UC DAVIS

TAHOE: STATE OF THE LAKE REPORT 2021

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.

Editor: S. G. Schladow
Co-Editors: A. Toy, S. Watanabe

The UC Davis Tahoe: State of the Lake Report 2021 is dedicated to the commitment and perseverance displayed by the entire UC Davis TERC staff, student, and faculty body in fulfilling our mission in the face of extraordinary difficulties brought on by the coronavirus pandemic.

Throughout very difficult and stringent conditions, field sample collections and laboratory analyses continued, except during a six week stay-at-home order. Public education transitioned from an in-person, hands-on approach to a fully virtual experience. The administrative burden of hiring staff and students, ordering equipment and supplies, and meeting compliance standards took place from home offices and dining rooms. The unending task of writing proposals, reports, and scholarly publications continued unabated, as did the generation of exciting new ideas.

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INTRODUCTION

The University of California, Davis has conducted continuous monitoring of Lake Tahoe 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 variability, long-term change, and human activity are affecting the lake's clarity, physics, chemistry, and biology. We also present a portion of the data collected in 2020 — presenting all of it would be a monumental task. While Lake Tahoe is unique, the forces and processes that shape it are the same as 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 the knowledge gained 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 take into account a host of other considerations.

This annual report is intended to inform non-scientists about the variables 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 and those that are observed over decades.

Important parts of this report are updates on research 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 new insights gained through this research will help keep Lake Tahoe at the cutting edge of science in the 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 sampling commenced. I would, however, like to acknowledge (in alphabetical order) the contributions to this year's report by Brant Allen, Karen Atkins, Kian Bagheri, Carmen Bedke, Brandon Berry, Fabian Bombardelli, Mike Bruno, Tom Burt, Luciana Cardoso, Yuan Cheng, Bob Coats, Troy Corliss, Alicia Cortés, Cole Dickson, Stephen Drake, MJ Farruggia, Alex Forrest, Nick Framsted, Susan Frankel, Drew Fredrichs, Baylee Goodwin, Anne Graham, Scott Hackley, Tina Hammell, Simon Hook, Camille Jensen, Yufang Jin, Melissa Kibbee, Kenneth Larrieu, Jack Lewis, Anne Liston, Kevin Livingston, Patricia Maloney, Elisa Marini, Elise Matera, Jasmin McInerney, Antonina Myshyakova, Aaron Ninokawa, Holly Oldroyd, Anne Nolin, Kanarat Pinkanjananavee (Job), Justin Ries, Gerardo Rivera, Steve Sadro, Goloka Sahoo, Heather Segale, Katie Senft, Steven Sesma, Samantha Sharp, Roland Shaw, Zack Silber-Coats, David Smith, Sheri Smith, Adrianne Smits, Micah Swann, Lidia Tanaka, Ruth Thirkill, Raph Townsend, Alison Toy, Sean Trommer, Sergio Valbuena, Aaron Vanderpool, Lindsay Vaughan, Shohei Watanabe, and Andy Wong 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 California Tahoe Conservancy, Lahontan Regional Water Quality Control Board, Tahoe Regional Planning Agency, U.S. Geological Survey, and UC Davis.

Sponsors for current projects include the following: California Department of Fish and Wildlife, California Tahoe Conservancy, Incline Village General Improvement District, Nevada Department of Tourism and Cultural Affairs, Nevada Division of Environmental Protection, Nevada Division of State Lands, Parasol Tahoe Community Foundation, Tahoe Fund, and Tahoe Truckee Community Foundation.

Our monitoring is frequently done in collaboration with other research institutions and agencies. In particular, we would like to acknowledge the California Conservation Corp, 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 (USGS), the University of Miami at Ohio, Universidad Austral de Chile, 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, League to Save Lake Tahoe, Parasol Tahoe Comunity Foundation, Tahoe Fund, Tahoe Lakefront Owners' Association, Tahoe Regional Planning Agency, Tahoe Water Suppliers Association, and True Point Solutions. We sincerely thank these organizations for their dedication in supporting science to save the lake.

Sincerely,

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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 essential for decision-making by elected officials and public agencies tasked with restoring and managing the Tahoe ecosystem. 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; 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.

This annual *Tahoe: State of the Lake Report 2021* presents data from 2020 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 future consequences of climate change on the physical environment at Lake Tahoe; the accelerating rate of ecological change in the nearshore, made all the more clear through the use of new approaches and advanced sensing and analysis tools; the emerging and growing prevalence of microplastic pollution in both the watershed and the lake; the impacts of smoke from distant wildfires on Lake Tahoe; the varied impacts of extreme heat and temperature stress on forest health; and finally an introduction to some of the work being done by graduate students and researchers affiliated with TERC.

The future climate change impacts for the Lake Tahoe Basin are substantial. While the projected air temperature increases of 8 °F and the 50 percent reduction of snow by the latter part of the century seem dramatic, what may be more important are the changes that arise on account of this increasing temperature. For example, drought intensity due to both the warming and loss of soil moisture place the Tahoe forests at far higher risk of mortality, insect attack, and wildfire than they are presently. The loss of snow and its replacement by rain will increase peak stream flows by 2–3

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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 2021 report, water year data are from October 1, 2019 throught September 30, 2020. Calendar year data are from January 1, 2020 through December 31, 2020.

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times their current peaks, placing infrastructure at heightened risk. The rapidly rising lake levels during such events has the potential to exceed the capacity of the dam at the outlet and is likely to result in uncontrolled releases downstream. Lake Tahoe itself will be increasingly prone to stagnation during ever longer, warmer summers with the potential for a loss of oxygen at depth.

The nearshore regions of the lake, where millions of people recreate every year, are also at a growing risk. The largest threat here is the increasing presence of filamentous algae (metaphyton) that wash up on the beaches and decompose. The metaphyton grow, in part, due to the concentration of lake nutrients by the invasive Asian clam, which has been present in Lake Tahoe since 2008. Warmer water and higher nutrient loads expected with future climate change will further exacerbate this growth. Microplastic pollution is also an increasing issue, with much of it being introduced at the shoreline.

Wildfires are an increasing presence, even when they are not burning within the basin. Fine particles which reduce visibility and cause the air quality to reach dangerous levels impact public health and the lake in many ways. The reduction in sunlight during these events changes algal growth and heat transfer within the lake. More importantly, the large reduction in UV radiation is changing grazing patterns by zooplankton within the lake. The impacts of this change are currently being explored through ecological modeling of the lake. Other impacts from wildfires, such as the addition of particles and nutrients to the lake are also the subject of ongoing research.

Meteorologically, the long-term trends that have been prevalent do not change 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 in a given year can be far more variable, and 2020 was a relatively warm year. The annual average maximum temperature was 58.2 °F, an increase of 3.2 °F from 2019. The 2020 annual average minimum was 32.4 °F, which was 0.9 °F warmer than the previous year. At 20.1 inches, 2020 precipitation was below the long-term average measured at Tahoe City. The low values of 2020 came after just four years of average or above average precipitation. Snow represented 45.1 percent of the 2020 total precipitation.

The water level in Lake Tahoe varies throughout the year due to inflows, outflows, precipitation, and evaporation. In 2020, on account of the dry winter, the annual rise in lake level was very muted. From January through December 2020, overall lake level fell 1.9 feet. Based on historical water level data, it is likely that

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Lake Tahoe will fall below its natural rim in October 2021.

Despite year-to-year variability, the annual average surface water temperatures show an increasing trend. The average temperature in 1968 was 50.4 °F. For 2020, the average surface water temperature was 52.8 °F, warmer than in 2019. The overall rate of warming of the lake surface is 0.38 °F per decade. 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 6, 2020, Lake Tahoe's maximum mixing depth was observed to be 476 feet (145 m). This relatively shallow mixing likely contributed to the warmer surface temperatures experienced during winter, and the low winter clarity.

The stability of the lake is an important concept that expresses its resistance to vertical mixing and determines whether it is stratified. High stability can mean that oxygen is not transferred to deep portions of the lake, that pollutant bearing inflows enter the lake closer to the surface, and that the types and vertical distribution of phytoplankton changes. In 2020, the stability index was the third highest ever recorded. The length of time that Lake Tahoe is stratified has been increasing each year, another consequence of climate change. Since 1968, the stratification season length has, on average, increased by one month, effectively increasing the length of summer and decreasing the length of winter. In 2020, the length of the stratified season was 200 days.

The reduction of nutrient and fine particle loads to the lake is a fundamental part of the restoration efforts at Lake Tahoe, driven largely by the Total Maximum Daily Load (TMDL) program. The stream-borne nitrogen and phosphorus loads from the Upper Truckee River were generally lower in 2020, in line with the below average precipitation for the year. In-lake nitrate and total hydrolyzable phosphorus concentrations increased slightly, a result of the absence of deep mixing in 2020. The concentration of fine particles in the surface of the lake has been elevated since the record inflows of 2017. The reasons for the persistence of these particles are an area of current research.

Biologically, the primary productivity of the lake has increased dramatically since 1959. By contrast, the biomass (concentration) of algae as measured by chlorophyll concentration in the lake has remained relatively steady. For the period of 1984–2020, the average annual chlorophyll-*a* concentration in Lake Tahoe was 0.70 micrograms per liter. Most of the chlorophyll is concentrated in a band at a depth of approximately 150–200 feet, known as the "deep chlorophyll maximum." The peak in the chlorophyll

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occurred relatively late in the summer of 2020. Diatoms were the most common algal group (60 percent of the cells) in terms of the abundance of individual cells. Of these, *Synedra* formed the largest percentage of the biomass, accounting for over 80 percent of the diatoms during spring, summer, and fall. Although *Cyclotella* was a relatively low fraction of the percentage of the biovolume of diatoms in 2020, it was the second most dominant species in June and July and still had a large impact on clarity due to its tiny size. The attached algae (periphyton) on the rocks around the lake were near average values in 2020, based on a synoptic survey of 53 observations. As usual, the California side of the lake continued to display higher concentrations of periphyton.

In 2020, the annual average Secchi depth was 63.0 feet (19.2 m), almost unchanged from the previous year and reflective of the near-constant values that have been attained over the last 20 years. The highest individual clarity value recorded in 2020 was 81.2 feet (24.8 m) on February 12. The lack of complete vertical mixing of the lake in 2020 is the main reason for this low maximum clarity value. The poorest clarity reading was 50.8 feet (15.5 m) on May 15. While the average annual clarity is now better than the preceding decades, it is still short of the clarity restoration target of 97.4 feet (29.7 m). The winter (December–March) clarity value of 64.0 feet was the lowest winter clarity on record and was 17 feet lower than the previous year. Winter precipitation was below the long-term average and such conditions would typically be expected to yield higher clarity values. The reasons for the low winter values are still not fully understood. Summer (June–September) clarity was 59.1 feet (18.0 m), a loss of over 6 feet from the previous year. This is significantly better the lowest summer value of 50.5 feet in 2008.

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: 39 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
- It would take a single, pin-head sized Daphnia one week to clear a gallon of Tahoe water of all fine particles
- On a bad day there currently are over 60 billion *Mysis* shrimp in Lake Tahoe
- On a good day in the future, there will be less than 15 billion *Mysis* shrimp, allowing the *Daphnia* population to rebound and help restore ecological health
- 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, California, flows through Truckee and Reno, and terminates in Pyramid Lake, Nevada
- Number of monitoring TERC maintains in the Tahoe Basin: 224
- 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)

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.Since 1968, UC Davis has conducted continuous scientific monitoring of Lake Tahoe, creating the foundation on which to base restoration and stewardship efforts.

TERC's activities are based at 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 except during pandemics.

In Tahoe City, California, we operate a field station (housed in a fully renovated, former state fish hatchery) and the Eriksson Education Center. Tahoe City is also the mooring site for our research vessels, the R/V John LeConte and the Bob Richards. The R/V Ted Frantz operates out of Clear Lake, California and the R/V Tom is based in Davis, California.

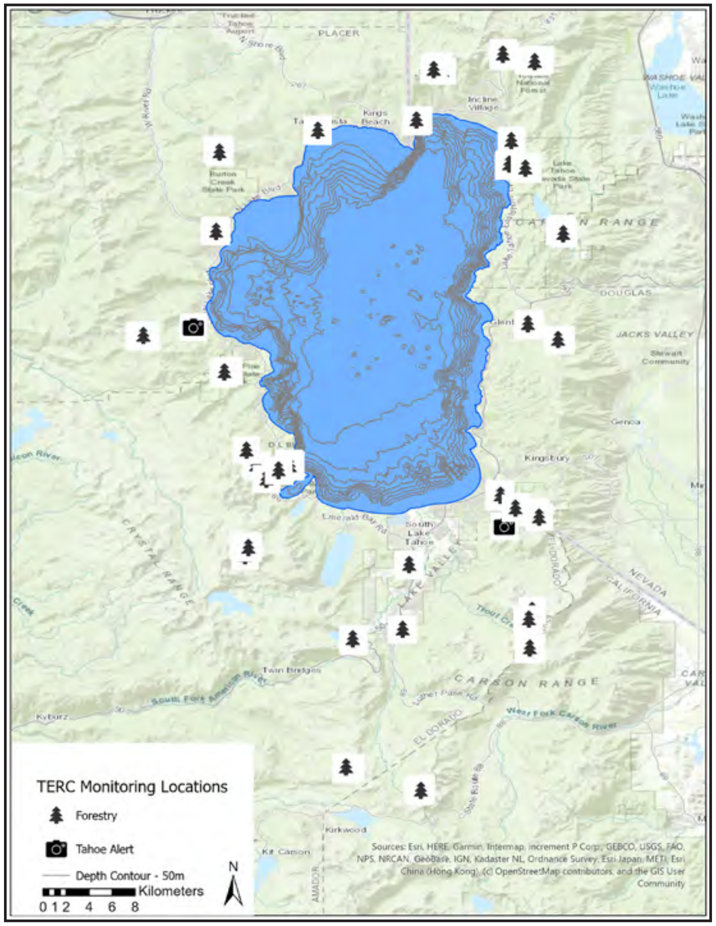
Additional laboratories and offices are located on the UC Davis campus at the Center for Watershed Sciences and in Wickson Hall.

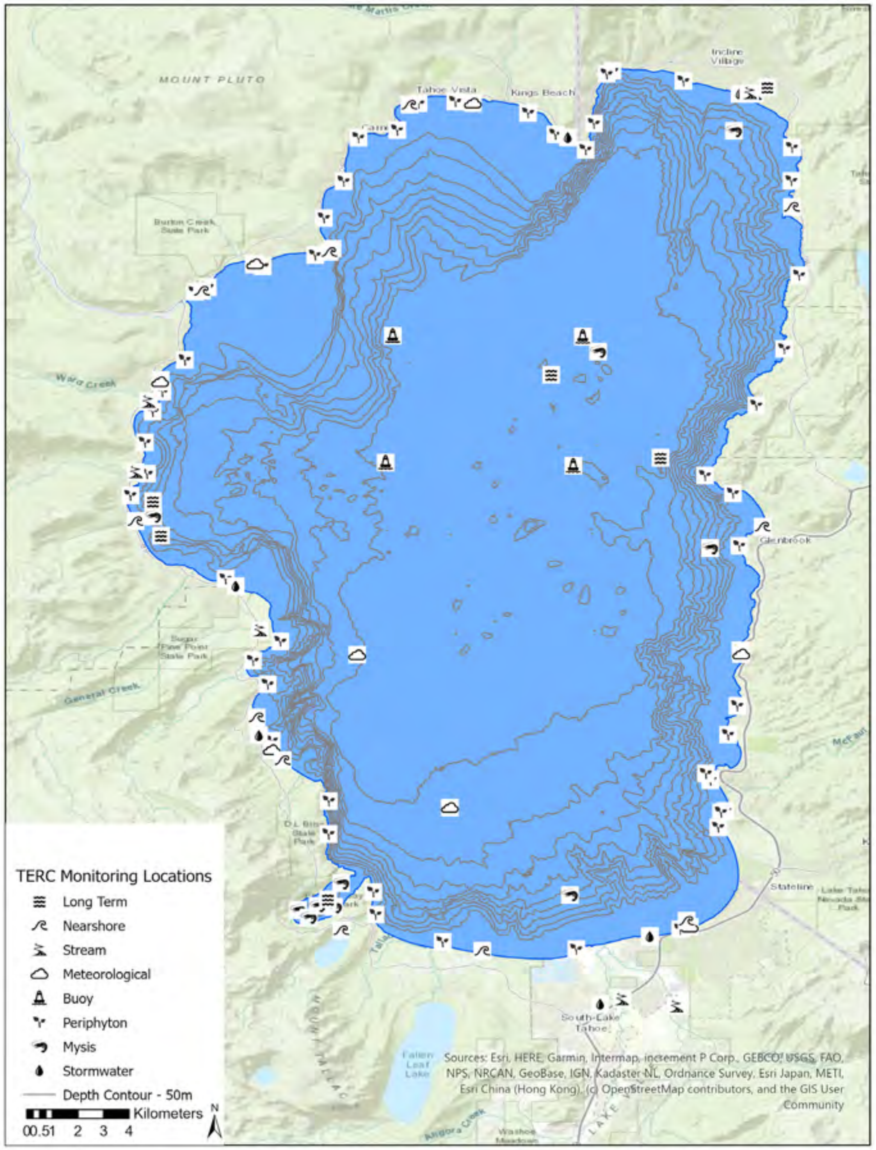
At locations throughout the basin, we have sensors continuously reporting on the health and well-being of the lake and its environs, all contributing to making Lake Tahoe the smartest lake in the world.

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
2021

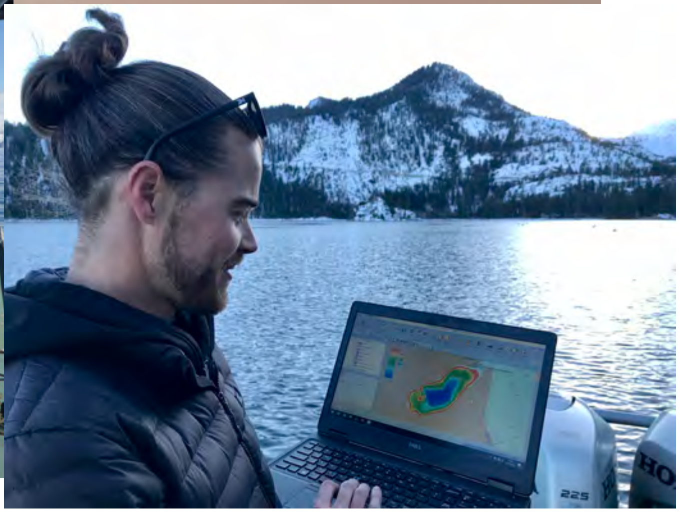
CURRENT DIRECTIONS

UC DAVIS
Tahoe Environmental Research Center

Current Research Synthesis

Since 1959, UC Davis has been engaged in monitoring the status and health of Lake Tahoe and its watershed. These monitoring data are an invaluable resource for assessing the impact of changes that have occurred due to anthropogenic factors and to natural variability.

Additionally, we engage in focused and often shorter-term research that seek to answer specific questions or to gain understanding of processes and events. This research relies on the long-term monitoring data for context, but it is distinctly separate. The results of this research — conducted by TERC students, postdoctoral researchers, faculty, and staff, often in collaboration with other institutions, companies and agencies — has made Lake Tahoe the smartest lake in the world, and arguably the most influential.

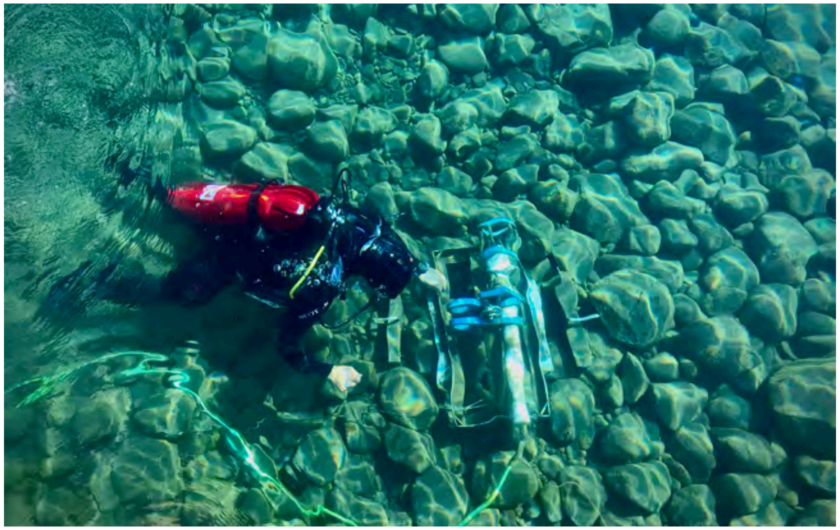


Photos: B. Allen, S. Hackley, and A. Toy

Current Research Synthesis, continued

The current research summarized this year covers a broad range of areas, and much of it is the result of work conducted over the last several years. Some of the research is now complete and the results are just starting to have an influence with management and decision-making. Much of it is still underway or in its initial stages. The topics we are focusing on this year are:

- Climate Change and Some of its Future Consequences at Lake Tahoe: A brief overview of a recently completed modeling study of how climate change may impact the meteorology, hydrology, and processes within Lake Tahoe.
- Lake Tahoe's Nearshore Region: A great many factors are at play in the nearshore of Lake Tahoe. The results from a number of completed and ongoing projects are introduced here. These include the historical changes in attached algae (periphyton), new approaches to understanding periphyton growth under future climate conditions, the emerging concerns of filamentous algae (metaphyton) washing up on beaches, and dramatic changes to water color due to spring snowmelt.
- Plastics pollution at Lake Tahoe and elsewhere is finally gaining the attention it deserves. Here we describe a particularly egregious example of how easily this can occur and the grassroots solutions that are being pursued.



Photos: A. Toy and B. Allen

Current Research Synthesis, continued

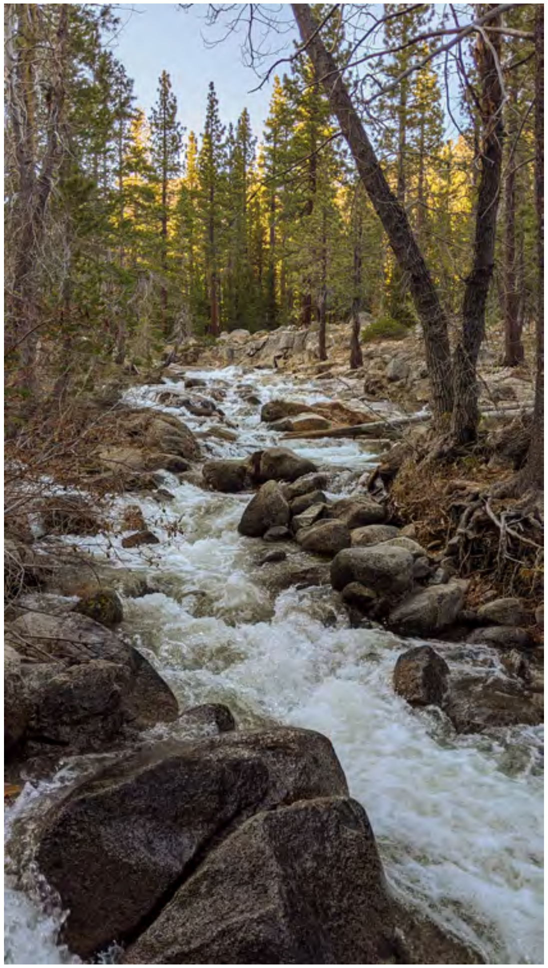
• The Impacts of Wildfires on Lake Tahoe: Though there has not been a major wildfire in the Tahoe Basin since the Angora Fire of 2007, the basin is increasingly subject to transported smoke from the rapidly increasing wildfires throughout the west. 2020 was a particularly bad year, and here we consider just two of the impacts that smoke has — the measurable reductions of sunshine (solar radiation) that occurs for many days on end and the reductions of harmful UV radiation. Other impacts, such as the addition of nutrients and particulates to the water itself are part of an ongoing NSF project.
• The high temperatures and drying conditions exacerbated by climate change are having an impact on our forests. In the short-term, there are a range of strategies that TERC is exploring. These include harvesting native seeds that have demonstrated resilience to drought and insect attack, and using these genetically diverse seeds for reforestation in partnership with local and statewide agencies.
• Finally, we present a quick overview of projects that some of our graduate students and researchers are undertaking. Some of these are on topics that may seem far removed from Lake Tahoe, and others are taking place at locations far from the Sierra Nevada. They all, however, impact our understanding of what happens at Lake Tahoe and prepare us for the dramatically different conditions that we will face here in future decades.

Photos: L. Bronson and M. Swann

Climate Change and Some of its Future Consequences at Lake Tahoe

The signature of climate change is strong in most of the data collected at Lake Tahoe. This is seen, not just in the air temperatures and declining snow fraction, but also in the increasing stability exhibited by the lake as well as the alterations in stream hydrology. Both California and Nevada have recognized the shared urgency of addressing future climate change. To that end, both states now utilize the same set of four future climate prediction models and the same two sets of assumptions about future levels of carbon in the atmosphere known as Representative Concentration Pathways (RCPs). RCP 4.5 and RCP 8.5 are generally recognized globally as suitable planning estimates for lower and higher levels of atmospheric carbon emissions, although current emission rates may in fact exceed those assumed under even RCP 8.5.

With funding from the California Tahoe Conservancy (CTC) a team comprised of Sean Trommer, Goloka Sahoo, Robert Coats, Jack Lewis, Zack Silber-Coats, and Geoff Schladow have been evaluating the changes that Lake Tahoe and its watershed may exhibit, due to climate change, over the period of 2006 to 2100. The evaluation predicted climate model outputs to drive watershed and lake models, and some of the results of those models are presented below. A particular emphasis was placed on quantifying the extreme conditions that climate change is expected to exacerbate. The results here mainly reflect RCP 8.5 as it is more reflective of current carbon emission levels.



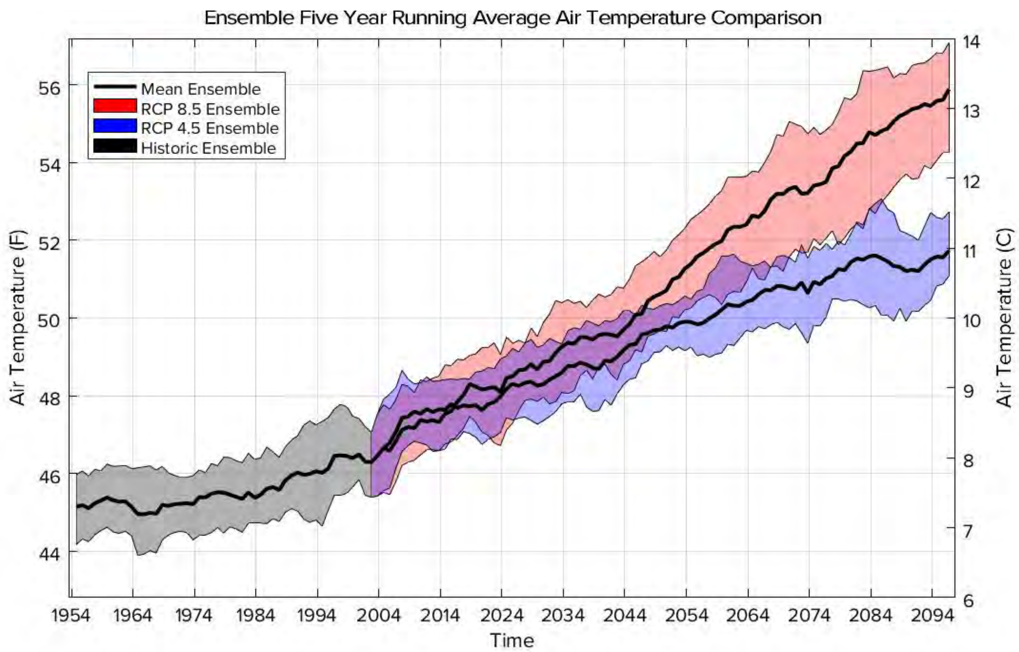
Maximum stream flows are expected to increase throughout the basin as a result of climate change. Photo: A. Toy

Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Air Temperatures

The four climate models are in strong agreement that daytime and nighttime (Tmax and Tmin) air temperatures will continue to increase. The trends for Tmax and Tmin under the RCP 8.5 scenario indicate an accelerating warming trend. From 2006 to 2100, the model ensemble mean indicates an increase of 9.5 °F (5.3 °C) for both Tmax and Tmin at lake level.

Note that all model results (the shaded areas) indicate predictions in the range of +/- 1.5 °F.

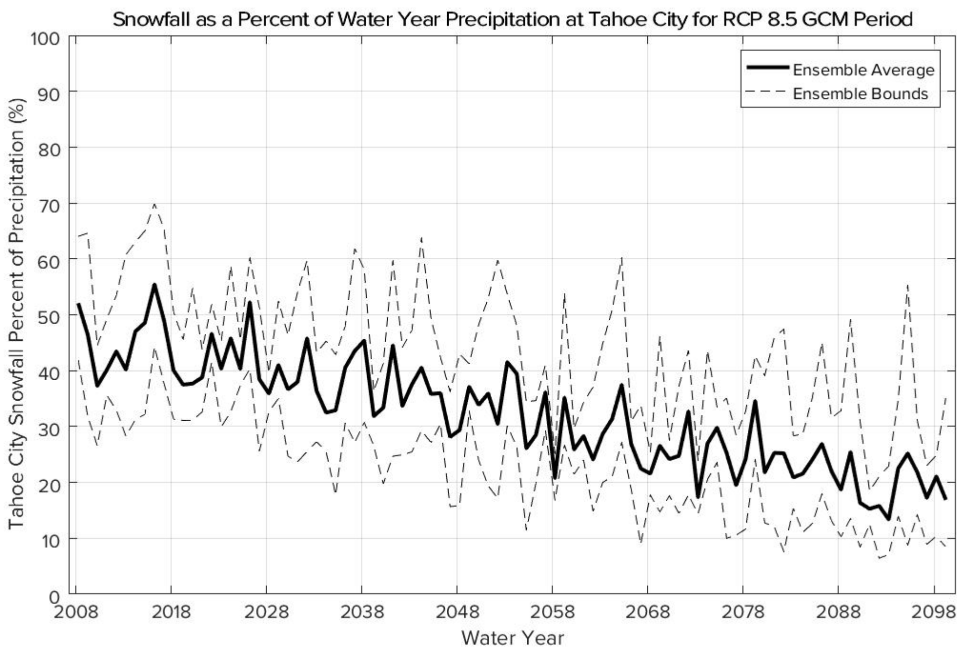


Ensemble five-year running average air temperature and range of variability for the historic, RCP 4.5, and RCP 8.5 scenarios at lake level. The ensemble average for each scenario is shown with a solid black line while the range for all scenarios is shown with a shaded region.

Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Percent of Precipitation Falling as Snow

The results for all model-scenario combinations indicated downward trends in the percent of precipitation falling as snow. Over the past monitoring record, the percent of precipitation falling as snow at Tahoe City has declined at a rate of 1.76 percent per decade. All models under RCP 8.5 predicted a shift at Tahoe City at double the historic trend. For the entire Basin, the average decline rates were only slightly lower than the rates at Tahoe City (at lake level). The ensemble bounds in the figure indicate both the potential magnitudes of extreme years (high and low snow) as well as the expected interannual variability.

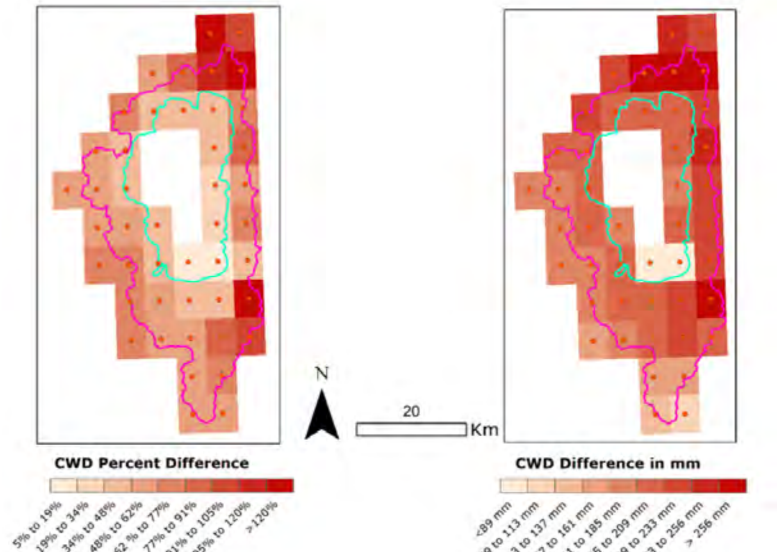


Ensemble average and range (bounds) of snow as a fraction of water year precipitation at Tahoe City for RCP 8.5.

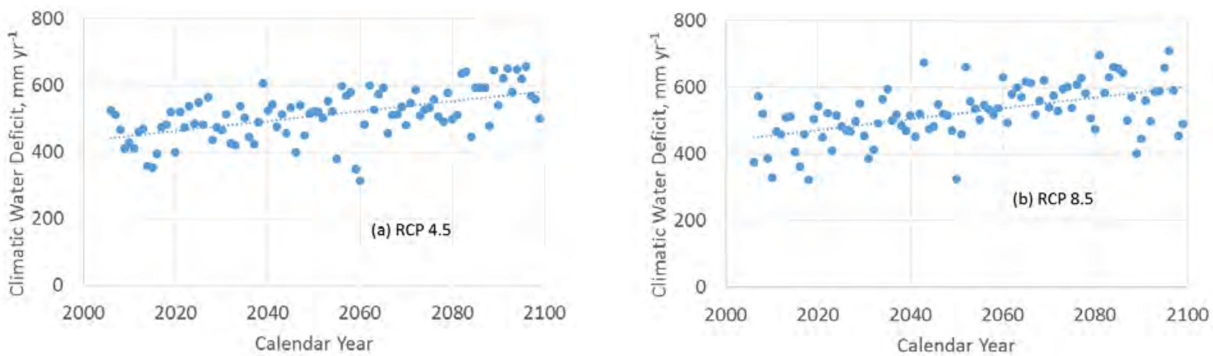
Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Drought Intensity

Drought conditions are expected to intensify in the coming decades. The Climatic Water Deficit (CWD) is the calculated annual evaporative demand that exceeds available water. It integrates climate, energy loading, drainage, and changes in soil moisture in a single variable, and is considered to represent the terrestrial ecological impacts of climate change. There is an upward annual projected CWD trend for both RCP 4.5 and RCP 8.5 for three of the four models (the outlier model also predicts much higher future precipitation which accounts for this result). Spatially, the increase in CWD is higher along the drier east side of the Basin, where soils are relatively poor and Available Water Capacity is low.



The modeled geospatial change in CWD from 1950–2005 to 2070-2099, for the average of the four models under RCP 8.5. On the left is the percent change and on the right is the absolute change in mm per year.



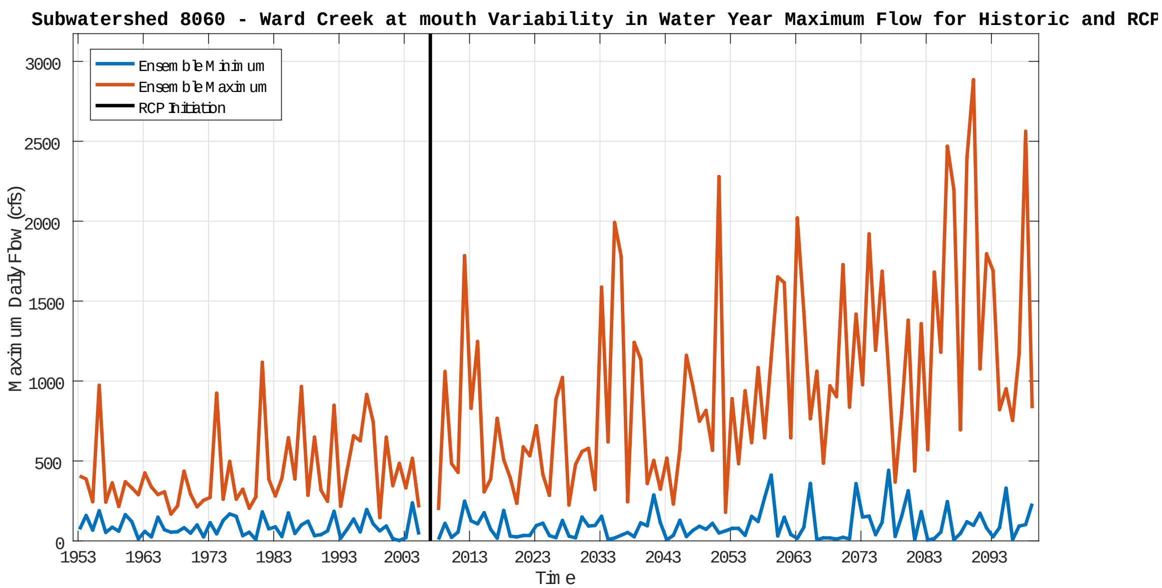
Annual Climatic Water Deficit, averaged across the Tahoe Basin and for all four General Circulation Models. The figure (left) is for RCP 4.5 and the figure (right) is for RCP 8.5.

Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Maximum Daily Stream Flow Rate

Largely on account of more precipitation falling as rain rather than snow and the loss of storage in the snowpack, maximum stream flows are expected to increase dramatically. Similarly, due to the overall drying conditions, the minimum flows are expected to decrease. As an example, the anticipated flow at the mouth of Ward Creek, CA, are shown.

The red line shows the annual maximum daily flow for the ensemble average for all four GCMs under RCP 8.5. The blue line shows the corresponding minimum annual flows. The main feature that emerges is the overall rise in maximum streamflow, with some years indicating flows in excess of 2500 cubic feet per second (cfs). Such flows would almost certainly result in flooding and infrastructure damage. It is important to bear in mind that the lines are the averages of all four models and are the average daily flows. Individual model results display even greater extremes and substantially higher instantaneous flowrates within a day.

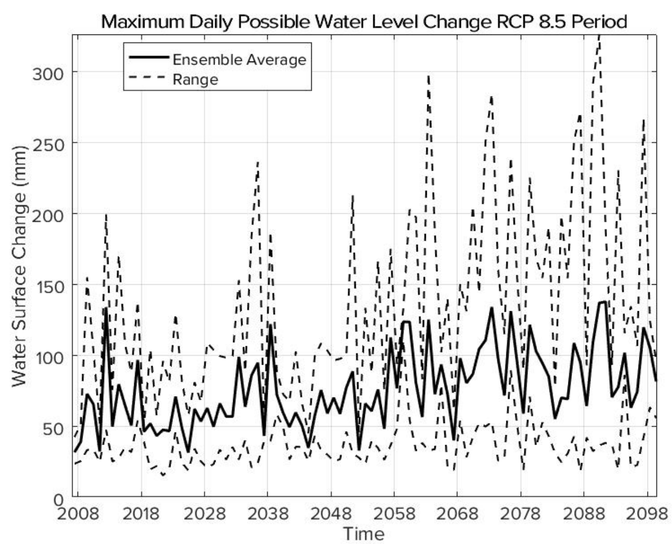


Variability in annual maximum daily flow rates between the four GCMs for Ward Creek under RCP 8.5. The vertical black line separates the modeling of the historical period (to the left) from the modeling based on future climate model projections that began in 2006.

Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Lake Level

It is not possible to predict the future water level of Lake Tahoe as it is very dependent on how releases from the dam at Tahoe City are managed in the future. However, based on the expected peak stream inflows for all streams, it is possible to estimate the potential lake levels in extreme future years. The figure below shows the result for the average of all four climate models under RCP 8.5 and the maximum and minimum values from the full set of models. The results suggest that while the future mean lake level rise is four inches per day, the extreme values of individual models should be the focus of management concerns. Each of the individual model results is based on the current state of knowledge of climate change and hydrology, and must be, at a minimum, considered plausible. Those extreme values are for water level rises as great as one foot (300 mm) per day. With only six feet separating the lake's natural rim and the top of the dam that holds back the water, the risks of overtopping of the dam at increasing frequencies in the future should be taken into consideration with greater urgency. Under those predicted rapid water level increase rates, the release rate of the dam would be insignificant in affecting the rise, and the capacity of the Truckee River unable to accommodate the ensuing release.

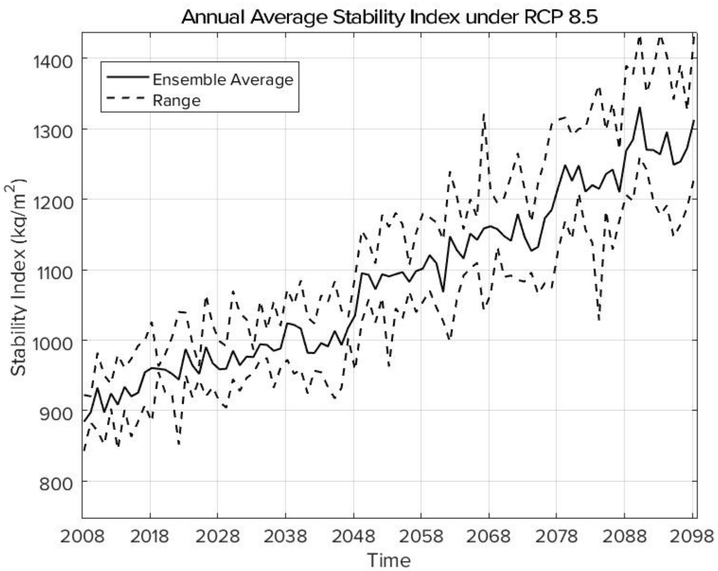


The largest single day water level rise each year under RCP 8.5. Results are shown as both the average value of all four models (solid line) and the maximum range of variability for the individual models (dashed lines).

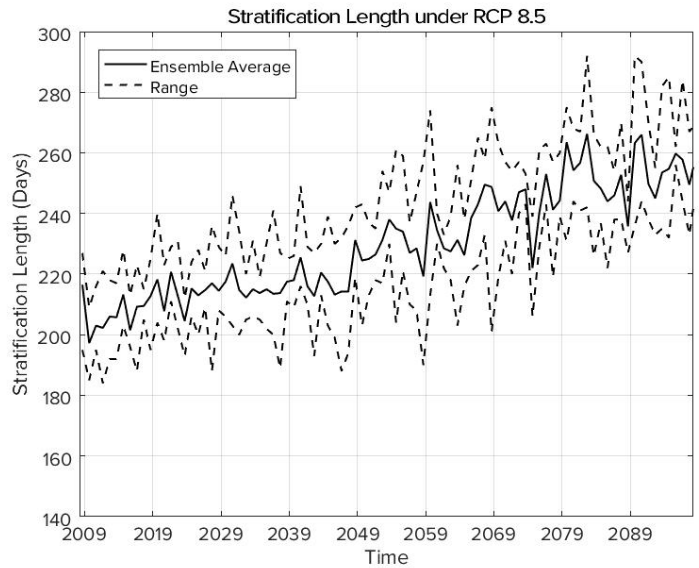
Climate Change and Some of its Future Consequences at Lake Tahoe, continued

Lake Stability

The hydrodynamic stability of Lake Tahoe (its resistance to vertical mixing) has been quantified with the stability index (SI). Under RCP 8.5, the average stability index increases at a rapid rate through the end of the century. While the duration of stratification for Lake Tahoe has increased by approximately 30 days in the last 50 years, the ensemble average length of stratification is anticipated to increase by an additional 50 days under RCP 8.5.



Mean annual average stability index average across all climate models for RCP 8.5 (solid line). Variability between the individual models is shown by the maximum and minimum value for each year (dashed lines).

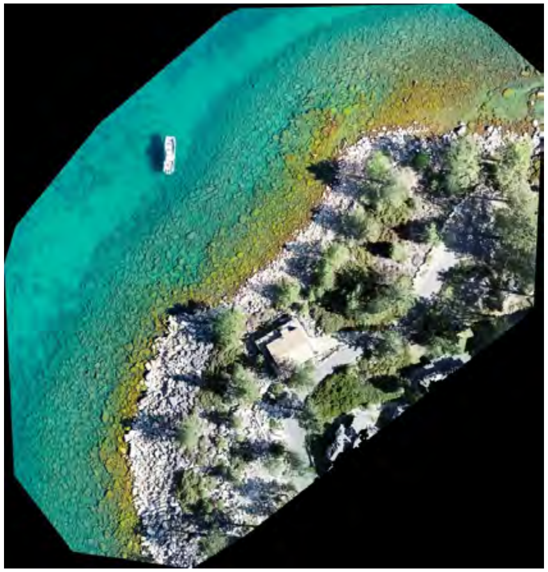


Mean length of stratification across all GCMs for RCP 8.5 (solid line). Variability between the individual models is shown by the maximum and minimum value for each year (dashed lines).

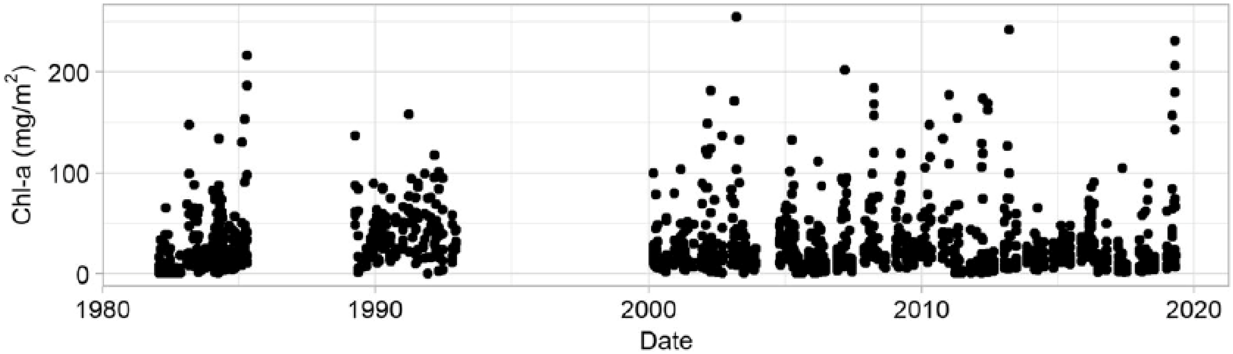
Lake Tahoe's Changing Nearshore Region

The nearshore of a lake is the most complex region. Streams, urban drains, and groundwater enter the lake in the nearshore zone. Most recreation occurs near the shoreline, making it more prone to the introduction of pathogens, non-native species, and other contaminants such as plastics. This complexity exhibits itself through the variations in the rates of change of water quality indicators. Such changes can vary across time scales from decades, seasons, and even to hours and days, making monitoring and research all the more challenging.

In the pages that follow, we summarize some of the research that is being conducted on Lake Tahoe's nearshore and present some of the preliminary findings.



A fringing band of brown, stalked diatoms are attached to rocks at Zephyr Point, NV. Orthomosaic: B. Berry



Periphyton chlorophyll a measured at 20 inches below the surface from all sampling stations showing the long-term stability of periphyton biomass. From: K. Atkins

Lake Tahoe's Changing Nearshore Region, continued

Periphyton – The Historical Record

Periphyton, or the brownish algae attached to the rocks around Lake Tahoe's nearshore, is receiving increasing attention due to anecdotal reports of increasing bloom frequency and severity. Periphyton blooms may be increasing globally in response to climate warming and changes in nutrient inputs to lakes, a pattern that is potentially concerning since they can decrease both water quality and the aesthetic value of nearshore areas.

Recent PhD graduate Karen Atkins has published a research article that summarized UC Davis' data on periphyton on rocks collected over the last 40 years from around the entire shoreline. While there were large year-to-year variations, for the entire period of monitoring, the periphyton biomass has not increased around Tahoe, a result that has surprised many. The most likely reason is that a large increase occurred in the 1960s and 1970s prior to the commencement of monitoring. This is consistent with the memories of many long-time residents, who recall "gin clear" boulders on the shoreline during the 1950s and 1960s.

Despite this long-term consistency in the biomass of periphyton, Lake Tahoe may still be changing. For example, in the last two years, TERC researchers have made new observations. Mysterious underwater "rings" have appeared on rocks at several locations around the lake. This new phenomenon may be an area for future UC Davis research.

Stalked diatoms attached to shoreline rocks. Photo: B. Allen

"Rings" have been observed near the shoreline at many sites around Lake Tahoe. Photo: B. Allen

Lake Tahoe's Changing Nearshore Region, continued

Periphyton – Current Research on Factors Regulating Growth

Measurements and modeling of the impact of climate change suggest that the nearshore environment will be changing at an ever-increasing rate in future decades. The expected warming water temperatures and earlier influx of high stream nutrient concentrations will definitely drive changes in the lake biota.

In order to better understand the impact of these factors on periphyton blooms in Lake Tahoe, PhD student Nick Framsted is examining the role of temperature, nutrients, and their interactive effects on periphyton metabolic rates. By measuring changes in dissolved oxygen in sealed incubation chambers containing rocks collected from the nearshore, he is quantifying the rates of gross primary production (GPP), ecosystem respiration (ER), and net ecosystem production (NEP). These metabolic rates provide information about periphyton growth and growth efficiency.

Laboratory setup for periphyton metabolism experiments. Photo: N. Framsted

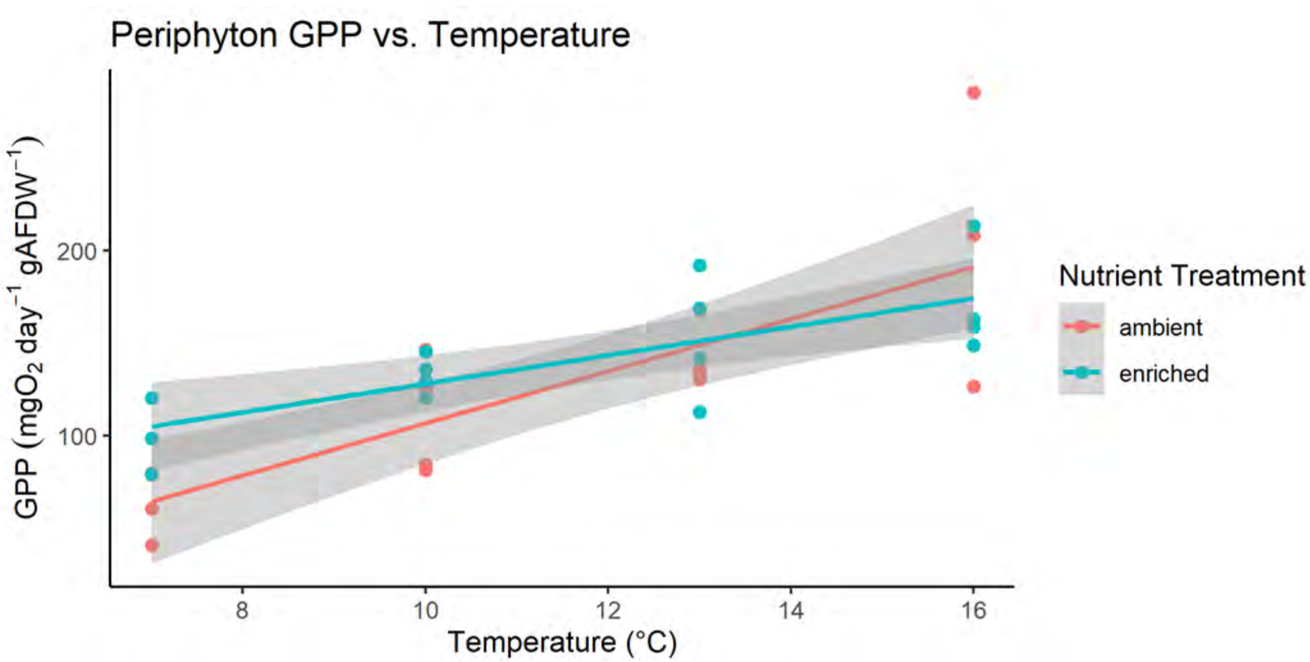
Lake Tahoe's Changing Nearshore Region, continued

Periphyton – Current Research on Factors Regulating Growth

Each season, a set of samples are analyzed at the seasonal mean water temperature and at a series of warmer temperatures going up to 10 °C above the ambient to simulate warming from climate change. Nutrient concentrations are also varied between current values (ambient) and augmented levels (enriched), to simulate nutrient loading associated with increased runoff or other anthropogenic sources.

Preliminary data from the 20/21 winter indicate that temperature significantly increases metabolic rates in periphyton. While nutrients appear to stimulate increased GPP, the relative effect of temperature is larger.

More experiments will be conducted to test for interactive effects and to determine if this trend varies across seasons. By providing a mechanistic understanding of periphyton growth responses, these results will allow us to predict future algal growth rates under climate change scenarios and help develop management strategies for Lake Tahoe.



Preliminary data showing the impact of temperature increases on gross primary productivity. From: N. Framsted

Lake Tahoe's Changing Nearshore Region, continued

Metaphyton

In the last 15 years, an increasing length of Lake Tahoe's shoreline has been impacted by the growth of excessive amounts of metaphyton. The south and southwest shores are the most heavily impacted. Unlike attached periphyton, metaphyton are unattached, green filamentous patches of algae that accumulate along the bottom of the lake close to the shoreline. Research show that metaphyton is often collocated with non-native Asian clams, and its growth is fueled by the highly-concentrated nutrients in the excretions of the clams. Depending on lake depth and the local currents, metaphyton have the potential to be washed up on shore where they form deep beds of decomposing organic matter. The public concern about increasing periphyton degrading the nearshore may actually be the result of the increasing quantities of metaphyton on the beaches.

By using a combination of satellite, helicopter and drone imagery, as well as in situ sampling to ground-truth species abundance, TERC researchers and collaborators are able to quantify the changing areal distribution of metaphyton as well as the causes of its growing impact.

Sampling patches of metaphyton on Lake Tahoe's south shore. Note the clam shells on the sandy bottom. Photo: B. Allen

Regan Beach in 2014, a year of low water level, when washed up metaphyton were common. Photo: S. Hackley

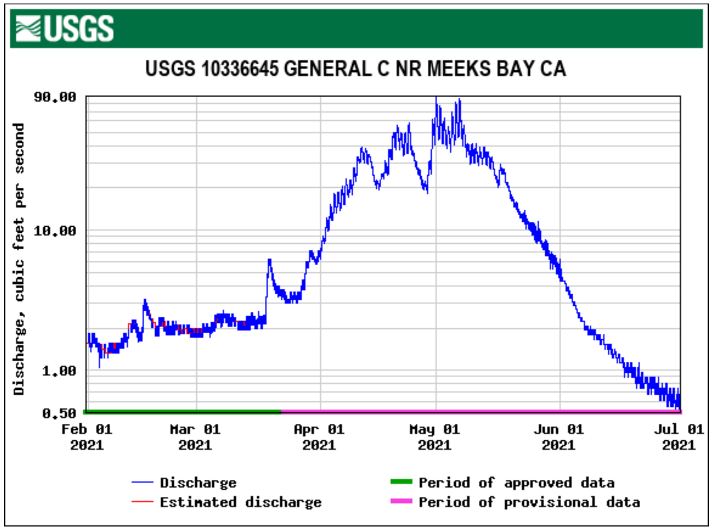
From top left, clockwise: Andy Wong launching a multispectral drone from R/V Bob Richards; cameras mounted on a helicopter; Brandon Berry completing a metaphyton drone survey: an orthomosaic image produced from the individual helicopter images.

Lake Tahoe's Changing Nearshore Region, continued

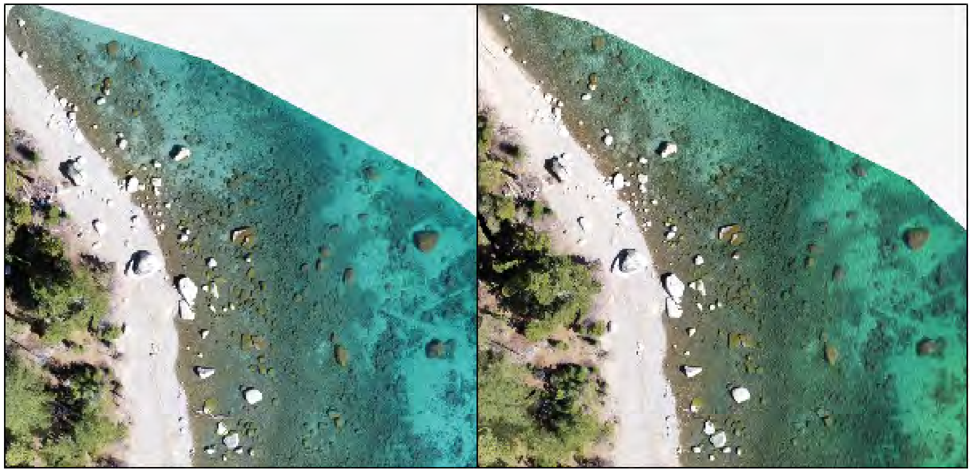
Nearshore Water Quality

The water quality in the nearshore is prone to very rapid changes. TERC's Nearshore Network of real-time sensors has shown that most afternoons, when winds blow from the southwest, wave breaking on the east shore elevates turbidity levels well above ambient standards. This highlights the challenges that regulators face in setting meaningful standards.

Another source of nearshore water quality change is from streams. General Creek, on the west shore of Lake Tahoe, is one of the most pristine streams in the basin with most of its watershed being part of Sugar Pine Point State Park and Desolation Wilderness. The creek discharges into the lake at Sugar Pine Point State Park. The two images below, taken 16 days apart in April 2021, show how spring runoff from General Creek can cause the water color to change from blue to green. The image on the left from April 6 occurred when General Creek's discharge was 16.2 cubic feet per second (cfs), while the image on the right from April 22 was for a discharge of 41.2 cfs. The peak discharge in 2021 was 64.2 cfs on May 6. The addition of dissolved organic material plus nutrients that stimulate algal growth were sufficient to change the nearshore waters from blue to green.



Runoff hydrograph for General Creek from the USGS NWIS database.



Orthomosaic images of the nearshore at Sugar Pine Point on April 6, 2021 (left) and April 22, 2021 (right). Photo: B. Berry

Tahoe's Plastic Problem

"There is a great future in plastics. Think about it. Will you think about it?". If you are old enough to remember the movie *The Graduate* from 1967, then you will no doubt recall those lines. The plastics of the future are now the plastics of the present, and it is not all great. Take a recent example from Moon Dunes Beach in Tahoe Vista, when thousands of tiny polystyrene pellets littered the shoreline. The source — a Big Joe Pool Petz Noodle Butterfly, sold across the country at multiple large box stores.

Discovered by TERC staffer Alison Toy, her social media posts quickly alerted over 50,000 people and by the next morning, thanks to the help of the community, most of the pellets were quickly cleaned up. Most, but not all, the others were carried away by the currents where they have either been ingested by fish and birds or are breaking down into even tinier pieces to become microplastic pollution.

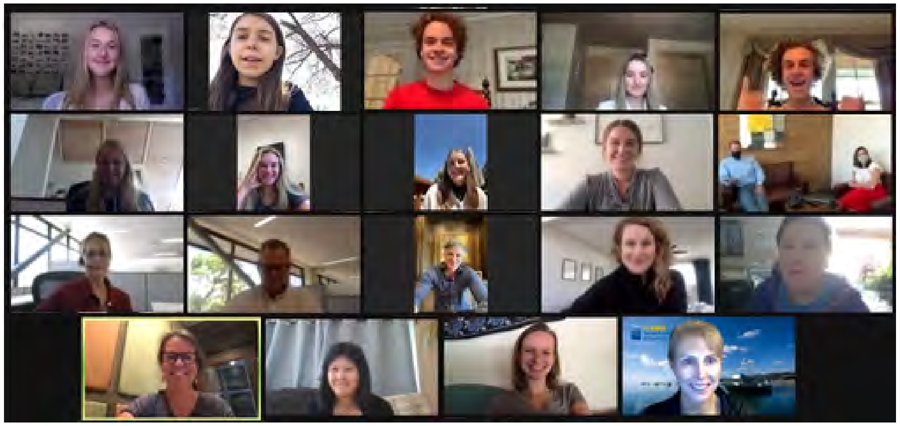
A Big Joe Pool Toy found punctured on Moon Dunes Beach. Photo: A. Toy

Thousands of polystyrene pellets from the Big Joe Pool Toy litter the shoreline. Photo: A. Toy

Tahoe's Plastic Problem, continued

Clearly, there are a few irresponsible people who simply leave their mess behind, be it a Big Joe or the trash from their day at the lake. But it is also irresponsible, with today's awareness, for businesses such as Costco, Target, and Walmart to sell items like these in the first place. It does not take much imagination to see how destructive these pellets could be in any environment.

How can we start to change this culture? TERC and other nonprofit partners have worked with local high school students to foster the transition of knowledge about plastic contamination to action. The students surveyed local stores and assessed plastic problems that businesses could readily address. After the students presented their findings to the Raley's grocery stores executive team, Raley's agreed to create lasting, sustainable change at their stores by eliminating plastic straws and plastic silverware by switching to paper and reusable options. A range of additional actions are also being considered. There is still a long way to go, but with increased awareness and the engagement of the next generation we are making real progress in the Tahoe Basin.



Envirolution Club Members Jade Bullock, Sophia Phillips, Ben Anderson, Lily Murnane, Evan Anderson, Kili Lehmkuhl, Alani Powell, and Amelia Swanson presented their plastic assessment via Zoom to Raley's Executives Sarah England, Mark Koppang, Chelsea Minor, Laura Croff, Kevin Konkel, Keith Knopf, and Megan Riggs; all under the guidance of Madonna Dunbar (TWSA); Ashley Phillips (SWEP); and TERC Educators Alison Toy, Elise Matera, and Heather Segale. Photo: E. Matera

The Impacts of Wildfires on Lake Tahoe

While 2020 will always be remembered as the year of COVID, it was also the year of incredible wildfires impacting California and the western United States. In California there were almost 10,000 "incidents" including five of the six largest wildfires ever recorded in California. A total of over 4.1 million acres burned, double the previous annual record.

While there were no significant fires within the Tahoe basin in 2020, the impacts of the fires in the western states were experienced by all in the Basin. For much of August and September, visibility was poor and air quality ranged from unhealthy to hazardous.

Despite being many miles away, wildfires continued to smother the Tahoe-Truckee area including Martis Valley off of highway 267. Photo: N. McMahon

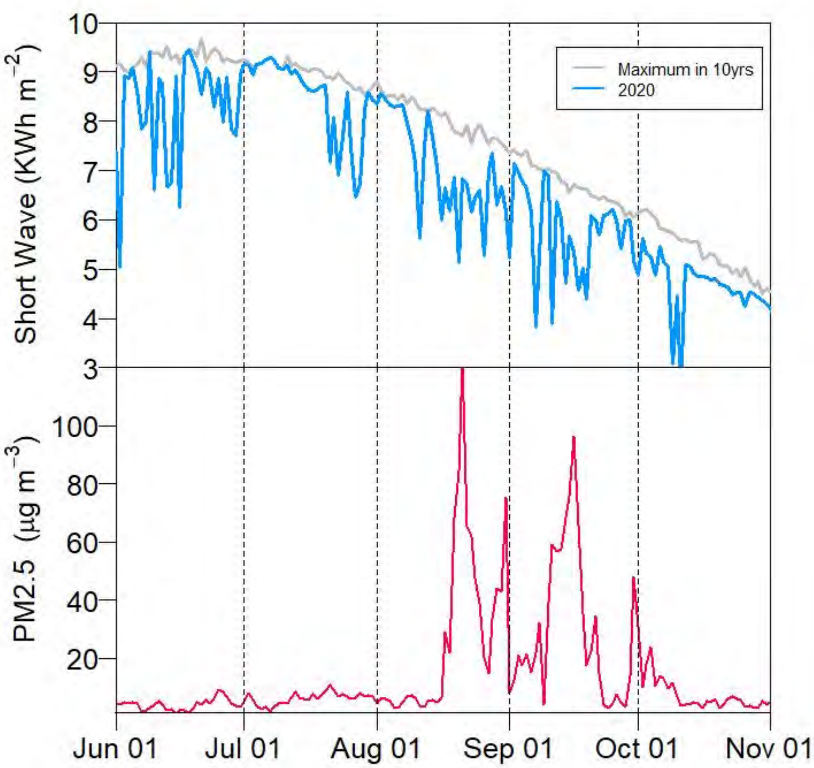
TERC researchers diligently continue data collection despite less than desirable air conditions. Photo: K. Senft

The Impacts of Wildfires on Lake Tahoe, continued

The blue line in the figure shows the daily average shortwave (solar) radiation based on 10-minute readings at TERC's long-term station at the US Coast Guard pier at Lake Forest in June through November 2020. The gray line is the maximum value of the daily average value shortwave radiation from the previous 10 years (2010–2019). Focusing on June and July, one can see that there are obvious "dropouts" in the 2020 values, relative to the long-term maximum values. These dropouts are normal and represent the impacts of cloudy days. Comparing any individual year with the long-term average would yield a similar looking plot, with low periods interspersed with returns to the long-term maximum.

The months of August and September are different. Here, the dropouts are larger and longer, and for almost the entire period the short-wave radiation is below the long-term average. On some days the radiation is reduced by 50%. This sustained reduction in solar radiation is the direct result of wildfire smoke generated hundreds of miles away.

The red graph shows the concentration of PM2.5 particles measured in Tahoe City by the California Air Resources Board. PM2.5 are inhalable fine particles with diameters of 2.5 micrometers and smaller, that have been linked to a number of health problems. The EPA's national standard for PM2.5 is 12 micrograms per cubic meter.



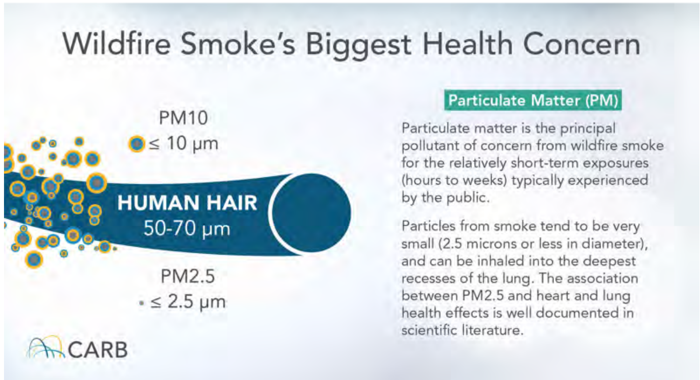
The top graph shows the measured daily solar radiation at Lake Tahoe (blue) compared with the maximum of the last 10 years. The bottom graph shows the measured PM2.5 from CARB station in Tahoe City, CA. Peaks show the impact of wildfire smoke from areas outside the Tahoe basin.

The Impacts of Wildfires on Lake Tahoe, continued

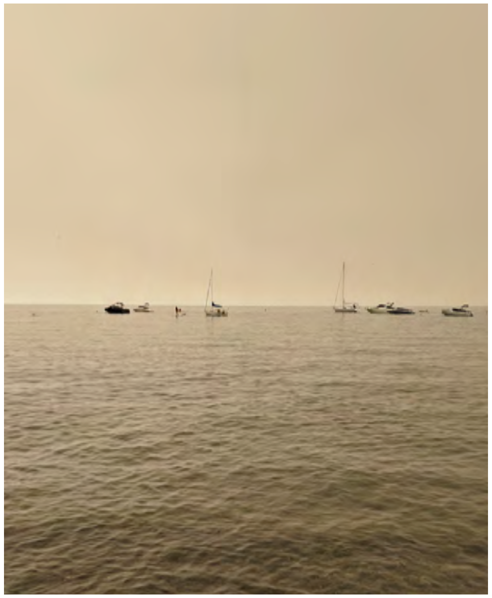
The data for the months of June and July have values below this standard, with some days even approaching zero. From August 13 through October 8, however, the data show the impacts of wildfire smoke. Hardly a day was below the standard, with most days PM2.5 concentrations exceeding 50 micrograms/per cubic meter.

What would the lake health impacts from wildfires be? There are two aspects to this. First there are impacts from the reduction of shortwave radiation and UV radiation described above, and second, there are the additions of smoke and ash constituents to the water.

Past research from the King Fire in Yosemite in 2014 has shown that there are impacts even without visible signs of ash falling on the lake. Wildfire smoke transported from far away reduced both solar radiation and UV radiation, just as they did in 2020. The research showed that a reduction in the UV radiation alone, by just 9% from one day to the next, resulted in a 14 ft. upward shift in the location of zooplankton in the lake. This changed the location at which grazing was taking place which could impact both the lake clarity as well as the overall foodweb. Additionally, UV reductions also decrease the potential for solar disinfection of waterborne parasites.

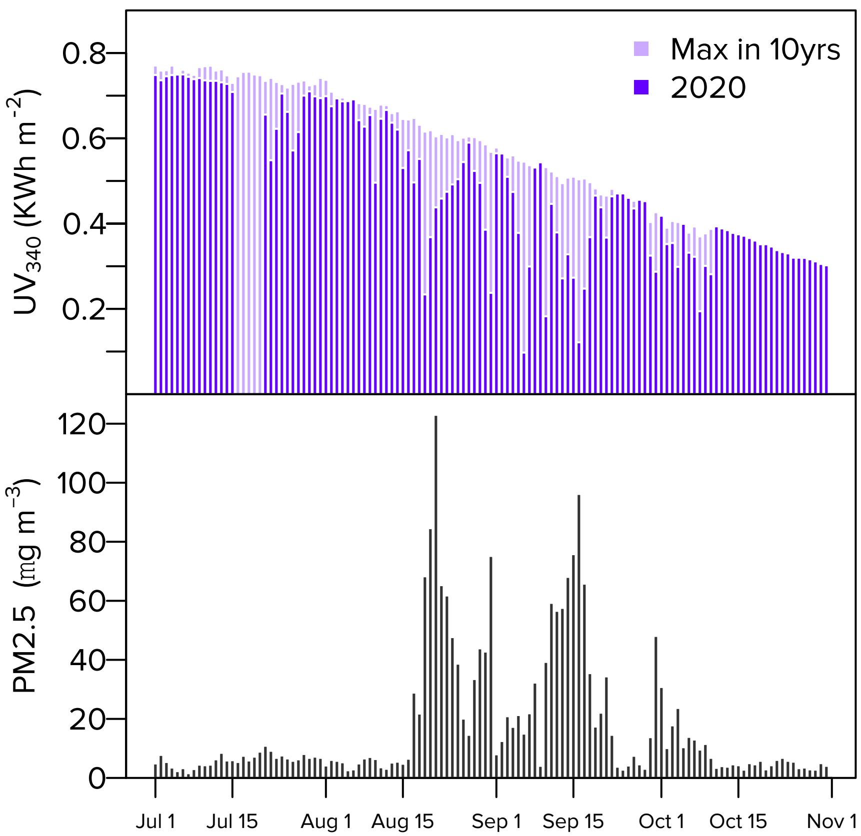


Source: https://ww2.arb.ca.gov/wildfire-smoke-health



While ash may not be visible, the very fine particulate matter in the air causes Tahoe's blue hues to take on new tones.
Photo: A. Toy

The Impacts of Wildfires on Lake Tahoe, continued



In 2020, the UV reductions are far greater than those recorded in 2014. The figure shows the maximum daily UV recorded in the previous 10 years, plotted alongside the 2020 daily UV. During July, August, and September, due to the high PM2.5 concentrations, daily UV was significantly depressed for over 10 days at a time with reductions of up to 80% below normal values.

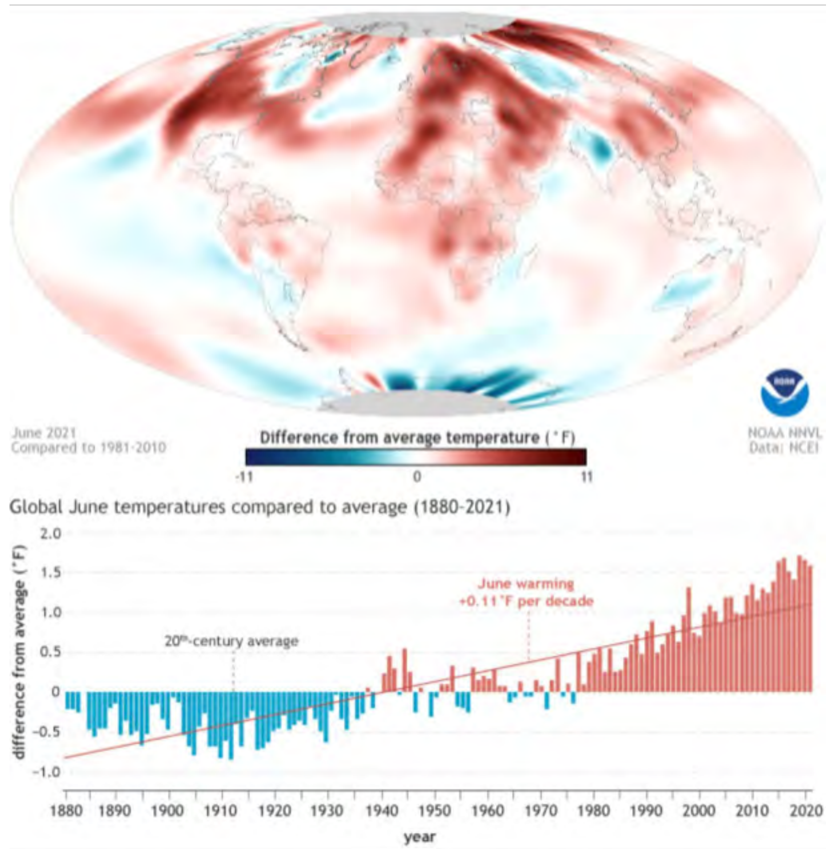
The impacts of this 6-week reduction in UV and in solar radiation on the lake food web are unknown as concurrent measurements on the zooplankton vertical distributions were not taken. However, as large wildfires are likely to be a part of our ever-lengthening summers for many years to come, it is likely that there will be significant changes occurring to the lake biota

The second aspect, the addition of fine particles, nutrients, toxic chemicals and other smoke constituents is an even more complex issue. Most deposition occurs on the land and continues to be washed into the lake many months after the fires have been extinguished when winter returns. TERC, along with collaborators at the University of Nevada, Reno, and Crater Lake National Park, have been funded by the National Science Foundation to research the impacts of direct particle deposition on lakes from the 2020 fires in the western United States. Though still ongoing, the research is looking at a range of over 20 lakes of different sizes, latitudes, and altitudes. The team is using direct in-lake sampling, autonomous underwater gliders, and spaceborne remote sensing to address the problem.

Extreme Heat and Temperature Stress of Tahoe Forests

According to NOAA's National Centers for Environmental Information (NCEI), June 2021's global surface temperature was 1.58 °F (0.88 °C) above the 20th century average of 59.9 °F (15.5°C) — the fifth-warmest June in the 142-year record. June 2021 was the 45th consecutive June and the 438th consecutive month with temperatures above the 20th-century average. Much of the western United States experienced an extreme heat event in that particular month.

TERC's Forest and Conservation Biology Lab is proactively working to understand and manage extreme heat and drought impacts both in the Tahoe Basin forests and throughout California.



Global June temperatures from NOAA/NCEI. Source: https://www.climate.gov/news-features/understanding-climate/june-2021-was-fifth-warmest-record

Extreme Heat and Temperature Stress of Tahoe Forests, continued

Amplifying Resilience to Drought Using Local and Genetically Diverse Seed

Land managers are at a critical juncture in the management of resources for adaptation and uncertainty. In particular, the selection of seed and source material, either local or non-local, for restoration has become a fundamental and much-debated decision. Given the scale of ecosystem disturbance, there is an urgent need to procure native seed across taxonomic groups to secure the diversity and local adaptation in wild populations. TERC's Forest and Conservation Biology Lab has developed restoration strategies using the progeny of local and diverse sugar pine "survivors" from the 2012–2016 drought to promote forest resiliency against drought in the Lake Tahoe Basin. This approach can serve as a model to many other terrestrial ecosystems throughout California.

The lab is studying important plant traits of 100 surviving "mother trees" of sugar pine from the Lake Tahoe Basin to determine, through a common garden study, if these "survivors" carry unique genes that give rise to plant traits such as water-use efficiency, plant defense chemistry to bark beetles, phenology, and resource partitioning. Such traits will allow them to be more resilient to drought and bark beetle outbreaks. This work is funded by the California Tahoe Conservancy.

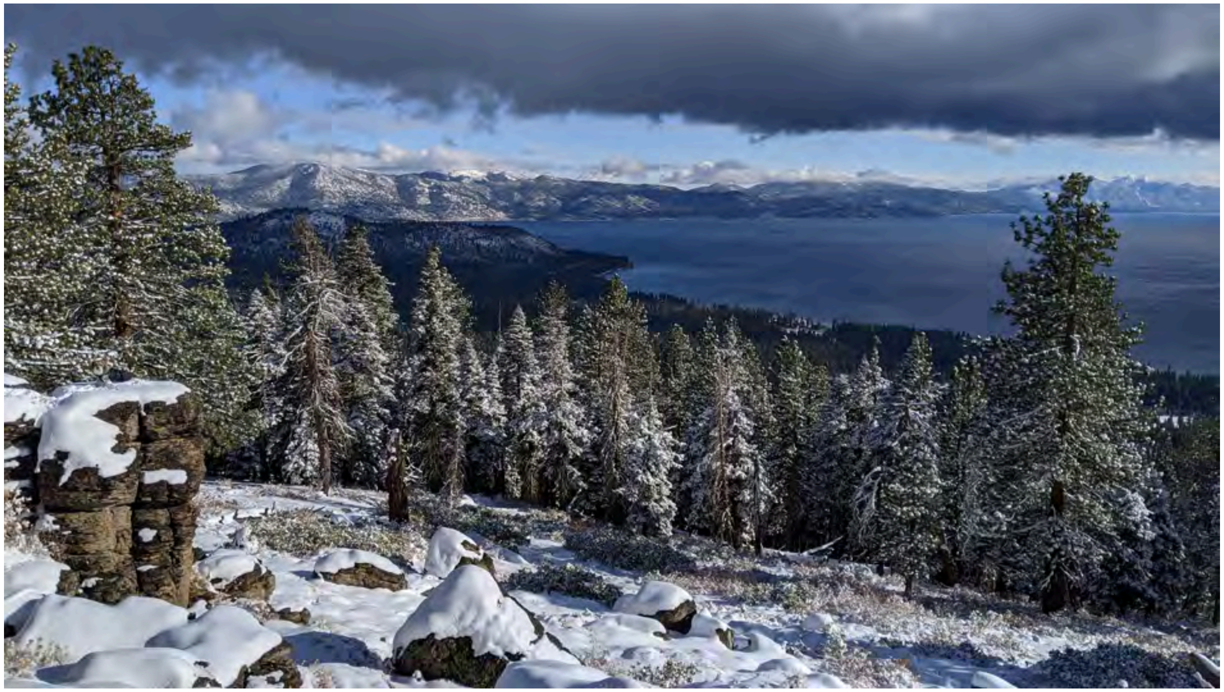
Initial height measurements.
Photo: C. Jensen

Sugar pine seedlings arranged in four experimental blocks.
Photo: C. Jensen

Extreme Heat and Temperature Stress of Tahoe Forests, continued

Amplifying Resilience to Drought Using Local and Genetically Diverse Seed, continued

Our ecological and genetic studies with sugar pine and other five-needled white pines provide valuable information regarding seed material for restoration and reforestation. The work to date is providing strong evidence that using local and diverse seed sources promotes forest resiliency and provides "insurance" against climate change. We are at a tipping point, facing an unprecedented loss of California wildlands and all the associated ecosystem services they provide. Collections from extant plant populations and individuals that have proved to be resilient to anthropogenic and natural stressors should be prioritized for seed collection. Novel restoration strategies guided by a better understanding of how native plants evolve in response to selective pressures such as drought and temperature stress hold the potential to increase not only the pace and scale of ecosystem restoration, but to amplify population resiliency to contemporary pressures and stressors.



A view of Tahoe Forests and Lake Tahoe. Photo: A. Toy

Extreme Heat and Temperature Stress of Tahoe Forests, continued

Ongoing Native Seed Collections

California is a biodiversity "hotspot" and given the scale and extent of wildland loss there is an urgency for procuring native germplasm across taxonomic groups to secure the diversity and local adaptation found in wild populations. As part of this effort, the Forest and Conservation Biology lab continues to make cone and seed collections from sugar pine, western white pine, and other forest tree species throughout California, Nevada, Oregon, and northern Baja Mexico for gene conservation, restoration, and seed-banking.

Tom Burt (bottom right) making a gene conservation collection from a population of sugar pine at Toro Peak in the Santa Rose Mountain Range in southern California. Photo: T. Corliss

A Smattering of Tahoe-Related Research Projects

Every year, UC Davis TERC students and researchers work on a range of research projects, either directly at Lake Tahoe, that draw upon the results of the long-term data at Lake Tahoe, or that can be directly applied to environmental restoration at Lake Tahoe. The following pages highlight some examples of that work in 2020.

The broad range of research taking place at meso-eutrophic Clear Lake. Though very different than Lake Tahoe, contrasting the two lakes helps us better understand the underlying processes. Photo: M. Swann and K. Pinkanjananavee

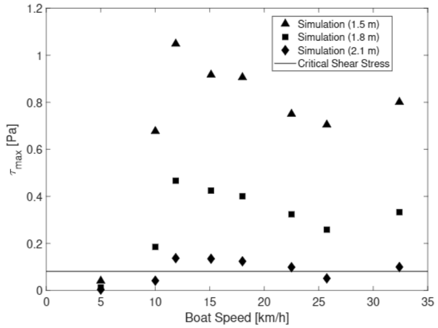
A Smattering of Tahoe-Related Research Projects, continued

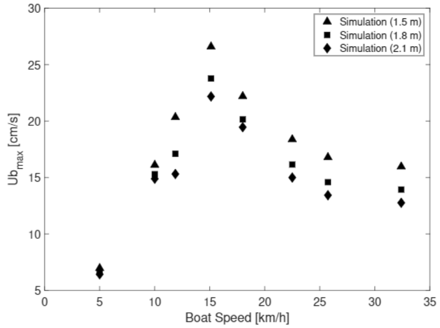
Sergio Valbuena - Impacts of Boat Wakes in the Nearshore Zone

No-wake zones are common in most lakes, yet their scientific basis is poorly understood. The combination of shallow water depths and high boat activity results in complex flows and waves that have the potential to resuspend sediment and nutrients from the lake bed. To this end, a field campaign was undertaken in 2019 where multiple wave and turbidity sensors were used to characterize the lake bed-sediment interaction during summer. Field observations recorded instantaneous turbidity changes associated with boat activity. Turbidity was observed to return to baseline values within five minutes of boat passage. Boat-induced wave impacts were estimated using the wave measurements for a specific range of boat characteristics. Boat wakes accounted for approximately 30% of the total wave activity registered on the south shore of Lake Tahoe. The boat-induced wave contributions to sediment resuspension overall were low in comparison to the wind forcing effects on the wave generation.

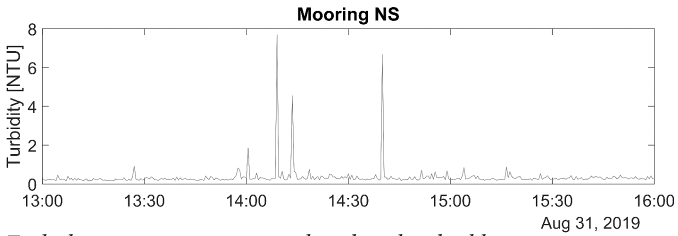
Lastly, numerical simulations of propeller wash from boats were conducted. Using a range of boat speeds and water depths it was concluded that boats exceeding a speed of 5 mph (8 km/h) can induce sediment resuspension at depths as great as 3 m (10 feet), with the peak resuspension at a speed of 10 mph (15 km/h).

Sergio prepares instruments to measure boat wake impacts. Photo: G. Schladow





(Top) Shear stress estimations at different water depths for boats at different speeds. (Bottom) Estimated water velocity induced by boat passage underneath the hull of the vessel.



Turbidity increases associated with individual boats.

A Smattering of Tahoe-Related Research Projects, continued

Micah Swann – A Tale of Four Lakes

Micah's research centers on the threats posed to lake ecosystems from declining dissolved oxygen in their deep waters, and the role that climate change and land-use may play in this. The four lakes that are at the core of his work are Lake Tahoe (CA-NV), a high altitude oligotrophic lake with strong development pressures over the last 60 years; Clear Lake (CA) a hyper-eutrophic and severely impacted lake in California's coastal range, with a long history of human development, agriculture, and mining; and two near-pristine lakes in Northern Patagonia, Lake Llanquihue and Lake Ranco, which are seeking to emulate practices at Lake Tahoe in anticipation of impending development pressure and climate change.

Each lake is different, both from the perspective of its limnology and its anticipated future trajectory. In order to inform his study, Micah has been collecting and analyzing field data, while running three-dimensional lake models using current and predicted future conditions. In the next 12 months, he will be spending considerable time in Chile, working through the lake advocacy NGO Chile Lagos Limpios.

The funding for Micah's research has come from the California Department of Fish and Wildlife, UC Davis Global Studies, the Eivind Lange Fellowship, the ARCS Foundation, California Lake Management Society (CALMS), and the Boyd Foundation.

Micah retrieving instrument mooring from the depths of Clear Lake. Photo: R. Thirkill

A Smattering of Tahoe-Related Research Projects, continued

Samantha Sharp – Observing Harmful Algal Blooms from Space

Samantha studies cyanobacterial (harmful algal) blooms using a combination of hyperspectral satellite data and in situ hyperspectral measurements. While previous research in this area of study enables the detection of cyanobacteria, Samantha is seeking to build on this by additionally differentiate between individual cyanobacterial groups. This is important as not all cyanobacteria are toxic. With the exception of locations such as the Tahoe Keys on occasion, harmful algal blooms have not been an issue of concern at Lake Tahoe. However, this may change in the future as warming lake temperatures and increasing nutrient concentrations move the lake toward conditions favoring cyanobacteria.

An important part of this research is to better understand the measurement of algae within water using fluorescence. When algae and cyanobacteria receive light energy in excess of the amount required for photosynthesis, they dissipate this energy as heat through a process known as non-photochemical quenching (NPQ). This causes a daytime reduction of fluorescence and, therefore, results in an under-estimation of the biomass of algae and cyanobacteria. This is a particularly severe issue at Lake Tahoe, where the clear water allows NPQ to occur to depths in excess of 60 ft. Through continuous 24-hour sampling from a site off Homewood (CA), Samantha seeks to develop a correction for NPQ that can be used at Lake Tahoe and other high clarity lakes.

Samantha's funding is provided through a NASA Graduate Fellowship.

Samantha sampling for cyanobacteria in Clear Lake, CA. Photo: M. Swann

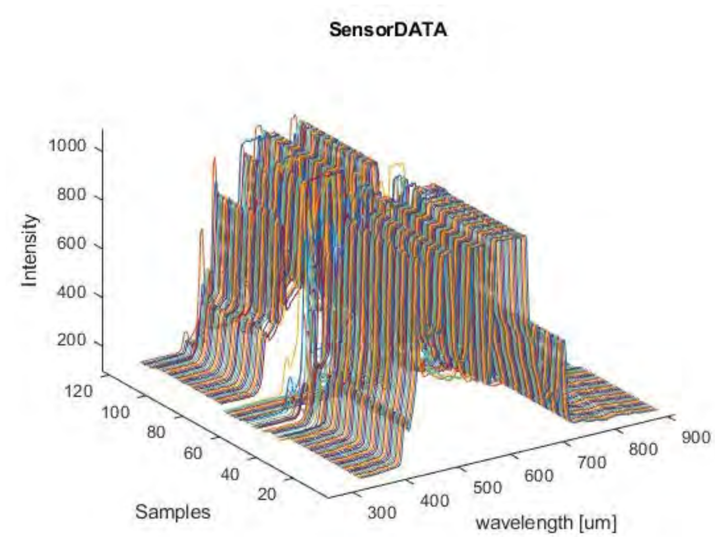
A Smattering of Tahoe-Related Research Projects, continued

Kanarat (Job) Pinkanjananavee - Rapid and Affordable Cyanobacterial Detection

Job is developing an in situ spectrophotometer for identifying cyanobacteria genera that could ultimately provide an early warning system for harmful algal blooms (HABs). HABs are currently estimated to cost the U.S. economy up to $1B annually. Using a Hamamatsu C12880MA mini-spectrometer with an Arduino mainboard, the software is currently being tested. Trial deployments may commence as early as fall 2021, with the likely test location being Clear Lake (CA), a lake known for extremely large (and toxic) cyanobacterial blooms. If the development is successful, instruments could be deployed in Tahoe and elsewhere in 2022.

Job's funding is from the U.S. Bureau of Reclamation.

Job's spectrophotometer prototype out of its protective casing. Photo: K. Pinkanjanavee



Sample spectrophotometer output from a Clear Lake test deployment.

HABs out at Clear Lake. Photo: K. Pinkanjanavee

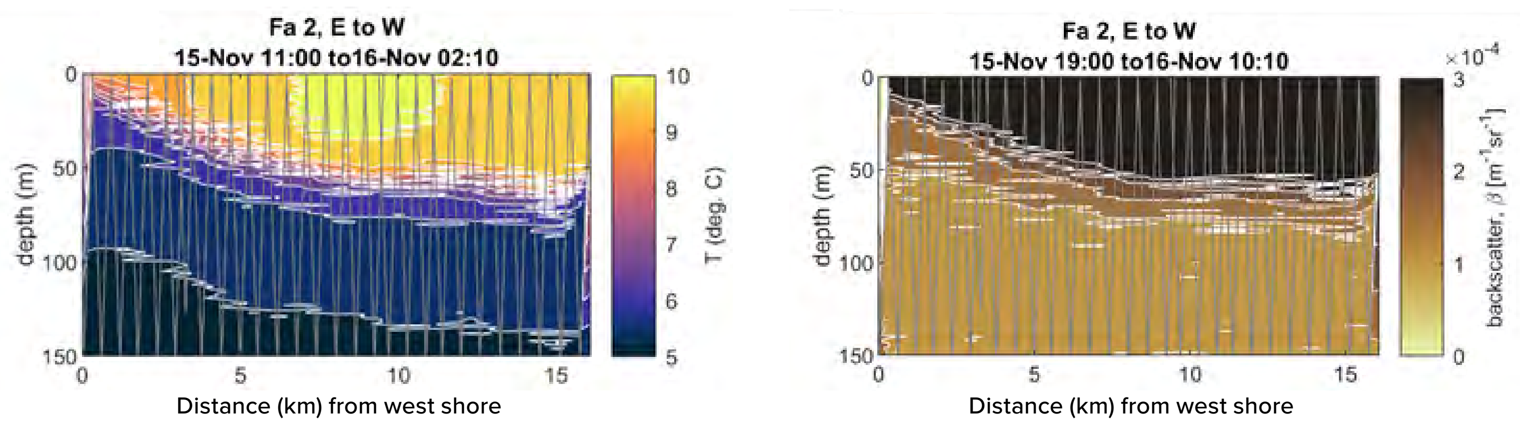
A Smattering of Tahoe-Related Research Projects, continued

Jasmin McInerney – The Art of Measuring Lakes Autonomously

Jasmin's research interests are centered on understanding lake physics using autonomous underwater gliders as a primary measurement tool. Jasmin has deployed gliders in Antarctica, Lake Superior, Lake Geneva and of course, Lake Tahoe. Gliders have the great advantage of being able to run using a very small amount of power, as they utilize their buoyancy to propel themselves. At Lake Tahoe, for example, the glider can run for up to a month, travelling back and forth across the lake while at the same time plunging and rising over 500 feet. It can do this day and night and during intense weather when traditional boat surveys would be dangerous.

In Lake Tahoe Jasmin has been investigating the inter-seasonal variation of internal waves and their effect on suspended particulate matter and chlorophyll distribution. Internal waves are large amplitude waves that arise within the lake due to the variation of temperature with depth. The figure below shows an internal wave that is rising (upwelling) on the west shore. In this example, the images show the impact of an internal wave moving clear (low backscatter) water from the depths of the lake to the surface. The clear water in this case contains very few particles and can help to improve the Secchi depth of the lake. Unfortunately these clear, bottom waters also contain high concentrations of nutrients. When the nutrients are brought to the surface, they can stimulate algal blooms.

The funding for Jasmin's research comes from the Korea Polar Institute and the Robert L. Wiegel Scholarship for Coastal Studies.



Temperature contours (left) and optical backscatter contours (right) on a west-east transect in fall 2017. The grey lines indicate the glider path. The horizontal axis is distance (km) from the start point near Homewood on the west shore.

A Smattering of Tahoe-Related Research Projects, continued

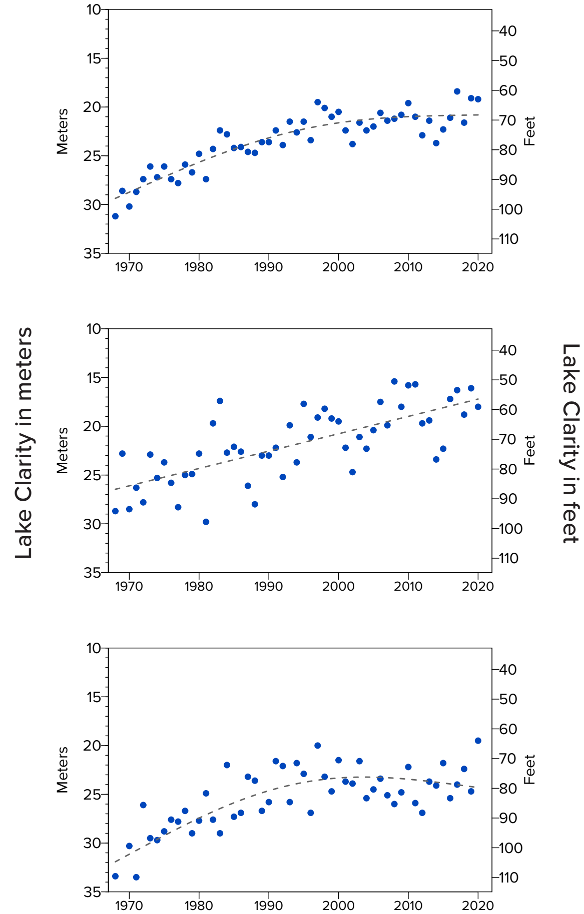
Alicia Cortés (TERC), Shohei Watanabe (TERC), and Lidia Tanaka (TERC) - Understanding Seasonal and Long-Term Clarity Trends

During 2020, an interdisciplinary team of researchers from UC Davis (TERC), the U.S. Geological Survey, and the Desert Research Institute investigated the drivers of seasonal and long-term clarity trends. The work was conducted on behalf of the Tahoe Science Advisory Council (TSAC).

The analyses conducted by the TERC researchers showed that clarity is controlled predominantly and negatively correlated with the in-lake density of fine inorganic and organic particles in suspension (with diameters in the range of 1.0–4.76 microns). The origins of these fine particles are from small diatoms (*Cyclotella*) that have proliferated in the lake in recent decades and external loads of fine sediments primarily from urban areas.

In-lake physical processes also influenced seasonal and historic trends, with the depth of winter mixing having a significant impact on seasonal trends. Clarity improves during the winter as a result of deep mixing. Increases in lake temperatures due to climate change have resulted in the lake becoming stratified earlier and remaining stratified longer. The increase in temperatures at the surface of the lake, combined with changing stream temperatures affect the insertion depths of incoming stream flows.

Regarding biological drivers of clarity, in addition to the negative impact of large numbers of *Cyclotella* on fall and summer clarity, the reappearance of zooplankton species like *Daphnia* in the absence of the predator *Mysis* shrimp is expected to contribute positively to both seasonal and annual clarity due to the ability of *Daphnia* to remove both inorganic and organic fine particles.



Lake clarity during annual (top), winter (middle) and summer (bottom) periods. The dashed trend line is produced using a generalized additive model.

A Smattering of Tahoe-Related Research Projects, continued

Holly J. Oldroyd (UC Davis), Stephen Drake (UNR), and Anne Nolin (UNR) - Snowmelt and Hydro-meteorology

For the last three winters at the Sagehen Field Station outside of Truckee, CA a study has been underway to understand various types of snowmelt events. Such events are critical for understanding water balances and informing water resource management decisions. Several factors make predicting and quantifying water loss from the snowpack challenging. These are related to natural variations in the landscape, such as tree cover and topography, that cause significant differences in ablation (snow loss) processes over spatially small scales. Understanding these processes is critical for developing hydrologic and meteorologic models at much larger scales.

One important process is water loss from the snowpack to the atmosphere through evapo-sublimation. This can account for as much as 25% of the seasonal snow loss. In the 2019 and 2020 campaigns, the team deployed several "flux towers" along a transect between dense forest and open meadow. The findings indicated large differences in fluxes across horizontal distance, vertical heights, and surface types. Clear-sky evapo-sublimation rates increased with wind speed and were often at a maximum near midday when solar energy was at its peak. Evapo-sublimation rates were greatest in the snow-covered forest canopy but were constrained by the lower wind speeds within the forest.

The models that are being developed through this research have direct impact to the water balance within the Tahoe basin. The fraction of the snowpack that provides water to the lake, streams, and soil is the balance of what is left after evapo-sublimation. As forest density changes with landscape-scale forest thinning, and as climate change exerts meteorological changes, having the ability to predict the impact of evapo-sublimation on water availability will allow for improved water resource management.

Eddy-covariance flux tower and spatial variations in snowpack and snowmelt. Photo: S. Drake

TAHOE: STATE OF THE LAKE REPORT 2021

METEOROLOGY

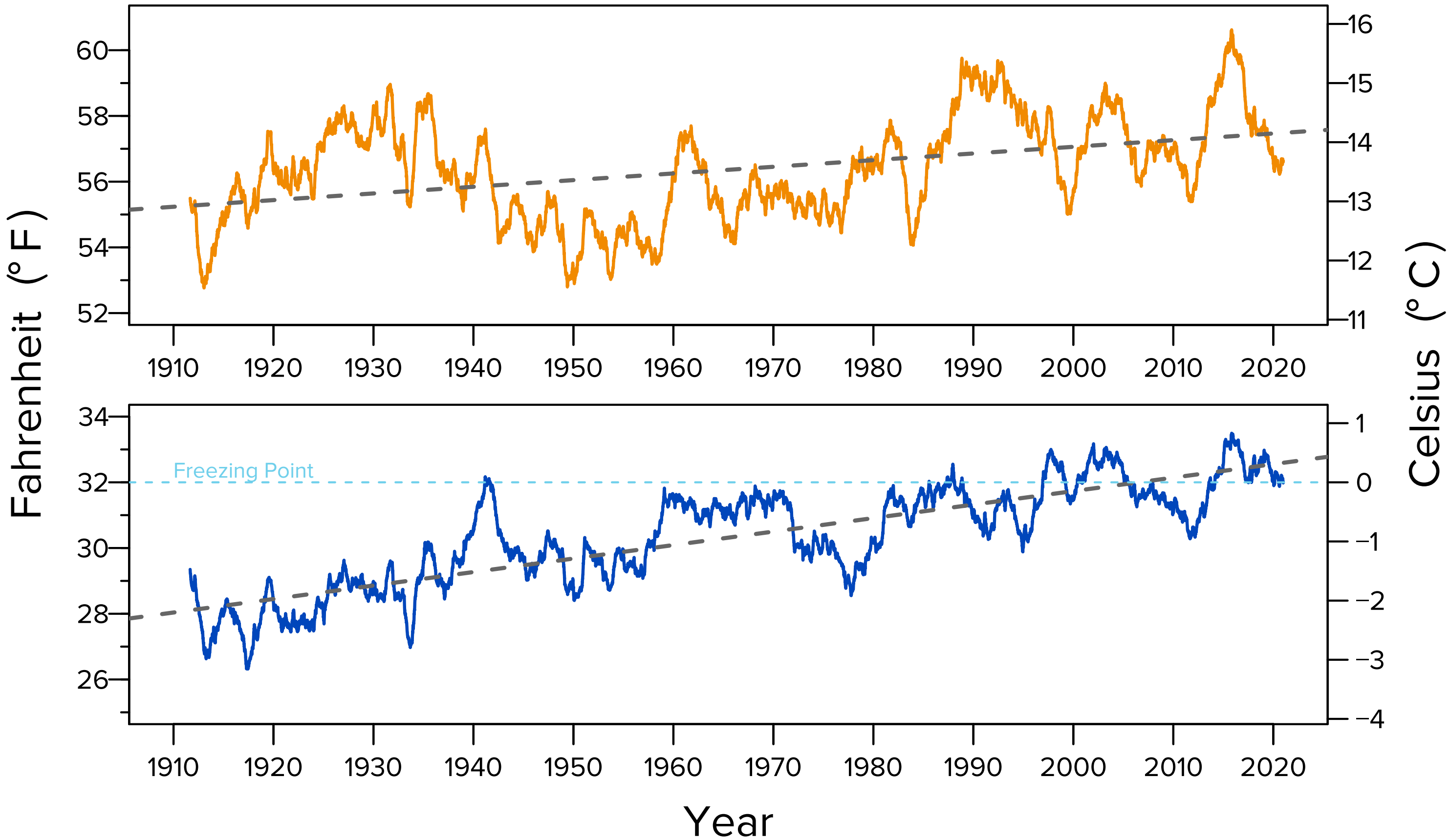
UC DAVIS
Tahoe Environmental
Research Center

Air temperature - smoothed daily maximum and minimum

Daily since 1911

Over the last 109 years, daily air temperatures measured at Tahoe City have increased. The long-term trend in average daily minimum temperature (bottom figure) has increased by 4.49 °F (2.49 °C) and the long-term trend in average daily maximum temperature (upper figure) has risen by 2.22 °F (1.23 °C). The trend line for the minimum air temperature has exceeded the freezing temperature of water for the last 15 years, leading to 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.

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

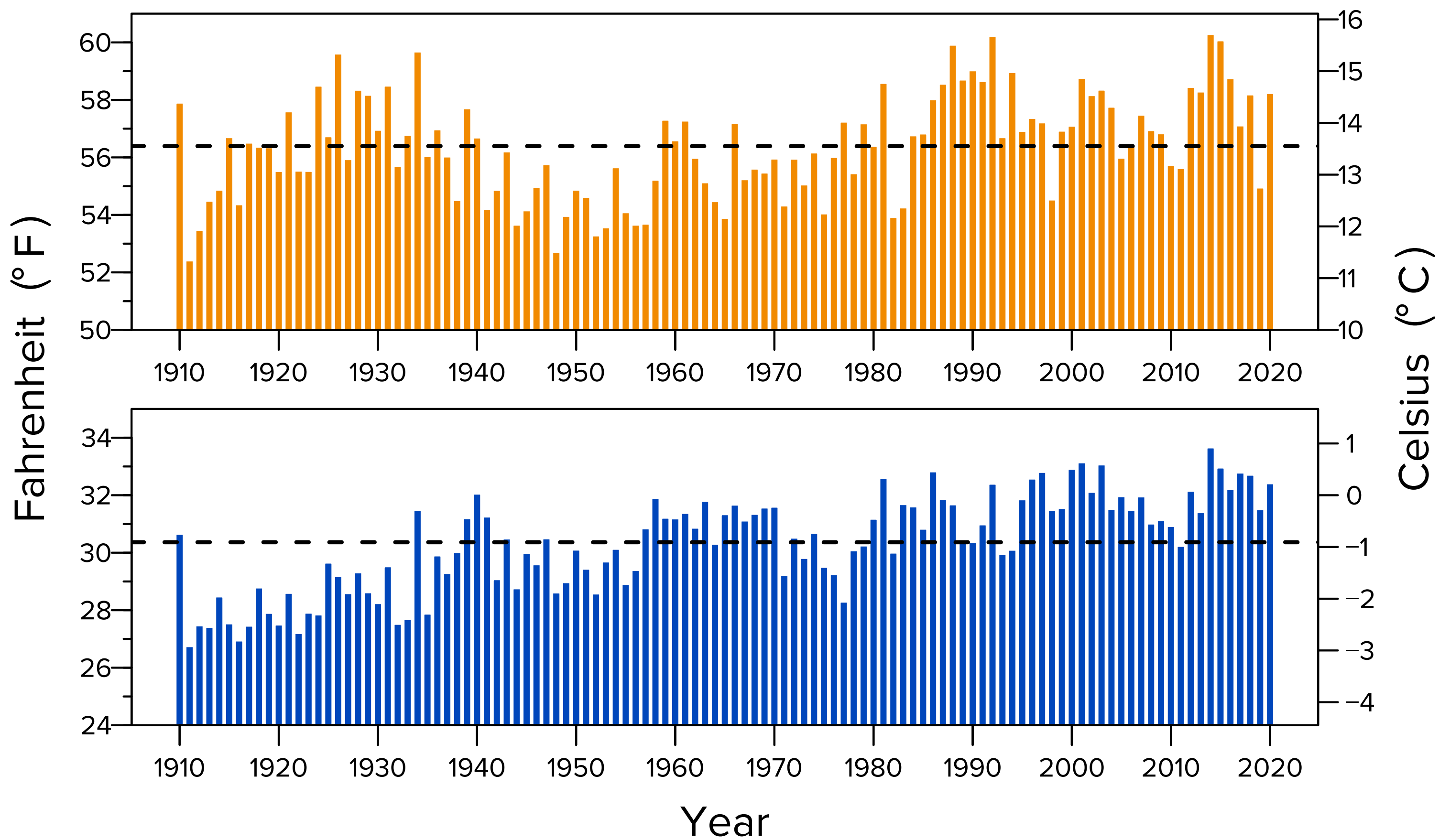


Air temperature - annual average maximum and minimum

Since 1910

Annual average maximum (upper figure) and minimum (lower figure) air temperatures in 2020 were both warmer than the previous year and above the long-term average (dashed line) temperature. The annual average maximum temperature was 58.2 °F (14.6°C), an increase of 3.2 °F from the previous year. The 2020 annual average minimum was 32.4 °F (+0.2 °C), which was 0.9 °F warmer than the previous year. The long-term averages for the maximum and the minimum are 56.4 °F (13.6 °C) and 30.34 °F (-0.9 °C), respectively.

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



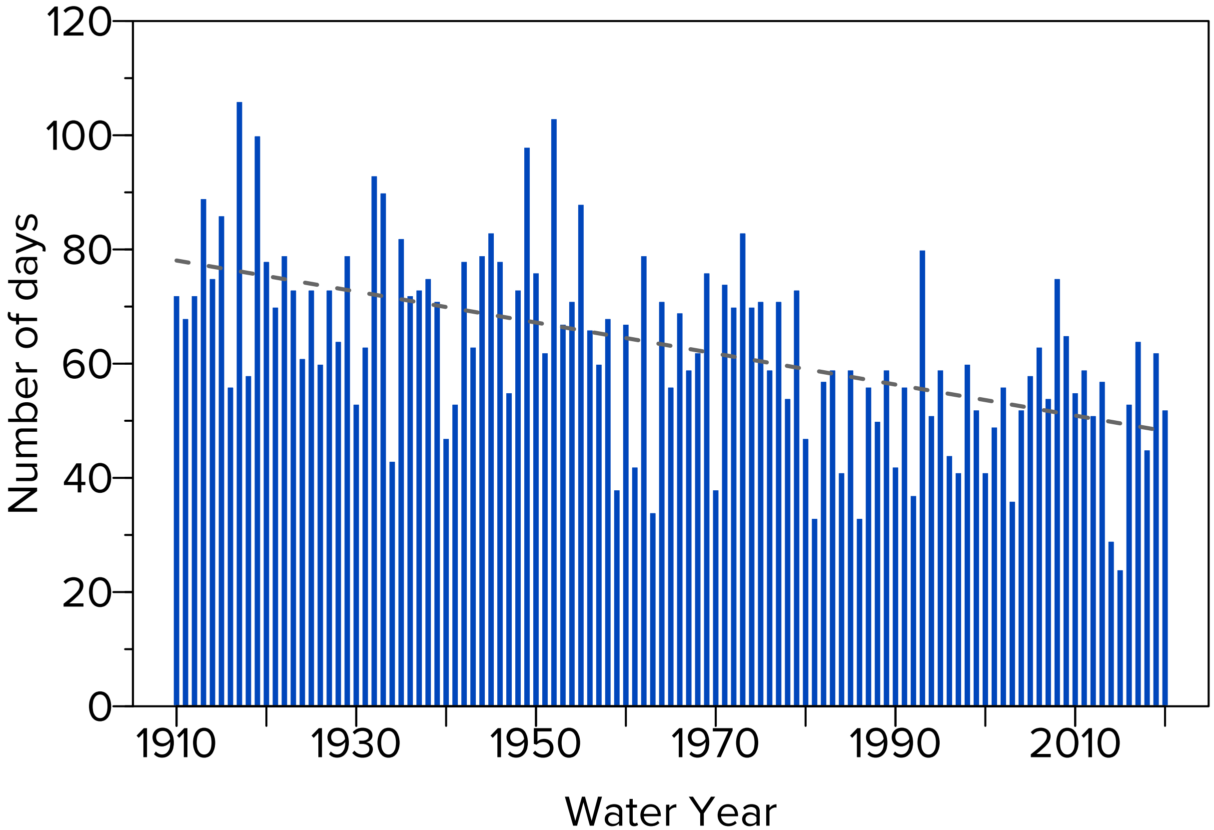
Below-freezing air temperatures

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 almost 30 days since 1911. In WY 2020, the number of freezing days was 52, above the declining long-term trend line. This is consistent with the measured air temperatures in 2020.

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.

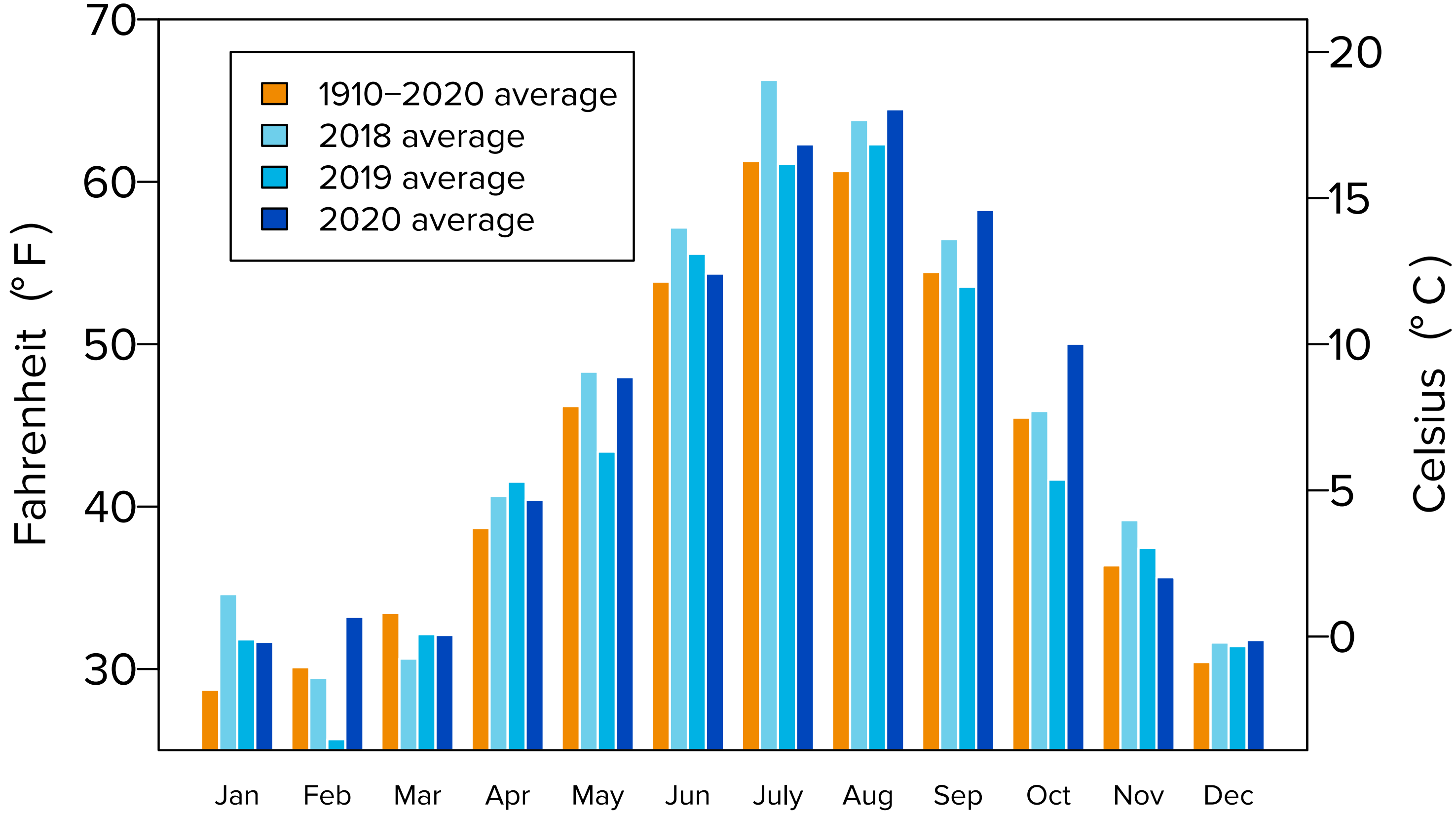


Monthly air temperature

2018, 2019, 2020 and 1910 to 2020

In 2020, monthly air temperatures were generally similar to 2018 and 2019. However, for the months of February, August, September, and October, temperatures were warmer than the previous two years (and the long-term average). This the warmest September since 1956, and the eighth warmest on record.

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

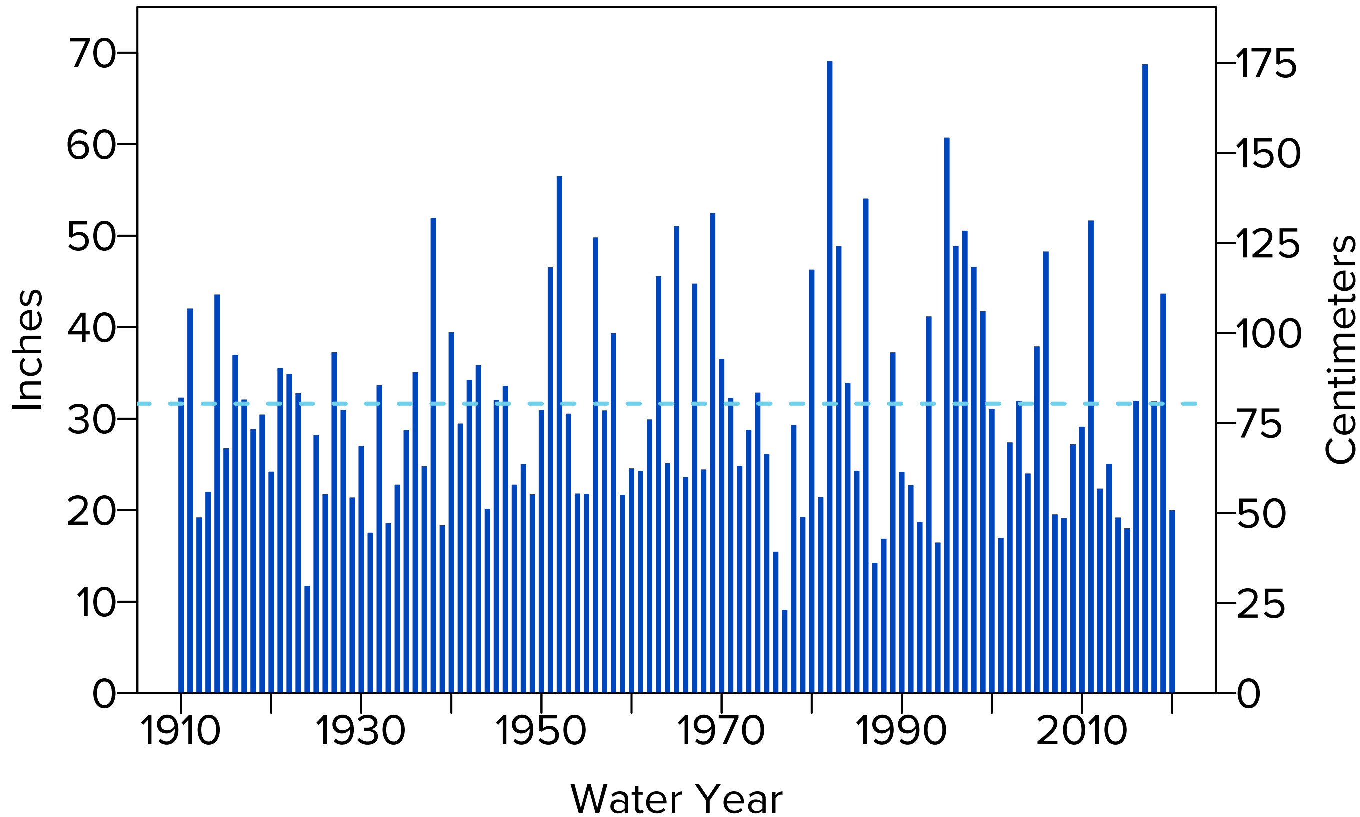


Annual precipitation

Yearly since 1910

From 1910 to 2020, average annual precipitation (water equivalent of rain and snow) at Tahoe City was 31.4 inches. The maximum recorded was 69.2 inches in 1982. The minimum recorded was 9.2 inches in 1977. At 20.1 inches, 2020 was well below the long-term average (shown by the dashed line). The low values of 2020 was preceded by four years of average to above-average precipitation. This, combined with the low precipitation of winter 2021, indicates the return of drought conditions. 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.

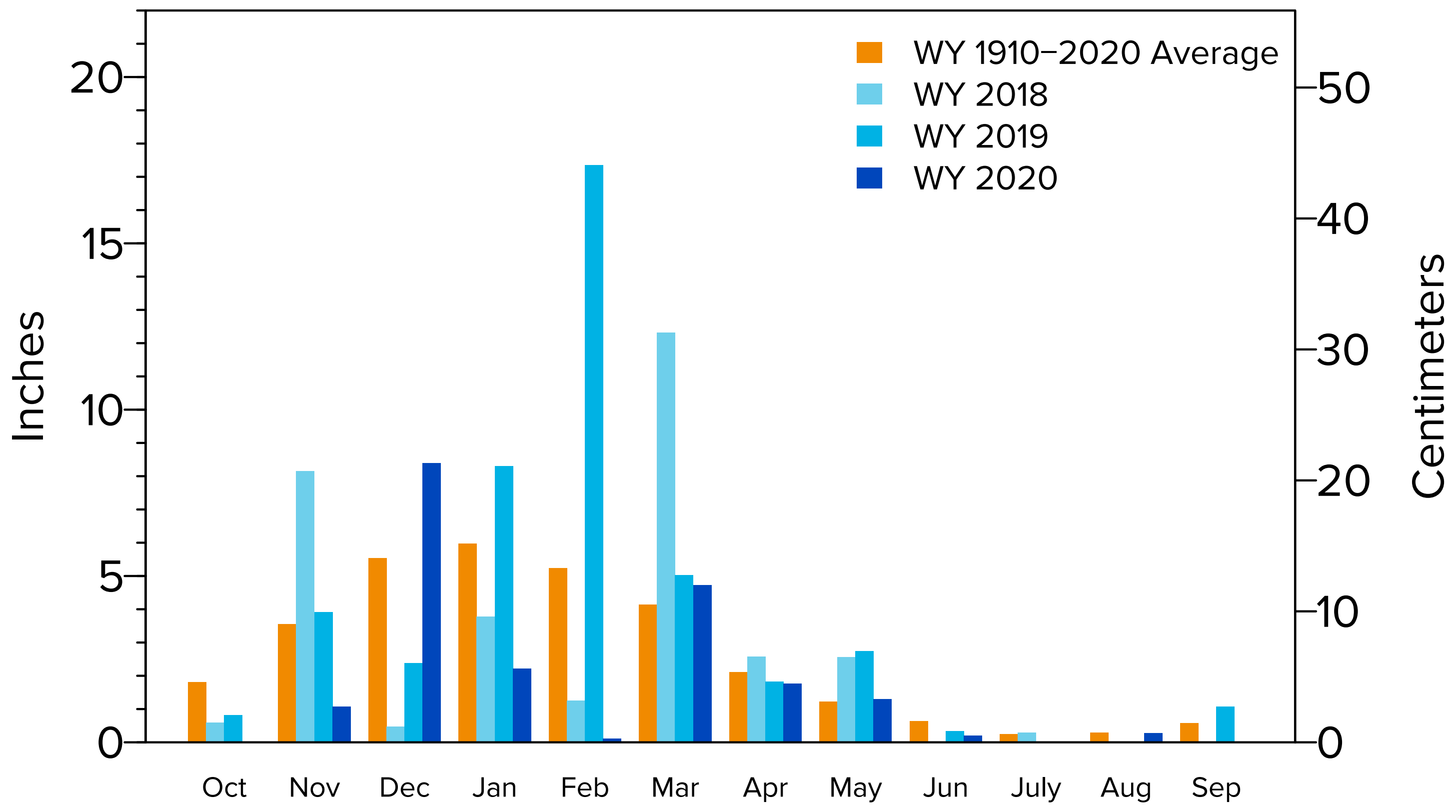


Monthly precipitation

2018, 2019, 2020 and 1910 to 2020

The 2020 Water Year was well below the long-term average in total precipitation at 20.1 inches compared with the long-term average of 31.4 inches. Precipitation in the month of February was only 0.12 inches (snow-water equivalent), the second lowest value on record. This is a stark comparison to the record high February snow of 17.4 inches in 2019. The 2020 Water Year extended from October 1 through September 30.

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

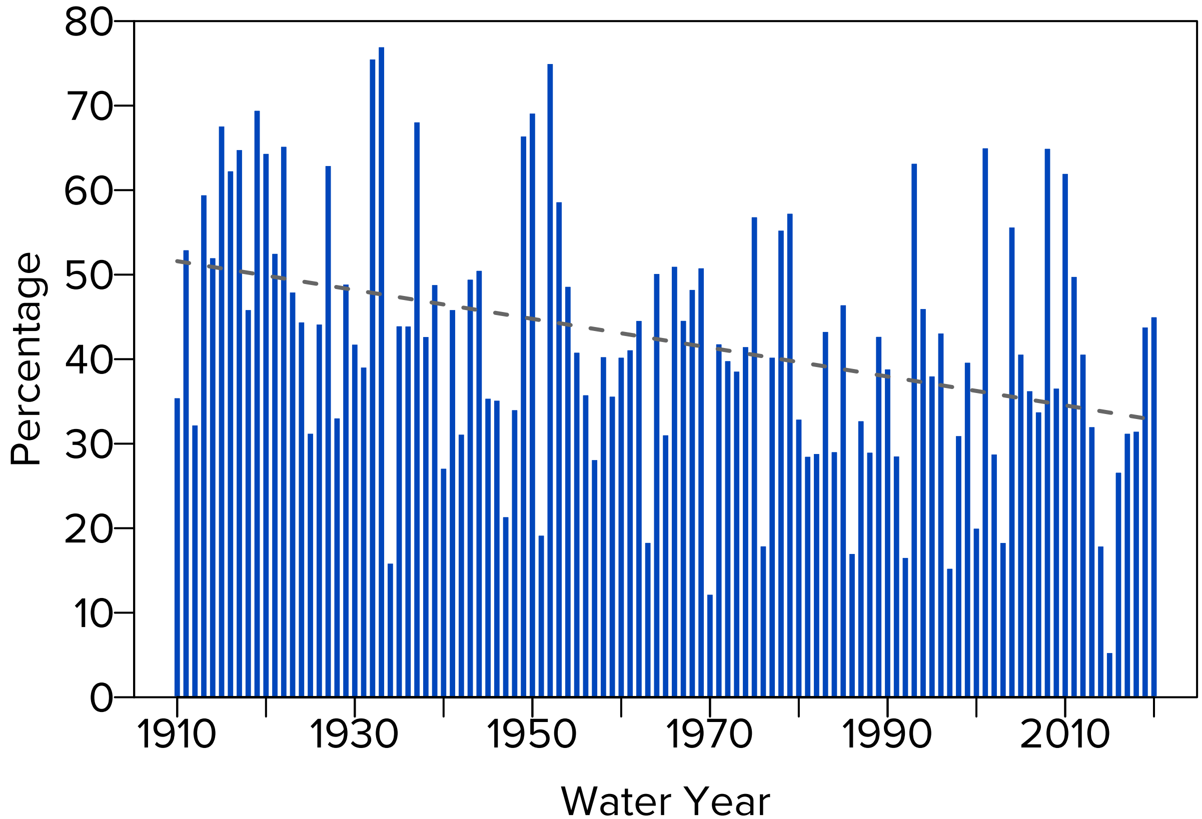


Snow as a fraction of annual precipitation

Yearly since 1910

Snow has declined as a fraction of total precipitation, from an average of 52 percent in 1910 to 33 percent in 2020, according to the trend line. In Tahoe City, snow represented 45.1 percent of the 2020 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.



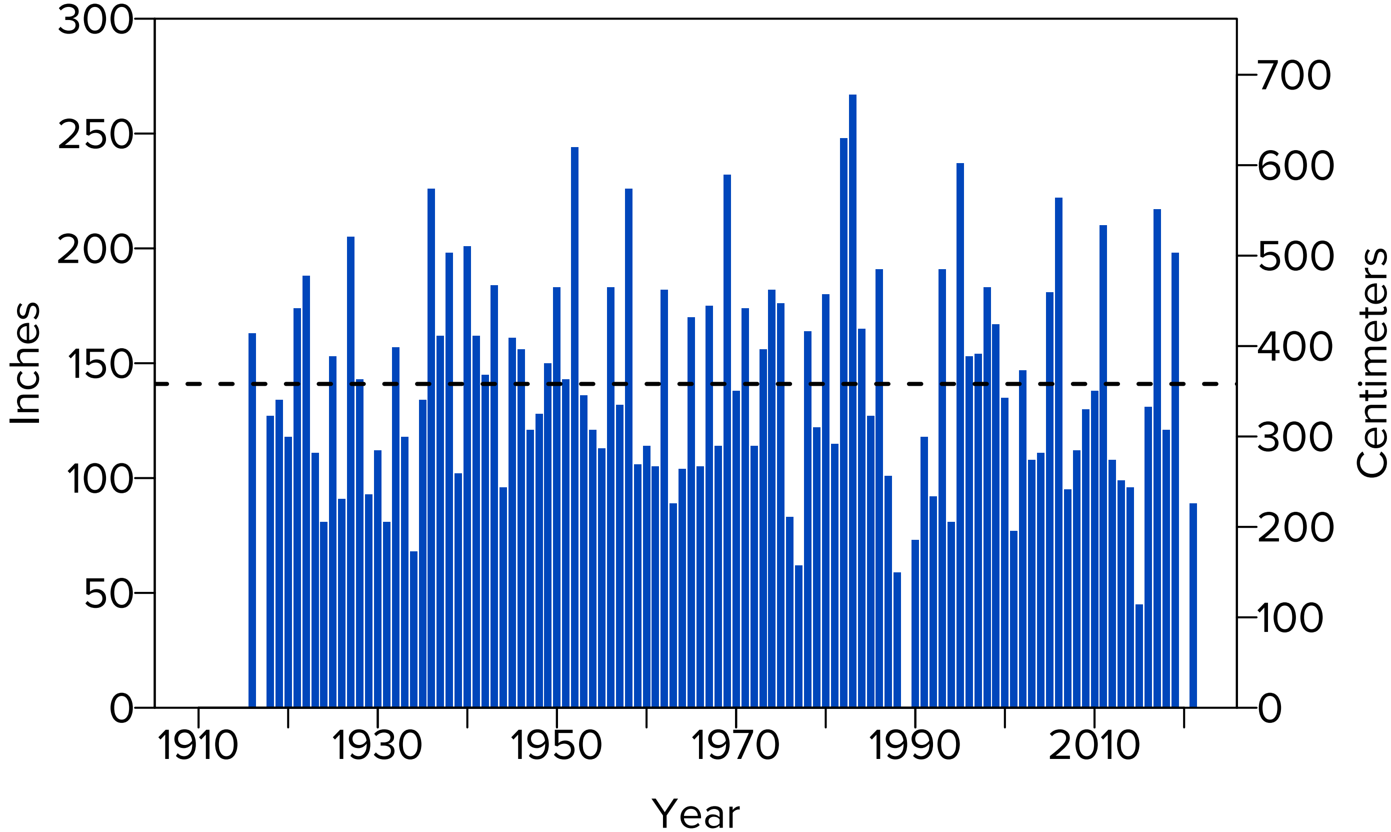
April snowpack

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.).

Note: April snow depth data are not available for 1917 and 1989. In 2020 the April snowpack reading was not taken due to work restrictions imposed by the COVD-19 pandemic. However, for March 29, 2021, the value was 89 inches. The largest amount on record was 267 inches on April 5, 1983. The average snow depth (shown by the dotted line) over the period 1916–2020 was 142.4 inches.

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

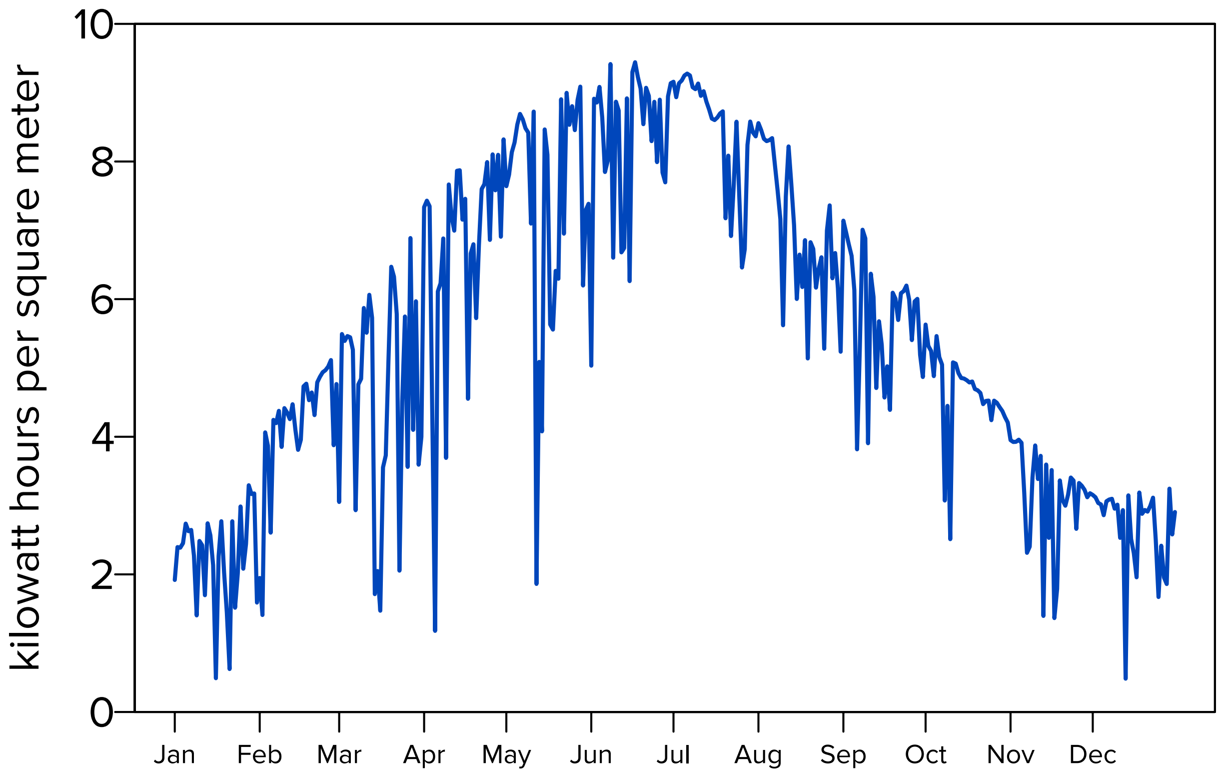


Daily solar radiation

In 2020

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 noteworthy that solar radiation on a clear day in mid-winter can exceed that of a cloudy day in mid-summer. August 2020 is particularly noteworthy, as the values were consistently below the expected range. This was a month of very intense smoke in the Tahoe Basin. On August 19, 2020, the Air Quality Index (AQI) in South Lake Tahoe was 212, synonymous with a very polluted city. That was also the lowest solar radiation day for the month of August.

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 2021

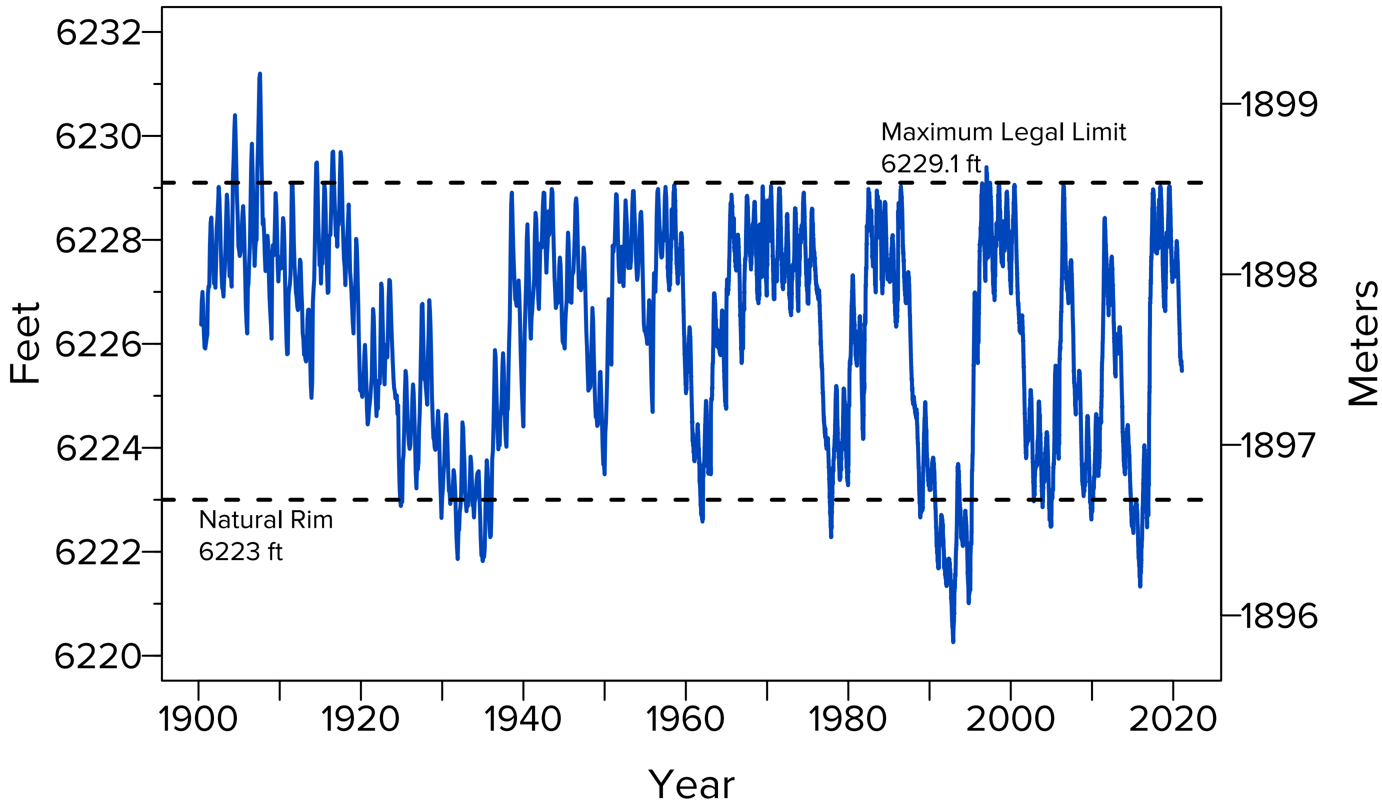
PHYSICAL PROPERTIES

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 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 2020, the highest lake level was 6,227.98 feet on June 4, and the lowest was 6,225.60 feet on December 11. The natural rim of the lake is at an elevation of 6,223 feet. Lake Tahoe was above its rim for the entire year. When the lake is below its rim, outflows via the Truckee River cease. Several episodes of lake level falling below the natural rim are evident in the last 120 years. The frequency of such episodes appears to be increasing. The lowest lake level on record is 6,220.26 feet on November 30, 1992.

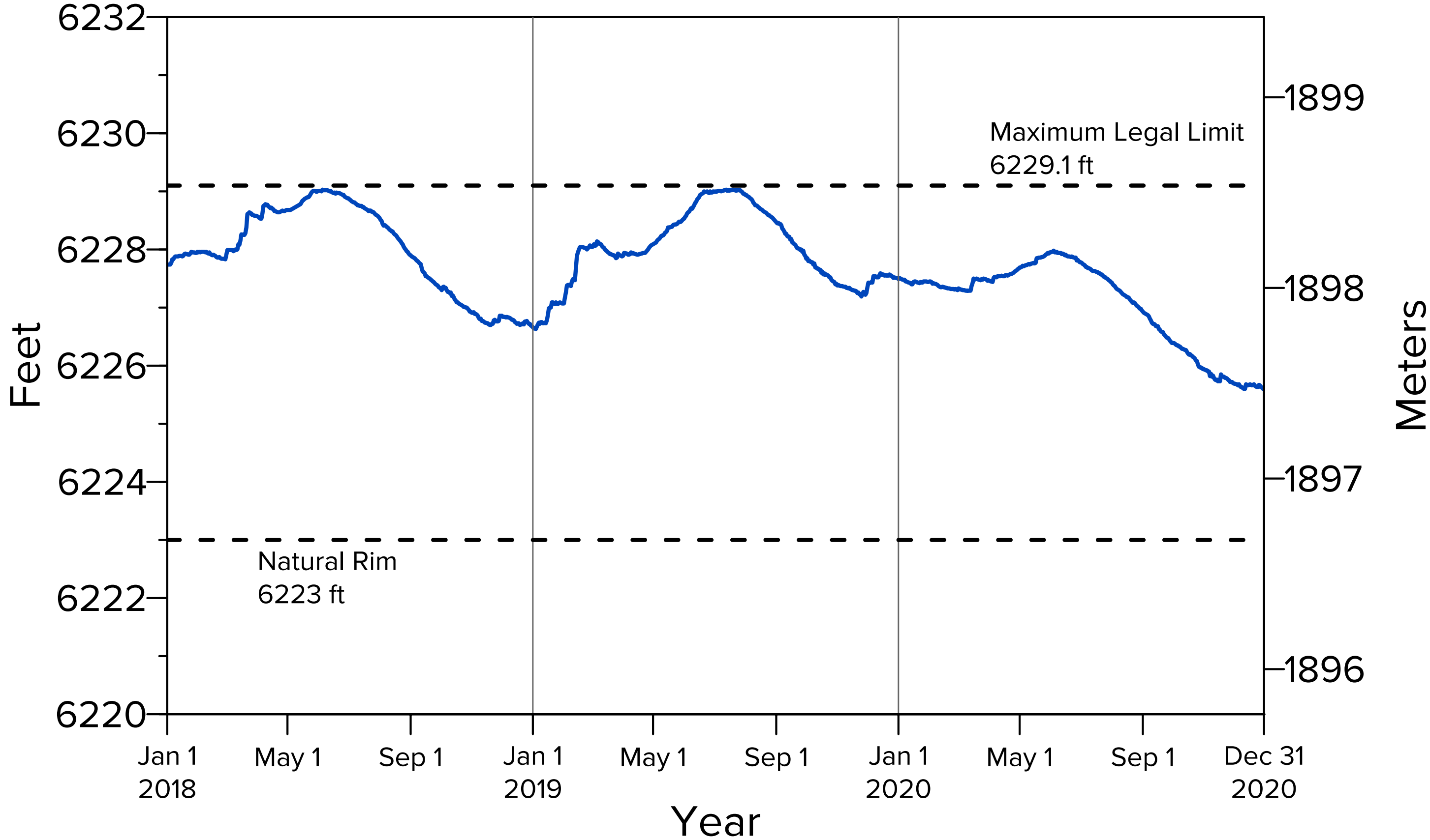
Data source: US Geological Survey level recorder in Tahoe City.



Lake surface level

Daily since 2018

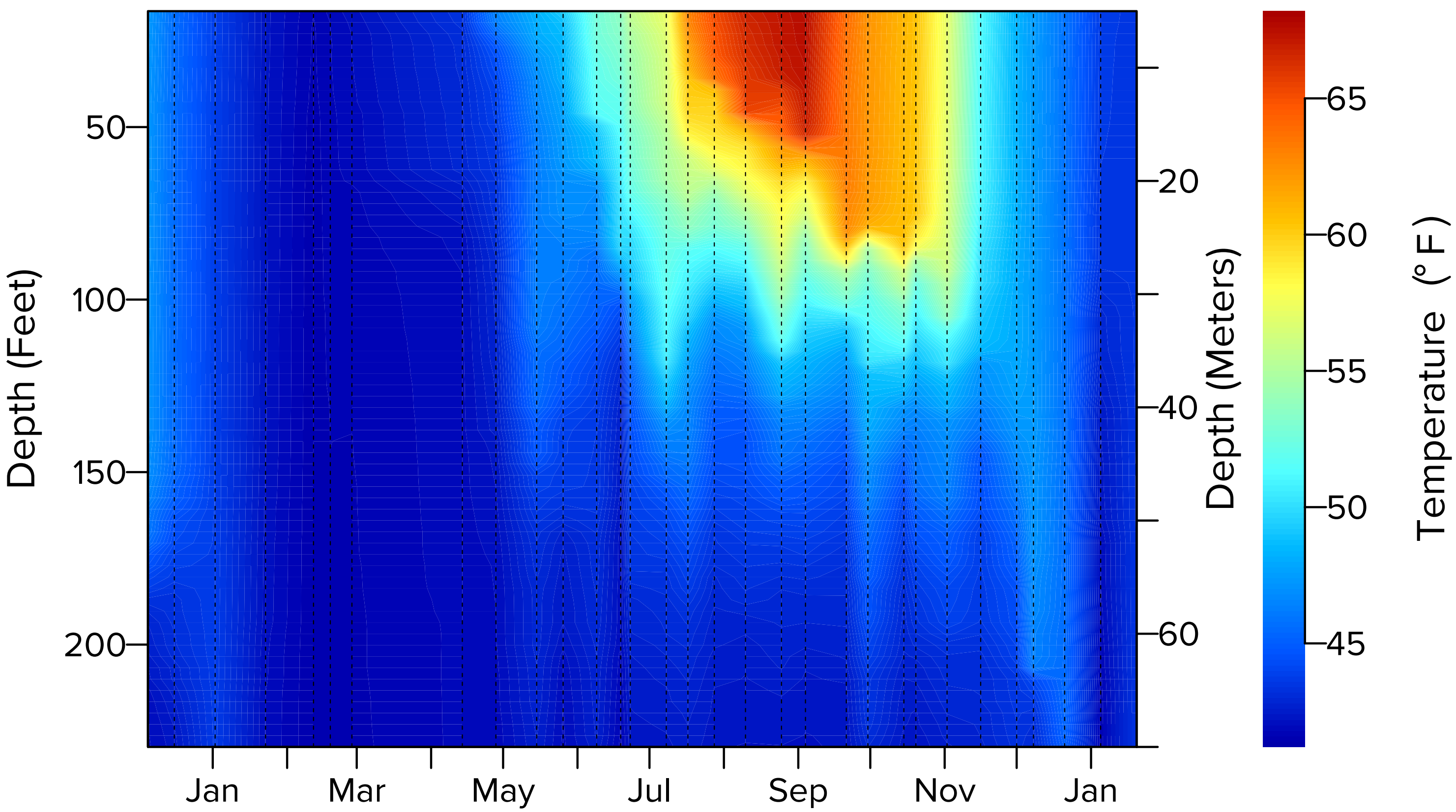
Displayed below is a subset of lake surface data extracted from the same data as in Fig. 8.1 for the most recent three years from 2018–2020. This more time-restricted presentation of recent lake level data allows us to see the annual patterns of rising and falling lake level in greater detail, particularly as we head towards a return to drought conditions and low lake levels. In 2020, on account of a dry winter, the annual rise in lake level was very muted. From January through December 2020, overall lake level fell 1.9 feet. Based on historical water level data, it is likely that Lake Tahoe will fall below its natural rim in October 2021.



Water temperature profile

In 2020

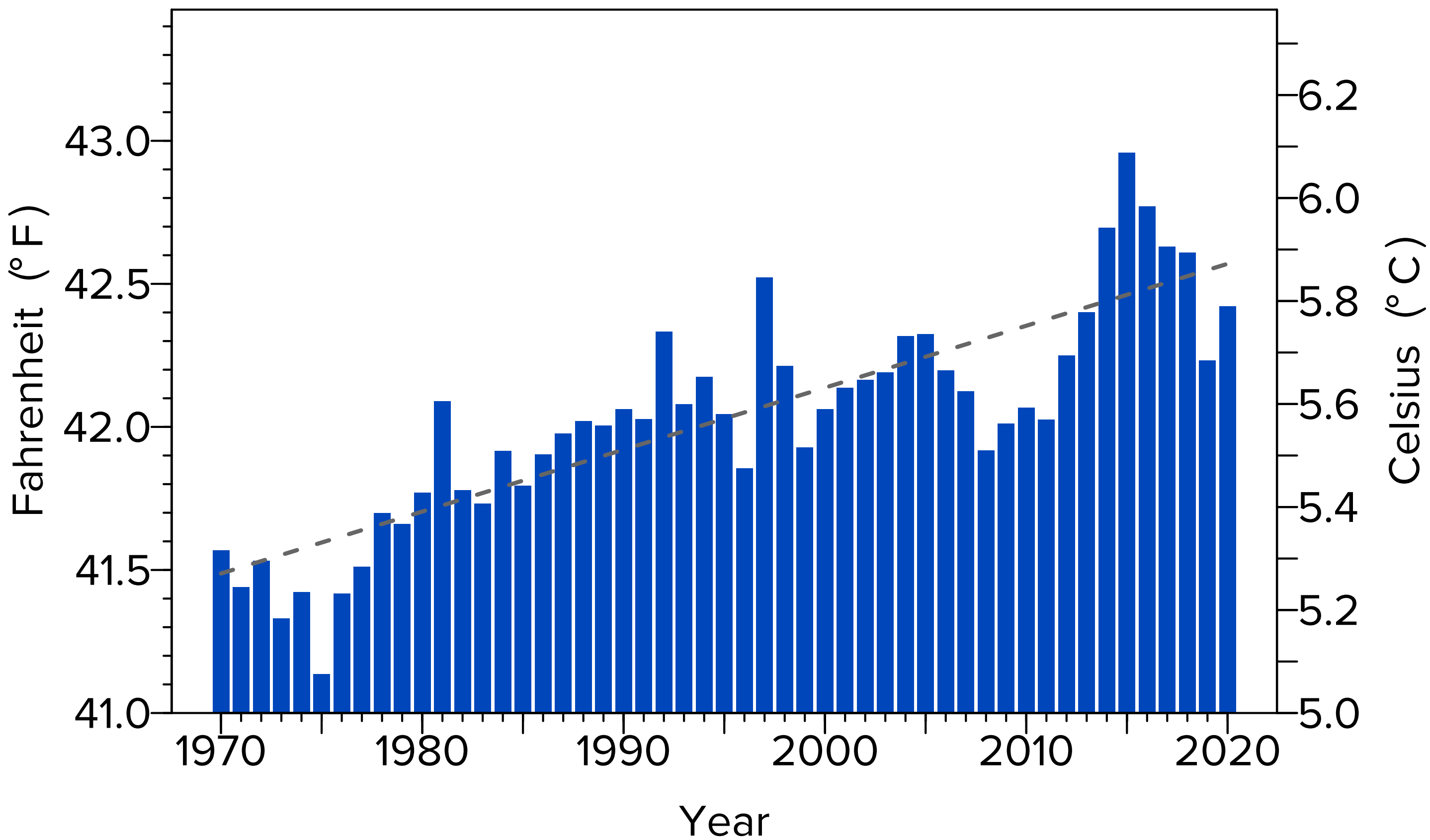
Water temperature profiles are measured in the lake using a Seabird CTD (conductivity, temperature, depth) profiler at the times indicated by the dashed vertical lines. The six-week gap in March and April was due to COVID-19 restrictions. The temperature is accurate to within 0.005 °F. The vertical distribution of water temperature is a very important lake attribute, as it represents lake density, with warmer, lighter water trapped at the surface during the summer months. Here the temperature in the upper 230 feet (70 m) is displayed as a color contour plot. In 2020, the lake temperature followed a typical seasonal pattern. In February and March, the lake surface was at its coldest, while it was at its warmest in August and September. The thickening and cooling of the warm water zone toward the end of the year is part of the cycle of winter mixing, a process that is important in bringing oxygen to the deeper parts of the lake.



Annual average water temperature

Since 1970

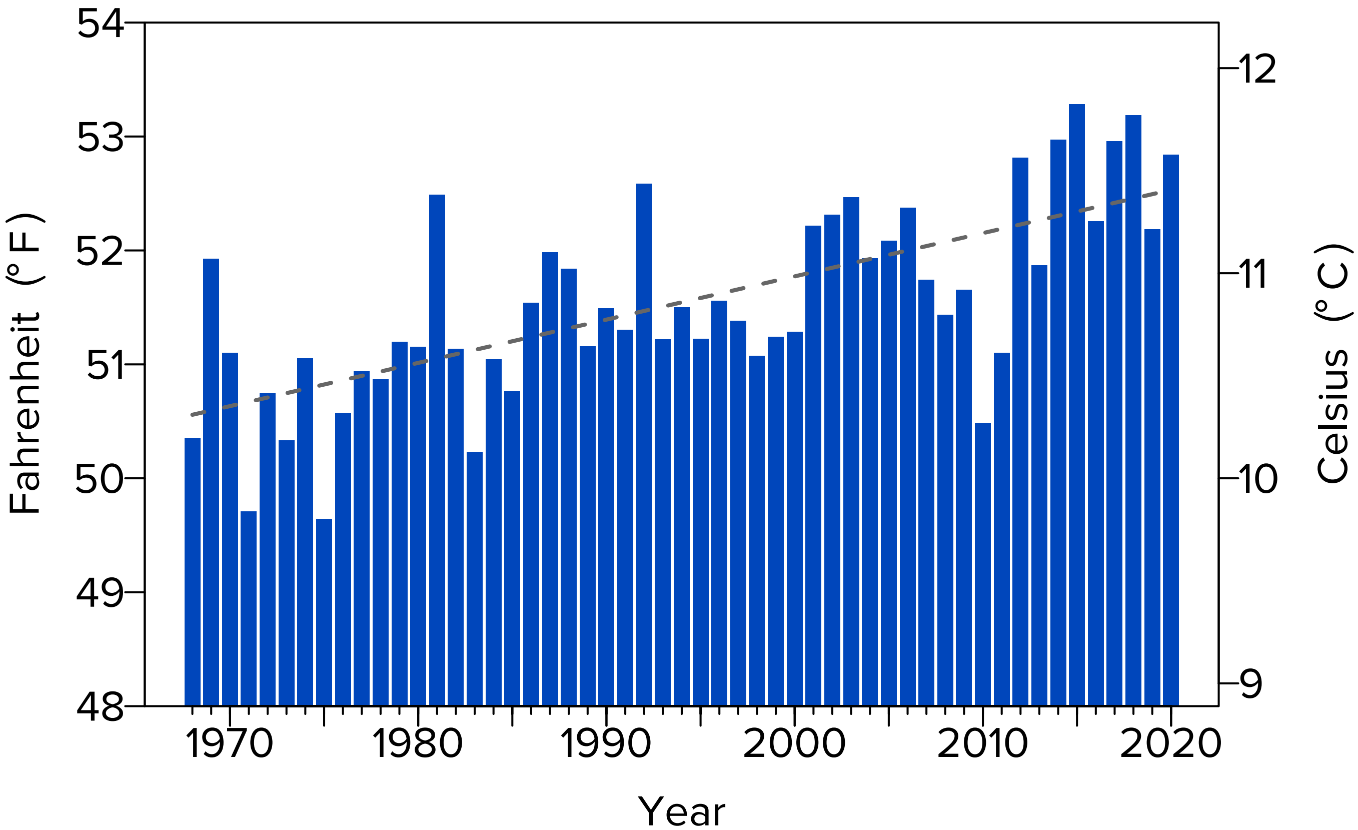
The volume-averaged temperature of the lake for each year since 1970 is shown. The trend line indicates that water temperature has increased by approximately 1.1 °F (0.61°C) since 1970. The annual rate of warming is 0.22 °F/decade (0.12 °C/decade). The monthly temperature profile data from the top to the bottom of the lake has been smoothed, and seasonal influences removed to best show the long-term trend. Up until the late 1990s, the warming rate was high, but there were still a relatively large number of deep mixing years between 1997 and 2011, plus top to bottom mixing in 2019 caused the average lake temperature to cool. However, the longer-term warming trend appears to be returning.



Annual surface water temperature

Yearly since 1968

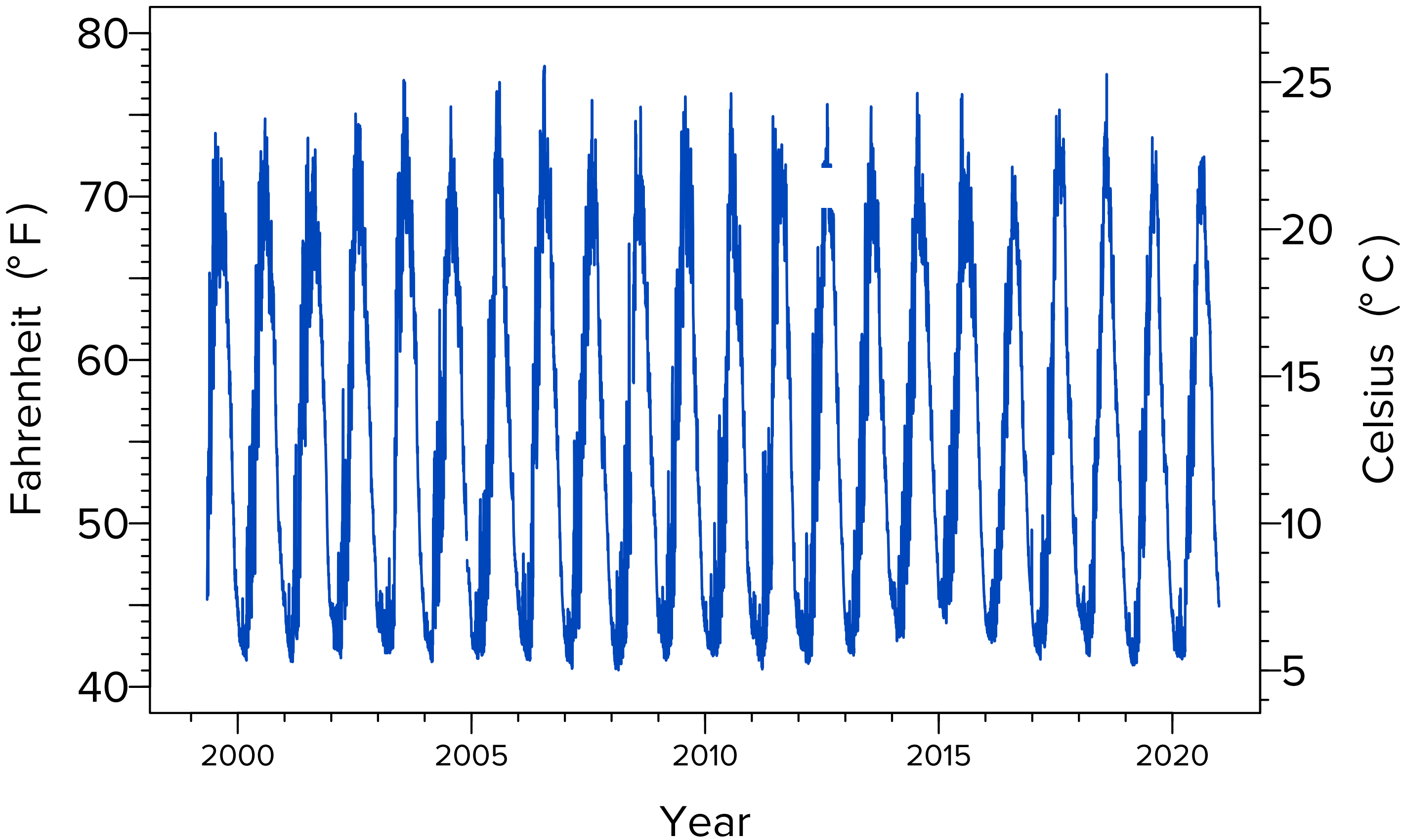
Surface water temperatures have been recorded monthly at the Mid-lake and Index stations from TERC's research vessels since 1968. Despite year-to-year variability, the annual average surface water temperatures show an increasing trend. The average temperature in 1968 was 50.4 °F (10.2 °C). For 2020, the average surface water temperature was 52.8 °F (11.6 °C), warmer than in 2019. The overall rate of warming of the lake surface is 0.38 °F (0.21 °C) per decade.



Maximum daily surface water temperature

Surface temperature measured since 1999 every 2 minutes

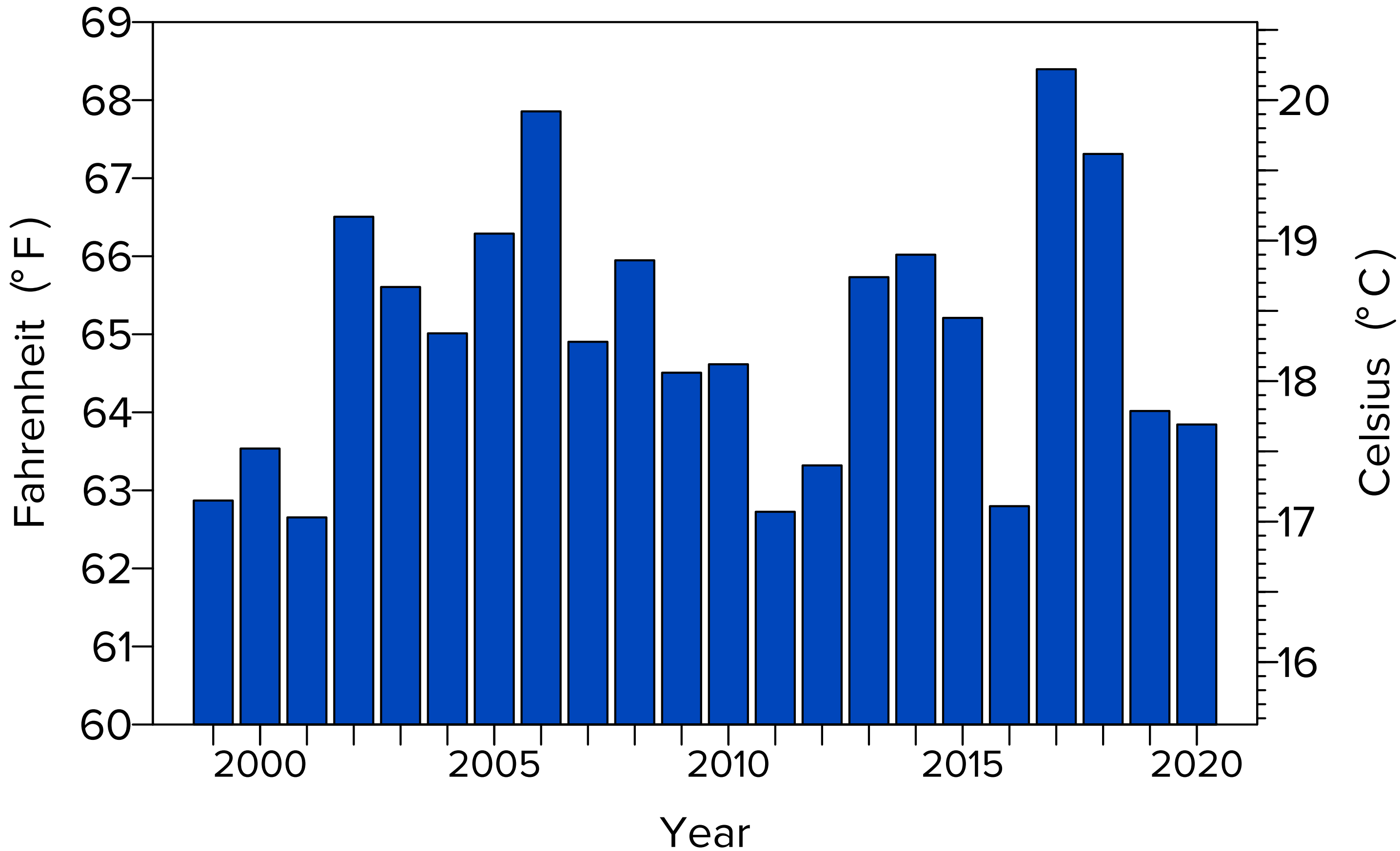
The maximum daily surface water temperature of summer 2020 was one of the coolest since continuous data collection commenced in 1999. The highest maximum daily surface water temperature (summer) was 72.4 °F (22.5 °C), recorded on September 5, 2020. These low summer temperatures may have been influenced by the wildfire smoke that blanketed the region. The lowest maximum daily surface water temperature (winter) was 41.7 °F (5.4 °C), which was recorded on March 17, 2020. This was relatively warm, owing in part to the absence of deep mixing. These data are collected in real-time by NASA-JPL and UC Davis from four buoys located over the deepest portions of the lake.



July average surface water temperature

Measured since 1999 every 2 minutes

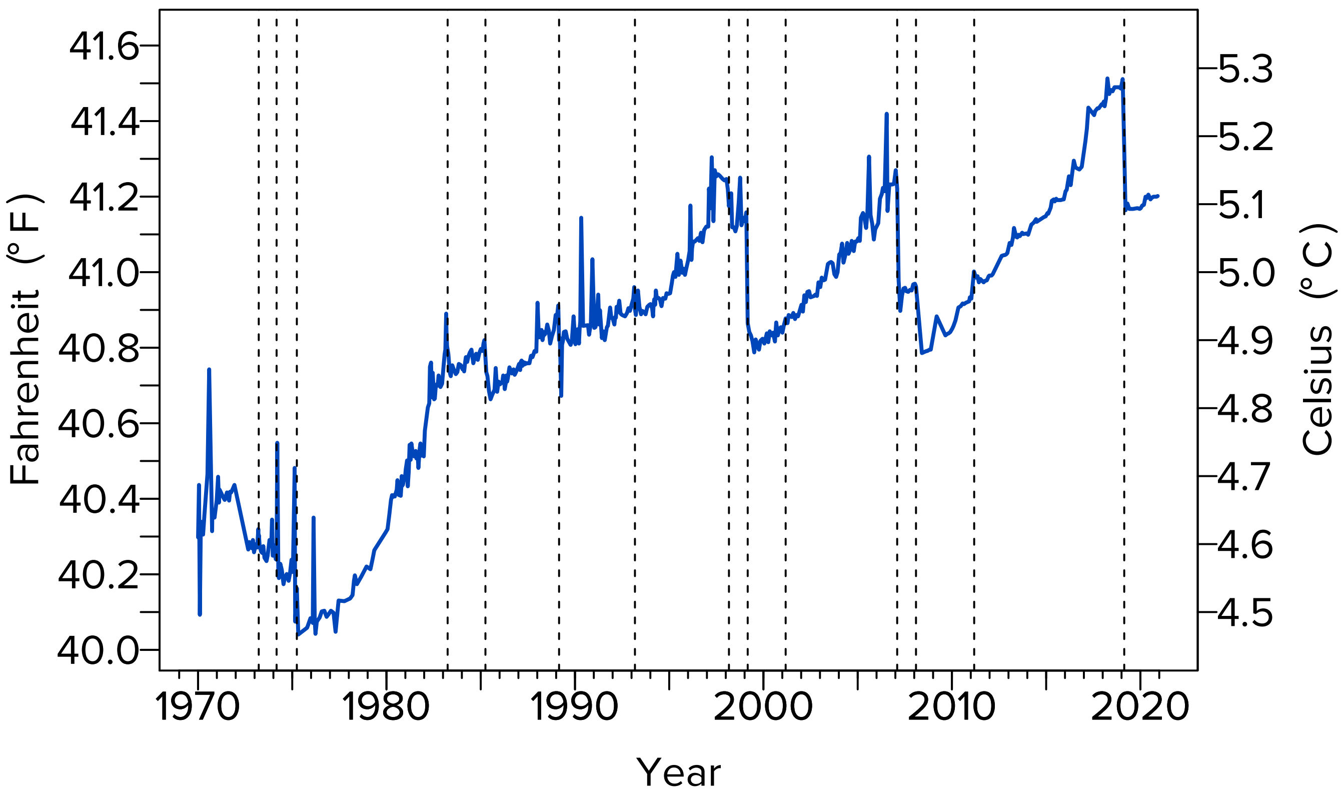
Surface water temperature has been continuously recorded since 1999 from four NASA/UC Davis buoys over the deepest portions of the lake. Shown here are 22 years of average surface water temperatures in the month of July when water temperatures are typically warm and the greatest number of people are swimming in the lake. In 2020, July surface water temperature averaged 63.8 °F. This was 1.2 °F below the average of 65.0 °F for the entire 22-year period of record. The warmest July temperature was 68.4 °F in 2017.



Deep water temperature

Monthly since 1970

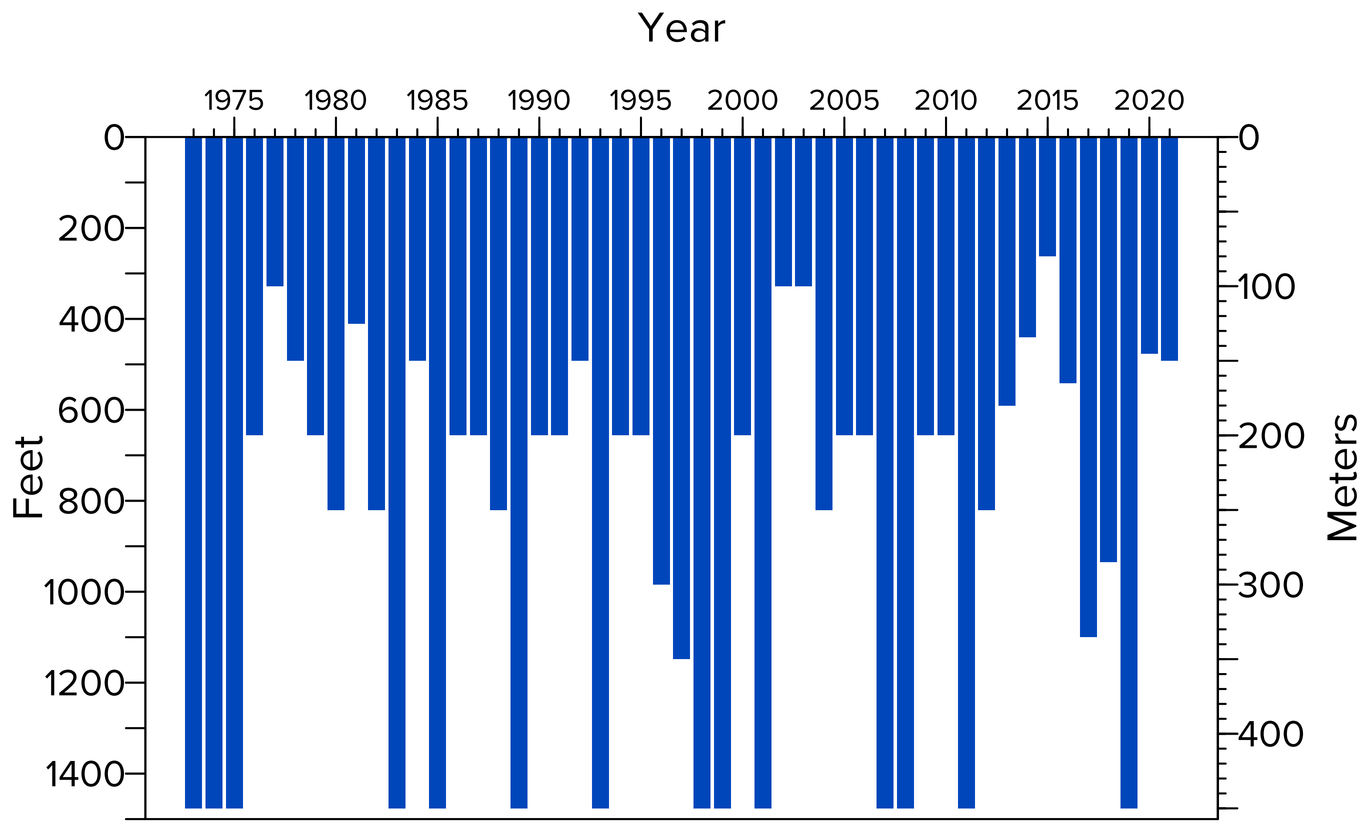
The water temperature at a depth of 1,320 feet (400 m) is indicative of conditions in the deeper waters (hypolimnion) of Lake Tahoe. The deep-water temperatures show a complex pattern of warming and sudden cooling. Warming, due to geothermal heat input, occurs when the lake does not mix deeply. During deep mixing events (shown by the dashed lines), the temperature can drop "precipitously" over a short period of time, although these drops are generally less than 0.3 °F. Generally, bottom temperatures are warming. In 2020, there was no deep mixing (see Fig. 8.9) and deep water temperatures rose slightly. Between the last two deep mixing events in 2011 and 2019, the rate of deep 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. The short spikes of temperature increase during the warming phases are temporary effects caused by the motions of internal waves and other lake motions in the hypolimnion.



Depth of mixing

Yearly since 1973

Lake Tahoe mixes each winter as surface waters cool and sink downward. In a lake as deep as Tahoe, the intense cooling of winter helps to determine how deep the lake mixes vertically. 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. The deepest mixing typically occurs between February and March. On February 6, 2020, Lake Tahoe was observed to have mixed to a depth of 476 feet (145 m). This relatively shallow mixing likely contributed to the warmer surface temperatures experienced during winter. On March 17, 2021, Lake Tahoe was observed to have mixed to a maximum depth of 492 feet (150 m). 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.

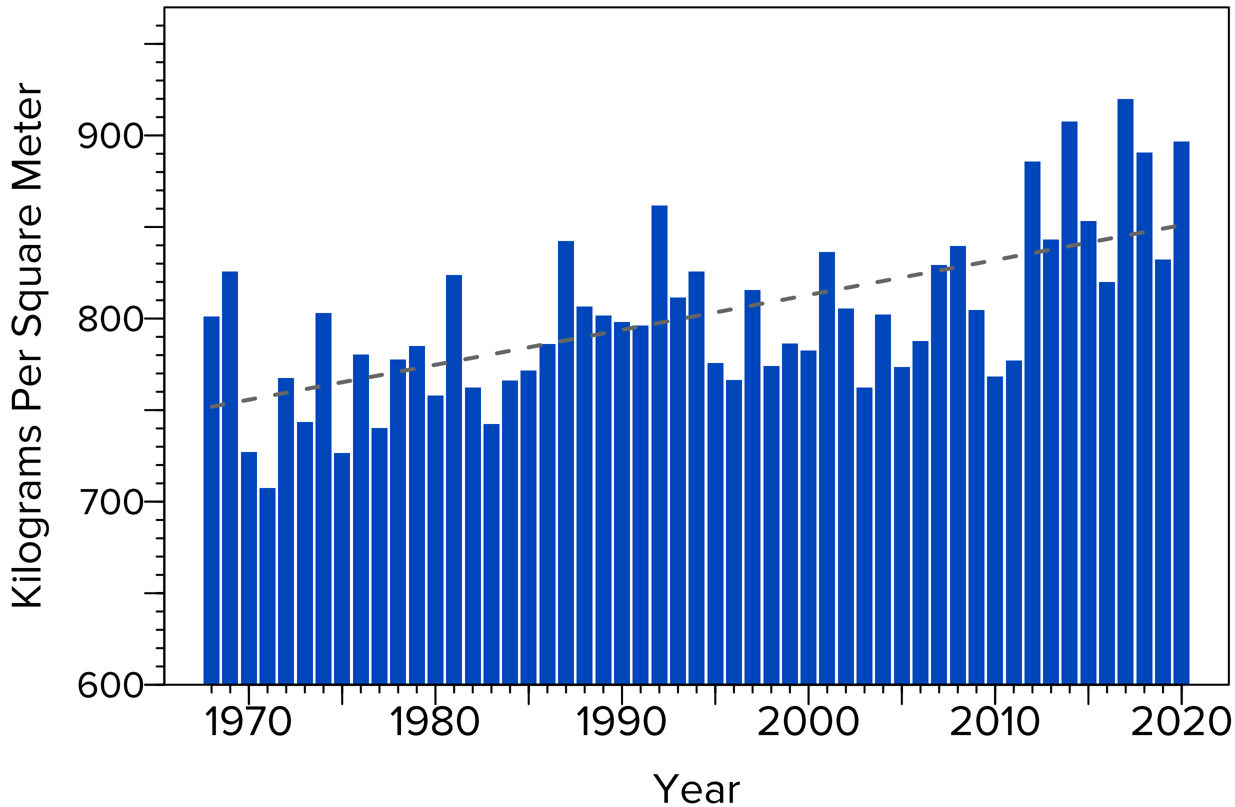


Lake stability index

Since 1968

When the lake has a vertical distribution of temperature, it has a corresponding distribution of density, with warm and lighter water at the surface and colder, denser water below. As the temperature difference 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 fully mix the water column 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 10–20 day intervals. There has been an overall increase in lake stability by over 13% in the last 52 years.

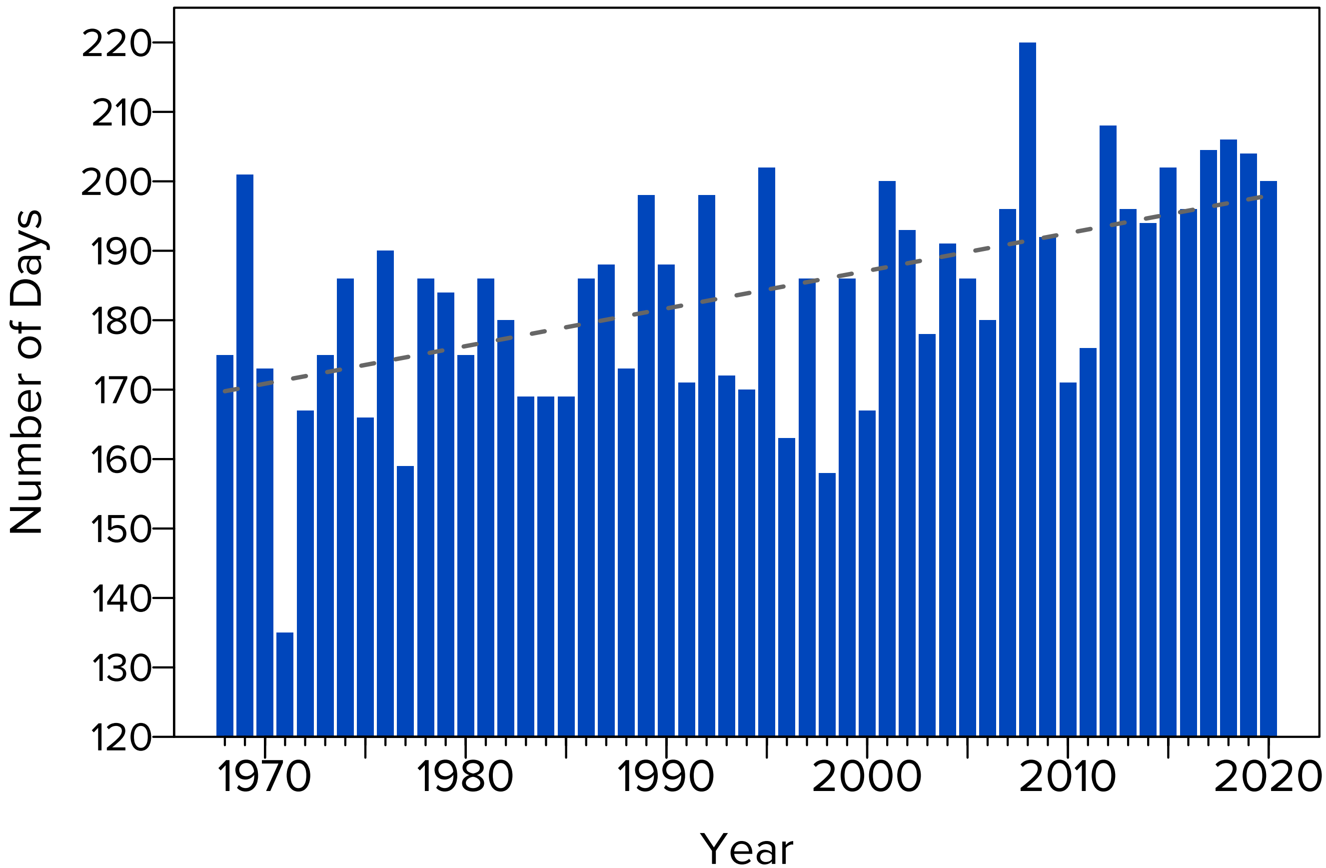
In 2020, the stability index was the third highest ever recorded.



Stratified season length

Since 1968

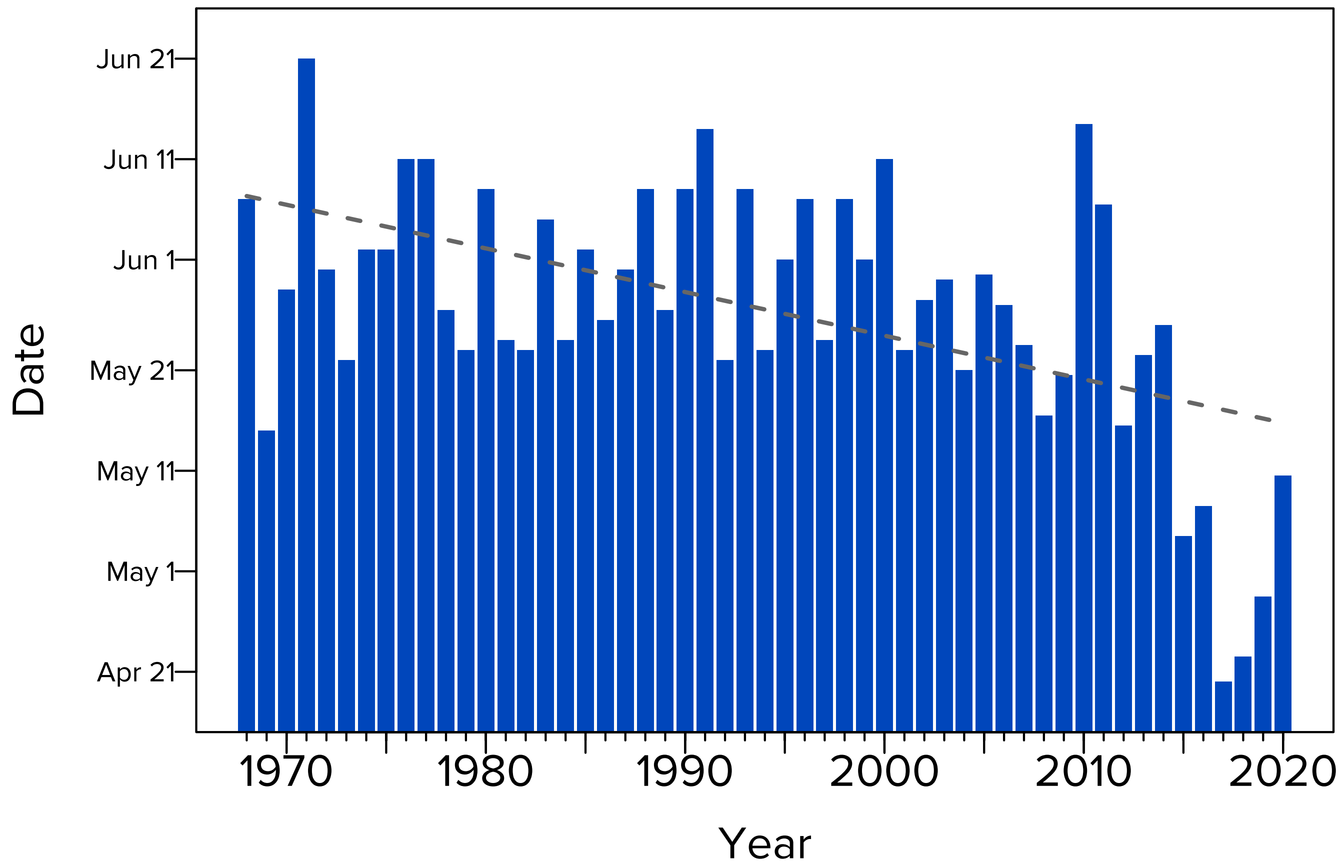
The stability index is a measure of the energy required to mix the lake and can be evaluated for every day of the year. We define the stratification season as the number of days when the stratification index exceeds a value of 600 kilograms per square meter. Since 1968, the length of the stratification season has increased, albeit with considerable year-to-year variation. Overall, the stratification season has lengthened by 28 days since 1968. In 2020, the length of the stratified season was 200 days.



Beginning of the stratification season

Since 1968

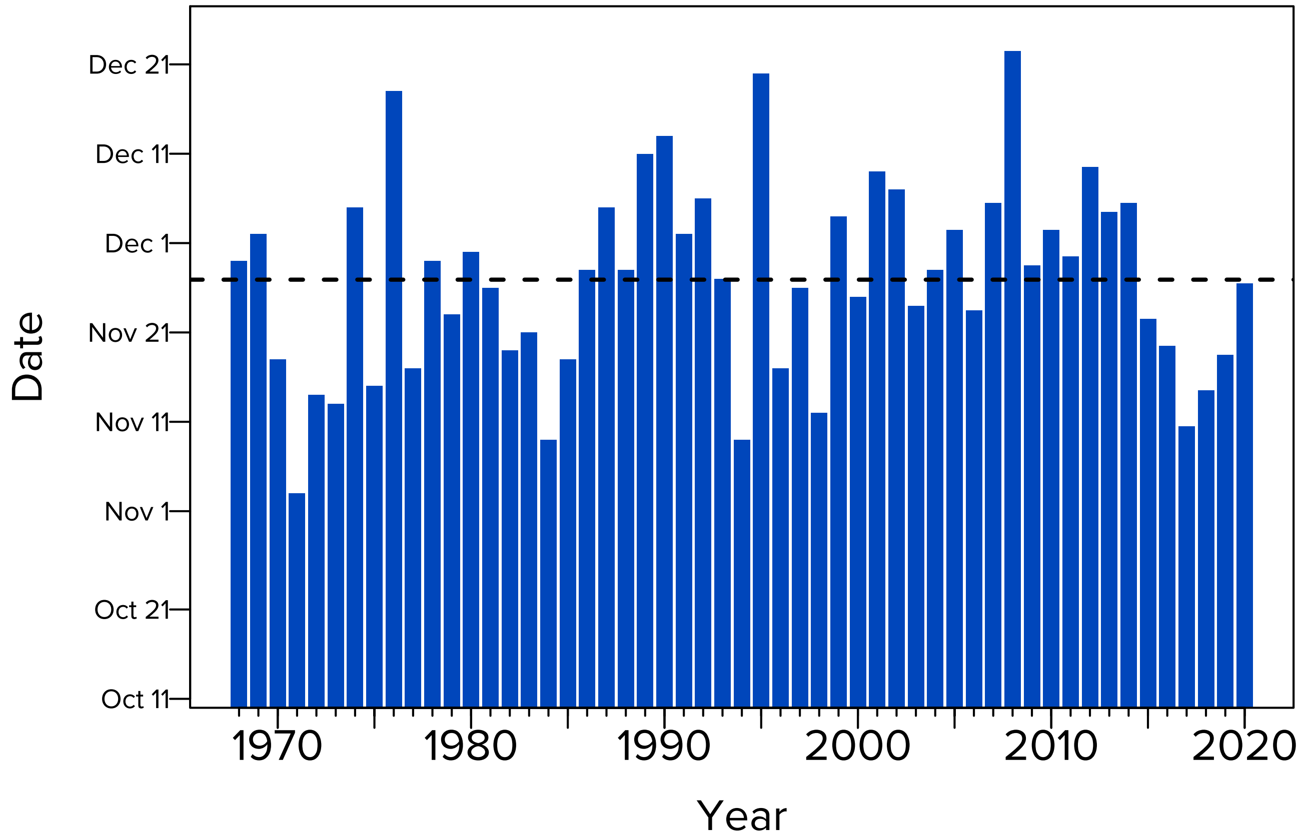
The amount of time that Lake Tahoe is stratified has been lengthening since 1968. One reason for this is the increasingly early arrival of spring as evidenced by the earlier commencement of stratification. Stratification occurs approximately 22 days earlier than it did in 1968. The commencement of the stratification season is typically in late May or early June. In 2020, stratification began on May 9 (Day 129).



End of stratification season

Since 1968

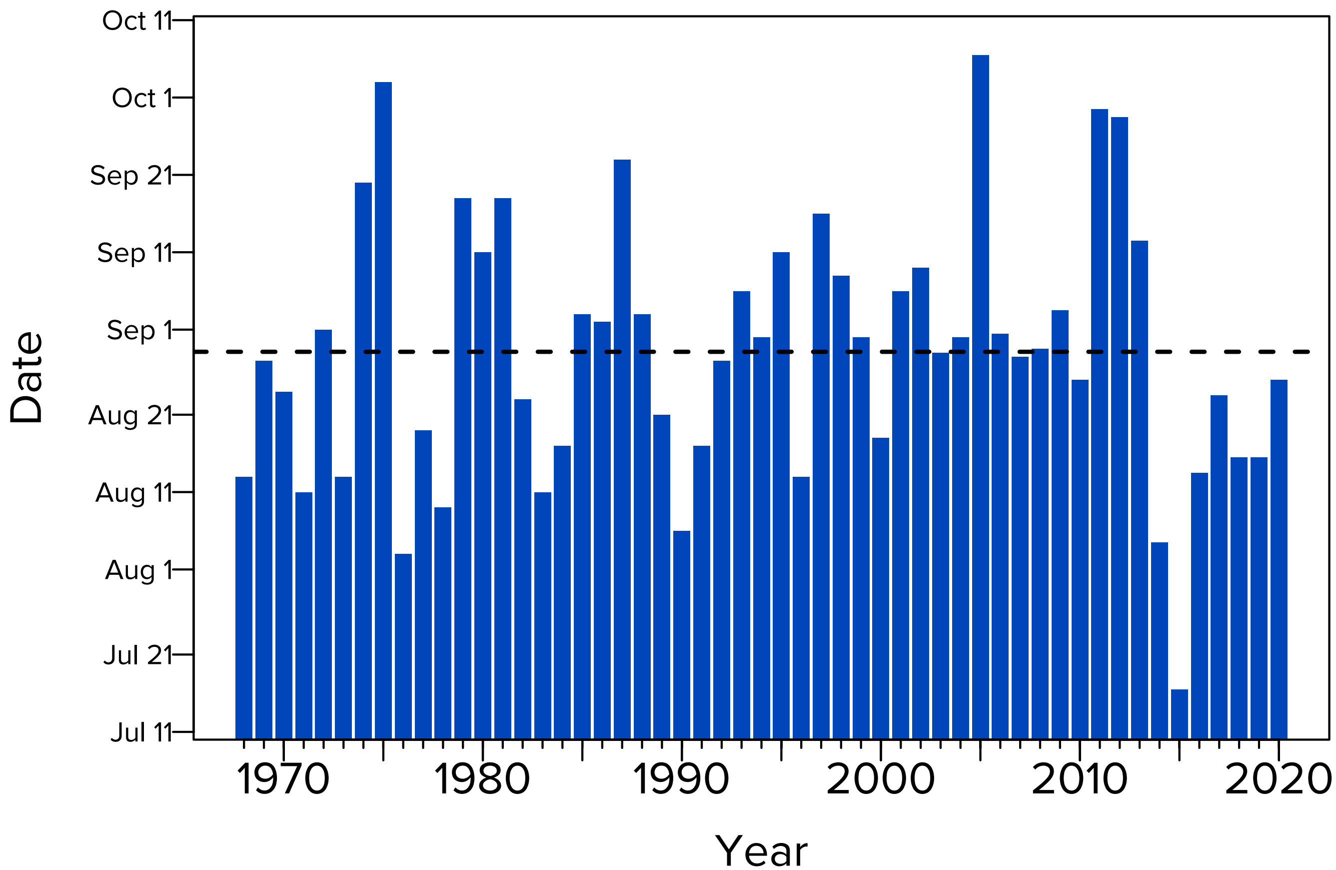
The amount of time that Lake Tahoe is stratified has lengthened by almost a month since 1968. The end of the stratification season has been extended, but not as much as the onset of stratification has been advanced (Fig. 8.12). Over the 52-year record, the end of stratification has been extended by approximately six days. This can have important implications for lake mixing and water quality, such as the buildup of nitrate at the bottom portions of the lake.



Peak of stratification season

Since 1968

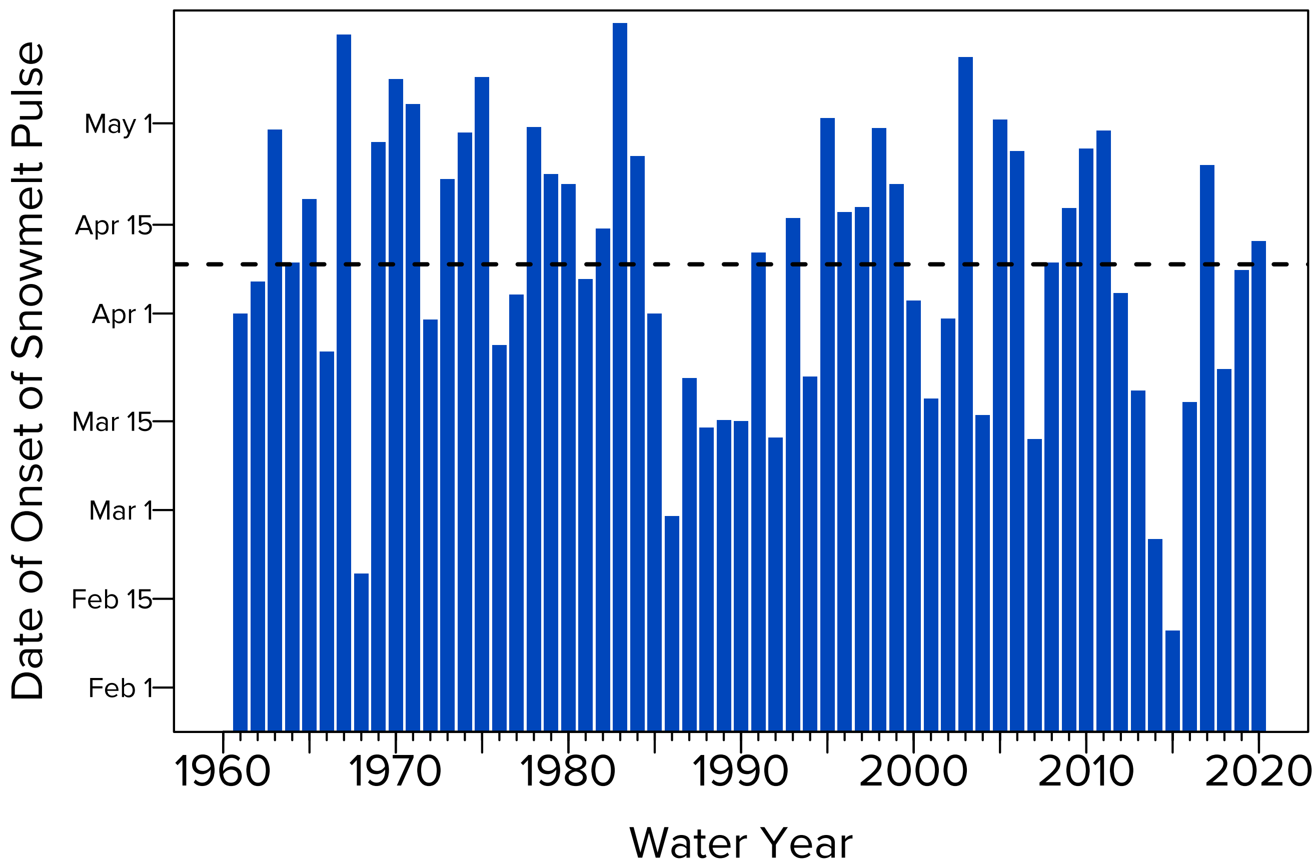
The day of the year when lake stratification reaches its maximum value has been plotted. There is considerable year-to-year variation, but over time little has changed in when the peak occurs. In 2020, the peak occurred on August 29, which is close to the long-term average (dashed line).



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 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 2020, the onset occurred on April 11, slightly later than the long-term average. 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, we used the peak of the stream hydrograph to estimate this property.



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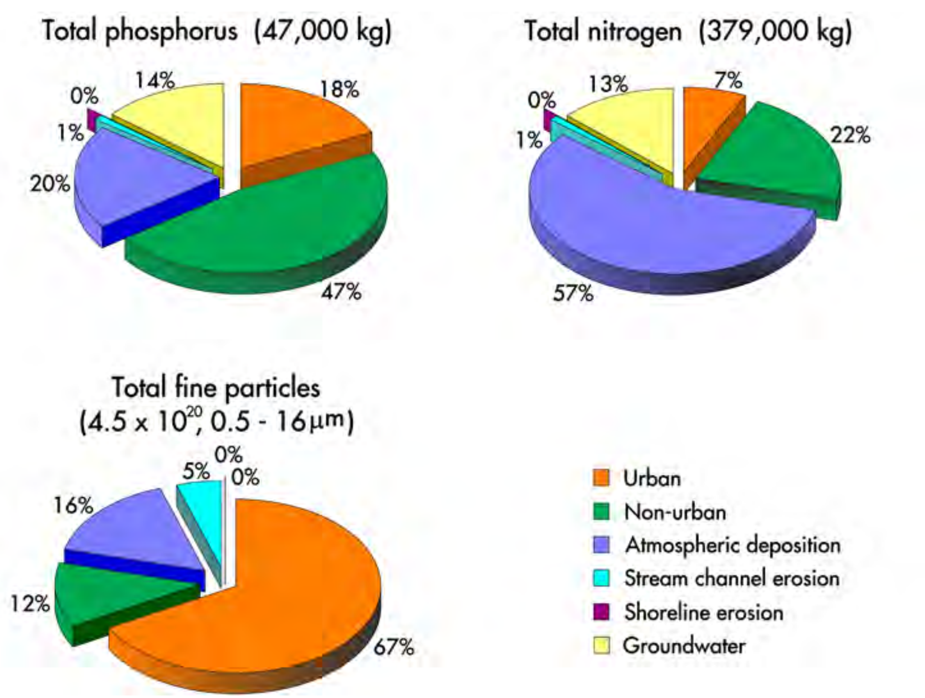
STATE
OF THE
LAKE
REPORT
2021

NUTRIENTS AND PARTICLES

UC DAVIS
Tahoe Environmental
Research Center

Sources of clarity-reducing and blueness-reducing pollutants

Research has quantified the primary sources of nutrients (nitrogen and phosphorus) and 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 stormwater that originate from the urban watershed (67 percent), even though these areas cover only 10 percent of the basin's land area. Part of the atmospheric particle load is also from these urbanized areas. 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.

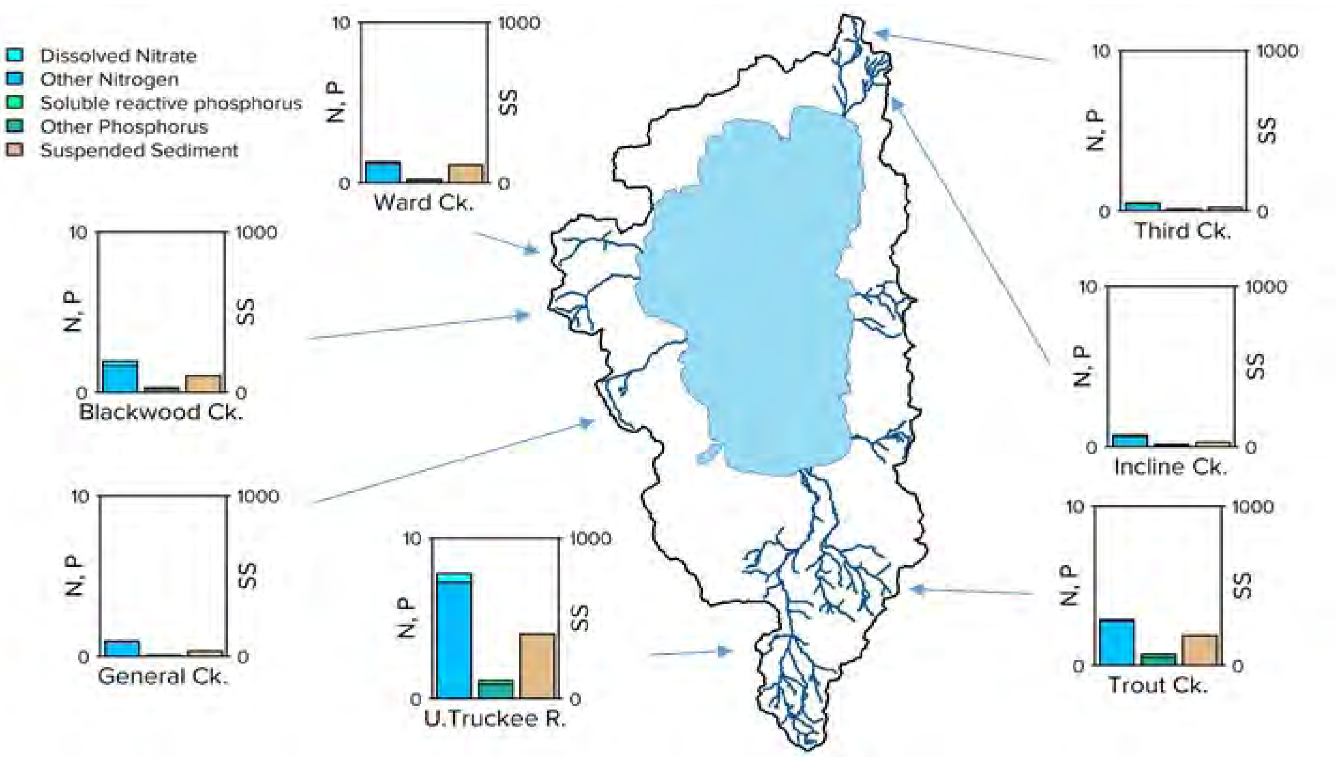


Pollutant loads from seven watersheds

In 2020

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 2020, 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 Incline Creek and Blackwood Creek, can also be very significant contributors.

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

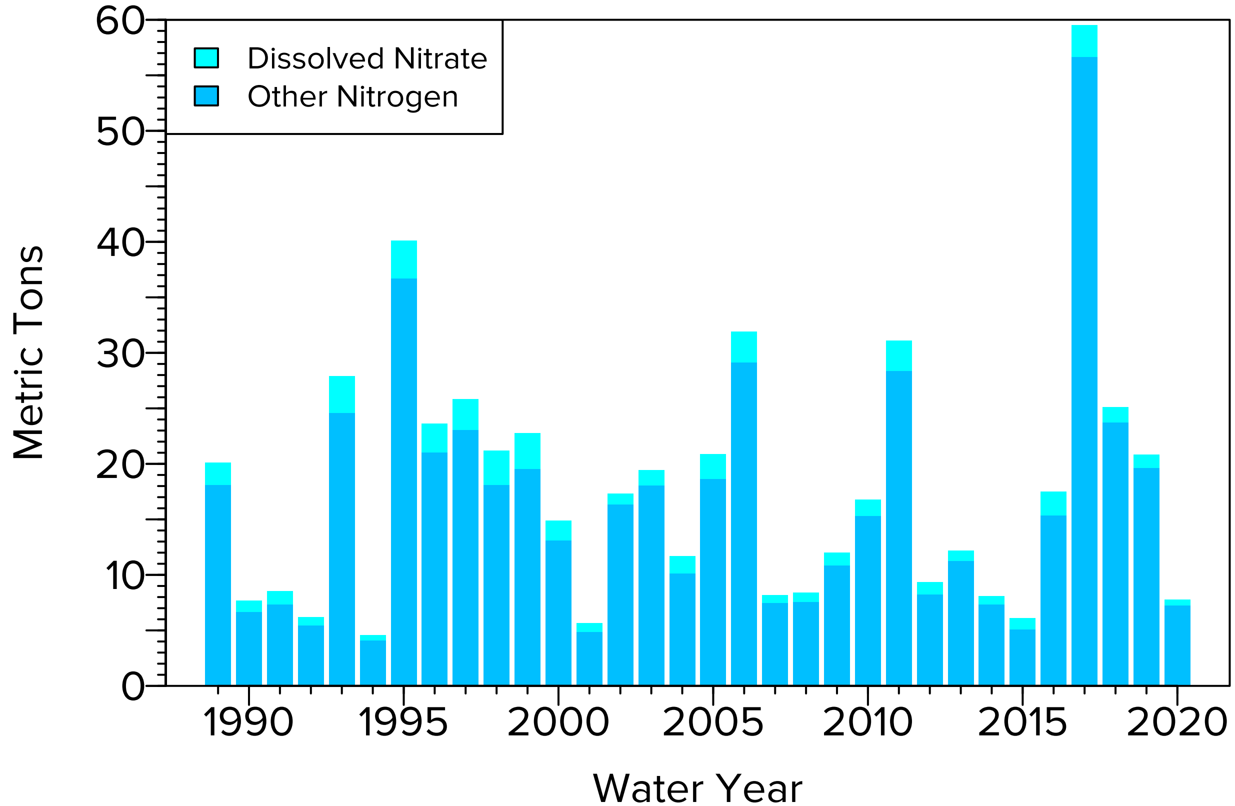


Nitrogen contribution by Upper Truckee River

Yearly since 1989

Nitrogen (N) is important because it, along with phosphorus (P), stimulates algal growth. The Upper Truckee River is the largest of the 63 streams that flow into Lake Tahoe, contributing about 25 percent of the inflowing water. The river's contribution of dissolved nitrate and the remainder of the total nitrogen load are shown here. 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. 2020 had 20.1 inches of precipitation and an above-average total nitrogen load of 7.8 MT. Nitrate load was 0.52 MT The long-term mean annual total nitrogen load is 17.9 MT/yr while the for nitrate it is 1.7 MT.

One metric ton (MT) = 2,205 pounds.

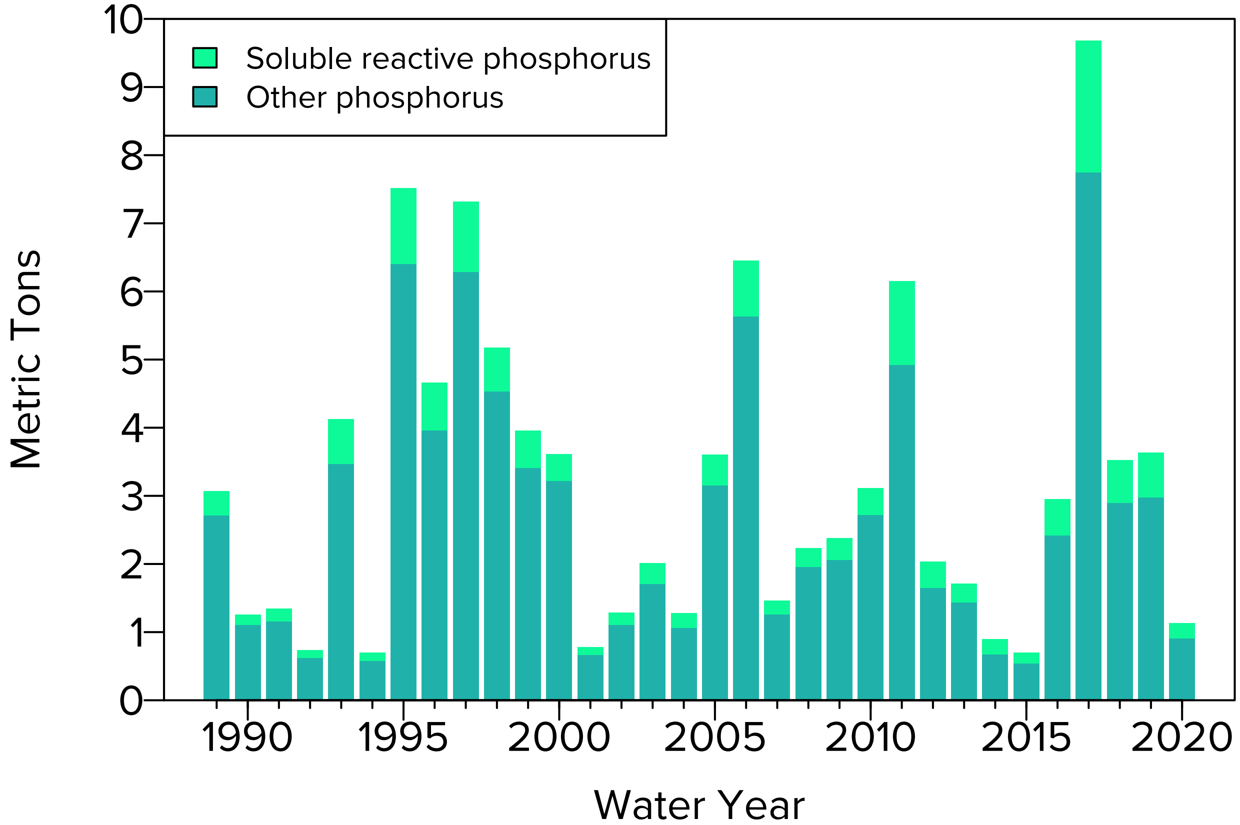


Phosphorus contribution by Upper Truckee River

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 load largely reflects the changes in precipitation. Below average precipitation in 2020 resulted in a total phosphorus level of 1.1 MT and SRP load of 0.23 MT. These compare with the long-term averages of 3.1 and 0.49 MT respectively. 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.

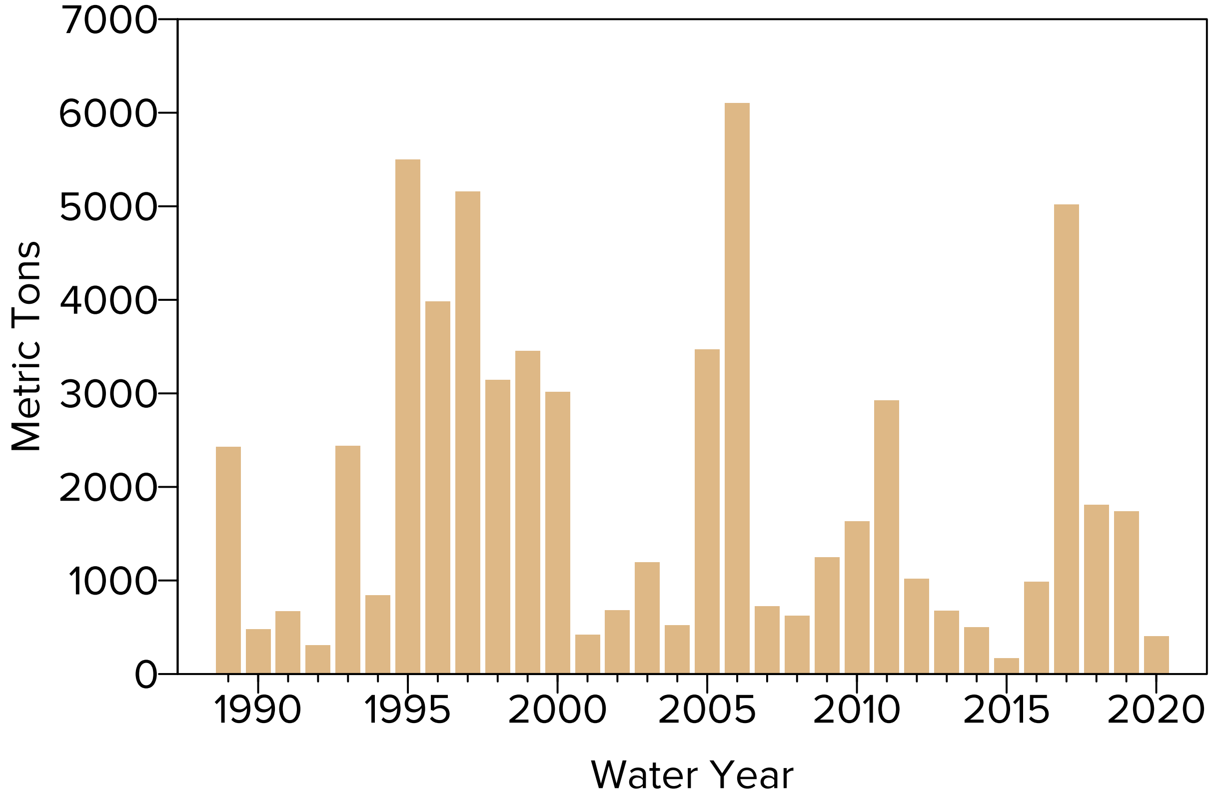
One metric ton (MT) = 2,205 pounds.



Suspended sediment contribution by Upper Truckee River

Yearly since 1989

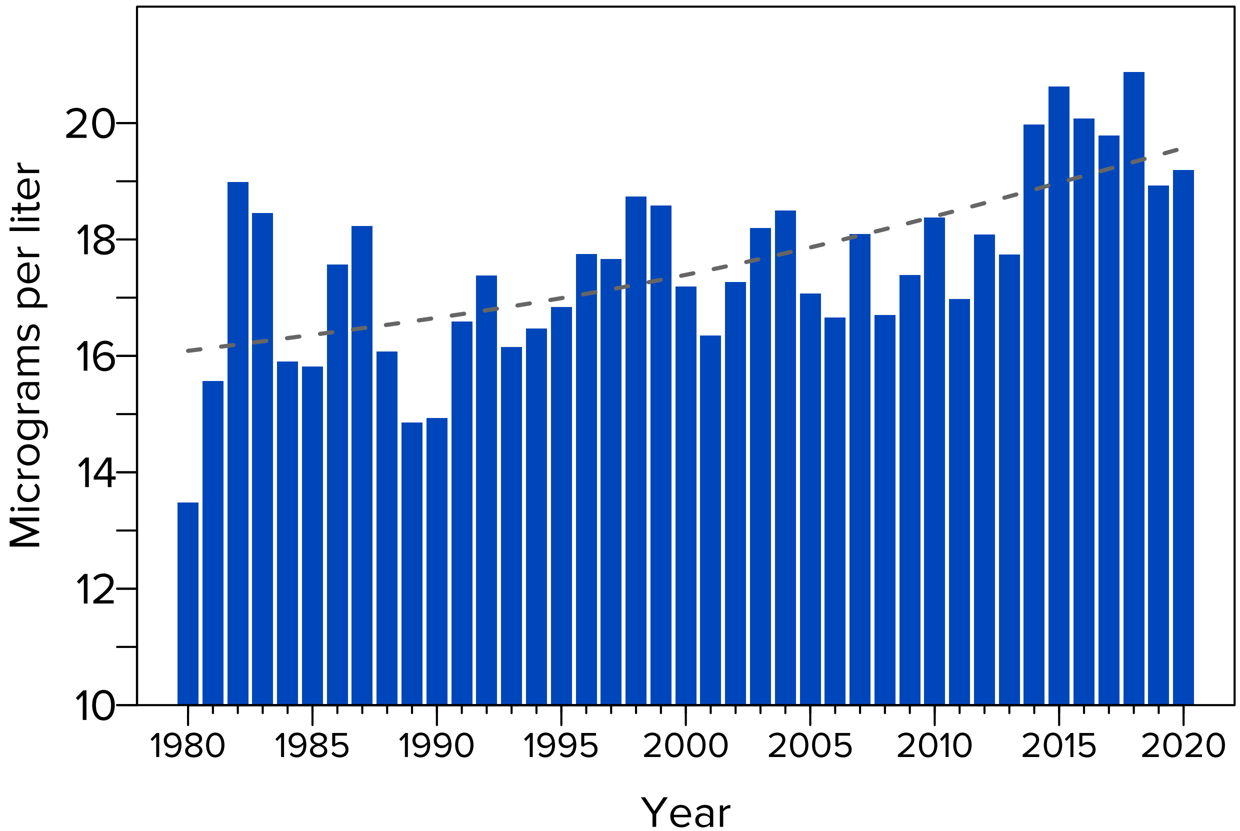
The load of total suspended sediment delivered to the lake by the Upper Truckee River is related to landscape condition and erosion as well as to precipitation and stream flow. Inter-annual variation in sediment load over shorter time scales is more related to the latter. Plans to restore lake clarity emphasize reducing loads of very fine suspended sediment (in the size range of 1–4 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 2020, the suspended sediment load from the Upper Truckee River was 404 MT. The highest load ever recorded was 6100 MT in 2006. The average annual load is 1,977 MT.



Lake nitrate concentration

Yearly since 1980

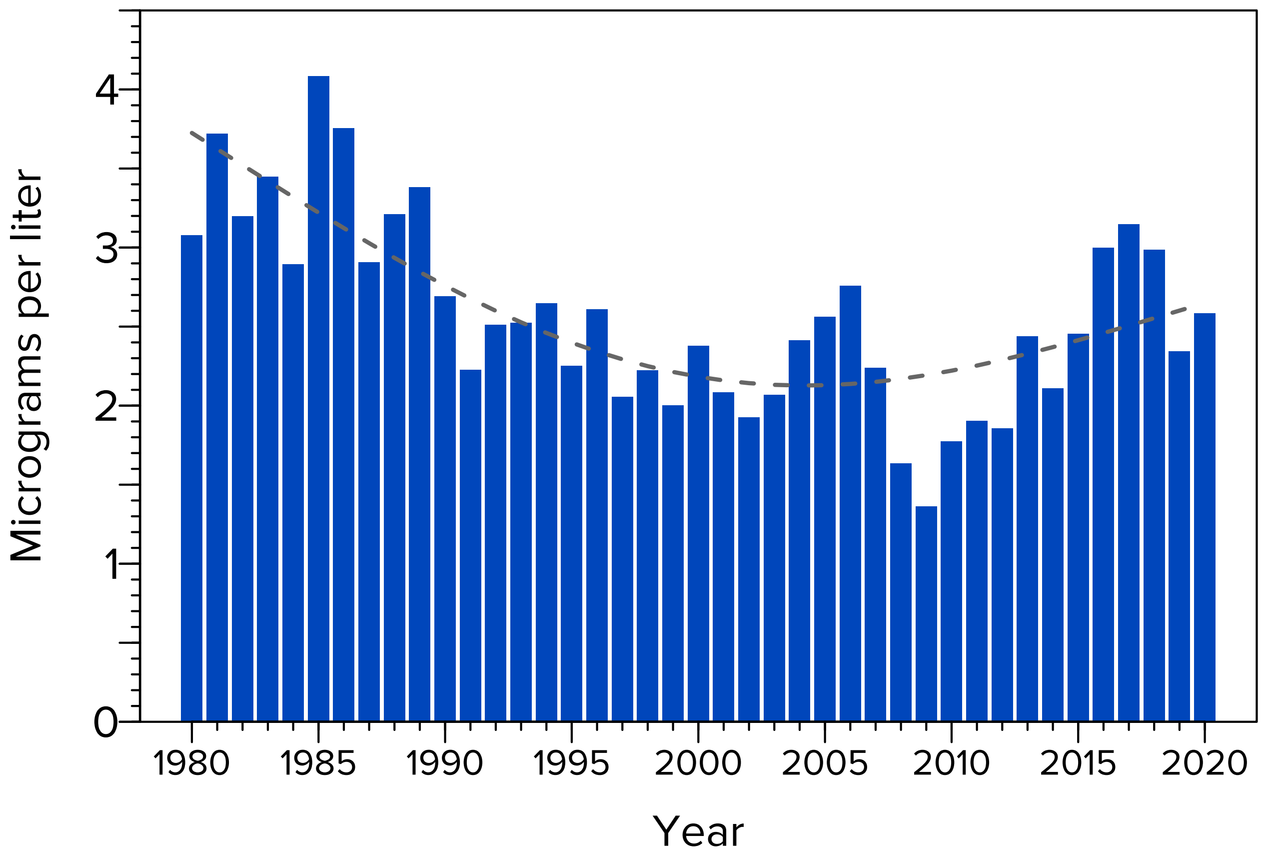
Until 2012, the volume-weighted annual average concentration of nitrate-nitrogen had remained relatively constant year-to-year, ranging between 13–19 micrograms per liter. Since that time, however, the lake's nitrate concentration has been increasing, as evident in the trend line produced with a Generalized Additive Model. In 2020, the volume-weighted annual average concentration of nitrate-nitrogen was 19.2 micrograms per liter. The previous year (2019), lake nitrate concentration declined due to the deep mixing that occurred and redistributed the nitrate that had been accumulating at the bottom of lake for the previous eight years, making it available for algal uptake. In 2020, with only shallow mixing, nitrate has recommenced accumulating, resulting in an increase in lake nitrate concentration. Water samples are taken at the MLTP (mid-lake) station at 13 depths from the surface to 1,480 feet.



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 had been declining although in the last 16 years the values have been increasing. In 2020, the volume-weighted annual average concentration of THP was 2.59 micrograms per liter. Water samples are taken at the MLTP (mid-lake) station at 13 depths from the surface to 1,480 feet.



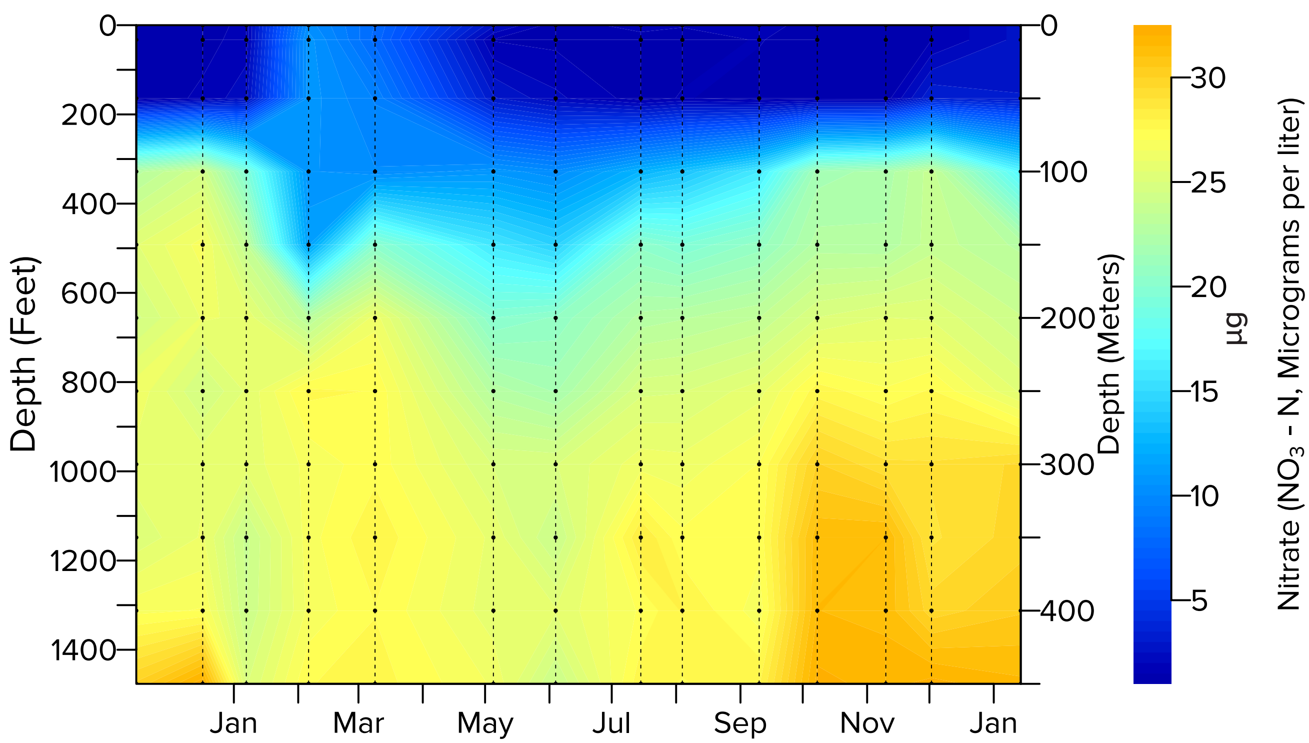
Nitrate distribution

In 2020

Water samples are collected from the middle of the lake approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) 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 mixing did not homogenize the nitrate distribution. Instead, a sharp "nitricline" is evident between depths of 300 and 600 feet throughout the year.

Although most of the "new" 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.

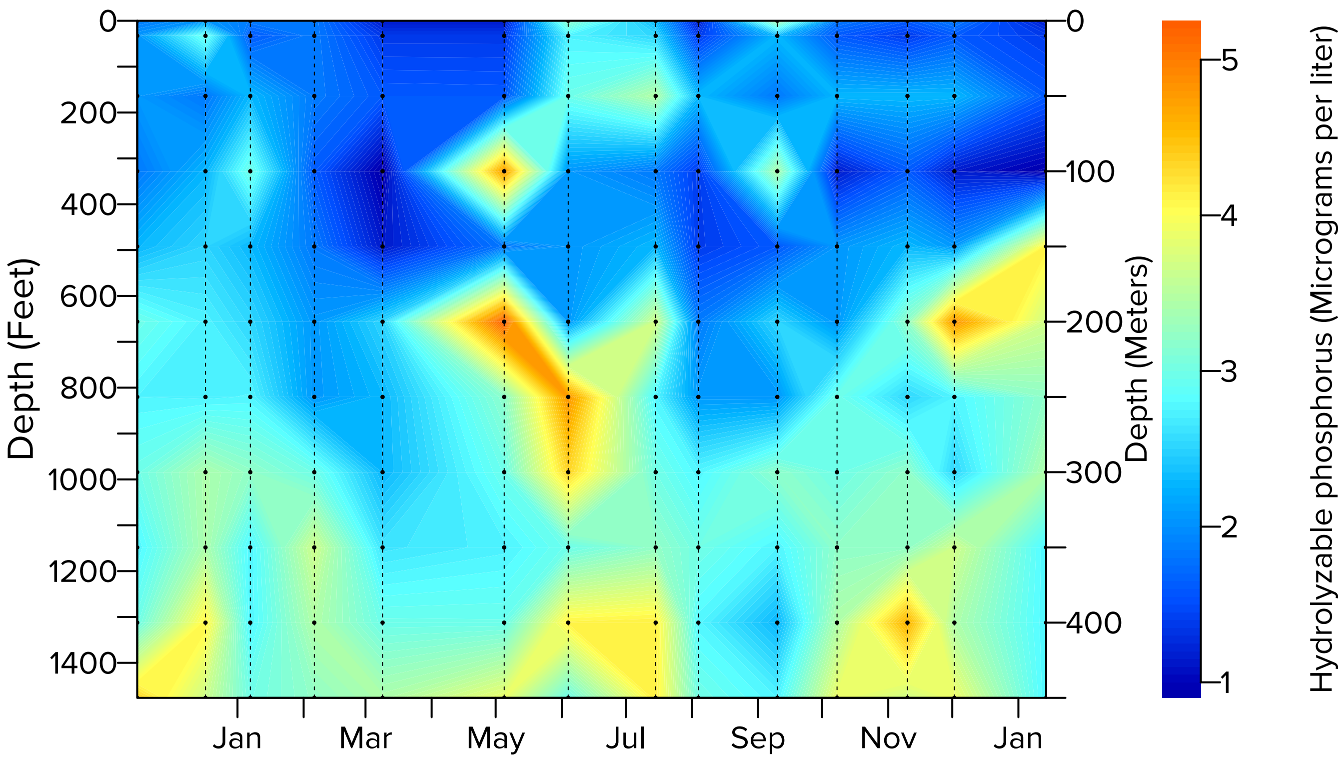


Total hydrolyzable phosphorus distribution

In 2020

Water samples are collected from the middle of the lake approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) 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 April through June. The relatively elevated values near the surface in spring and summer suggest that in 2020, nitrogen was the nutrient that limited algal growth, rather than phosphorus during that time period. The elevated concentrations of phosphorus deep in the lake throughout the year were the result of the absence of deep mixing in 2020.



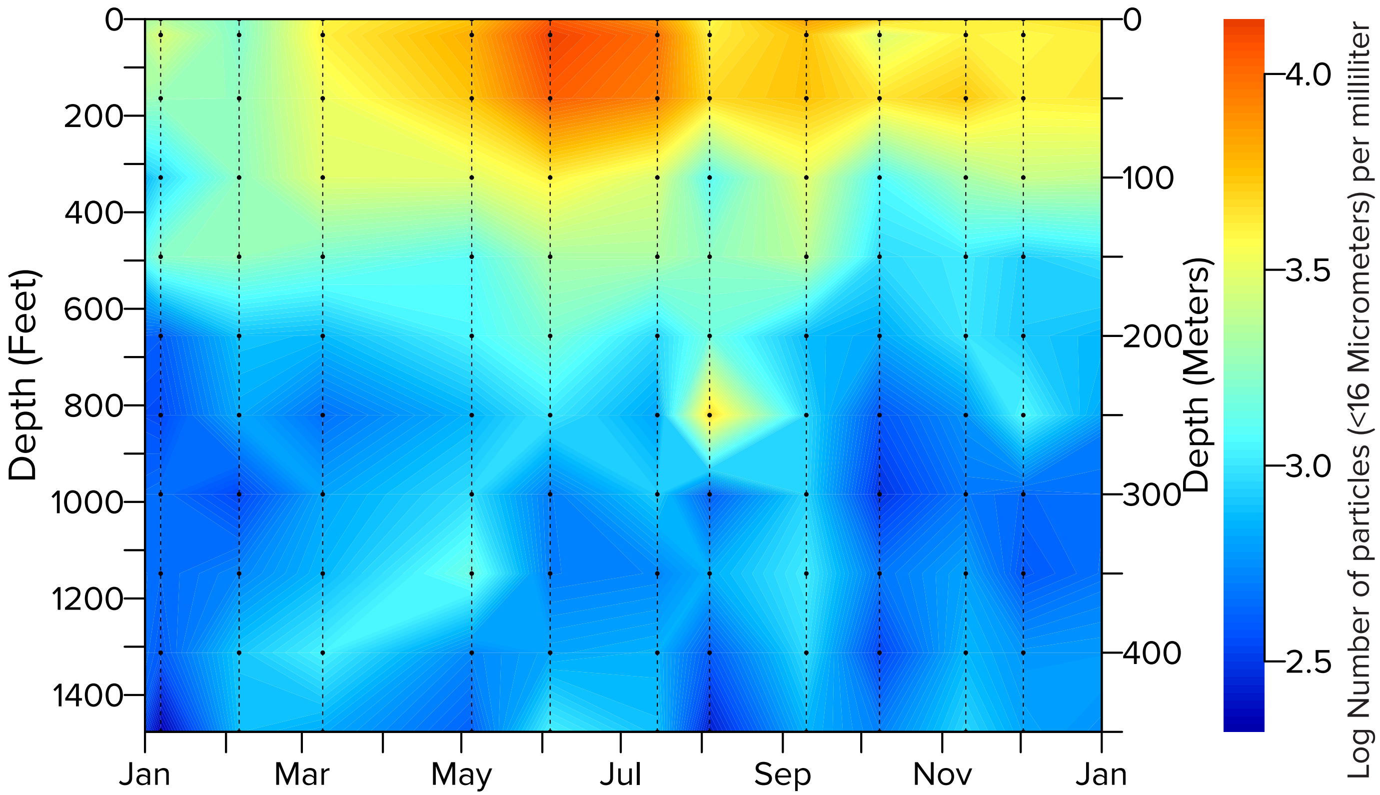
Fine particle distribution

In 2020

Water samples are collected from the middle of the lake approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) and analyzed in the TERC laboratory for the concentration of fine particles in 15 different bin sizes.

Here the distributions of fine particles (in the size range of 1–4 microns) are shown in the form of color contours. Particles can be both inorganic particles (such as clay or silt) or very small algal diatom particles.

Unlike the nutrients in Figs. 9.8 and 9.9, 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 July. The particles do not decrease in the upper layer as quickly as nitrogen or phosphorus, as they are not taken up by algal growth. The fine inorganic particles gradually clump together (aggregate) which allows them to more rapidly settle to the lake sediments at the bottom.



TAHOE: STATE OF THE LAKE REPORT 2021

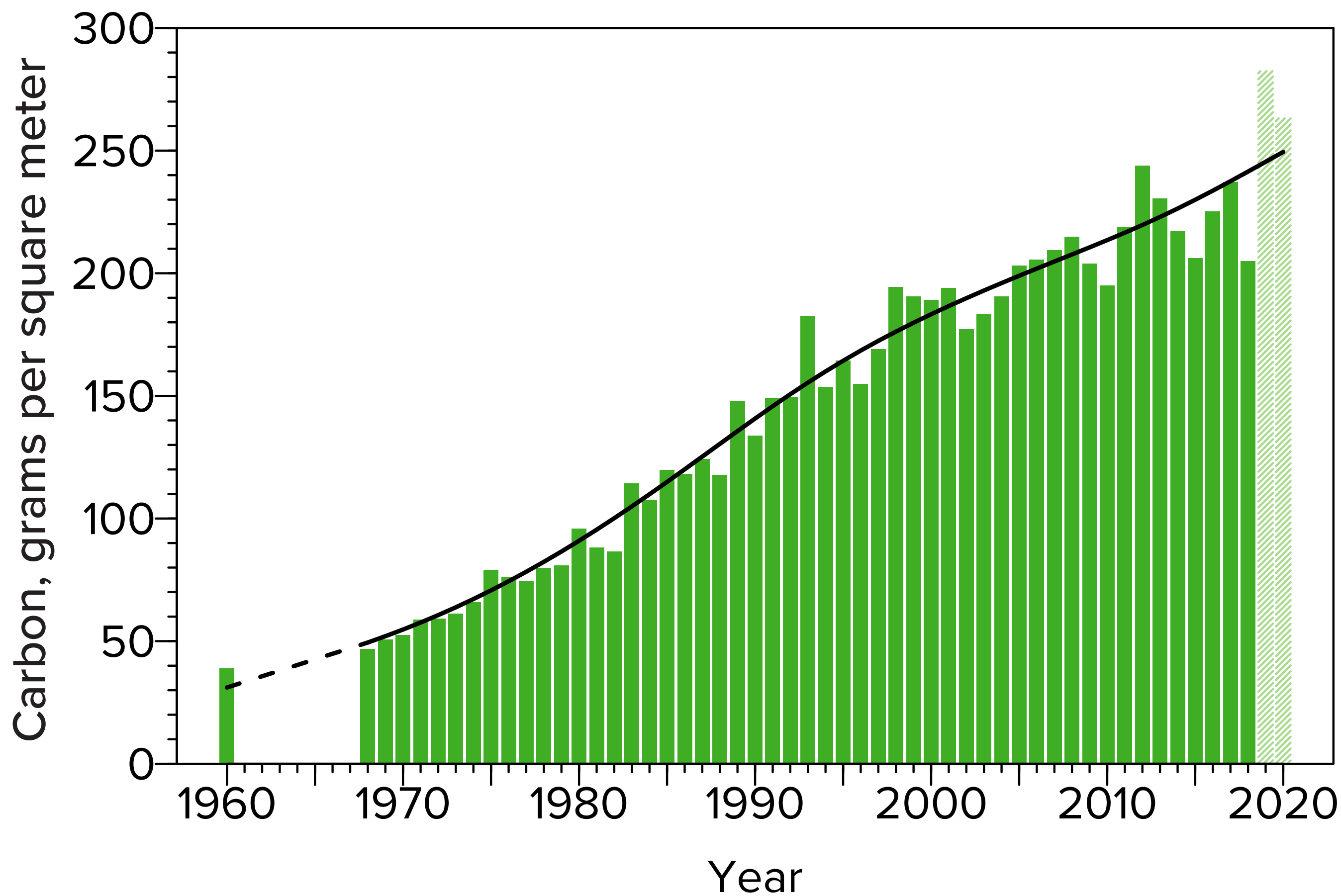
BIOLOGY

UC DAVIS
Tahoe Environmental Research Center

Algae growth (primary productivity)

Yearly since 1959

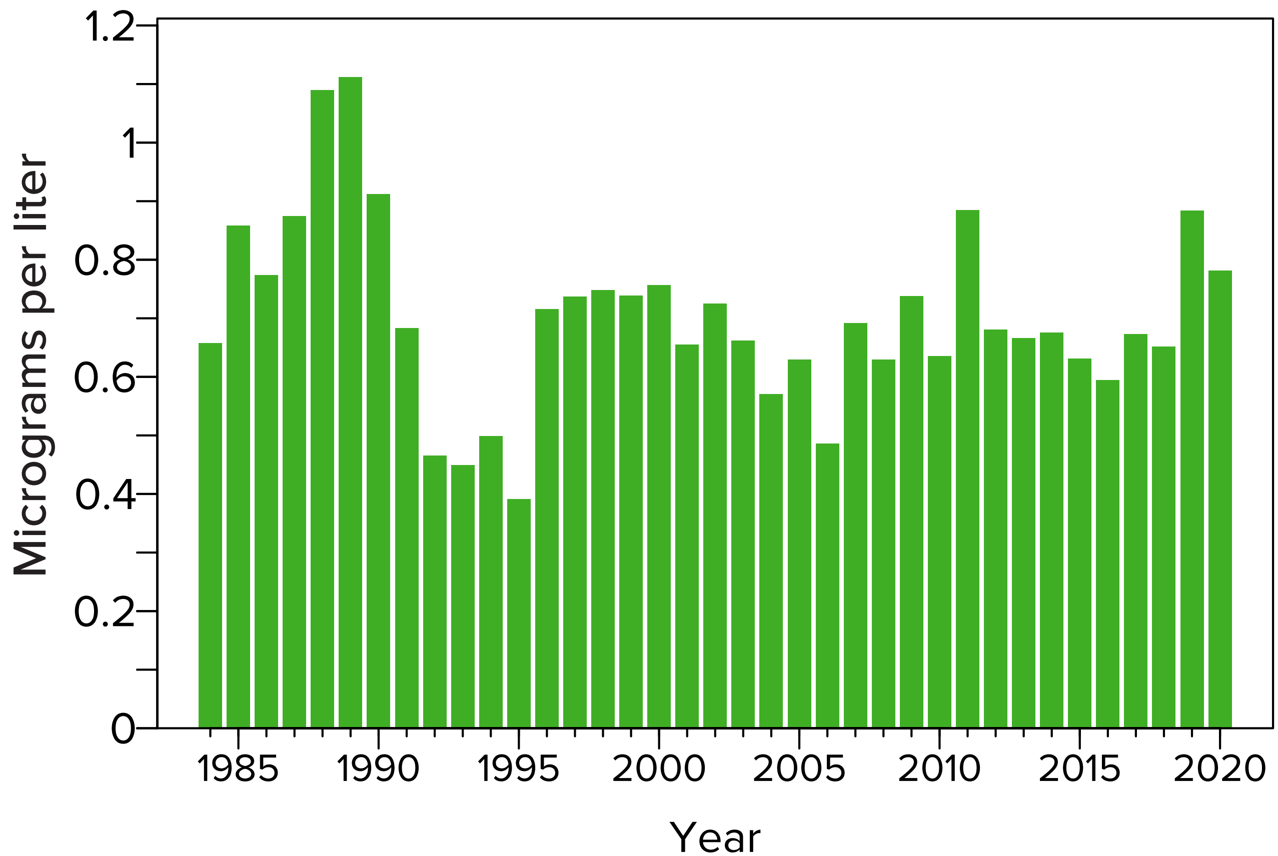
Primary productivity is a measure of the rate at which algae produce biomass through the process of photosynthesis. It was first measured at Lake Tahoe in 1959 and has been continuously measured since 1968. Supported by nutrient loading into the lake, changes in the underwater light environment, and a succession of algal species, the trend shows primary productivity has increased substantially over time. 2019 and 2020 data are considered to be "provisional" due to a change in instrumentation that started in 2019.



Algae abundance

Yearly since 1984

Algae (phytoplankton) are the base of the Lake Tahoe food web and essential for lake health and the well-being of the entire ecosystem. The amount or biomass of free-floating algae in the water is determined by extracting and measuring the concentration of chlorophyll-*a*, a photosynthetic pigment that allows plants to convert energy from the sun. Though the value varies annually, it has shown remarkable consistency over the last 35 years. The average annual concentration for 2020 was 0.78 micrograms per liter. For the period of 1984-2020 the average annual chlorophyll-*a* concentration in Lake Tahoe was 0.70 micrograms per liter.

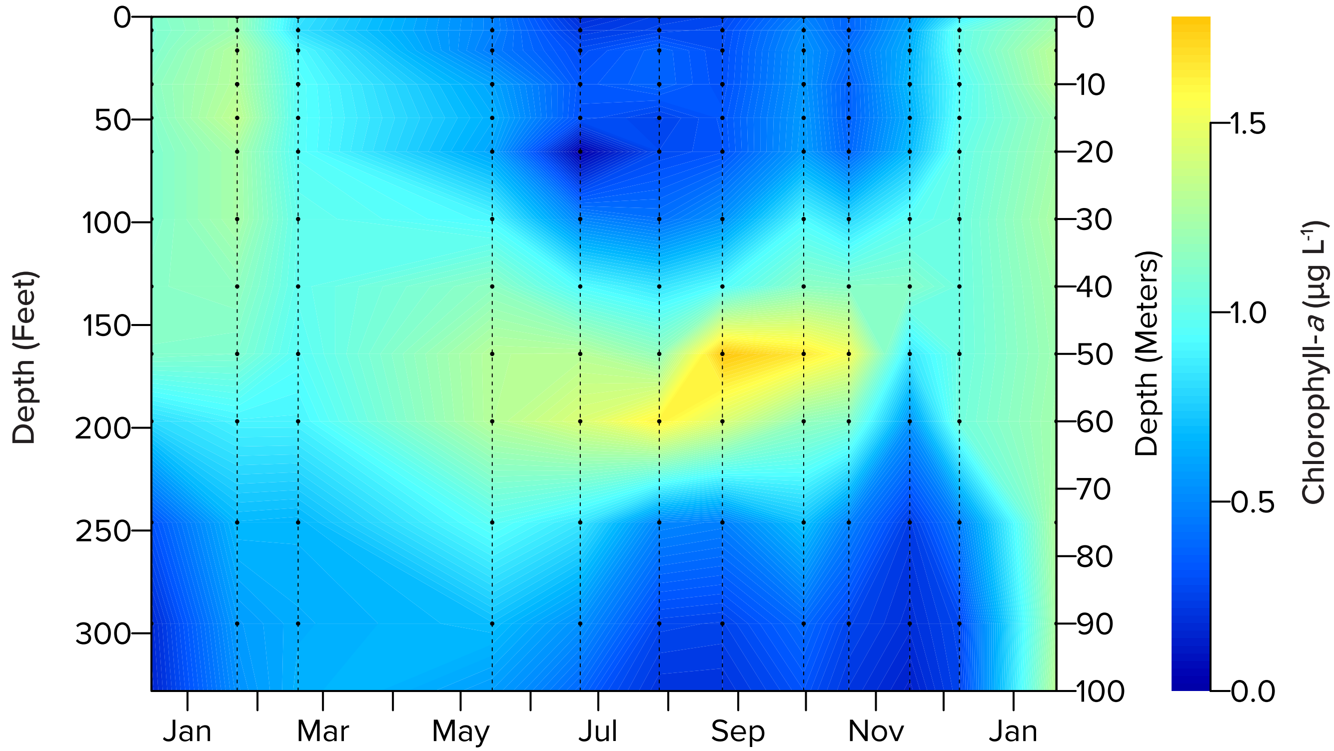


Chlorophyll-*a* distribution

In 2020

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

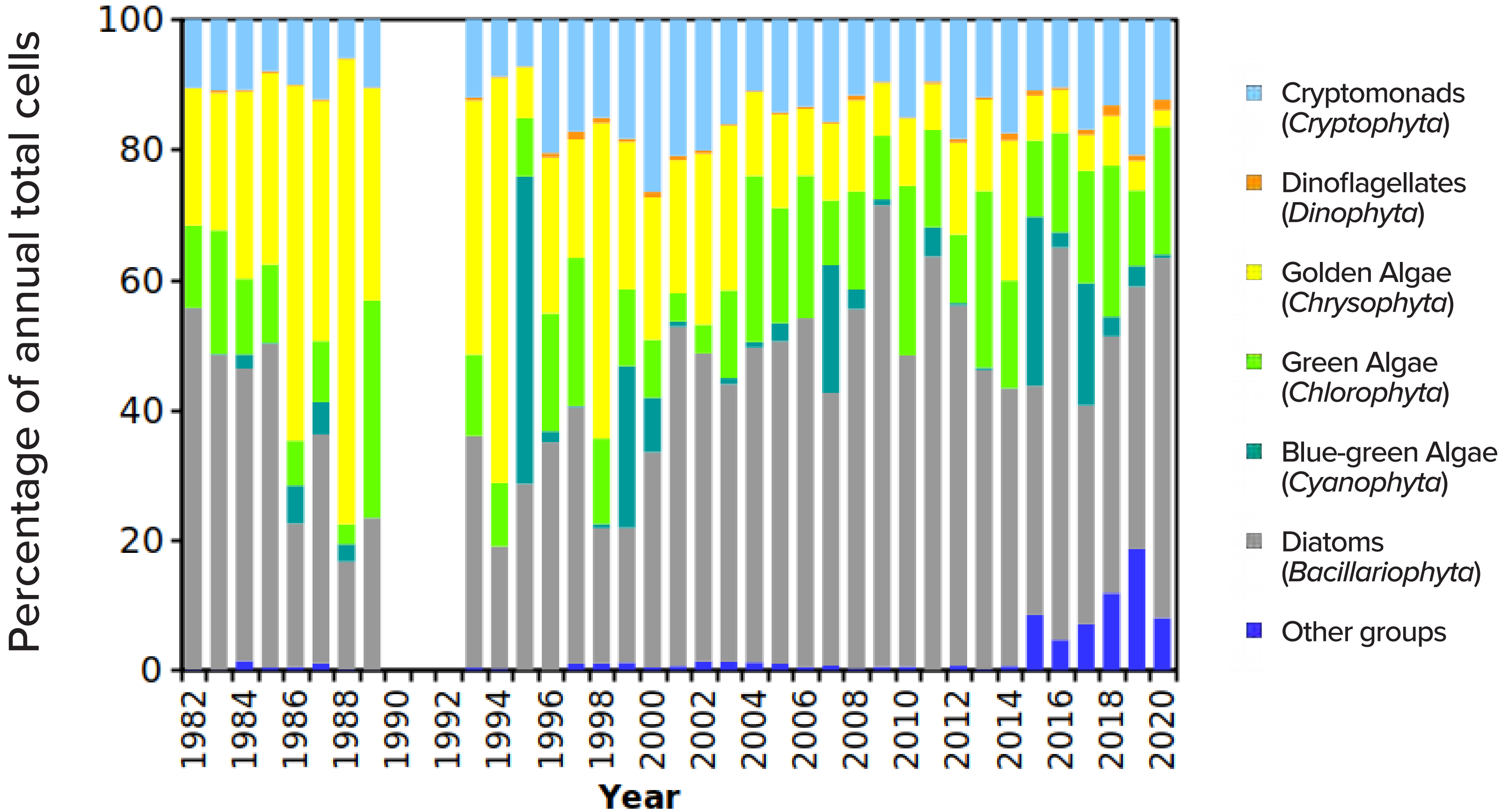
With the onset of thermal stratification in spring, the majority of the high chlorophyll-*a* algae were confined to a discrete band. The time of maximum chlorophyll-*a* concentration was relatively late in 2020, occurring in the August–September period, and centered at a depth of 150–200 feet. In November and December, the commencement of annual vertical mixing redistributed the algae over a broader depth range.



Annual distribution of algal groups

Yearly since 1982

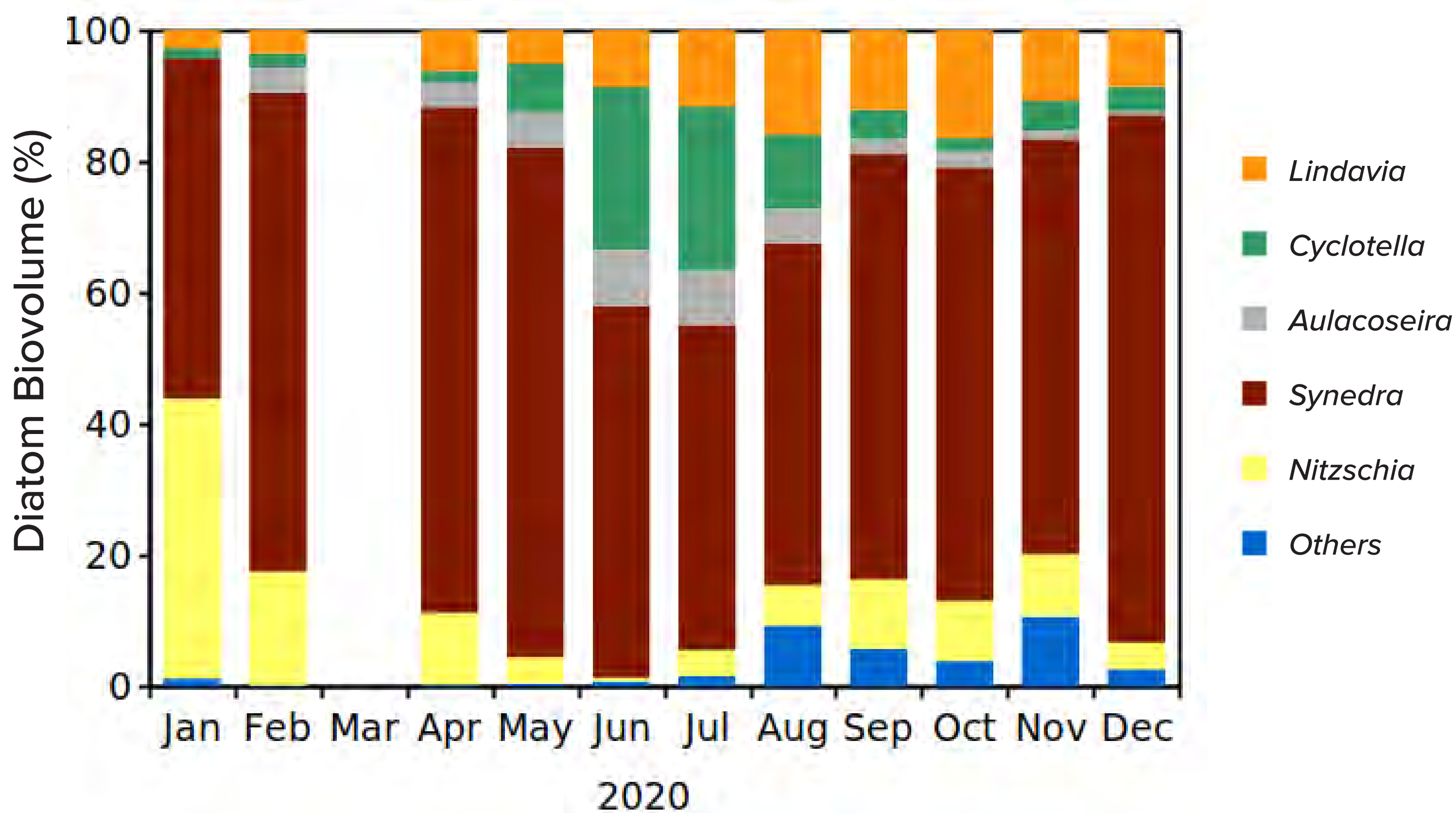
The amount of algal cells from different groups varies from year to year. Diatoms are the most common type of alga, comprising almost 60 percent of the total abundance of algal cells and green algae (Chlorophytes) are next, comprising 15 percent of the total. Interestingly, over the last six years, there has been a sustained presence in the total fraction of "minor" algal groups. While the proportion of the major algal groups show a degree of consistency from year-to-year, TERC research has shown that the composition of individual species within the major groups is changing both seasonally and annually, in response to lake conditions. From 1990–1992 a lack of funding precluded measurements.



Abundance of dominant diatom species

Monthly in 2020

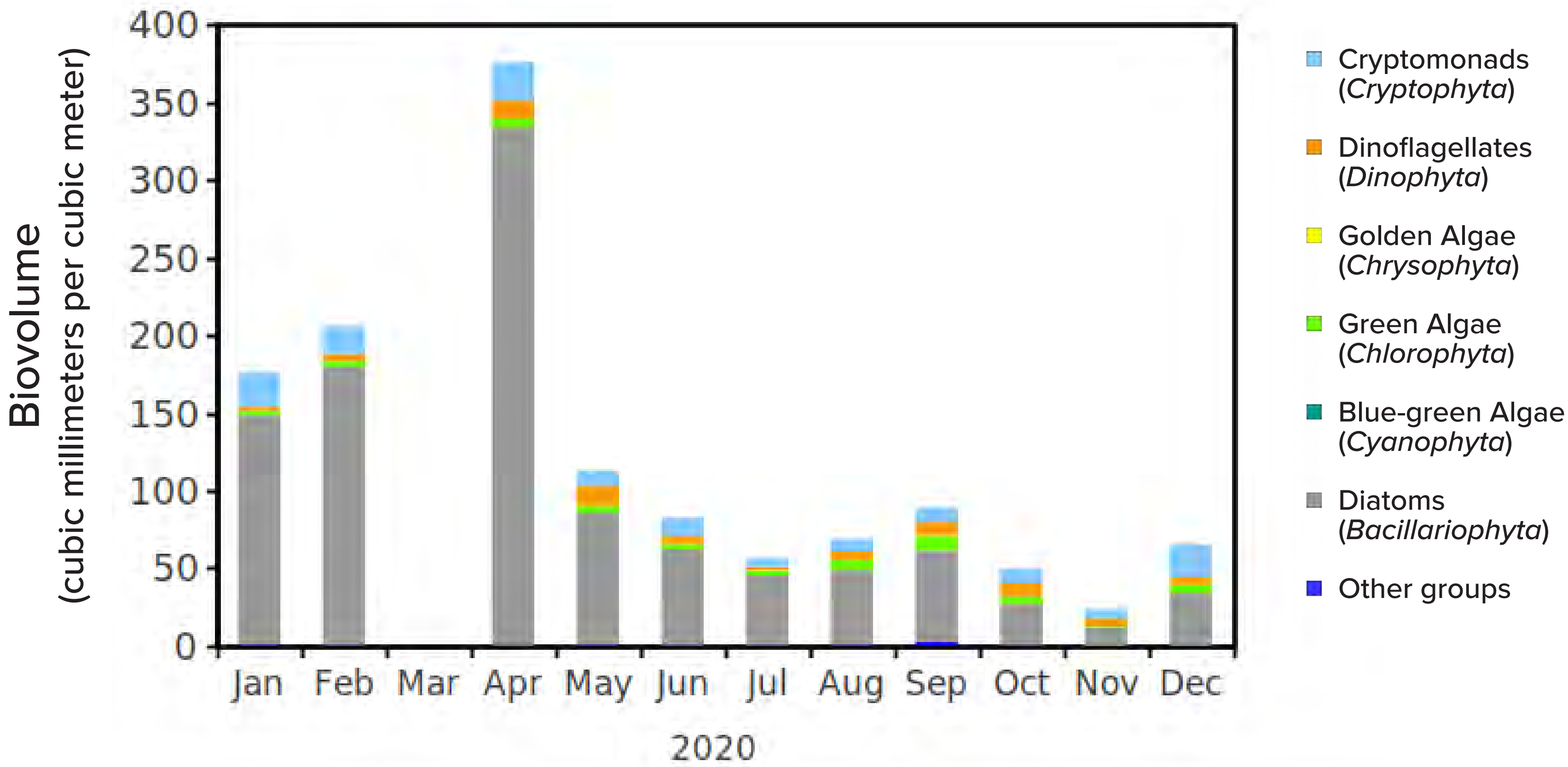
Since 1982, diatoms have been the dominant algal group at Lake Tahoe for all but a few years. Diatoms are unique in that they contain a cell wall made of silica, called a frustule. The dominant diatom species at Lake Tahoe in 2020 are shown below. Large variations in the relative composition are evident by month. *Synedra* was the dominant diatom species during every month of the year, forming over 80% of the diatoms during spring, summer, and fall. Although *Cyclotella* was a relatively low fraction of the percentage of biovolume of diatoms in 2020, it was the second most dominant species in June and July and still had a large impact on clarity. Its very small size means that while its contribution to the biovolume may be small, the actual number of light scattering cells can be extremely large. March sampling could not occur on account of COVID-related stay-at-home orders.



Algal groups as a fraction of total biovolume

Monthly in 2019

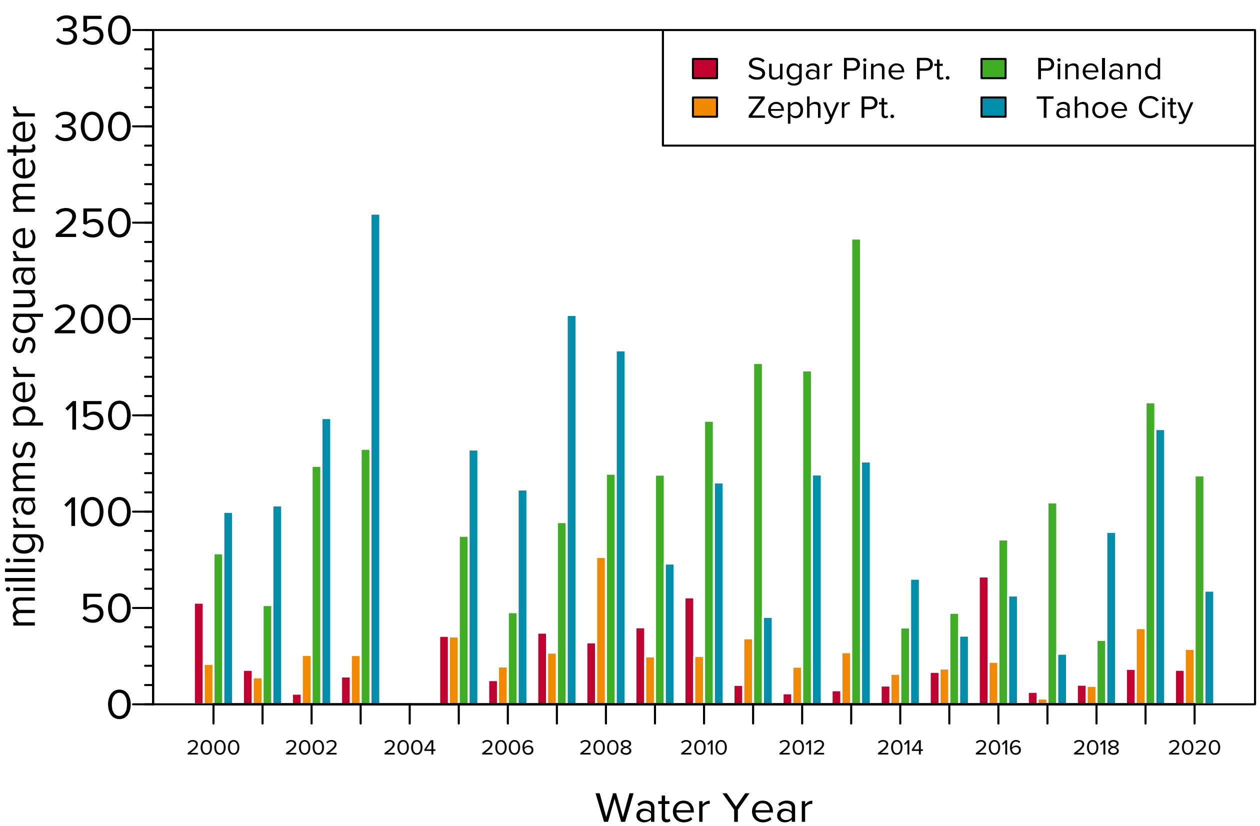
The biovolume of different algal genera vary month to month, as well as year to year. In 2020, diatoms again dominated the biovolume of the phytoplankton community in every month. The peak in the biovolume occurred in April 2020. This "spring bloom" was earlier than the usual May timeframe. The peak biovolume in 2020 was 370 cubic millimeters per cubic meter, almost double the usual biovolume. The typical "fall bloom" was absent in 2020.



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 four sites from January to June. In 2020, concentrations at the four sites were close to their long-term average, with the exception of Tahoe City which was only half its long-term average. Sugar Pine Point, part of a State Park, had its typical, low values. Monitoring periphyton is an important indicator of near-shore health, but it is very challenging to characterize on account of both the temporal and spatial variability inherent in the system.



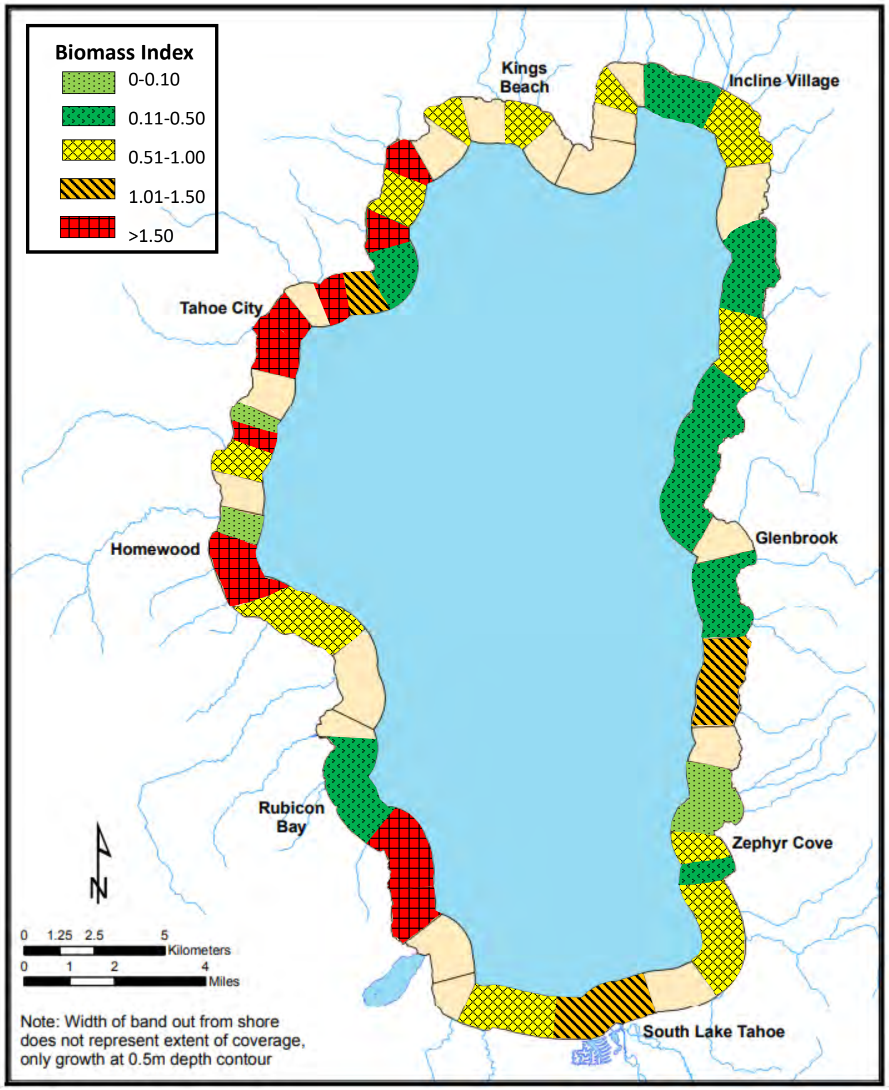
Shoreline algae distribution

In 2020

Periphyton biomass was surveyed around the lake over a three-week period during the spring of 2020, when it was estimated to be 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. Fewer sites had high PBI in 2020 than the previous year. The majority of the high PBI sites were on the California side. Compared to previous years, this is considered to be a near-average year. 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.

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 2020



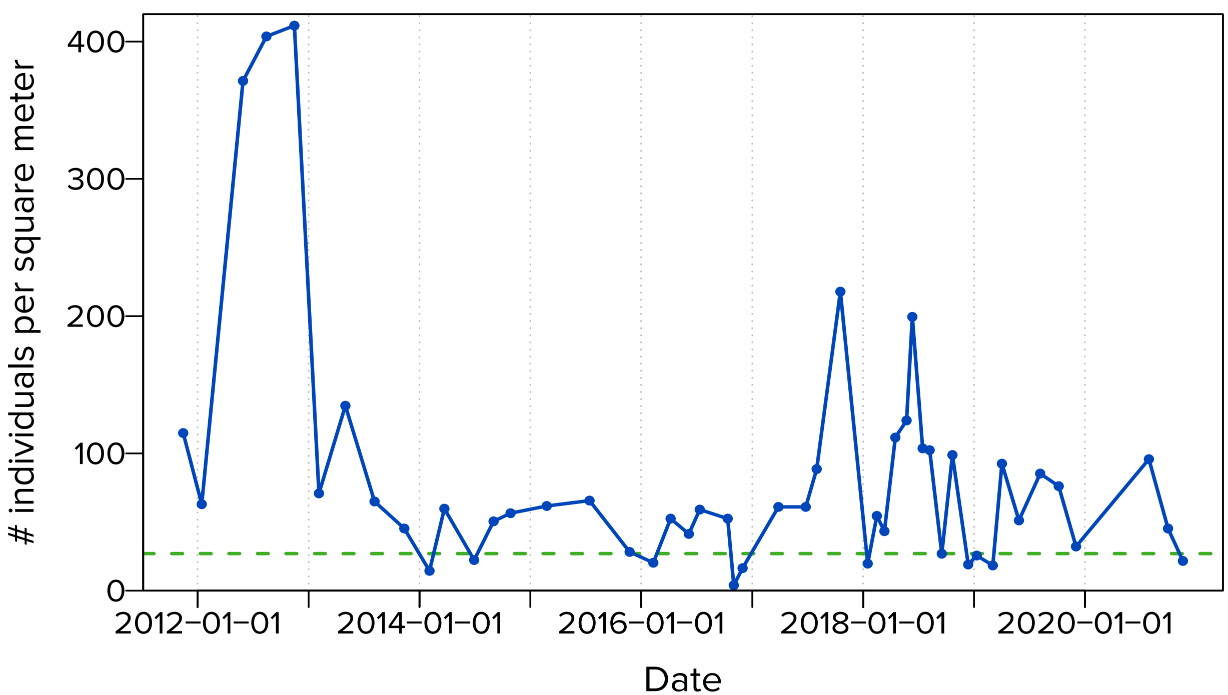
Mysis population

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 *Daphnia* and *Bosmina*. Since that time these zooplankton have been rarely observed. *Daphnia* and *Bosmina* were an important food source for native minnows, which in turn provided food for kokanee salmon and rainbow trout.

Research on *Mysis* essentially stopped in the 1980s. Since 2012, regular surveys have recommenced in Lake Tahoe and in Emerald Bay, albeit it at a baseline scale. Because *Mysis* migrate to the bottom of the lake during the day, they are sampled at night. The sampling net is pulled vertically through the water from the tow depth (TD) indicated at three sites at 3-monthly intervals. South Shore Deep (TD = 200m), LTP Index (TD = 100m) and MLTP (TD = 200m).

The mean *Mysis* densities (expressed as number of individuals collected divided by the net opening area) show large interannual variability. It is not possible to ascertain the extent to which this is due to the low number of sampling sites. The green dashed line at 27 individuals per square meter represents the *Mysis* population level below which *Daphnia* and *Bosmina* could once again become established and thrive.



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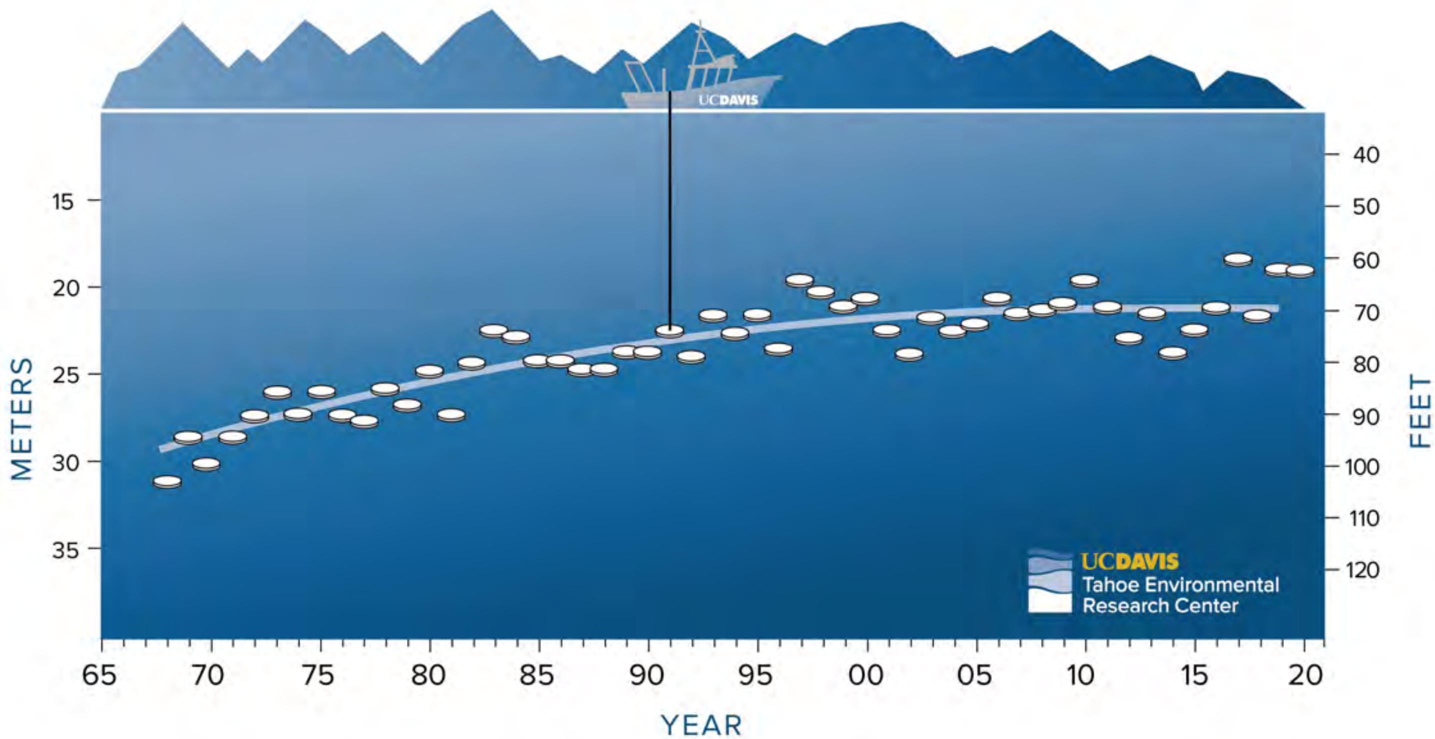
CLARITY

Annual average Secchi depth

Yearly since 1968

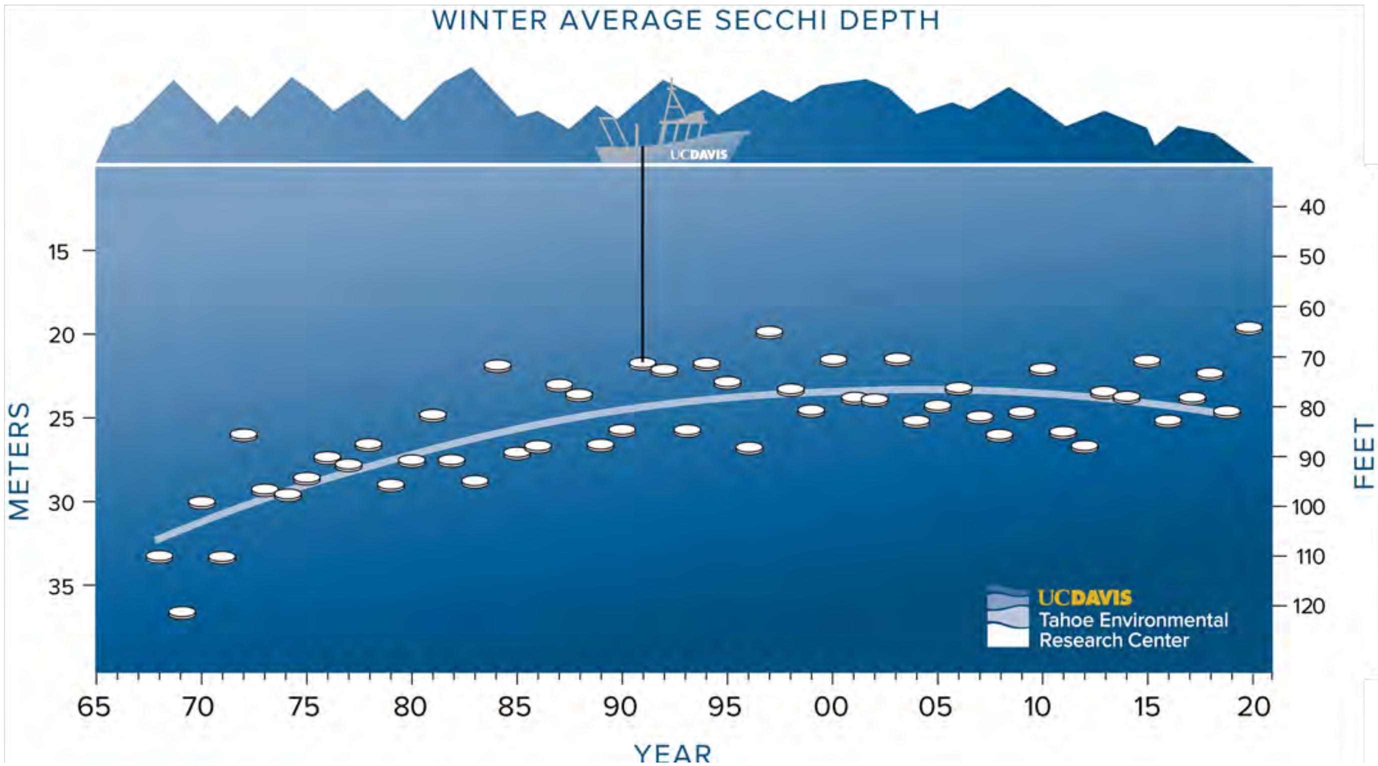
The Secchi depth is the depth at which a 10-inch white disk, called a Secchi disk, remains visible when lowered into the water. In 2020, the annual average Secchi depth was 63.0 feet (19.2 m), almost unchanged from the previous year and reflective of the near-constant values that have been attained over the last 20 years. The greatest individual value recorded in 2020 was 81.2 feet (24.8 m) on February 12. The lack of complete vertical mixing of the lake in 2020 is the main reason for this low maximum clarity value. The poorest clarity reading was 50.8 feet (15.5 m) on May 15. The clarity in 2020 was the result of a combination of factors including the absence of deep mixing of the lake, above average stream loads, algal blooms, and the impact of lake stratification. While the average annual clarity is now better than in earlier decades, it is still short of the clarity restoration target of 97.4 feet (29.7 m) set by federal and state regulators, a goal agencies and the Tahoe Basin community continue to work toward.



Winter Secchi depth

Yearly since 1968

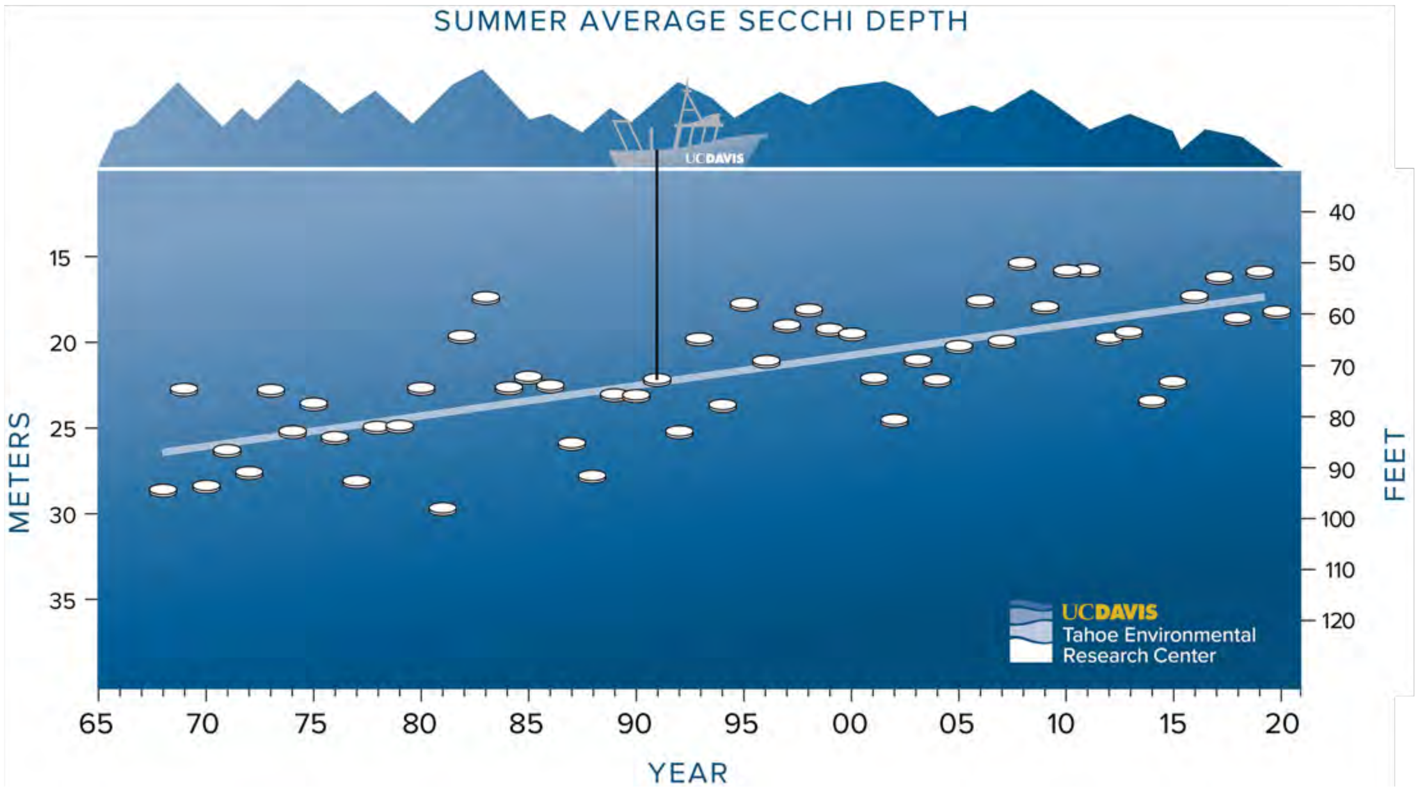
Average winter Secchi depth was 64.0 feet (19.5 m), based on seven readings between December 2018 and March 2019. No readings were taken during March due to COVID-19 restrictions. This was the lowest winter clarity on record, and was 17 feet lower than the previous year. Winter precipitation was below the long-term average and such conditions would typically be expected to yield higher clarity values. The reasons for the low values are still not fully understood.



Summer Secchi depth

Yearly since 1968

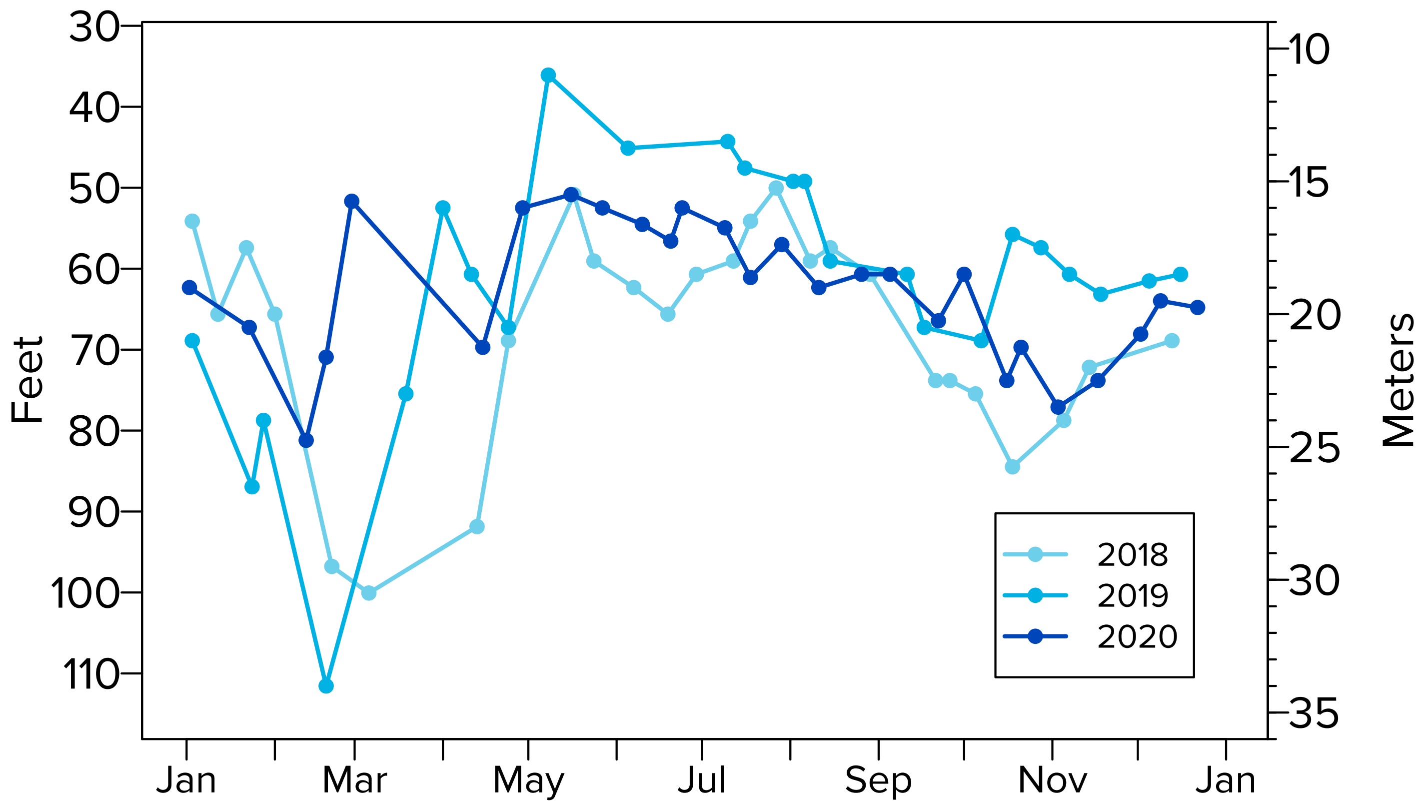
Summer (June–September) clarity in Lake Tahoe in 2020 was 59.1 feet (18.0 m), an increase of over 6 feet from the previous year. This is significantly above the lowest summer value of 50.5 feet in 2008. Summer is typically the season of poorest clarity. The long-term summer trend is dominated by a consistent degradation. In the past two decades, scientists have observed a divergence in winter and summer clarity. In the winter months, lake clarity values have tended to stabilize while in summer, clarity continues to decline. The cause of this divergence is currently under review, but factors related to changing lake stratification and food web changes are believed to play important roles.



Individual Secchi depths

2018, 2019, 2020

Here, the individual Secchi depth readings from the Index station on the west side of the lake for 2018, 2019, and 2020 are plotted. Secchi values can be seen to sometimes vary considerably over short time intervals. This figure makes clear the abnormal winter conditions for 2020 when the absence of deep mixing did not produce the usual winter clarity improvement.



TAHOE:
STATE OF THE LAKE
REPORT
2021

EDUCATION AND OUTREACH

UC DAVIS
Tahoe Environmental Research Center

Education and outreach

In 2020

Achieving healthy aquatic and terrestrial ecosystem conditions requires education and outreach to provide science-based information to people of all ages and backgrounds and to foster responsible action and stewardship.

In 2020, TERC interacted with 3,224 visitors through tours, field trips, and lectures, both in-person and virtually. This represented a 75% decrease over the previous year as the Tahoe Science Center was closed to nearly all in-person programming due to the COVID-19 pandemic in early March 2020, and transitioned to virtual programming.

Virtual student field trips over Zoom accounted for 25% of the total 2020 interactions and kept science in front of students, both locally and further afield, during a tumultuous school year. The TERC education team was still able to reach 1,058 students and conduct 69 virtual field trip sessions, including a new program on forest health based on the latest TERC Forest Ecology Lab research to increase understanding of the impacts of climate change on the trees in our forest.

TERC also continued educating the public through online lectures, presentations to community organizations, and in-person outdoor programming.

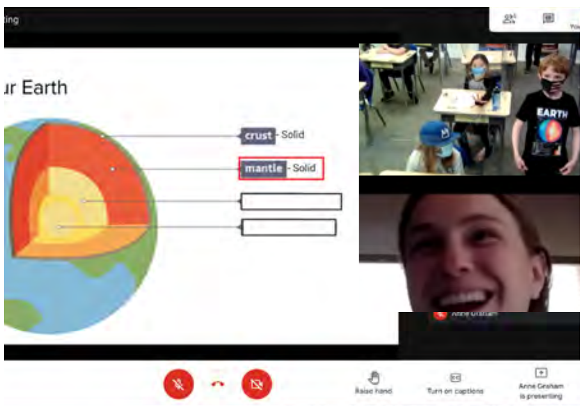
Educational exhibits

Plans for 2021

In 2021, the Tahoe Science Center will reopen by reservation only and utilize a new reservation system in partnership with Incline Village-Crystal Bay Visitor Center.

As part of the reopening, many new activities and products are planned. The Education team will create a hybrid virtual and in-person docent training program. Volunteer docents are a vital part of offering in person tours again. A new version of *Citizen Science Tahoe* as a web application will allow users to more easily access observation templates. A new *Tahoe's Plastic Problem* microplastics exhibit will focus on the problems and impacts of plastic pollution on freshwater ecosystems. A virtual *All About Lake Tahoe* Science Expo will provide students access to the Tahoe Science Center content through engaging and visually stimulating experiments.

All programs and outreach efforts aim to increase engagement with locals and visitors and expand their awareness, knowledge, and understanding of environmental issues at Lake Tahoe and the importance of science and research to provide solutions to these problems.



AmeriCorps member Anne Graham teaches a lesson on the layers of the Earth and is excited to see a student wearing a matching Earth T-shirt to school the day of the virtual field trip.

New exhibit on microplastics and plastic pollution includes hands-on activities and interpretive panels (funded by the Nevada Division of Environmental Protection).
Photo: H. Segale

AmeriCorps member Elise Matera reads the picture book *Mae Among the Stars* about the first African American woman to go to outer space. This book served as a segue to discuss earth and space science topics relevant to the students' grade levels.
Photo: B. Goodwin