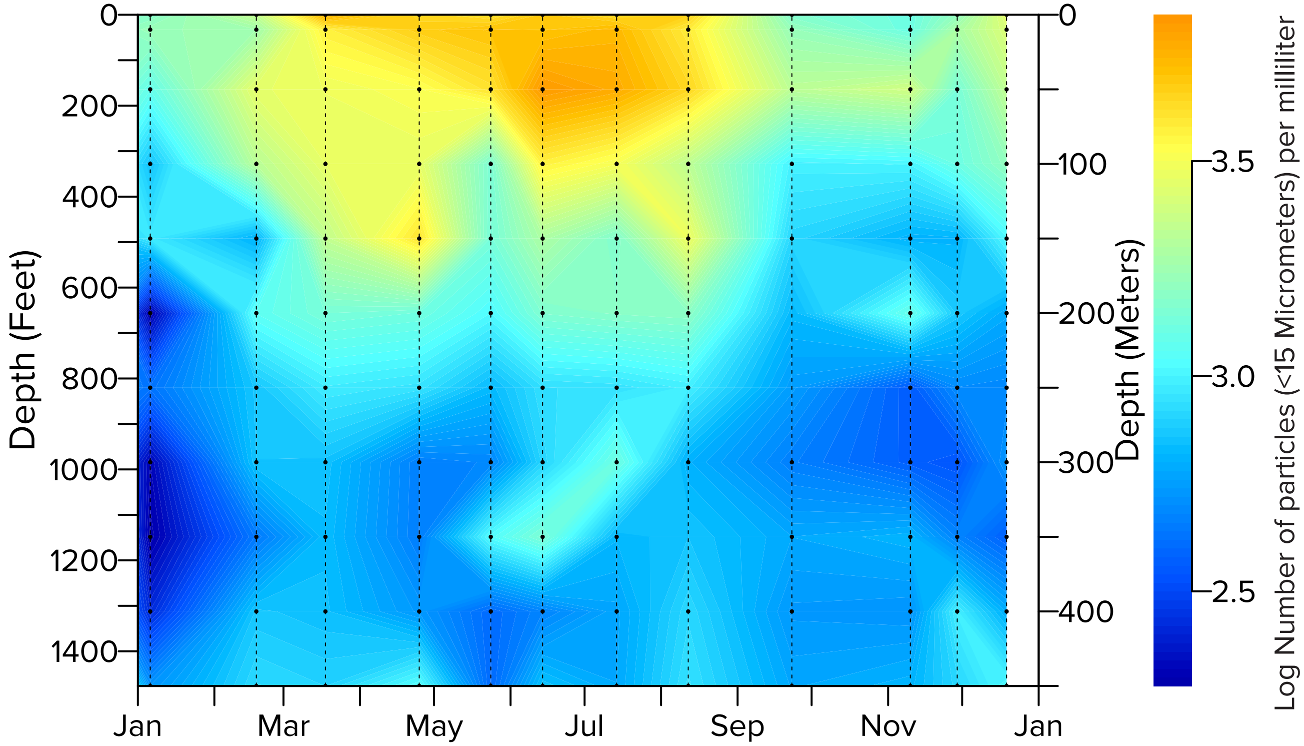
Fine particle distribution

In 2022

Water samples are collected approximately monthly (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) at the MLTP station. These samples are analyzed in the TERC laboratory for concentrations of fine particles in 15 different bin sizes. The distributions of fine particles (in the size range of 1–6 microns) are shown in the form of color contours. Particles can be inorganic particles such as clay or silt or organic particles such as very small algal diatom particles.

Unlike the nutrients in Figures 9.9 and 9.10, fine particles are in low concentrations deep in the lake throughout the year. The entry of particles in the upper part of the lake (above 300 ft) associated with spring snowmelt is evident in May through August. Remarkably in 2022, there was a large decline in the particle concentration in the upper 300 feet of the lake to levels below which have been observed in the recent years. This is consistent with the very high Secchi depths that were recorded in the last part of 2022 (See Fig. 11.4). The particles do not decrease in the upper layer in the same way as nitrogen or phosphorus, as they are not taken up by algal growth. Instead, fine inorganic particles gradually clump together (aggregate) which allows them to settle to the lake bottom more rapidly. Additionally, they can be removed by zooplankton grazing.

Data source: TERC lake monitoring.



TAHOE:
STATE
OF THE
LAKE
REPORT
2023

BIOLOGY

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Algae growth (primary productivity)

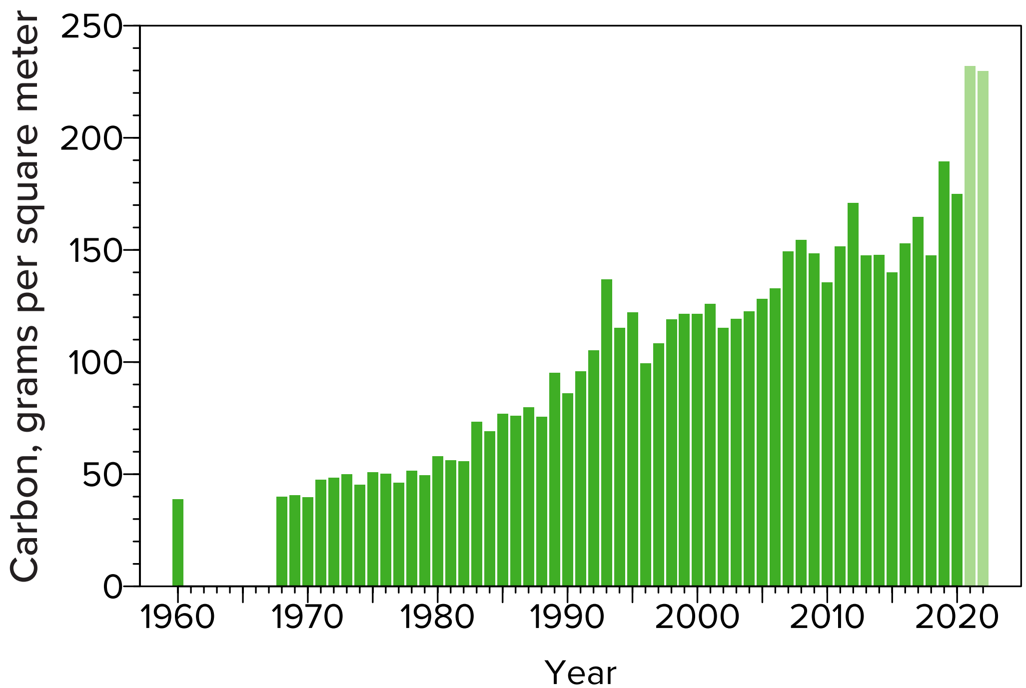
Yearly since 1959

Primary productivity is a measure of the rate at which algae produce biomass (carbon) through photosynthesis. It was first measured at Lake Tahoe in 1959 and was measured continuously since 1968. Supported by nutrient loading into the lake, changes in the underwater light environment, and the succession of algal species, the long-term trend shows that primary productivity has increased substantially over time. After a comprehensive review of changes in the methodologies used for this complex measurement over time the dataset has been revised. While the long-term increasing trend has not changed, the magnitude of the annual averages was reduced by an average of 32%.

The corrected data show that over the last 55 years, there was a 480% increase in primary productivity. In 2022, the annual average primary productivity attained a very high value of 230 mg of carbon per m^2, similar to the value for 2021. Both years displayed extremely high standard deviations (250 and 322 mg of carbon per m^2, respectively), indicative of highly fluctuating month-to-month values.

While significant uncertainties remain, the increase in primary productivity in 2022 is believed to be associated with a combination of environmental factors that favored the seasonal dominance of larger phytoplankton such as the diatom *Synedra*, the major biomass contributor, and the filamentous cyanobacteria, *Leptolyngbya sp.* which was the most abundant species in both 2021 and 2022.

Data source: TERC lake monitoring.



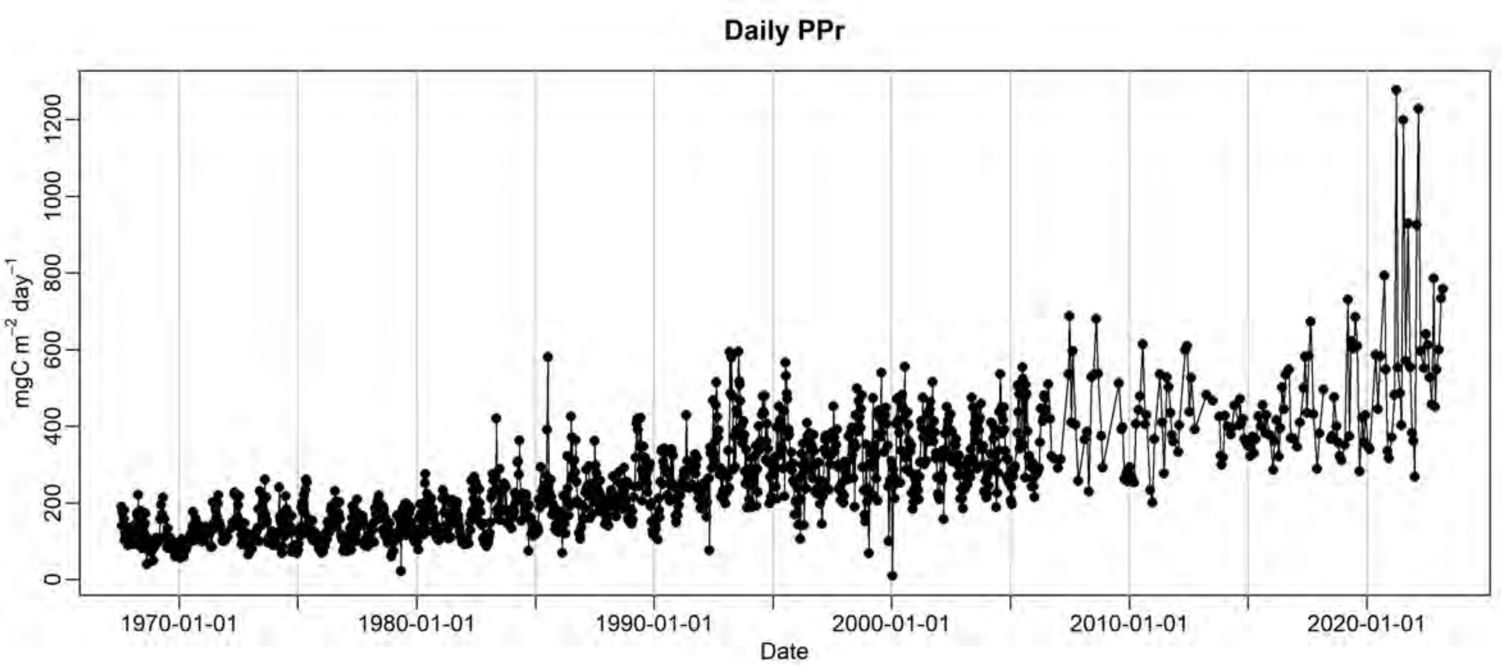
Algae growth (primary productivity)

Monthly since 1968

The primary productivity (PPr) is determined through measuring the depth-averaged uptake of isotopic Carbon-14 in a set of transparent and opaque bottles deployed for four hours at 12 depths (2, 5, 10, 15, 20, 30, 40, 50, 60, 75, 90, and 105 m). The bottles span the entire euphotic zone (the light penetrating zone). The vertical distribution of the phytoplankton that are responsible for the primary production is not uniform across the euphotic zone, but varies depending on light availability, nutrient concentrations, and the distribution of grazers (zooplankton).

In 2021 and 2022 the individual primary productivity readings showed an extremely high level of variability. Most of the peaks are represented as a single point, rather than a number of measurements trending toward and away from a peak. This suggests that the frequency of measurement (once a month) may not be fully resolving the time history of algal blooms.

Data source: TERC lake monitoring.



Biovolume

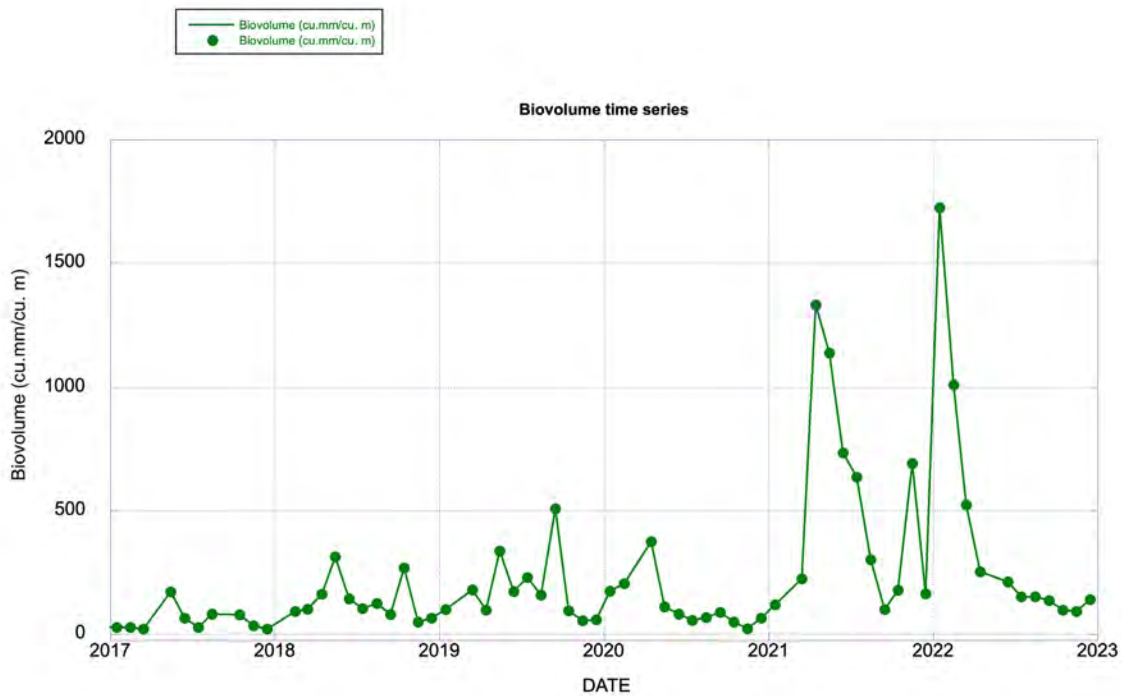
Monthly since 2017

The biovolume (or cell volume) of phytoplankton is an estimate of the concentration of algal biomass. It is a widely reported measurement of phytoplankton abundance in a water sample, based on a time-intensive measurement of water samples. The biovolume is estimated for each individual taxa from formulae for solid geometric shapes that most closely match the cell shape based on algal cell dimension measurements taken from a representative number of specimens. The process for estimation of the biovolume is currently being reviewed. At Lake Tahoe, samples for biomass estimates are taken from 5, 20, 40, 60, 75 and 90 m depths, and an integrated estimate is produced.

The biovolumes in 2021 and 2022 show several extremely high peaks that were not present in the years since 2017. These peaks are not coincident with the peaks in primary production as they represent a fundamentally different measurement. The primary productivity is a rate, while the biovolume is a concentration. Peaks in biovolume occur when the primary productivity is at a minimum.

It is worth noting that the presence of larger algae generally coincides with higher biovolumes, while smaller algae, though far more numerous in abundance, typically coincide with smaller biovolumes. It would require one million tiny alga cells (2 microns in size) to equal the same biovolume of a single large (200 microns) algal cell.

Data source: TERC lake monitoring.

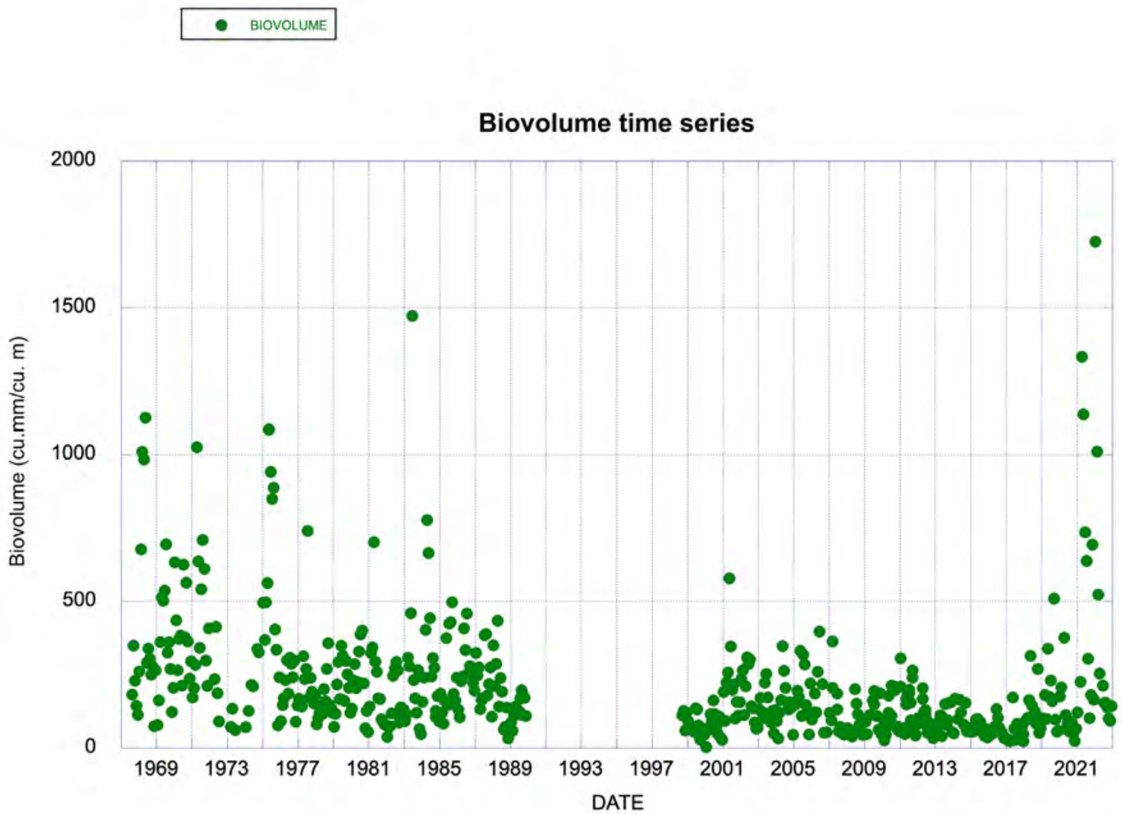


Biovolume

Monthly since 1968

When viewed over the full record, the peaks of 2021 and 2022 do not appear to be anomalous, but rather appear to be a returning to conditions that conditions that occurred in the 1980s and earlier. This observation is consistent with a dominance by larger alga in the 1980s and earlier and the occurrence for parts of the year dominated by larger alga (*Synedra*) in 2021 and 2022. This is a topic that is currently being studied by TERC researchers.

Data source: TERC lake monitoring.

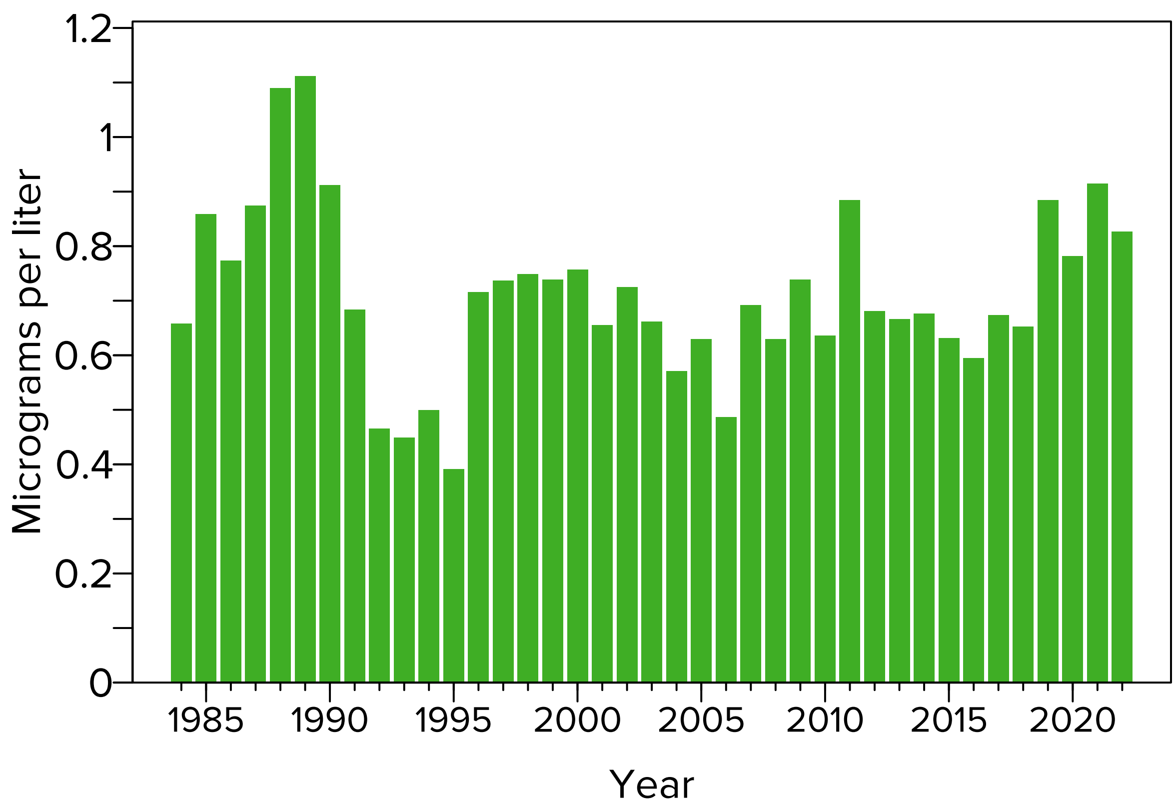


Phytoplankton chlorophyll annually

Yearly since 1984

Phytoplankton (algae) are the base of the Lake Tahoe food web and essential for lake health and the well-being of the entire ecosystem. One measure of the amount, or biomass, of free-floating algae in the water is determined by extracting and measuring the concentration of chlorophyll-*a*. Chlorophyll-*a* is a photosynthetic pigment that allows plants to convert energy from the sun. Though the value varies annually and at different depth throughout the lake, the average concentration has shown remarkable consistency over the last 25 years, and 2022 maintained this pattern. The average annual concentration for 2022 was 0.83 micrograms per liter, a slight decrease from the previous year. For the period of 1984–2022 the average annual chlorophyll-*a* concentration in Lake Tahoe was 0.71 micrograms per liter.

Data source: TERC lake monitoring.

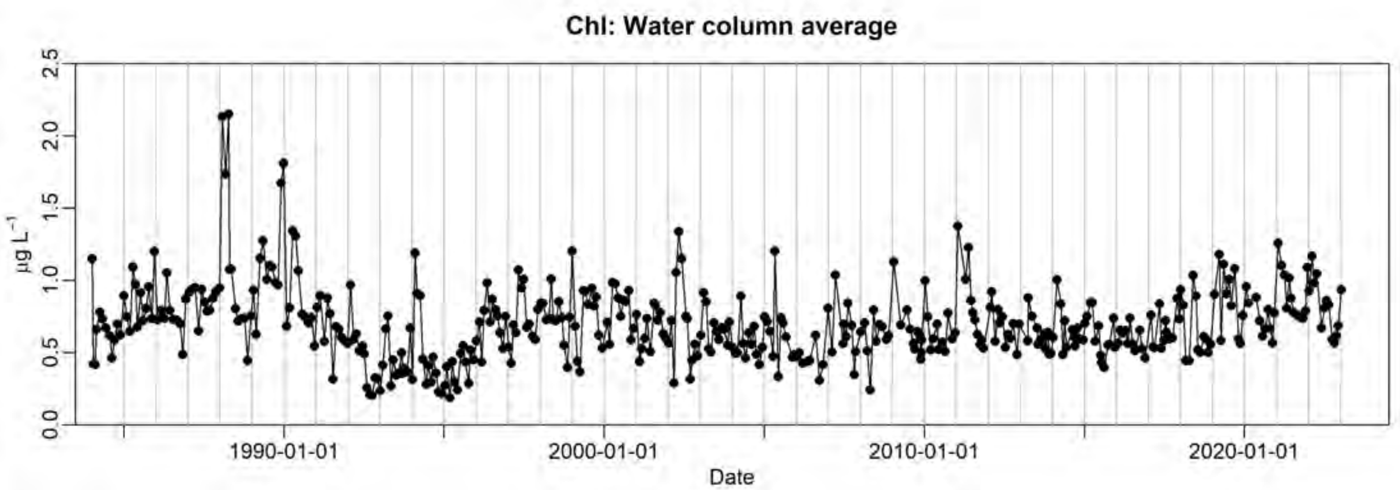


Phytoplankton chlorophyll

Monthly since 1984

The monthly chlorophyll-*a* values have generally reflected the annual trends, showing little systemic long-term trend. The monthly chlorophyll-*a* values have generally reflected the annual variation without presenting any long-term trend. However, the monthly data does show how chlorophyll-*a* concentrations change by a factor of two within each year. The biovolume in Figure 10.4, by contrast, shows a far larger dynamic range over each year.

The data were based on laboratory chlorophyll-*a* extractions from water samples collected at 13 depths of 0, 2, 5, 10, 15, 20, 30, 40, 50, 60, 75, 90, and 105 meters.



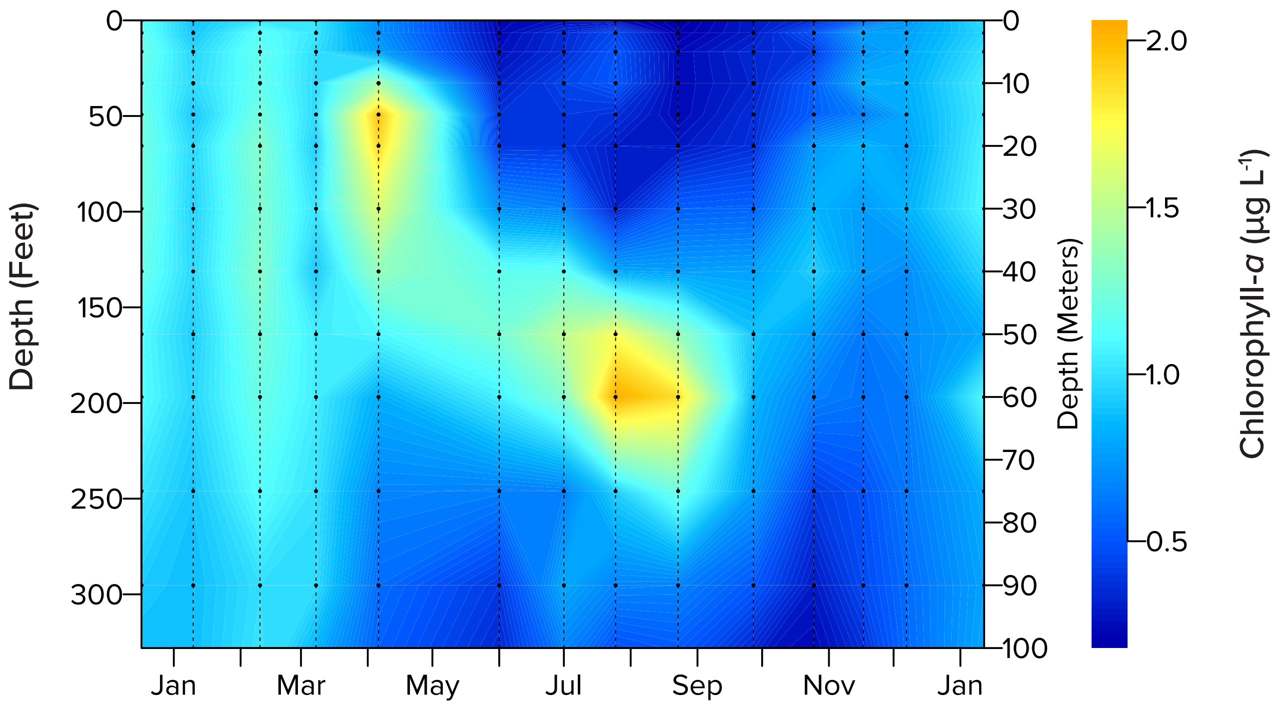
Chlorophyll-*a* spatial distribution

In 2022

The distribution of algae (measured as chlorophyll-*a* concentration) is the result of a combination of light availability, nutrient availability, grazing, mixing processes, and water temperature. This figure shows color contours of chlorophyll-*a* concentration to a depth of 350 feet. Below this depth, chlorophyll-*a* concentrations are near zero due to the absence of light. Lake Tahoe generally has a "deep chlorophyll maximum" (DCM) in the summer that occupies the range of 150–300 feet in the water column. In that range, the light and nutrient conditions are most favorable for algal growth.

In 2022, this pattern changed significantly. At the beginning of the year, chlorophyll was relatively high throughout the water column, an unusual occurrence. In September, the deep chlorophyll layer virtually disappeared and chlorophyll concentrations throughout the upper 300 feet of Lake Tahoe fell to extremely low levels. Based on all the data available for light, nutrients, mixing, and water temperature, none of these factors can account for this singular change in 2022.

The factor that is consistent with the large change in chlorophyll is the change in the nature of zooplankton community that took place in 2022 (see Fig. 10.12). Early in 2022, there was a large decrease in the copepod community. The consequent reduction in grazing pressure on phytoplankton could explain the high chlorophyll in January–March. Likewise, in the latter part of 2022, rotifers occurred in high concentration and eventually cladocerans and copepods returned. This could account for the disappearance of the DCM in September.



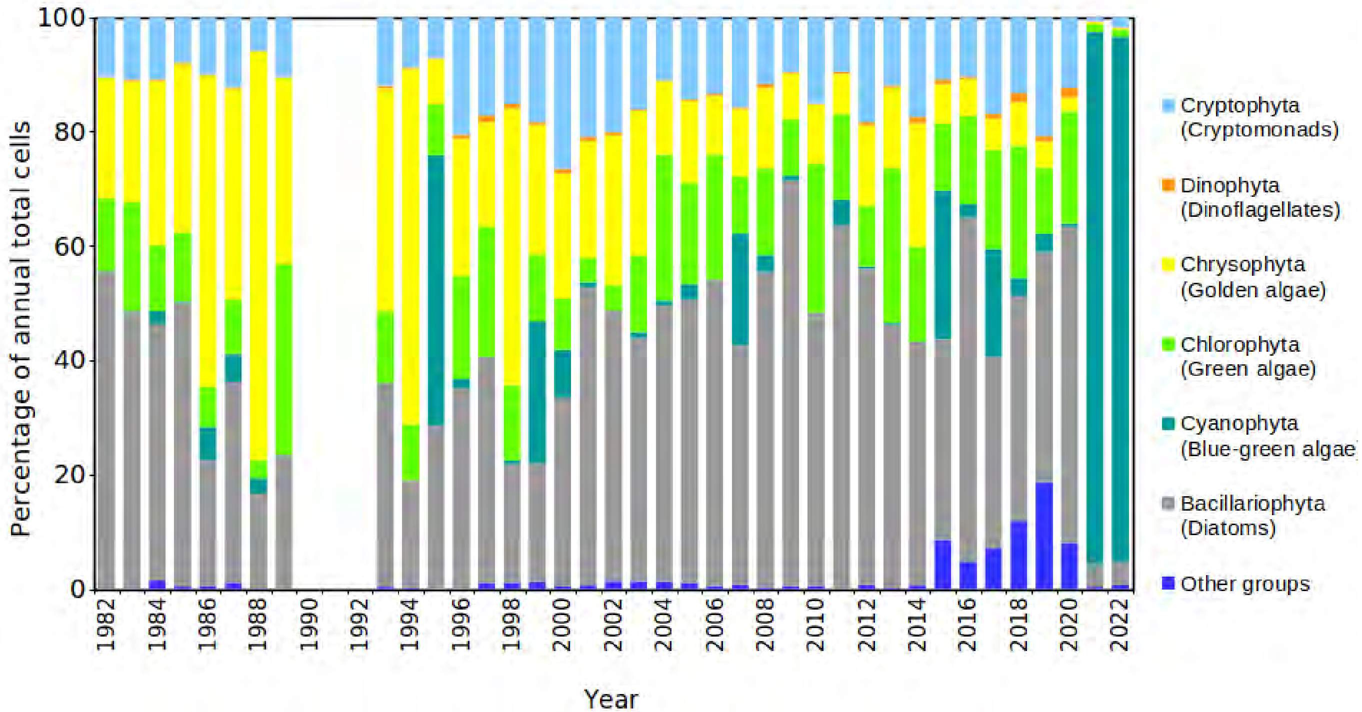
Distribution of algal groups

Yearly since 1982

There are six major taxonomic groups represented in the phytoplankton from Lake Tahoe. The total number of algal cells from different groups varies annually. Diatoms have generally been the most common type of algae. In 2022, a major shift in the phytoplankton composition continued for a second year with continued high abundance (based on cell counts) of the cyanobacteria *Leptolyngbya sp.* and with sporadic contribution of *Pseudanabaena sp.* Both are a multicellular filamentous cyanobacterial genus with similar morphologies. Note that picoplanktonic cyanobacteria are not included. These are the only two years on record in which a single taxon belonging to the cyanobacteria group dominated the phytoplankton assemblage. *Leptolyngbya* is a simple filamentous genus that in Lake Tahoe includes an extremely narrow species, generally with cells a mere 1–2 microns wide. This small size has large impacts on clarity. The cells are enclosed in a sheath and form filaments with variable length (from 50µm to 400µm, frequently ~100µm).

The 2021 and 2022 occurrences (see Figs. 6.10) are actually part of a single, contiguous event. In 2021, the *Leptolyngbya sp.* was dominant from October through December, and in 2022 it was dominant from January through March. The initial cause of the *Leptolyngbya* bloom is believed to be high atmospheric nitrate inputs associated with wildfire smoke.

Data source: TERC lake monitoring.

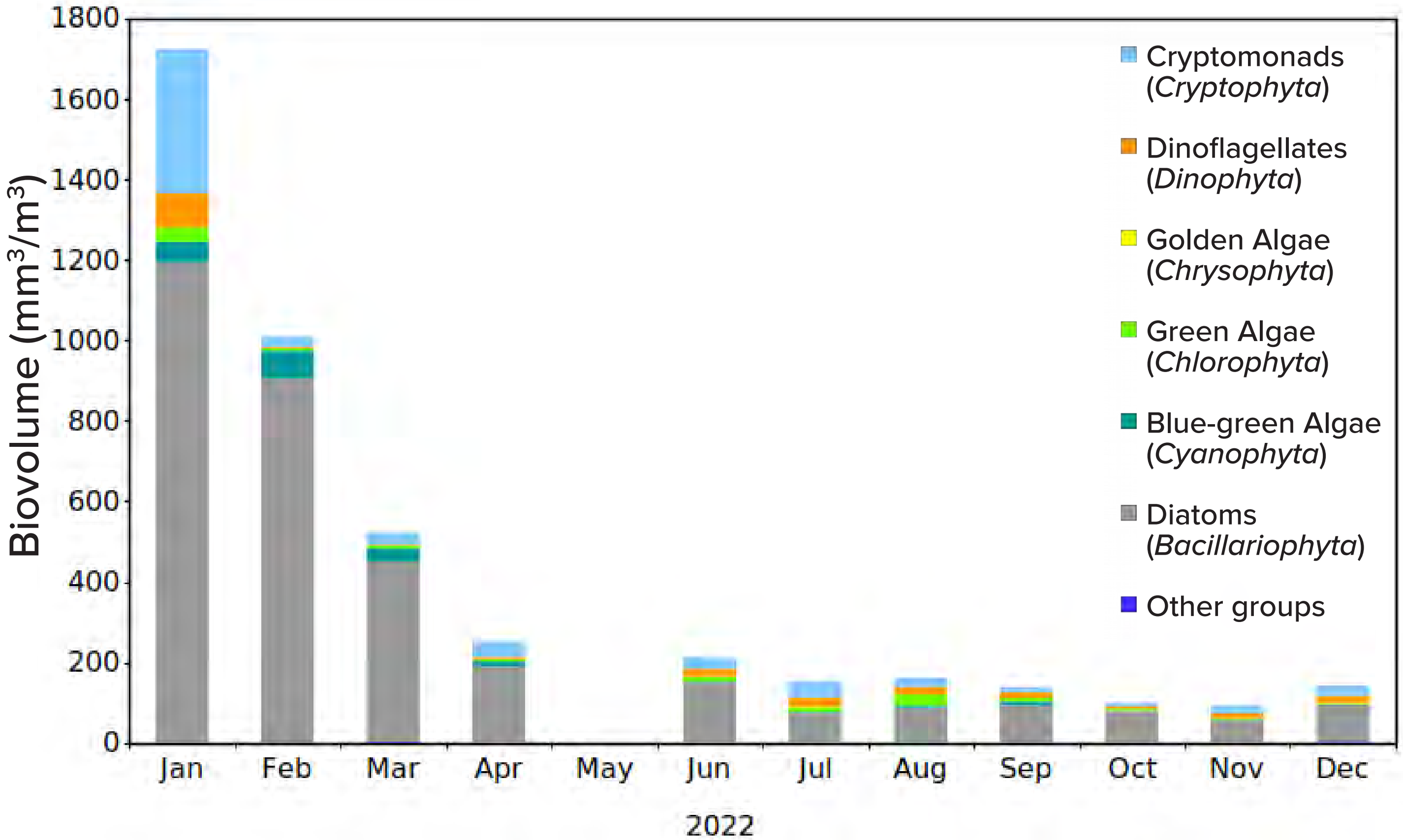


Algal groups as a fraction of total biovolume

Monthly in 2022

The total biovolume of different algal genera vary month to month as well as year to year. In 2022, despite the fact that cyanobacteria dominated algal abundance on the basis of the number of individual cells, diatoms again dominated the biovolume (proportional to the mass) of the phytoplankton community in every month. The peak in the monthly average biovolume occurred in January 2022 and was much higher than normal. This "winter bloom" is highly atypical. The bloom continued through March. As described previously, a possible explanation for the biovolume distributions was a marked decrease in the zooplankton grazing. Though they had little impact on the biovolume, the high abundance of small algae also produced very low clarity values at the same time (See Fig. 11.4)

Data source: TERC lake monitoring.

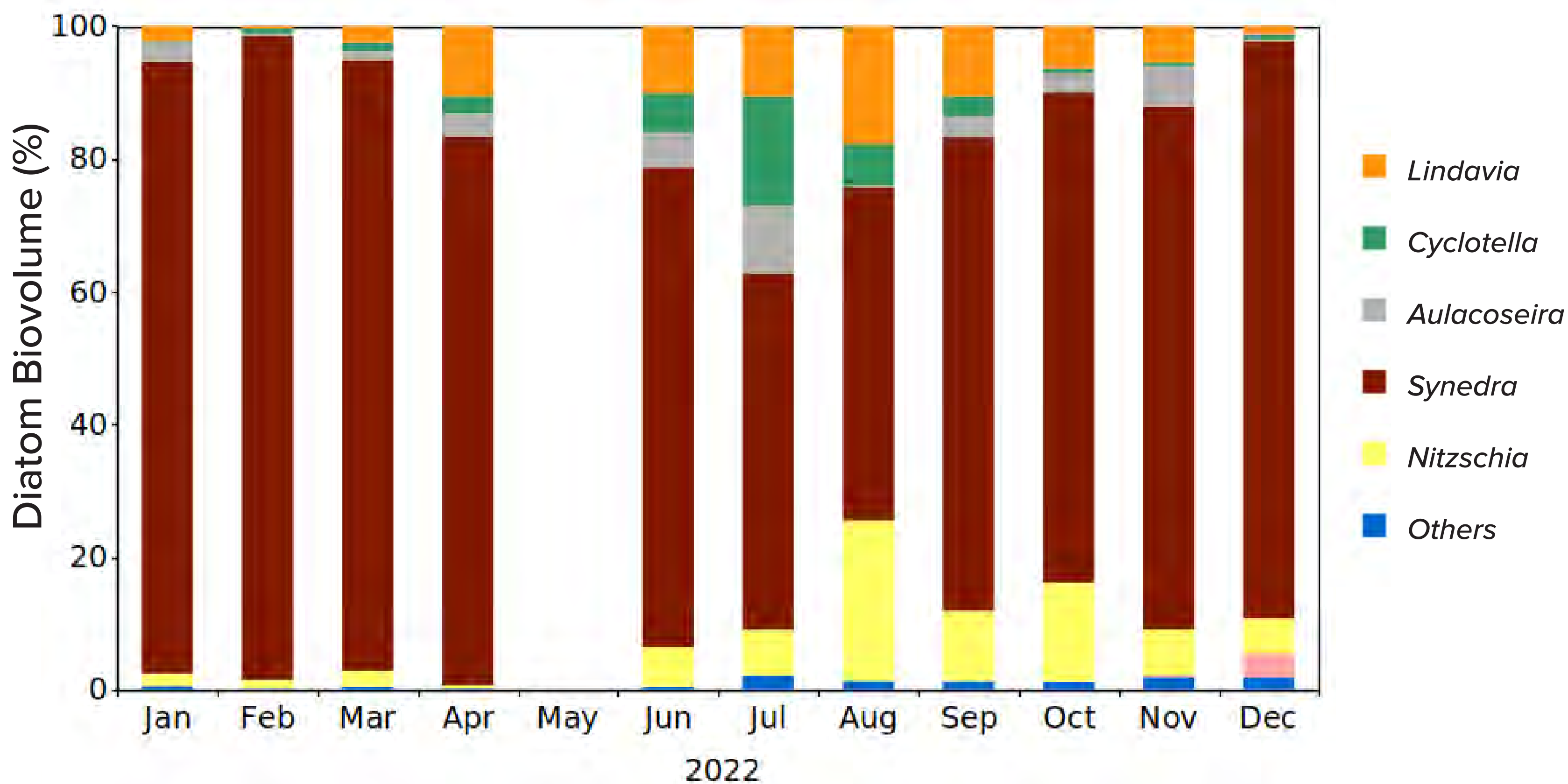


Abundance of dominant diatom species

Monthly in 2022

Since regularly monitoring commenced in 1982, diatoms have been the dominant algal group at Lake Tahoe for all but a few years. Diatoms are unique in that they contain a cell wall made of silica, called a frustule. The dominant diatoms at Lake Tahoe in 2022 are shown below. Normally there are large variations in the relative composition by month. In 2022, *Synedra* was dominant in terms of biovolume, forming the majority of the diatom biovolume during every month.

Data source: TERC lake monitoring.



Mysis population

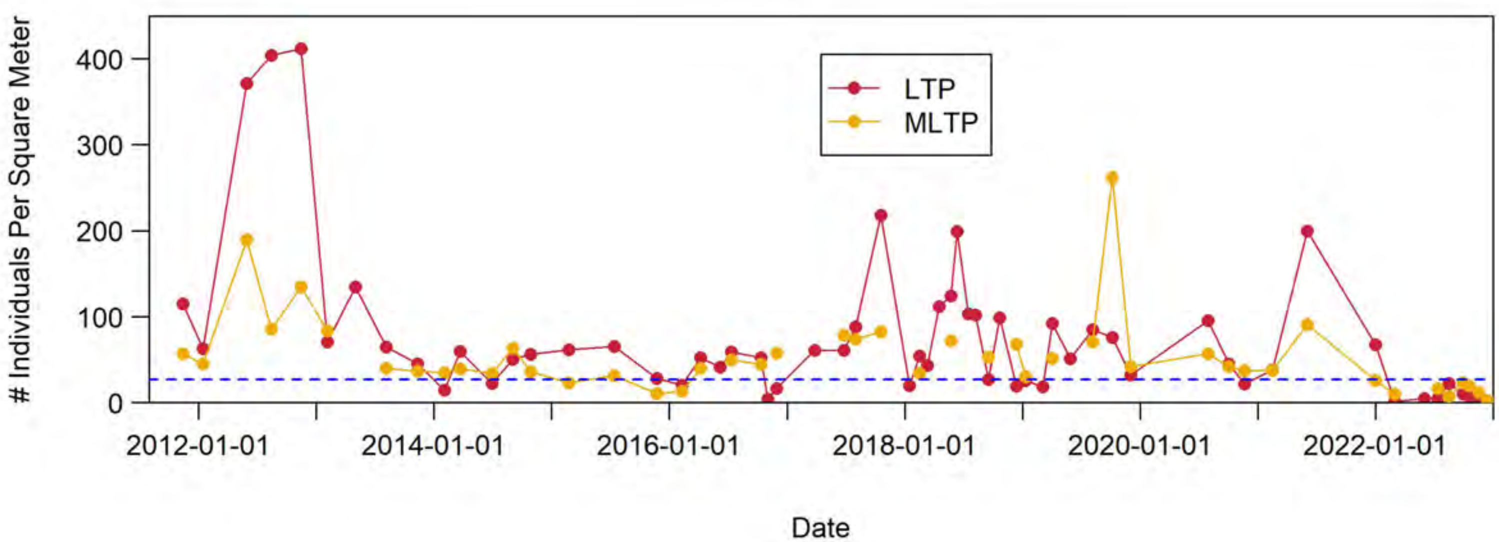
Since 2012

Mysis shrimp were introduced to Lake Tahoe in the 1960s in an attempt to improve the size of game fish in the lake. The intended result did not occur and instead the *Mysis* upset the existing lake food web. Within four years of their introduction, they had decimated the populations of the native cladocerans (*Daphnia* and *Bosmina*). Since that time, these zooplankton are rarely observed. *Daphnia* and *Bosmina* were once an important food source for native minnows, which in turn provided food for kokanee salmon and rainbow trout.

In the 1980s, research on *Mysis* essentially stopped. However, since 2012, TERC has recommenced regular surveys of Lake Tahoe and Emerald Bay. *Mysis* migrate to the lake bottom during the day, requiring all sampling to occur at night. The sampling net is pulled vertically in Lake Tahoe at 3-month intervals from three sites: South Shore Deep (200 m), LTP Index (100 m), and MLTP (200 m). Since early 2022, sampling has increased to monthly intervals.

The *Mysis* densities (number of individuals collected divided by the net opening area) in Lake Tahoe show considerable variability. The blue dashed line at 27 individuals per square meter represents the *Mysis* population level below which cladocerans can reestablish. In early 2022, *Mysis* numbers fell below that threshold and remained low through the end of the year. As *Mysis* in Lake Tahoe generally exhibit three- to four-year classes, the absence of all age classes suggest that it may take several years for the *Mysis* population to rebuild. It is hypothesized that *Daphnia* and *Bosmina* populations will increase in 2023, potentially bringing a significant increase in lake clarity.

Data source: TERC lake monitoring.



Zooplankton populations

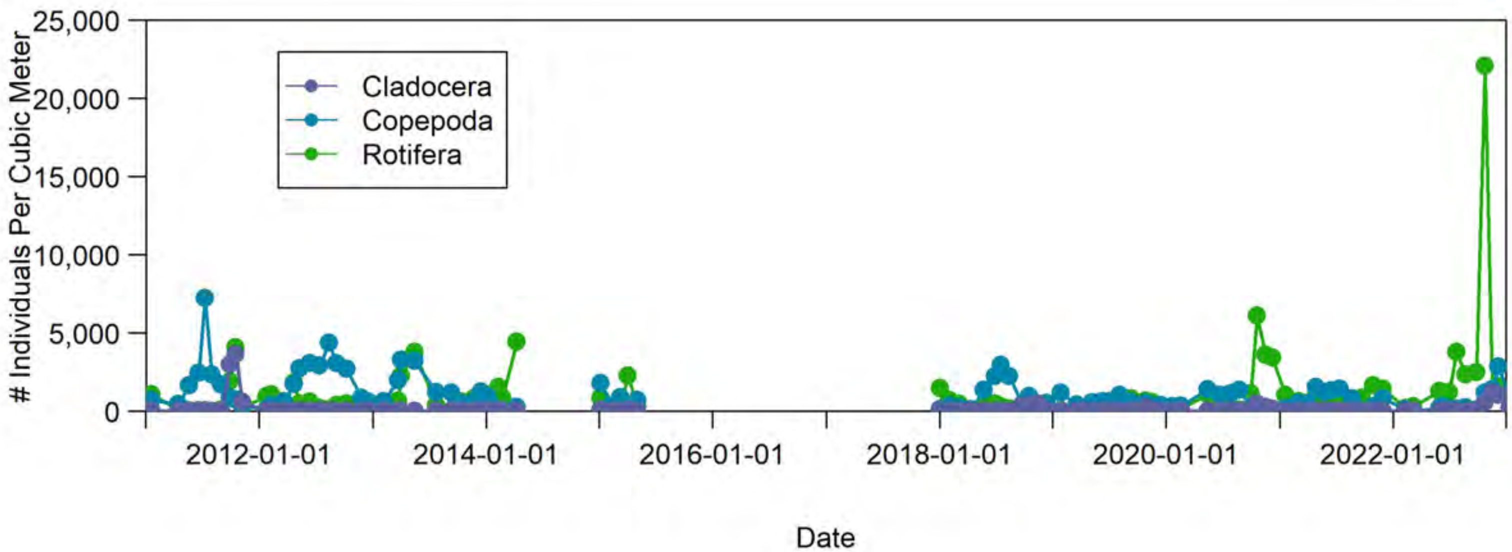
Since 2012

The zooplankton populations in Lake Tahoe have been monitored episodically since the 1960s, but due to a lack of funding there are many data gaps. Since 2012, TERC has sought to re-establish monitoring. The data shown below are from the LTP site, where zooplankton were collected with replicate vertical trawls from a depth of 330 feet to the surface during the middle of the day.

The figure shows the abundance of three groups of zooplankton — cladocerans (*Daphnia* and *Bosmina)*, copepods (*Epischura* and *Diaptomus*), and rotifers. The cladocerans are typically at very low values, a feature that first occurred after the introduction of *Mysis* shrimp in the 1960s. Notably at the end of the record, in September 2022, their numbers increase. The copepods are generally variable, but in late 2021 their numbers collapsed possibly due to a fungal infection.

The rotifers are also variable over time, but in mid-2022 their abundances increased dramatically.

Data source: TERC lake monitoring.

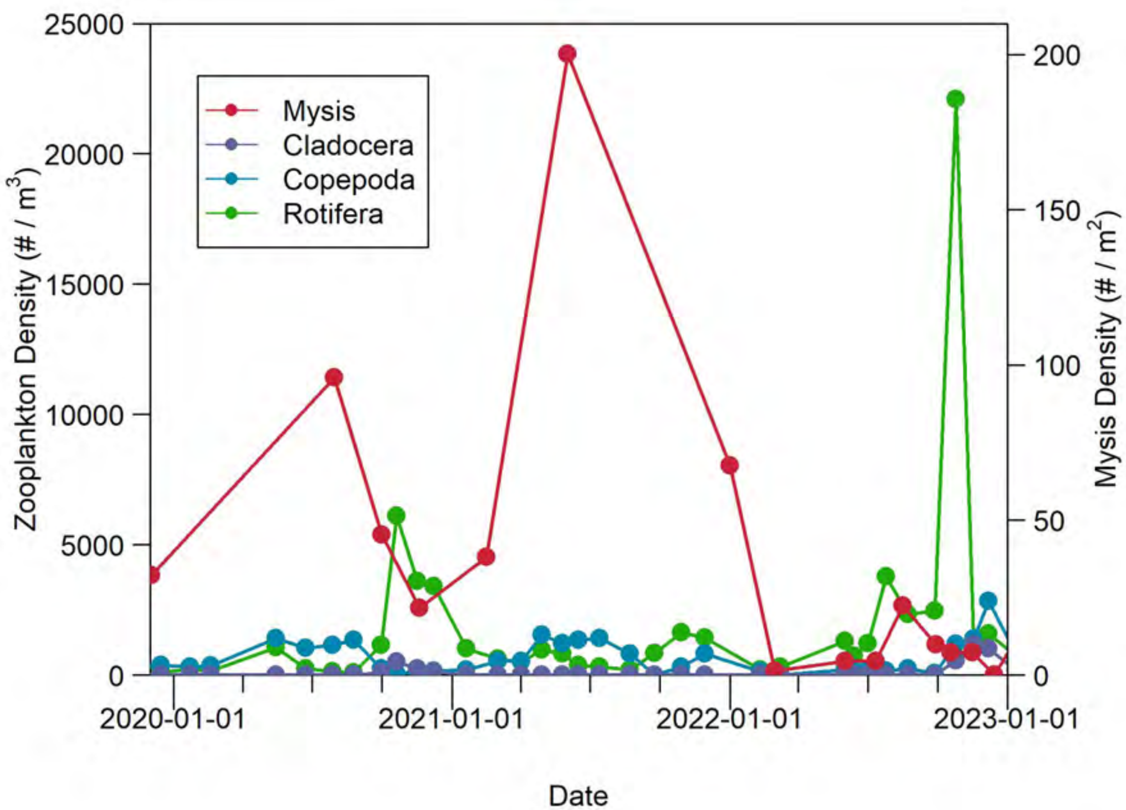


Zooplankton and *Mysis* populations

Since 2020

Below are the combined data from Figures 10.9 and 10.10 for the period January 2020 through December 2022. The changes in zooplankton and *Mysis* populations referred to in the previous two pages are more clearly seen here. Most notably those changes include the collapse of the copepod population, followed by the collapse of the *Mysis* population, followed by the increase in the rotifer population, and finally the increase in the cladocerans population.

It is noteworthy that during this period of time when there are major shifts in the Mysis and zooplankton populations, there were, at the same time, major changes in the primary productivity and the algal biovolume described previously. Additionally, the number of fine particles in the upper 50 meters of the lake (Fig. 9.9), the major determinant of lake clarity, also fell to their lowest concentration since 2016.



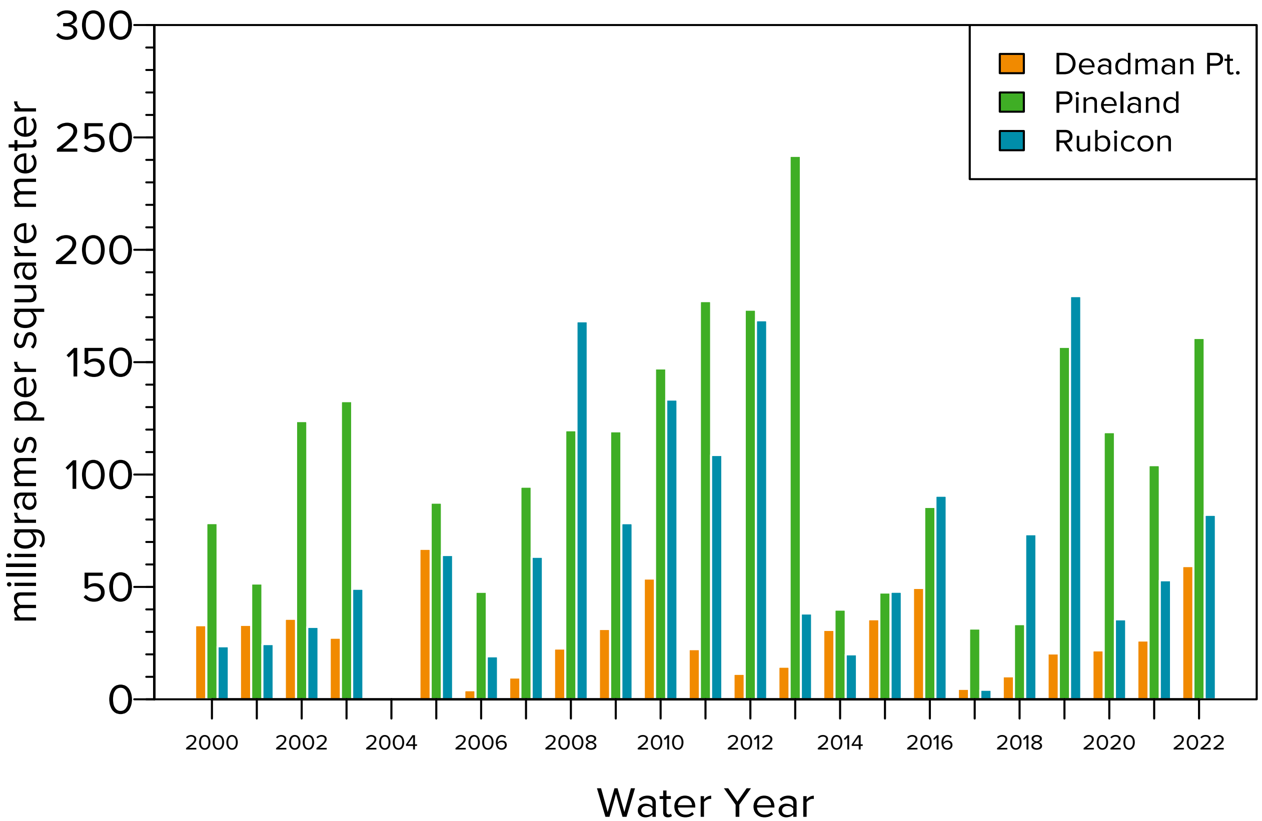
Peak shoreline algae concentrations

Yearly since 2000

Periphyton, or attached algae, makes rocks around the shoreline of Lake Tahoe green and slimy, or they sometimes form a very plush white carpet after being sun-bleached. This graph shows the maximum biomass measured at 1.5 feet (0.5 m) below the surface at three sites from January to June. In 2022, concentrations at the Deadman Point, Pineland, and Rubicon sites were all above their long-term average.

In 2023, TERC will be adopting a whole-lake aerial approach to better represent the spatial extent of periphyton blooms. During the latter part of 2022, there were widespread algal blooms in the northwest and southern shores of Lake Tahoe. The current sampling protocol of measuring at specific sites does not capture the critically important spatial extent of periphyton blooms.

Data source: TERC lake monitoring.



Shoreline algae distribution

In 2022

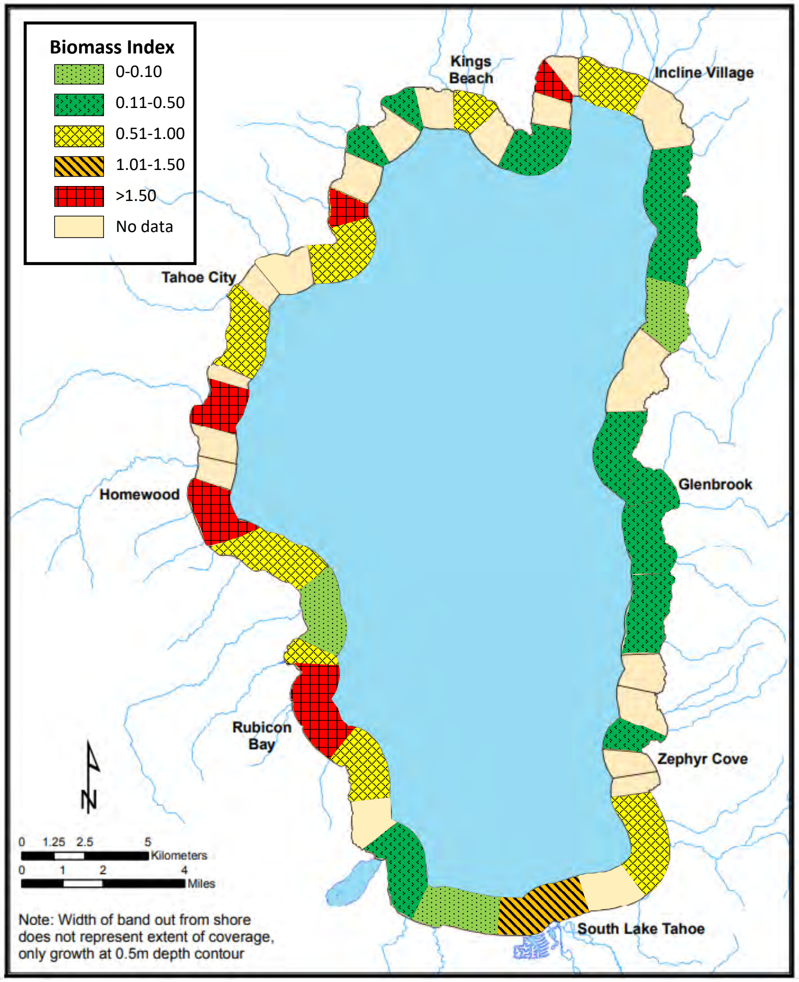
Periphyton biomass was surveyed around the lake over a three-week period during the spring of 2022, when periphyton is usually at its annual maximum. Over 50 locations were inspected by snorkel survey in 1.5 feet (0.5 m) of water. A Periphyton Biomass Index (PBI) is used as an indicator to assess levels of periphyton. The PBI is defined as the fraction of the local bottom area covered by periphyton multiplied by the average length (cm) of the algal filaments. There were more sites with a high PBI in 2022 than the previous year. The majority of the high PBI sites were on the California side. Most of the east shore had relatively low growth. This is in part a reflection of the high wave activity that causes the periphyton to slough, as well as generally lower amounts of precipitation and runoff along the east shore.

2022 was unusual in that periphyton peaked many months later than the usual spring bloom. Because of this the figure does not fully represent the severity of the 2022 algal bloom.

Data source: TERC lake monitoring.

Note: The width of the colored band does not represent the actual dimension of the onshore-offshore distribution. Similarly, its length does not represent the precise longitudinal extent.

Distribution of Periphyton Biomass at 0.5m Depth, Spring 2022



TAHOE: STATE OF THE LAKE REPORT 2023

CLARITY

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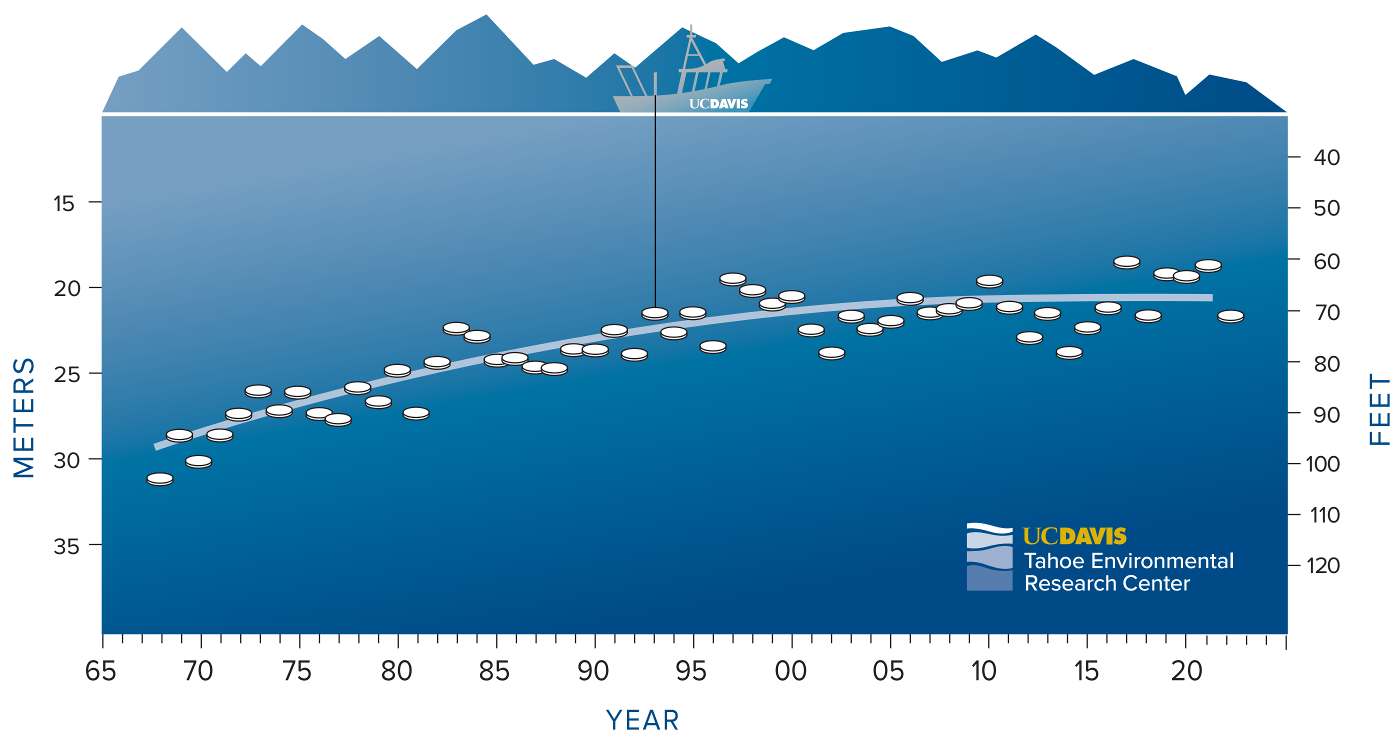
Annual average Secchi depth

Yearly since 1968

The Secchi depth is the depth at which a 10-inch white disk, called a Secchi disk, remains visible when lowered into the water. In 2022, the annual average Secchi depth was 71.7 feet (21.9 m), a 10.7 foot improvement from the previous year. The greatest individual value recorded in 2022 was an astounding 137.8 feet (42 m) on January 5, the second highest value ever recorded. This was the result of an ephemeral lake "upwelling." Upwellings are episodic events produced by strong winds and are not reflective of the overall lake clarity and health. The lowest clarity reading was 50.0 feet (15.24 m) on May 13. The clarity in 2022 was the result of a combination of factors including the absence of deep mixing of the lake in the first part of the year, and then the removal of fine particles and algae through zooplankton grazing in the second part of the year. The differences are explained in Figure 11.4.

The clarity restoration target of an annual Secchi depth of 97.4 feet (29.7 m) set by federal and state regulators, is a goal that agencies and the Tahoe Basin community continue to work toward.

Data source: TERC lake monitoring.

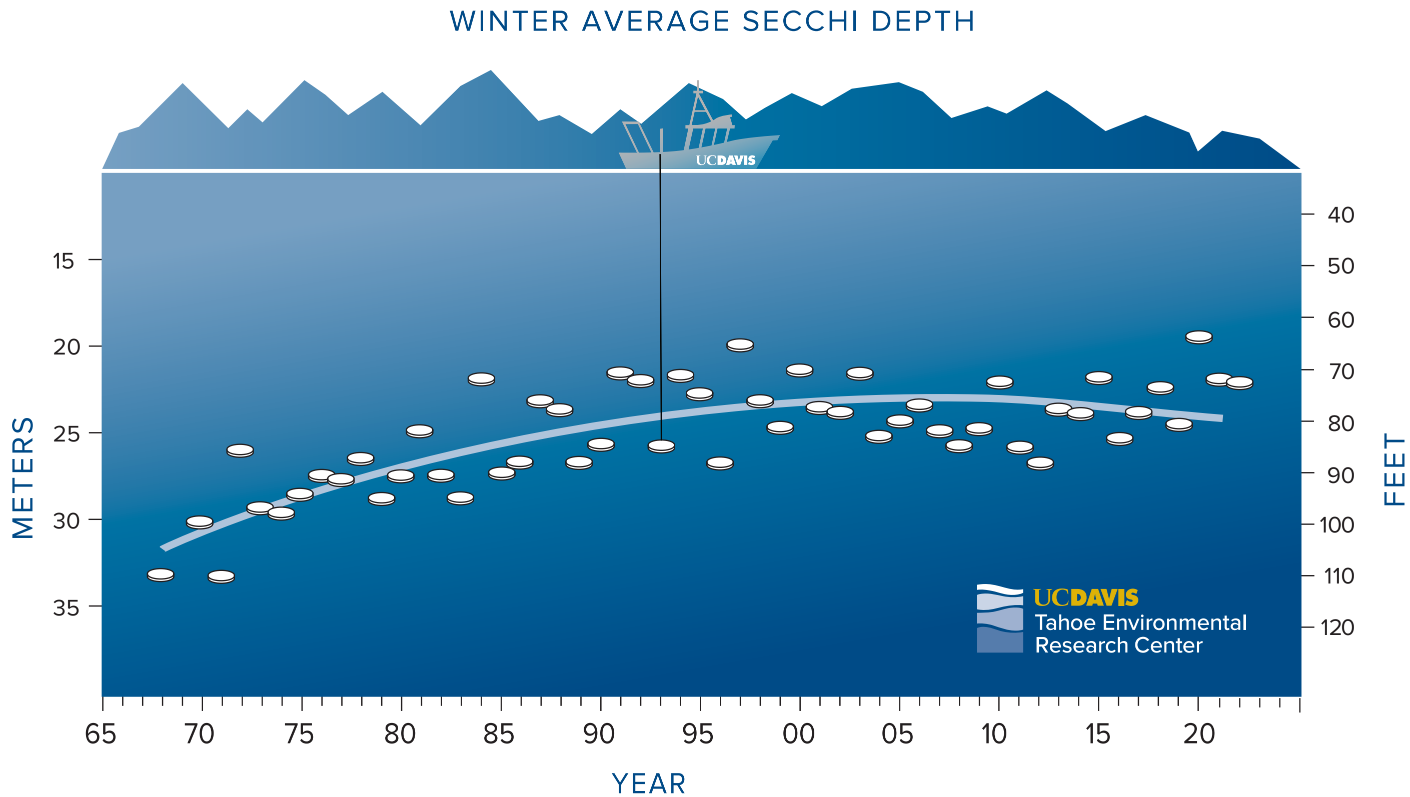


Winter Secchi depth

Yearly since 1968

Average winter Secchi depth was 72.2 feet (22.0 m), based on ten readings between December 2021 and March 2022. Winter precipitation was close to the long-term average and the clarity values were less than the long-term trend. The reasons for the low values are still not fully understood, although the record high algal biovolume (Fig. 10.6) and the unusually high cell abundances of tiny cyanobacteria (Fig. 10.4) may have played a role.

Data source: TERC lake monitoring.

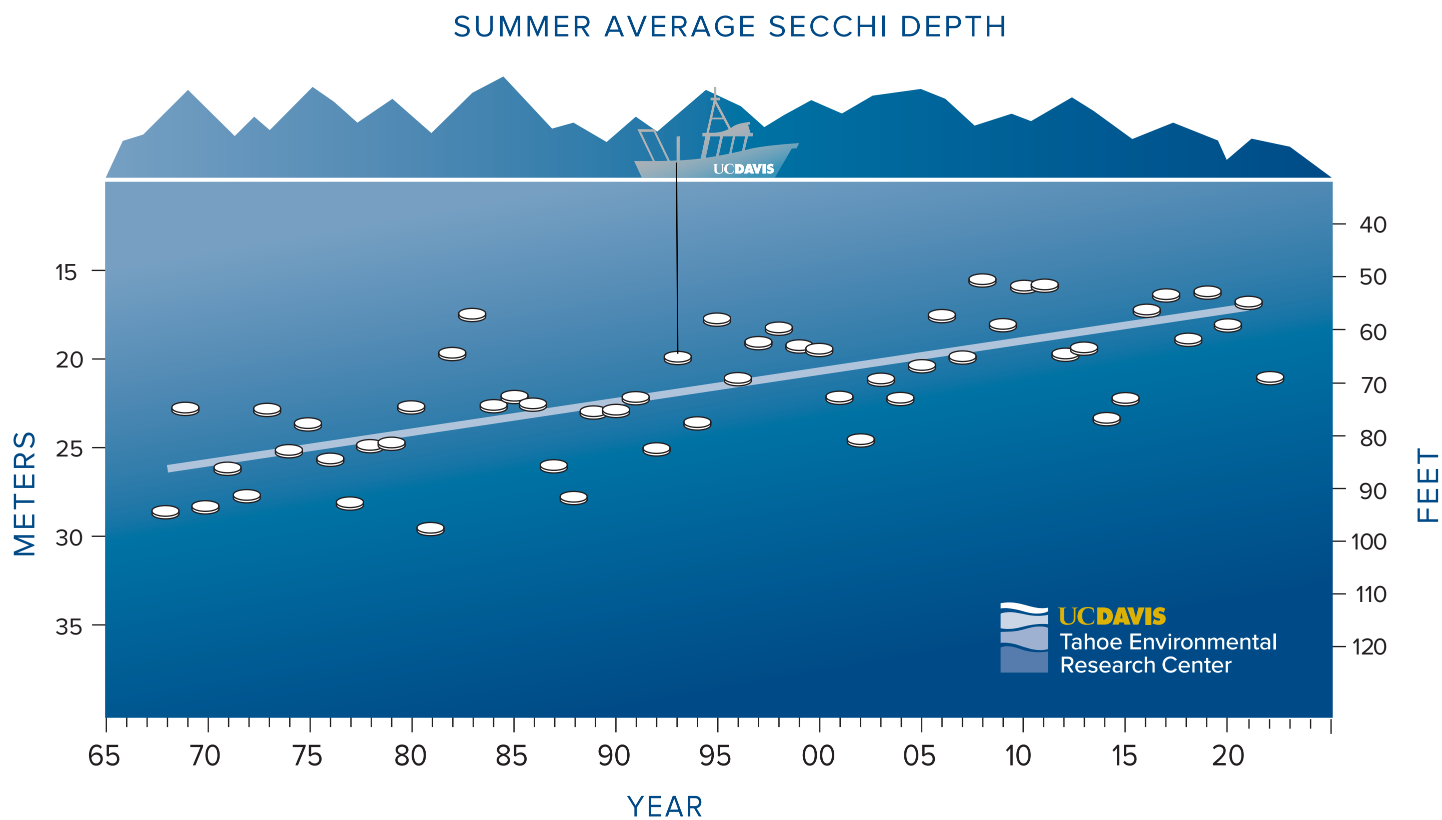


Summer Secchi depth

Yearly since 1968

Summer (June–September) clarity in Lake Tahoe in 2022 was 68.9 feet (21.0 m), an increase of over 20 feet from the previous year. This is significantly above the lowest summer value of 50.5 feet (15.4 m) in 2008. Summer is typically the season of poorest clarity. The long-term summer trend is dominated by a consistent degradation. As shown in Figure 11.4, the clarity in the month of July began to improve and from September onwards there were some of the highest Secchi depth readings in the last 40 years.

Data source: TERC lake monitoring.



Individual Secchi depths

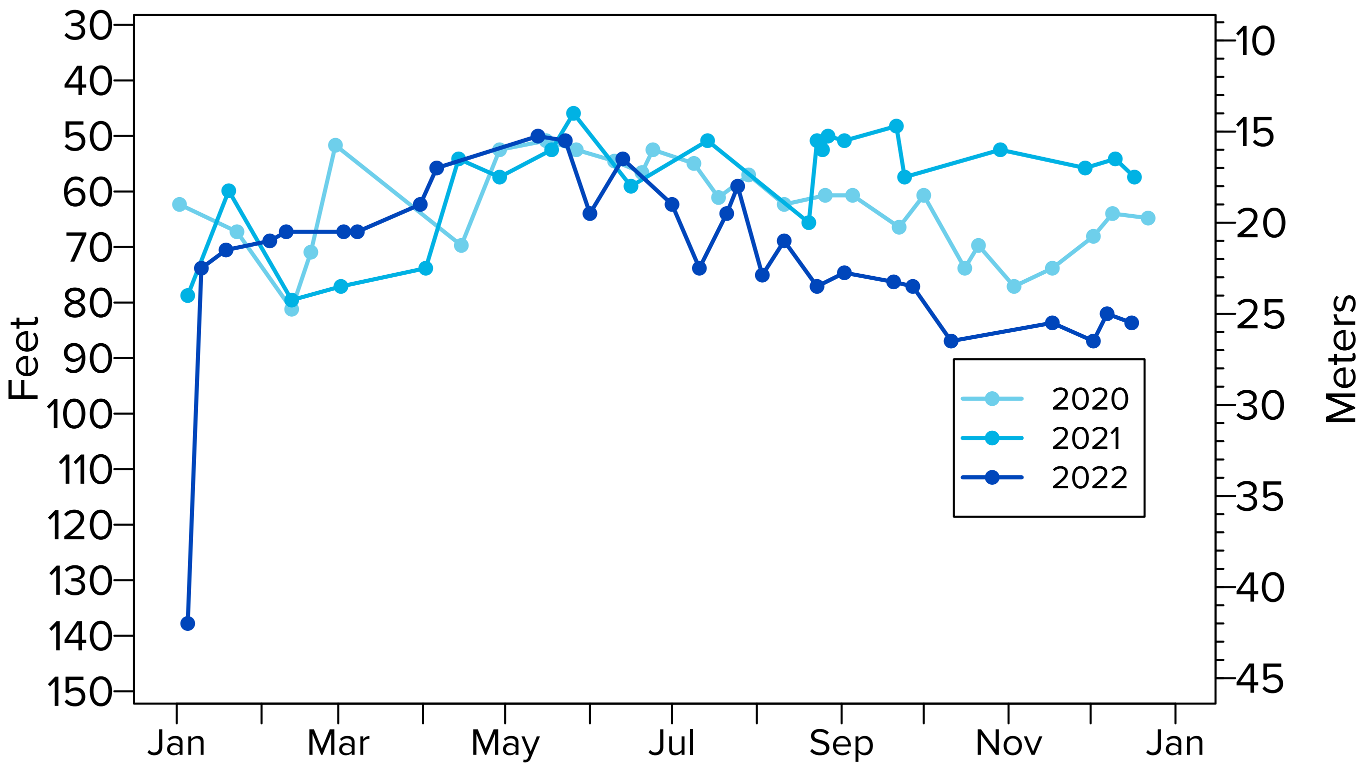
2020, 2021, 2022

The individual Secchi depth readings from the Index station on the west side of the lake for 2020, 2021, and 2022 are plotted. Secchi values can be seen to sometimes vary considerably over short time intervals. It is worth noting that a Secchi depth of 138 feet (42 m) was observed on January 5, 2022. This is the second deepest Secchi depth ever recorded at Lake Tahoe and was the result of a wind-driven upwelling, a temporary phenomenon that brings very clear hypolimnetic (bottom) water up to the surface.

The extremely low Secchi depth values at the end of 2021 were due to the unusual presence and very high abundance of the small cyanobacterial alga, *Leptolyngbya sp.* Because of its small diameter that ranges 0.9–1.3 microns, it is very effective at scattering light. The continued presence of *Leptolyngbya* in January–March of 2022 contributed to an overall winter clarity that was unexpectedly low.

This figure clearly shows that commencing in July, the 2022 Secchi depths started to substantially improve in comparison to the previous two years. From August through December, the average Secchi depth was comparable to clarity data recorded in the 1980s.

Data source: TERC lake monitoring.



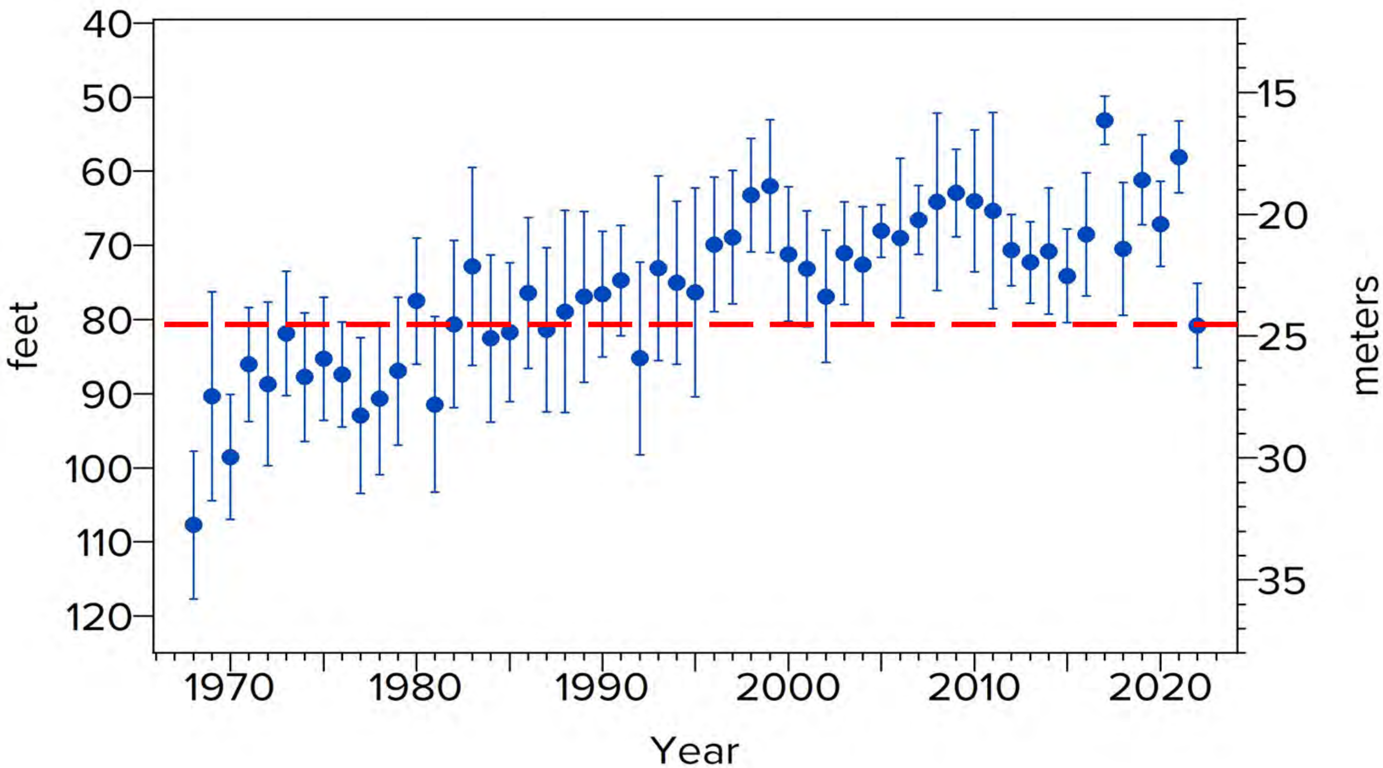
August through December Secchi depths

Yearly since 1968

The magnitude of the shift in lake clarity in the latter part of 2022, can best be appreciated by plotting the Secchi depth average for the period August through December, for each year of record. The dots represent the average Secchi depth over those months, and the whiskers represent the standard deviations. Here it is evident that the level of clarity observed has not been experienced consistently since the 1980s.

Given all the factors that we know that influence lake clarity, the extended improvement in clarity through December 2022 cannot be accounted for solely by factors such as nutrients, light environment, stream inflows, and lake temperatures. Additionally, food web changes prompted by the collapse of the introduced *Mysis* population, and the subsequent changes to the phytoplankton and the zooplankton populations are likely playing a major role. The linkages are complex and monitoring in the coming year may shed light on these processes.

Data source: TERC lake monitoring.



TAHOE:
STATE OF THE LAKE
REPORT
2023

EDUCATION AND OUTREACH

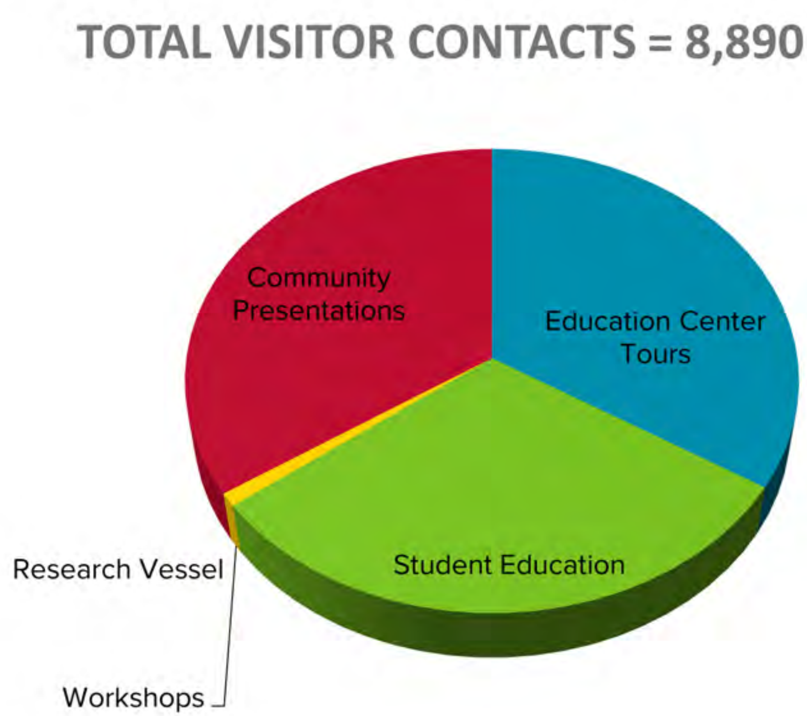
UC DAVIS
Tahoe Environmental
Research Center

Education and outreach

In 2022

Maintaining healthy aquatic and terrestrial ecosystems is greatly enhanced by education and outreach to provide science-based information to people of all ages and backgrounds and to foster responsible actions and stewardship.

In 2022, TERC interacted with 8,890 visitors through tours, field trips, lectures, and public events. The TERC education team reached 2,732 students during 73 field trips focused on Lake Tahoe geology, the aquatic food web, forest health, and climate change. TERC continued educating the public through lectures, community presentations, and outdoor programming. TERC brought science-rich content to 603 community members through 17 lectures. The Education and Outreach team participated in 31 community outreach events that reached 2,436 people. This represents a 72% increase in the number of visitors over the previous year. TERC anticipates that audience sizes and visitation rates will continue to bounce back and surpass pre-pandemic numbers with the expanded education offerings planned.



Educational exhibits

2023

The Tahoe Science Center continues to expand offerings with two new exhibits in the Underwater Lake Tahoe lounge and plans to expand accessibility to a Spanish-speaking audience and younger demographic.

A new scavenger hunt adventure that leverages augmented reality (AR) technology and the completed Find Tahoe Tessie (beta) App will be added to the Underwater Lake Tahoe room in 2023. The Underwater Lake Tahoe scavenger hunt allows visitors to discover the abundance of life that exists in the lake and their habitats. Additional AR elements will bring the Lake Tahoe aquatic organisms to life. TERC's Find Tahoe Tessie app has officially launched for beta testing. Find Tahoe Tessie encourages users to unlock various animations of Tahoe Tessie by answering questions regarding the impacts of climate change on the Tahoe aquatic ecosystem. While Tahoe Tessie isn't real, climate change is!

As part of the American Alliance of Museums (AAM) Museum Assessment Program TERC is expanding the accessibility of science education to Spanish-speaking visitors and a younger demographic (age eight and younger). Spanish translated speech bubbles will be added to the Tahoe Science Center that express guiding questions through the science center exhibits.

Spanish Springs High School students were eager to check out the scavenger hunt available in the Underwater Lake Tahoe Lounge at the UC Davis Tahoe Science Center™.
Photo: A. Toy

Dayton High School students were so excited to find Tahoe Tessie, they had to capture a photo. Here's hoping this picture wins the Find Tahoe Tessie photo contest!
Photo: A. Toy

New discussion questions geared towards English and Spanish speakers prompt thought-provoking conversation between visitors and TERC education staff.
Photo: A. Toy

Educational programs

2023

TERC programs aim to expand public awareness, knowledge, and understanding of environmental issues at Lake Tahoe. New programs allow TERC educators to grow in their knowledge of science communication and expand TERC's audience.

In 2022, ten TERC educators and three community partners participated in a 32-hour Certified Interpretive Guide (CIG) course through the National Association for Interpretation. As educators and interpreters of Tahoe science and research, TERC conducts tours, demonstrations, and leads many activities. This professional development opportunity allowed staff and volunteers to build on presentation skills and refine thematic interpretation elements of the Tahoe Science Center.

The TERC Internship for Scholars program is running again in 2023. This eight-week paid internship offers a cohort of undergraduate and post-graduate students a unique opportunity to be part of TERC's applied research and education programs. Interns work with a variety of staff, faculty, and graduate students to complete a poster project related to limnology, hydrology, aquatic chemistry, forest ecology, and science education. At the end of the program each participant receives a $3,000 stipend that comes from a large fund-raising effort from the UC Davis Give Day.

Programs that expanded TERC's education reach that are new in 2023 include: the UC Davis Summer Sessions at Lake Tahoe, Patterson High School Summer Camps, Tahoe City Evening Lecture Series, and a transition of TERC's Citizen Science Tahoe app to ESRI Survey123.

National Association for Interpretation Certified Interpretive Trainer™ Stephanie Ambrosia led the Certified Interpretive Guide™ 4-day certification workshop and engaged the group in a number of activities.
Photo: A. Toy

Seven undergraduate interns from a variety of universities come together to learn about science and research. Over the summer, they will learn to be better communicators of science and complete a project that contributes to TERC's overall mission and goals.
Photo: A. Toy

As part of a pilot summer camp program, underserved students from Patterson High School came to the Tahoe Truckee area. For all of the students, this was their very first time visiting the Tahoe area and participating in the science and outdoor activities offered.
Photo: C. McHenry