UC DAVIS

TAHOE: STATE OF THE LAKE REPORT 2020

Tahoe Environmental Research Center

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 2020 Tahoe: State of the Lake Report is dedicated to the 41 years that Scott Hackley worked as a UC Davis researcher at Lake Tahoe, before retiring in June 2020.

Scott went far beyond the call of duty and his job description by measuring streamflows during the peaks of epic storms, gathering water samples across those same streams when concern for personal safety would have cautioned most people to defer to another day, and conducting periphyton samples during winter and spring for decades in a leaky wetsuit. His replacement wetsuit arrived two months before his retirement.

Many of the data points contained in this report and all previous reports were produced by Scott. If you find the report to be too long and to contain too much data, please contact Scott directly. Thank you Scott, for all your years of hard work and meticulous research. We wish you the best in your retirement!

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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 2019–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 time scales of decades.

An important part of this Report are updates on research taking place independently of the long-term monitoring. These 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 these sections are exploring new ideas and approaches to address the ever evolving challenges to 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 of Brant Allen, Jonathan Arthur, Karen Atkins, Kian Bagheri, Brandon Berry, Mike Bruno, Tom Burt, Luciana Cardoso, Sudeep Chandra, Yuan Cheng, Danny Cluck, Bob Coats, Alicia Cortés, Stephanie Coppeto, Ben Daniels, Mark Enders, MJ Farruggia, Alex Forrest, Nick Framsted, Susan Frankel, Charles Goldman, Nick Gomez, Baylee Goodwin, Anne Graham, Scott Hackley, Tina Hammell, Simon Hook, Camille Jensen, Yufang Jin, Kwungwoo Lee, Anne Liston, Kevin Livingston,Patricia Maloney, Elisa Marini, Elise Matera, Jasmin McInerney, Antonina Myshyakova, Jo Myungchul, Holly Oldroyd, John Reuter, Bob Richards, Will Richardson, Gerardo Rivera, Derek Roberts, Steve Sadro, Goloka Sahoo, Heather Segale, Katie Senft, Steven Sesma, Samantha Sharp, Roland Shaw, David Smith, Sheri Smith, Adrianne Smits, Drew Stang, Erin Suenaga, Jae Sung, Micah Swann, Lidia Tanaka, Raph Townsend, Alison Toy, Sean Trommer, Seung Tae, Sergio Valbuena, Aaron Vanderpool, Shohei Watanabe, Brian Wiebe, Andy Wong, and Carmen Woods 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, the 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, the Parasol Foundation, the Tahoe Fund, and the 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 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 the 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 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 large part because it provides an independent basis for assessing the progress toward attainment of 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 increasingly using innovative approaches to enrich the long-term data record for Lake Tahoe. These include real-time measurements at over 25 stations around the basin; remote sensing from autonomous underwater vehicles, satellites, aerial drones; and computer modeling tools. These tools 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.

This annual *Tahoe: State of the Lake Report* presents data from 2019 in the context of the long-term record. While we report on the data collected as part of our ongoing, decades-long 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 progress being made toward the clarity and ecosystem restoration through the harvesting of *Mysis* shrimp and their use as high-grade dog treats; the metaphyton and periphyton growth that impact the lake's nearshore; efforts toward the understanding and the replanting of genetically resilient trees to replace the thousands of sugar pines lost in recent years; underwater robotic instruments to study harmful algal blooms; microplastic pollution; the under-recognized dangers that can be avoided when recreating on Lake Tahoe; and the reciprocal lessons that are being learned by studying deep lakes in Patagonia.

In the last eight years we have been trying to reconcile the connections between the introduction of *Mysis* shrimp in the 1960s, the long-term ecological record for Lake Tahoe, and the experiences of researchers at many lakes across the world. Finally, a consistent picture is emerging for Lake Tahoe. The available data suggest that *Mysis* were responsible for not only the removal of the *Daphnia* (the cleaners of fine particles from the lake), but also for the removal of large algae. This dual impact appears to have created a niche for the dominance of *Cyclotella*, allowing it to increasingly exert an impact on lake clarity, particularly in summer. The experience from Emerald Bay suggests that this may be reversible if *Mysis* are removed.

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[1]*"Previous year" for some parameters means data collated in terms of the water year, which runs from October 1 through September 30; for other parameters, it means data for the calendar year, January 1 through December 31. Therefore, for this 2020 report, water year data are from Oct. 1, 2018 through Sept. 30, 2019. Calendar year data are from Jan. 1, 2019 through Dec. 31, 2019.*

EXECUTIVE SUMMARY

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Experimentation with advanced technologies yields new insights about processes impacting the lake and the surrounding forests. The challenge is in maintaining long-term data records that may have commenced decades ago, while at the same time incorporating new approaches to enrich the monitoring data. This was the goal with our experimentation with UAV and helicopter surveys for metaphyton and periphyton monitoring. Combining remote sensing with traditional diver-based surveys will provide better estimates of interannual differences, and through that an understanding of potential agency actions. Similarly, the use of autonomous underwater vehicles to study harmful algal blooms is a forward-looking approach to an issue that is impacting other lakes increasingly, although not yet a problem for Lake Tahoe.

Wildfire and drought will continue to impact the health of Tahoe's forests. Through our efforts to establish a common garden and understand the plant traits of the most resilient trees in the basin, we are part of a broader effort to preserve and enhance our forests. Working with the California Conservation Corps we have already replanted thousands of trees in the most impacted areas.

Microplastics are of concern everywhere. While others are focused on the sources of the plastic, our researchers are looking for where they are showing up in the lake and in the water we may one day drink. Multi-depth surveys, analysis of biota, and sediment analysis are all being conducted. In parallel with this, an extensive public education effort was launched in partnership with the Tahoe Water Suppliers Association and Raley's supermarkets.

While lake physics may seem esoteric, it is at the core of much of what we see and experience at Lake Tahoe. This especially applies to recreational pursuits such as paddleboarding. Most years there are fatalities at Tahoe during what may seem like a benign sport in an idyllic location. Some of the unseen dangers are explained in this year's report.

Finally, there is also the opportunity to pass on lessons learned at Tahoe and to gain new perspectives from other communities. This is the motivation of a growing collaboration with Patagonian foundations, researchers, industries, and government agencies. Tahoe has a lot to share with the world, but also a lot still to learn.

Meteorologically, the long-term trends that have been prevalent do not change year-to-year. 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. 2019 was a cold year, colder in every month of the year except April compared to

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2017 and 2018. February was particularly cold with the monthly average air temperature being 4.4°F below the long-term average, making it the coldest February since 1956. Precipitation at Tahoe City was 43.8 inches, 12 inches above the average for the last 110 years. February was also the wettest month. 43.9 percent of the precipitation at Tahoe City fell as snow.

The water level in Lake Tahoe varies throughout the year due to inflows, outflows, precipitation, and evaporation. In the last three years it has been generally high due to the average to above-average precipitation. On July 1, 2019, the lake peaked at 6229.03 feet above mean sea level, less than one inch below its maximum legal limit.

Lake Tahoe has generally been warming since regular measurements commenced in 1968. In the last four years, the average water temperature (top to bottom) has cooled from its record warmest year in 2015. Its coolness this year can be partly explained by the fact that it mixed all the way to the bottom for the first time in eight years. During that mixing, the water temperature at the bottom of the lake fell by over 0.3°F in just a few weeks. July surface water temperatures were also significantly cooler. In 2019, the July surface average temperatures were 64.0°F, compared with 68.4°F in 2017.

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. The length of time that Lake Tahoe is stratified each year has been increasing, 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 2019, the stratification season length fell almost exactly on this long-term trend line, despite the cooler than average year.

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 above average, in line with the above average precipitation for the year. Both were well below the record loads from 2017. In-lake nitrate concentrations have displayed an increasing trend since 1980. In-lake total hydrolyzable phosphorus concentrations, after declining from 1980 to 2010, have been showing an increasing trend over the last decade. The reasons for these trends are not fully understood at the present time. The distribution of nitrate and total hydrolyzable phosphorus throughout the lake was radically

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different in 2019, on account of the deep mixing that occurred in March. Over the previous eight years, a high concentration layer of both had accumulated at the bottom of the lake.

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 over time. The annual average concentration for 2019 was 0.88 micrograms per liter. For the period of 1984-2019, the average annual chlorophyll-*a* concentration in Lake Tahoe was 0.70 micrograms per liter. The reason for the jump in 2019 is believed to be due to the infusion of nutrients due to deep mixing after a prolonged break, and the above average stream inflows. Most of the chlorophyll is concentrated at a depth of approximately 170 feet, known as the "deep chlorophyll maximum." From an abundance of individual cells viewpoint, diatoms were the most common algal group (60 percent of the cells). Of these, *Synedra* and *Nitzschia* formed the largest percentage of the biomass during every month of the year. *Cyclotella* was a low fraction of the diatoms in 2019, but it still had a large impact on clarity due to its extremely small size and large numbers. There were two peaks in biovolume – in May and September. The September peak of over 500 cubic millimeters per cubic meter, was far larger than most years. The attached algae (periphyton) on the rocks around the lake were particularly heavy in 2019, based on a synoptic survey of 53 observations. This is believed to be due to the relatively steady water level and the higher nutrient levels. The California side of the lake was especially high, although Zephyr Point in Nevada has its second highest value on record.

In 2019, the annual average Secchi depth was 62.7 feet (19.1 m), an 8.2 foot decrease over the previous year. The highest individual value recorded in 2019 was 112.0 feet (34.0 m) on February 19 and the lowest was 36.1 feet (11.0 m) on May 8, coinciding with a bloom of the tiny algal cell *Cyclotella*. The decrease in clarity in 2019, was the result of a combination of factors including the 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 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 81 feet was only slightly below the long-term mean of 84 feet. Summer (June-September) clarity was 53 feet (16.2 m). This is the fourth lowest summer value, with the lowest being in 2008. Summer is typically the season of lowest clarity values.

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
- A single *Daphnia* can consume 100,000 fine particles every hour
- It would take a single *Daphnia* one week to clear a gallon of Tahoe water of all fine particles
- When *Daphnia* returned to Emerald Bay, there were over 20 of them per gallon of surface water
- 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)

The UC Davis Tahoe Environmental Research Center (TERC) is a world leader in research, education and public outreach on lakes and watersheds, providing critical scientific information to help understand, restore, and sustain the Lake Tahoe Basin and other systems worldwide. Since 1968, UC Davis has undertaken the 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 free and 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 John LeConte and the Bob Richards. The R/V Ted Frantz operates out of Clear Lake, California and the R/V Tom is stored in Davis, California.

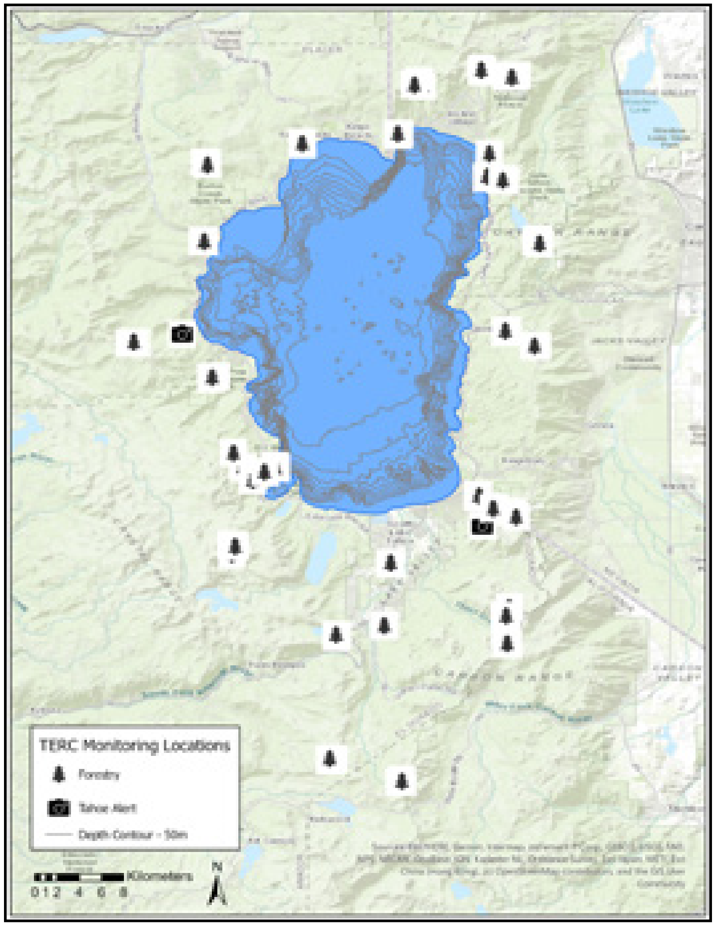
Additional laboratories and offices are located on the UC Davis campus at the Center for Watershed Sciences and in Wickson Hall.

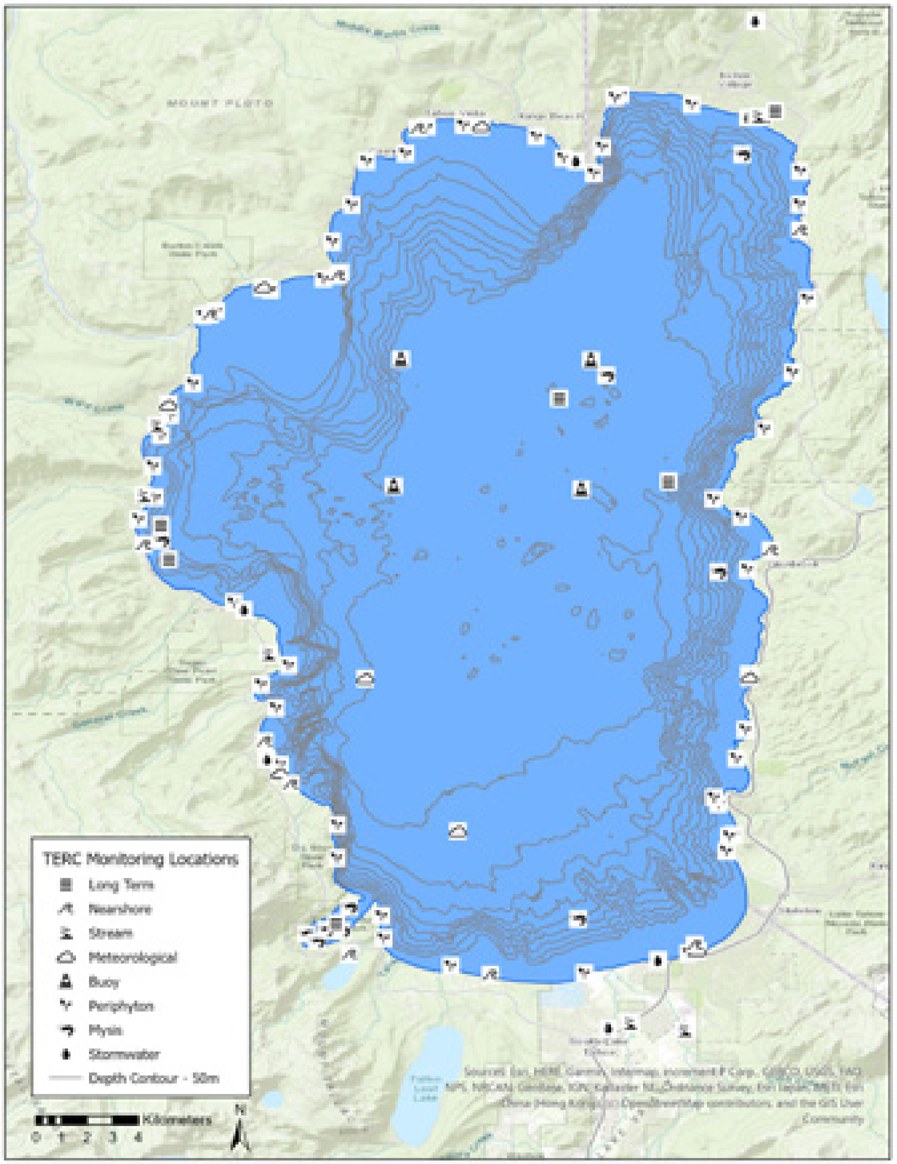
At locations throughout the basin, we have sensors continuously reporting on the health and well-being of the lake and its environs, all contributing to making Lake Tahoe the smartest lake in the world.

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;
- Tahoe 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
2020

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. The monitoring data are an invaluable resource for assessing the impact of changes that have occurred due to anthropogenic factors and natural variability.

Additionally, we engage in shorter-term research that seeks to answer specific questions or to gain understanding of processes and events. This research relies on the long-term monitoring data to provide a context, but it is distinctly separate. The results of this research–conducted by TERC students, postdoctoral researchers, faculty, and staff, and 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: S. Hackley, K. Senft, and A. Toy

Current Research Synthesis, continued

This year, our current research synthesis covers a broad range of areas. 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 influence management and decision-making. Many of the research projects are still underway or in initial stages. The topics we are focusing on this year are:

• The examination of the historic monitoring data has connected the introduction of *Mysis* shrimp to lake clarity. Combined with the results of a pilot project in Emerald Bay, we are launching a new private-public venture to commercially remove the *Mysis* and develop a new line of Tahoe dog treats high in protein and rich in one of the purest forms of Omega-3 fatty acids. This approach has the potential to restore lake clarity, even in the face of climate change, and be a sustainable model for environmental management.

• Metaphyton and periphyton are the nuisance algae that coat the shoreline of the lake at different times of year. Using our Citizen Science Tahoe App, we can all keep track of its spread.

• Metaphyton, which are believed to be proliferating due to the presence of Asian clams, have never been systematically monitored before. Using a combination of helicopter and drone flights, TERC has developed a very efficient methodology to track and quantify their spread.

• In fall 2019, TERC partnered with the California Conservation Corps to replant over 4,000 sugar pine seedlings around the Lake Tahoe Basin. Over 72,000 sugar pines were lost between 2012 and 2016 due to drought and bark beetle infestation.

Photos: A. Wong and A. Toy

Current Research Synthesis, continued

• Sugar pine genetics are being studied through a common garden, where the traits of over 2,100 seedlings are being evaluated.

• Robotic instruments are increasingly being used in TERC's research around the world. They are being used to study harmful algal blooms (HABs) in Clear Lake, California at a much finer scale than can be achieved by satellite remote sensing.

• Ice-covered lakes are of increasing interest to scientists around the world. TERC is studying these in both the Sierra and Canada.

• Plastic pollution is garnering much attention. Both our research and education teams are starting new projects to identify microplastics in Lake Tahoe and to increase awareness of the over-use of single-use plastic.

• COVID-19 has wrought huge changes across the globe. At Tahoe it has forced major changes in how we conduct essential research and provide public education in a safe and responsible manner.

• You don't need a physics degree to enjoy paddleboarding. But knowing a little about the physics of Lake Tahoe could save your life when enjoying this fun activity.

• The lessons learned at Lake Tahoe are being exported to Patagonia, Chile. TERC is a key partner in a large collaborative effort with a Chilean foundation, industry leaders, local and national governments, and private citizens to help plan the future of Patagonia's lakes.

Photos: A. Toy

Clearly, Mysids are a Problem

Landscape-scale environmental disturbance can take decades to manifest in a measurable way. When multiple impacts are occurring at the same time, a major culprit can remain hidden in the depths, even as data continue to accumulate. Such appears to be the story of clarity change at Lake Tahoe.

The 1960s were a decade of major change in the Tahoe Basin. Rapid urban development and sanctioned species introductions were carried out with little understanding of their long-term impacts. It took Dr. Charles Goldman ringing the alarm about Tahoe's diminishing clarity, along with the fledgling League to Save Lake Tahoe and the newly created Tahoe Regional Planning Agency, to help bring attention to the issue. Attention and remediation were quickly focused on Tahoe's rapid and uncontrolled urbanization, a pattern that was observed in many places across the world. When it came to declining lake clarity, the broken linkages within the aquatic food chain were largely out of sight and out of mind, and connections between the food chain and clarity were not recognized.

TERC recently re-examined decades of data to try and understand the role that introduced *Mysis* shrimp may have played in Tahoe's decades-long quest to restore clarity. Through the reinterpretation of the data, a new picture has emerged, one that offers great hope going forward. In this new vision, trillions of tiny shrimp share a large portion of the responsibility for clarity loss and their removal could be an important component of clarity restoration, even in the face of climate change.

Mysis diluviana. Photo: P.H. Olsen

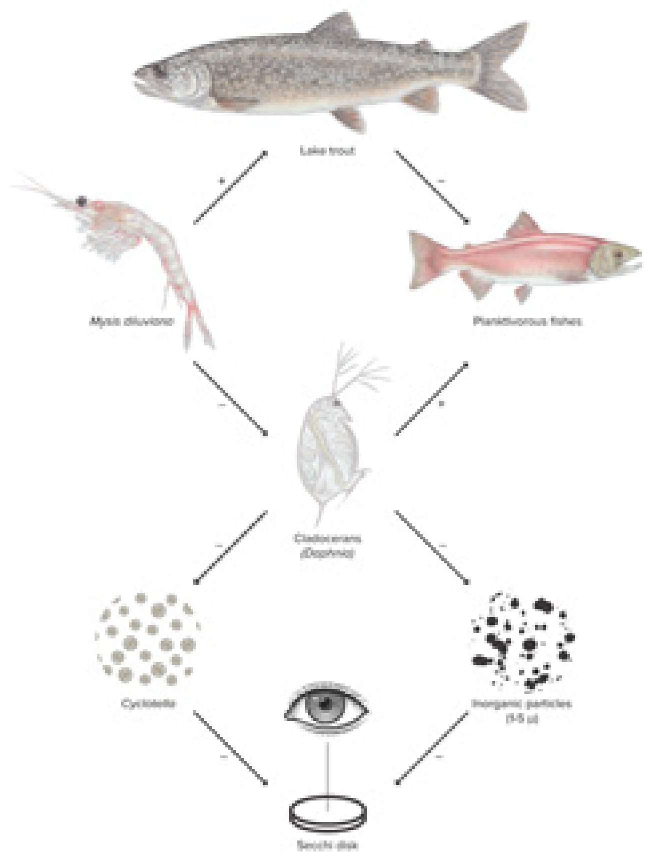
Clearly, Mysids are a Problem, continued

A population of half-inch long shrimp (*Mysis*) were intentionally deposited into Lake Tahoe and Emerald Bay in the early 1960s. By the early 1970s, they had become the dominant zooplankton species having totally consumed the much smaller and extremely efficient filter-feeding cladocerans (*Daphnia*).

Daphnia spent their time indiscriminately sweeping large quantities of small particles into their mouths. Their motivation was to consume tiny phytoplankton (open water algae) but often inadvertently ingesting fine sediment as well. Their undiscerning consumption naturally removed the fine particles known to be most critical in reducing lake clarity. These particles included fine silt and clay, and *Cyclotella* algae. The *Daphnia* packaged their waste products into larger particles that rapidly fell to the bottom of the lake.

This linkage between predatory *Mysis* and lake-clearing *Daphnia* was initially revealed in Emerald Bay between 2011 and 2017. Researchers discovered the *Mysis* population had disappeared from this small-scale analog of Lake Tahoe. Within months, *Daphnia* had returned to the bay and clarity improved beyond that of Lake Tahoe, an occurrence not recorded previously. When the *Mysis* returned after three years, the opposite effect occurred–the *Daphnia* were consumed and clarity returned to its previous low values. This story was detailed in the *2019 State of the Lake Report*.

While this is compelling for a small water body such as Emerald Bay, it begs the question whether the same response could be seen in the main body of Tahoe. An exhaustive review of 50 years of published data says yes!



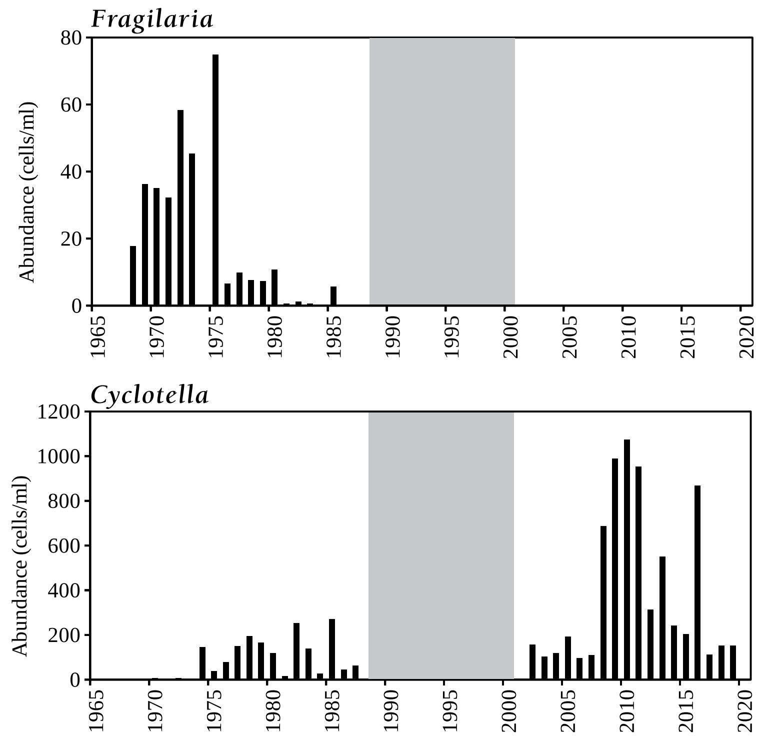
A new view of the relationship between the Lake Tahoe food web and lake clarity. Trace out what happens when you increase or decrease the Mysis. The plus and minus signs on each arrow indicate the direction of change. Illustrations: S. Adler, Figure: H. Segale

Clearly, Mysids are a Problem, continued

What is the evidence? Immediately following the establishment of *Mysis* and the subsequent loss of *Daphnia*, the size of Tahoe's phytoplankton changed radically. The once dominant alga *Fragilaria* (70 microns) was replaced by the very small alga *Cyclotella* (2-8 microns). Why did this happen? *Fragilaria* was too large for *Daphnia* consumption, so they preferentially fed on *Cyclotella*. *Fragilaria* was an ideal size for the omnivorous *Mysis*, and this larger alga was soon consumed. On the other hand, *Cyclotella*, at just one five-thousandth of the size of *Mysis*, were simply too small to bother with. With all the large, nutrient-hungry *Fragilaria* out of the picture, and a near-absence of predation pressure, *Cyclotella* flourished. But the real clincher was that the size of *Cyclotella* was ideal for reducing clarity.

So, to summarize, the *Daphnia* had kept the tiny *Cyclotella* in check while also consuming tiny particles washed in from the watershed. *Mysis* wiped out the *Daphnia*. *Cyclotella* then grew unchecked and fine sediments had no way to be removed other than sinking very, very slowly to the bottom of the lake.

Where does climate change come in? Tiny particles, whether *Cyclotella* or silt, can stay afloat in water for a long time. Climate change warms the surface of the lake for an extended period of time, helping those particles stay afloat and reducing the clarity.



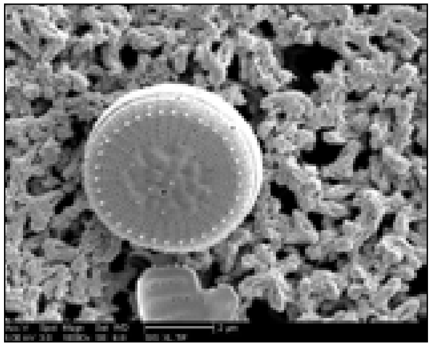
Average Fragilaria abundance at a depth of 16.5 feet and average Cyclotella abundance at a depth of 16.5 feet. Measurements at this depth were not available for the period 1988-2001 indicated by the gray boxes. For all other years a zero reading indicates a total absence of Fragilaria. Mysis were fully established by the mid-1970s.

Clearly, Mysids are a Problem, continued

Based on the review of historic Tahoe data and the lessons learned at Emerald Bay, a new approach is emerging. A reduction in the Tahoe *Mysis* population to allow the return of *Daphnia*, the Roomba® of surface waters. Abundant *Daphnia* would be expected to once again consume *Cyclotella* and other fine particles, improving water clarity, allowing for the return of larger phytoplankton such as *Fragilaria*, and thereby supporting planktivorous fish species.

This does not mean that the restoration activities undertaken at Tahoe to date, many of which were supported by scientific evidence, were the wrong ones. It would be patently wrong to say that preventing tons of nitrogen, phosphorus, and fine particles from entering was a mistake, would be patently wrong. The diversion of all sewage water entering Lake Tahoe, initiated in the early 1960s, was a very far-sighted achievement that was critically important for preserving Lake Tahoe. Likewise, the floodplain restoration projects have restored other habitat in addition to the lake itself.

What we have learned is that we now have two very powerful, science-based approaches for clarity and ecosystem restoration. The watershed restoration approach of limiting what enters the lake, and the lake ecosystem approach where the native food web provides us the environmental services of helping to restore both clarity and the natural function of the entire ecosystem.



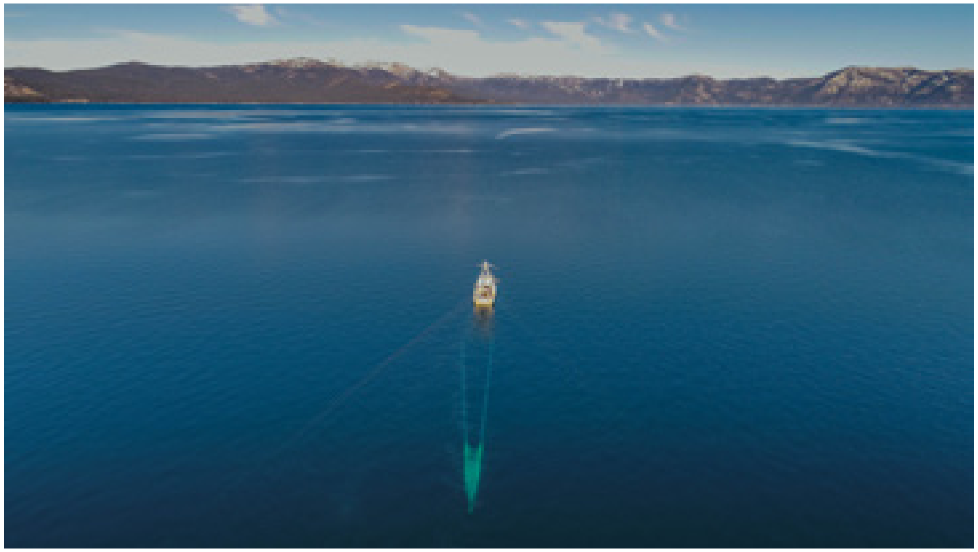
Cyclotella gordonensis

TERC researchers attach a Biosonics Split-beam Echosounder used to locate the highest abundances of Mysis shrimp to increase trawling efficiency.

Clearly, Mysids are a Problem, continued

The approach we are currently exploring to sustain reductions in the *Mysis* population is the utility of harvesting of *Mysis*. *Mysis* from Lake Tahoe happen to be one of the world's purest sources of Omega-3 fatty acids. This greatly sought-after substance is important for both human and animal nutrition, and is an essential ingredient for many food supplements. Working with the UC Davis Graduate School of Management and researchers from the UC Davis School of Veterinary Medicine, we will soon be ready to utilize the *Mysis*' Omega-3 fatty acids and launch a new venture into the world of gourmet dog treats. This venture, a non-profit-based approach, will be an opportunity for public agencies, private investors and university researchers to interact in a totally novel way.

If successful, this would not only have added a potential new tool for clarity restoration that can be combined with watershed load reduction projects, but it will also be an important step toward returning the native phytoplankton, zooplankton, and fish to Lake Tahoe. And unlike nearly all restoration efforts, it has the potential to generate funding to support continued research and restoration. Once again, Lake Tahoe will be at the forefront of environmental restoration in its broadest sense.



The UC Davis TERC Research Vessel trawling for Mysis in Lake Tahoe, 2018. Photo: B. Allen

An Alga for Every Season

Lake Tahoe's nearshore is where the public's impression of Tahoe's aesthetic quality begins. Visitors experiencing crystal clear water, clean granite rocks and beaches will leave with a more favorable impression than those wading through stringy green algae, slipping on boulders covered in slime, and smelling decaying algae washed up on beaches.

In recent years, there has been a growing number of complaints from the public about the perception of an increasing amount of nearshore algae. A 2017 report by TERC scientists Scott Hackley and John Reuter reviewed forty years of data on the abundance of attached algae (periphyton) in the nearshore and found no significant upward trend in algal biomass. A second review by UC Davis PhD student Karen Atkins, using data through 2019, came to essentially the same conclusion. Yet, public perception runs contrary. Why is that?

For over 50 years, the primary nearshore algae community was dominated by species that attach to hard surfaces, known collectively as periphyton. Periphyton can be seen throughout the year but grow to nuisance levels during the spring when they are fed by nutrients derived from lake mixing, snow melt, and ground water. Periphyton thrive until nearshore waters warm and ultraviolet radiation intensifies. Then mats of algae break free (or slough) from the substrate, buoyed by gas bubbles trapped in the algae mat. These mats may float around the lake for weeks, until they sink to the bottom or wash up on shore. This annual occurrence happens in April and May, when people are less likely to visit the shoreline, and by June, most evidence of algae is gone as a result of decomposition.

Regan Beach in South Lake Tahoe, 2014. Photo: S. Hackley

Sampling periphyton on the west shore. Photo: B. Allen

An Alga for Every Season, continued

A patch of sloughed periphyton floating near the west shore. Photo: B. Allen

Metaphyton growing near asian clam beds Photo: B. Allen

Sometime in the 2000s, a new nuisance alga began to make an annual appearance during the summer months along the south shore of the lake. Metaphyton, a class of bright green filamentous algae is now proliferating in shallow nearshore waters. Metaphyton is not attached to the substrate and is free to move with water currents. When the lake level is low, or during strong summer winds, the metaphyton can wash up on beaches turning clean, white sand into a smelly, green shoreline during the peak of the summer visitor season.

How did the metaphyton get here? Some metaphyton were known to be present in the lake in the 1910s. The difference now is that the concentrations and extent have increased, turning them into a nuisance species. The Asian clam invasion, which started in the early 2000s, around the same time that metaphyton became a nuisance, is one of the primary causes of this increase. The metaphyton blooms occur close to dense clam beds and high clam excretion rates of nutrients in summer occur just as the metaphyton begin to grow. The peak growth of metaphyton augmented with nutrients from Asian clams coincide with the height of the summer tourist season, typically in August, and may explain the increasing public comment about the condition of the nearshore.

Whether it is the furry periphyton growth in the spring and its sloughed mats, or the washed up metaphyton, or both, public perception of Lake Tahoe's nearshore is important to us and to local management agencies. With support from the Nevada Division of State Lands, we are developing new remote sensing techniques for tracking both algal communities using an unmanned aerial vehicle (drone) and a helicopter. There is also a great need for input from the public to help us track the spread.

You can assist monitoring efforts by recording your observations on our mobile Citizen Science Tahoe App (https://citizensciencetahoe.org).

Metaphyton Detection Using a Helicopter and UAV

The health of the lake is often judged by a narrow band of shallow water around its edge. The shore zone of Lake Tahoe is where the public interacts with the lake. In recent summers, metaphyton (unattached, filamentous algae) have been observed over the sandy bottom in nearshore waters of Lake Tahoe. Coupled with seasonal periphyton (attached algae) on shallow substrates, these algae degrade the aesthetic conditions of the nearshore of Lake Tahoe.

In a study supported by the Nevada Division of State Lands' Lake Tahoe License Plate Program, TERC and other UC Davis scientists developed innovative metaphyton monitoring techniques through remote sensing utilizing a helicopter and an unmanned aerial vehicle (UAV) or drone.

The helicopter-based surveys were shown to have great potential for rapidly visualizing the entire shoreline of Lake Tahoe in under two hours. Through helicopter imaging metaphyton were often "discovered" in surprising areas including on the Tahoe City shelf near the outlet and at Skyland on the southeast shore. Researchers were unaware of the extent of growth in those areas until viewed from above in the helicopter.

Metaphyton along bottom at Skylandia beach.
Photo: B. Allen

Attached algae (periphyton) on rocks at Regan beach.
Photo: S. Hackley

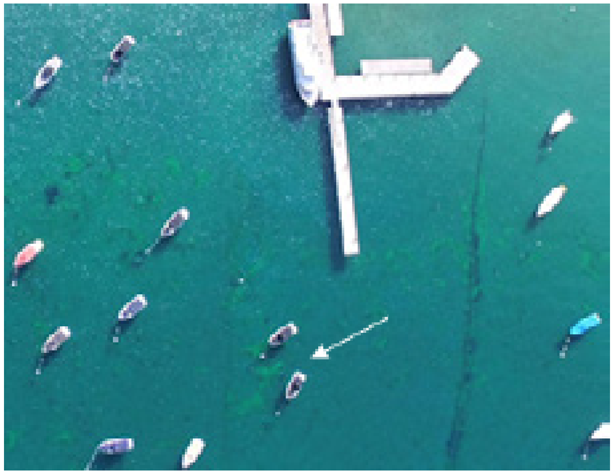
Metaphyton Detection Using a Helicopter and UAV, continued

The UAV proved to be cost-effective and efficient in quantifying the distribution of metaphyton over specific areas of Lake Tahoe's nearshore. The UAV monitoring process developed by TERC, coupled with in-lake biomass sampling, allows future metaphyton monitoring to efficiently assess the timing, distribution, and abundance of nearshore nuisance algae. The same UAV monitoring process also shows potential for estimating periphyton distribution during peak seasonal growth.

In addition to development of helicopter and UAV methods for determining regional distribution of metaphyton, the project studied the association of metaphyton with the occurrence of the invasive Asian clam (*Corbicula fluminea*) which were found to be a major contributing factor to the formation and sustenance of metaphyton patches in the southeast of Lake Tahoe.

These new approaches to monitoring metaphyton will allow for the accurate determination of the spread of these nuisance algae, and provide a very sensitive and cost-effective method for tracking the spread of Asian clams.

Brandon Berry flies the UAV (drone) over a Lake Tahoe site. Photo: B. Allen



Helicopter image of metaphyton (shown with white arrow) at Round Hill Pines. Photo: A. Wong

Sugar Pine Reforestation

Forest Health

From 2012 to 2016, intense drought conditions and bark beetle infestations resulted in the deaths of more than 126 million trees in California and 72,000 in the Lake Tahoe Basin. The TERC Forest and Conservation Biology Lab found significant mountain pine beetle-mediated mortality in sugar pine trees on the north shore of the Lake Tahoe Basin, from Crystal Bay to Tahoe City. Despite high levels of sugar pine mortality, there were numerous surviving sugar pine trees. In 2016, the lab cored from 100 live and 100 mountain pine beetle-killed sugar pine trees, to conduct a retrospective analysis of their tree rings. The pattern that emerged was that the live sugar pine trees utilized water more efficiently then neighboring beetle-killed sugar pines. So in September 2017, the lab collected from 100 local and diverse seed sources, essentially drought "survivors" throughout the Lake Tahoe Basin. Many of the collections came from high mortality locations on the north shore. Over 10,000 seedlings were cultivated at the U.S. Forest Service nursery in Placerville and later maintained at the UC Davis field station in Tahoe City until out-planted.

In fall 2019, TERC partnered with the California Conservation Corps (CCC) to replant over 4,000 seedlings around the Lake Tahoe Basin on state and federal lands. The rationale is to reforest with the progeny of local drought "survivors" to assist regeneration. Reforestation with this progeny will promote forest resiliency to changing and uncertain climatic conditions.

UC Davis forest ecologist Patricia Maloney plants a sugar pine seedling in Lake Tahoe Basin Management Unit. Photo: K. Kerlin

Precise geolocations allow for easier monitoring and tracking. Photo: P. Maloney

Sugar Pine Reforestation, continued

Forest Health

Plant populations can adjust to changing environmental conditions through a number of processes including local adaptation and episodic mortality. Natural resource managers are at a critical moment in how to best manage resources for adaptation and uncertainty, and the Forest and Conservation Biology Lab sees promise in these local and diverse drought "survivors."

The impact of this project, funded by the Tahoe Fund and the California Tahoe Conservancy, has attracted widespread attention to the work UC Davis TERC is conducting in the Sierra Nevada regarding reforestation and climate adaptation strategies.

It was featured on NPR (https://www.npr.org/2019/10/16/766200948/trees-that-survived-california-drought-may-hold-clue-to-climate-resilience); UCD Science & Climate News (https://climatechange.ucdavis.edu/news/the-survivors-sugar-pine-trees-and-the-future-forest/l); live at the LA Times (https://www.latimes.com/california/story/2019-11-18/sierra-trees-climate-change-adaptation-lake-tahoe); and (https://enewspaper.latimes.com/desktop/latimes/default.aspx?edid=fd40b32b-6dd0-408b-9f5d-169f84777403). The work has also attracted international attention in Der Spiegel (https://www.spiegel.de/international/world/california-survivor-trees-researchers-pin-hopes-on-resistent-pines-a-e1424af9-83b4-4433-8fff-752716e3d46b).

Sugar pine restoration planting with assistance from CCC members. Photo: K. Kerlin

Zack McHenry, CCC crew supervisor with an armload of pine seedlings for out-planting. Photo: K. Kerlin

Sugar Pine Genetics: A Test of Local and Diverse Seed Sources

Forest Health

Recovering sugar pines from drought, pest outbreaks, and fire often requires active restoration efforts. All land managers are then left with the difficult decision of selecting appropriate seed material. With funding from the California Tahoe Conservancy, the TERC Forest and Conservation Biology Lab is studying local (from within the Tahoe Basin) and diverse sugar pine seed sources used in reforestation for recovery from drought and bark beetle outbreaks. Additionally, the project is evaluating important adaptive phenotypic traits in a common garden in the lath house located at the Tahoe City Field Station. A common garden experiment is where plants from different genetic individuals are grown in a common environment to evaluate variation in a suite of plant traits (see below). The lab will also be tracking the survival and growth of over 4,000 out-planted sugar pine seedlings in the field. Both the common garden and field sources are the progeny of 100 genetically different sugar pine trees (“mother trees”) from the Lake Tahoe Basin.

Trees “pitch out” resin to try and prevent Mountain pine beetles from boring into the inner bark. Photo: P. Maloney

Sugar pine seedlings are marked to track date of bud burst in the spring. Photo: P. Maloney

Sugar Pine Genetics: A Test of Local and Diverse Seed Sources, continued

Forest Health

Tagging a variety of seedlings at the lath house in Tahoe City. Photo: K. Kerlin

Seedlings are tested for a myriad of traits. Photo: P. Maloney

The primary research goal is to evaluate 2,100 seedlings in the common garden by measuring the following plant traits: height growth, phenology (timing of bud burst in the spring), water-use efficiency, needle nitrogen content, plant defense chemistry, root to shoot ratio, and stomatal conductance. The lab will also conduct a drought experiment using a control block of seedlings (with ambient watering) and an experimental block for a drought/dry-down treatment. After four weeks, plants are evaluated for three key traits (water-use efficiency, stomatal conductance, and plant defense chemistry) that play a critical role in drought adaptation, plant defense response to insects, and resource partitioning.

Collaboration and outreach with federal and state resource managers is a primary goal in developing seed selection strategies for restoration and reforestation in the Lake Tahoe Basin and other regions in the Sierra Nevada. Such strategies will be fundamental for future forests to adapt and be resilient to ongoing environmental change.

Rise of Robots

Toxin-producing harmful algal blooms (HABs) are increasing in severity and prevalence in lakes, reservoirs, and rivers. While they are not yet present in Lake Tahoe, TERC is at the forefront of understanding the conditions under which they occur and is using innovative new tools to study HABs and predict their occurrence. In Clear Lake, California, HABs have occurred since at least the 1980s, producing scums on the surface of the water, noxious smells, and toxins that pose severe health risks to humans and animals.

In collaboration with the State Water Resources Control Board, the San Francisco Estuary Institute, and the Big Valley Band of Pomo Indians at Clear Lake, TERC is using multiple measurement techniques simultaneously to understand HABs. Robotics is at the core of the work, as sampling HABs can be both hazardous and time intensive. The work to date has involved Gavia, our autonomous underwater vehicle (AUV), aerial drones (UAVs), and satellite imagery to capture how these blooms are behaving both above and below the water. This project received a boost when PhD student Samantha Sharp was awarded a prestigious NASA Fellowship to extend this work both at Clear Lake and at Lake Tahoe.

While HABs are not currently an issue at Lake Tahoe, Samantha's work integrating multiple remote technologies to study algal blooms is something that is very applicable to Lake Tahoe and other lakes around the world.

HAB in Soda Bay, Clear Lake, CA (June, 2020). Photo: M. Swann

The Gavia AUV in Clear Lake, CA (August 2019).Photo: A. Forrest

Ice Fishing for Physics

It may have been thousands of years ago when Lake Tahoe was last frozen over in winter. However, many of the smaller lakes in the Tahoe basin and the Sierra do have annual ice cover. Ice-covered lake studies are not very common due to harsh winter conditions, treacherous working environments, and the lack of appropriate tools to measure the very subtle changes in temperature, oxygen, and other water quality variables that exist in the water under the ice. One example of the delicate balance that exists under the ice is the presence of slowly rotating gyres, natural phenomena that arise in part because of the Earth's rotation. These are believed to be one of the major processes that control water quality in this quiescent environment.

UC Davis PhD candidate Katie Hughes (left) and local resident Naisi LeBaron augering through 15" of ice at Lake Massawippi (February 2019) Photo: A. Forrest

Since 2018, researchers from TERC have been working with the University of Sherbrooke (Quebec) and the École Polytechnique Fédérale de Lausanne (Switzerland) to study an ice-covered lake—Lake Massawippi, Quebec, Canada. The lake's size, reliable ice-cover, and low snow conditions make it an ideal in situ laboratory. The team uses instruments installed under the ice to identify physical processes and to calibrate computer models.

Initial results from last winter are demonstrating the existence of these gyres and increasing our understanding of how these gyres drive mixing under the ice. Additionally, this documentation provides baseline conditions that improve predictions of how warmer future climates will impact the duration of ice cover, water supply, pollutant transport, and ecosystem health.

Plastics in Lake Tahoe

Microplastics, tiny pieces of plastic smaller than five millimeters, are impacting ecosystems worldwide. Microplastics have also been found at Lake Tahoe, despite efforts to clean up beaches and prevent litter.

TERC has been studying the location and extent of microplastic pollution in the lake and has launched efforts to educate visitors and change local consumers' plastic habits as part of the Drink Tahoe Tap® and Take Care Tahoe campaigns. With funding from the Nevada Division of Environmental Protection, the microplastics work is a collaboration between TERC researchers, educators, and several local partners.

A day at the beach (top) goes awry when plastic that is left behind ends up in the lake. Many of those plastics are broken apart and become microplastics. Photos: A. Toy

Photo: B. Wynne

Plastics in Lake Tahoe

Research

In 2016, TERC researchers began sampling the shoreline of Lake Tahoe to search for microplastics. The surprising quantity of microplastics found at all the beaches sampled has led researchers to begin sampling the lake itself.

For the deep (pelagic) waters, representative water samples are taken at multiple depths every three months. A specialized net (a manta trawl) is also towed across the lake surface and at a depth of 100 feet. Bottom sediment samples are collected with a box core sampler to capture denser plastics that have settled out of the water column. As drinking water comes directly from the Lake, water samples are collected quarterly from drinking water treatment facilities operated by Incline Village General Improvement District on the north shore and by Edgewood Water Company on the south shore.

Bioindicators are also an important part of this research. Asian clams, an invasive, filter feeding organism from the south shore and kokanee salmon stomachs provided by fishing guides will also be collected. These samples are sent to the Gjeltema Lab at UC Davis for Raman analysis using microspectroscopy. This provides data on particle size, chemical composition, and possible sources of the identified polymers. Our goal is not just determining where the Tahoe environment is impacted but knowing how we as a community contribute to microplastic pollution, and what actions can be taken to eliminate this self-inflicted harm.

Manta net trawling for microplastics in 2020 while researcher Katie Senft reviews some of the macroplastics found in a trawl sample (inset). Photos: B. Allen and K. Senft

Plastics in Lake Tahoe

Education and Outreach

In winter of 2019, TERC educators launched a campaign to reduce reliance on single-use plastics in the Tahoe basin. This campaign includes an exhibit, direct classroom programming, a community forum, and development of an outreach campaign to sell reusable water bottles at local Raley's grocery stores.

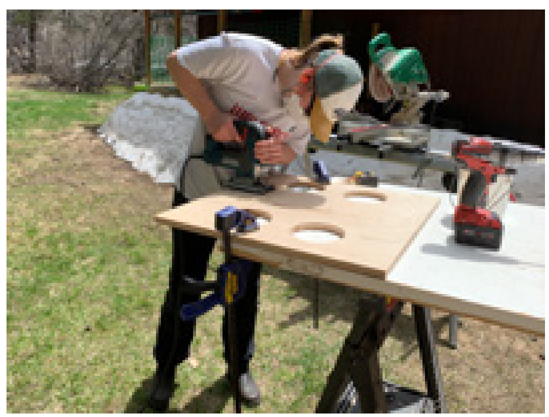
The exhibit on display at the Tahoe Science Center was also intended as an installation in the "Below the Blue: Lake Tahoe's Litter Crisis" art exhibition. The exhibit features a five-panel wall display, three tables of hands-on activities, and demonstrates how plastic items such as water bottles, straws, zip-top plastic bags, and plastic utensils go from just "a day at the beach" to impacting the entire ecosystem.

In collaboration with the Tahoe Water Suppliers Association (TWSA) and Sierra Watershed Education Partnership (SWEP), TERC has developed curricula to teach Tahoe students about the plastic problem facing Lake Tahoe. TERC educators met with Incline High School's Roots and Shoots Club and AP Environmental Science class to encourage students to investigate and discuss solutions to their school's plastic consumption and to eventually participate in broader local efforts to reduce usage of single-use plastic.

TERC organized a free online viewing of the documentary "The Story of Plastic." This was followed by an open forum where community members engaged with expert panelists from UC Davis TERC, UC Davis Gjeltema Lab, Desert Research Institute, League to Save Lake Tahoe, TWSA, Clean up the Lake, and California State Parks.

In partnership with Take Care Tahoe, Tahoe Fund, and Raley's grocery stores in Incline Village, TERC is encouraging residents and visitors to purchase Drink Tahoe Tap®-branded reusable water bottles. These bottles are displayed next to educational signage in Raley's stores. By using the Tap App we can all find locations in the Lake Tahoe Basin to refill reusable water bottles with the best tasting tap water in the world and avoid purchasing single-use plastic water bottles.

High school students sort through mesoplastics as a part of TERC's in-class laboratory session. Photo: H. Segale



AmeriCorps member Anne Graham working on a portion of the hands-on microplastics exhibits. Photo: H. Segale

AmeriCorps member Elise Matera teaching about the different types of microplasics and their sources. Photo: H. Segale

Pandemic Limnology

Boat Captain Brant Allen in protective gear and ready to perform only the most essential research duties. Photo: B. Allen

When COVID-19 emerged as a serious threat to health and life, it abruptly transformed how we worked, played, interacted with our communities and basically lived our lives. Within a day, we were all adjusting to working at home, sharing workspace with kids and roommates, and wondering how long it would last. At the same time, mother nature continued her transition from winter to spring, perhaps celebrating the reduced human impacts.

As scientists, we measure changes in the environment. Landscapes and large water bodies, like Lake Tahoe, respond to environmental changes at timescales of seasons and years, not days. So missing a week of data collection was unlikely to disrupt long-term studies. However, missing an entire season raised the specter of not being able to explain the next six months of environmental conditions and ensuing changes.

For our many graduate students, the stakes are even higher. Missing a season or a year of field data could interfere with spring plans to walk across the stage, diploma in hand. Professors must consider extending financial support to students beyond expected timelines and straining grant budgets. Funding agencies are also not in a position to help—nobody knows what future budgets will be.

In response to these concerns, TERC staff carefully evaluated what research was essential and how to safely get it done within the confines of local, state, federal, and University guidelines. Critical measurements, as winter turned to spring, were the depth and timing of lake mixing which transports stored nutrients to the surface waters, the erosive snowmelt runoff into the lake, and the response of nearshore algae growth to seasonal nutrient loads. Similarly, the maintenance of critical equipment, such as the instrument buoys on the lake, had to continue as failure in mooring lines could result in a tragedy. These were the measurements and activities that continued, albeit under new working conditions.

New safety procedures were designed, drafted, and submitted for approval. Under these new operating procedures, researchers worked alone to collect water samples and deploy instruments, and in teams of two when one researcher had to enter the water or extreme conditions warranted it. Personal protective equipment (PPE), long part of TERC's laboratory staff attire, was donned for field work. Face masks and latex gloves were worn at all times on the boats and only removed when replaced with a dive mask, snorkel, and neoprene gloves. Before leaving the marina, and upon return, the boats were thoroughly disinfected. The additional precautions added time and discomfort to the workday, but allowed researchers to maintain on-going projects and collect the most critical data needed for research to progress.

Reshaping Science Education in a Pandemic

March 6, 2020, it's the Friday before the launch of the 2020 Science Expo, TERC's annual week-long learning extravaganza that brings science to every 3rd, 4th, and 5th grade student in the Tahoe-Truckee area. This was also the same day San Francisco made a public health recommendation that at-risk populations limit outings and travel, and cancel non-essential large gatherings.

In the weeks before, we had recruited hundreds of volunteers, fine-tuned designs on over 30 hands-on science activities, and secured supplies. With hand-sanitizer, bleach wipes, and cleaning supplies unavailable, and with news updates coming with increasing frequency, TERC made the painful decision to cancel the event. By the following week all TERC staff were working remotely. The Science Expo banner hung in the empty science center for months to follow serving as a reminder of how quickly things can change.

On March 10, TERC closed the science center to public tours and school field trips and postponed in-person education programming. From March through June, the self-supported education program has experienced a loss of over $22,000. The small education team of two dedicated staff members and three AmeriCorps members had to shift gears and adjust to offering education programs virtually.

A Science Expo banner left hanging in an empty science center. Photo: B. Goodwin

Earth and space science activities set-up for the thousands of students who would miss out this year. Photo: A. Toy

Reshaping Science Education in a Pandemic, continued

Not content to simply wait out the pandemic, the TERC education team launched a massive effort to convert almost all programming to virtual modes. Visit the UC Davis Tahoe YouTube page to see videos of science experiments, volunteer docents explaining phenology and water conservation, and new thematic field trips. The team is currently developing a virtual tour of the Tahoe Science Center for the thousands of visitors who would, in better times, be visiting in-person.

New educational efforts have emerged. A Science-in-Place social media campaign with themes such as Tahoe Tuesdays, Watershed Wednesdays, and Fun Fridays increased our social media following by nearly 50 percent. Garden workshops, which are normally limited to 40 in-person participants averaged 420 viewers per workshop.

As part of a soft opening to new outdoor education programs, TERC is collaborating with the Tahoe Truckee Unified School District to run the Summer Literacy Program with a handful of students from the Tahoe Vista neighborhood. Books are selected with a Science Technology Engineering Math (STEM) emphasis and are complemented by engaging science activities. TERC is also collaborating with the Incline Village General Improvement District to deliver a summer science camp program. In accordance with current state mandates for both programs, all participants are required to wear masks, to answer a health questionnaire each day before participating, and to hand sanitize at the start and throughout programming.

The TERC education team is staying the course to fulfill our mission of using interdisciplinary education to advance knowledge of Lake Tahoe and the many interdependent forces that impact its watershed.

Masked students (siblings) in science summer camp collect beach samples for microplastics analysis. Photos: E. Matera

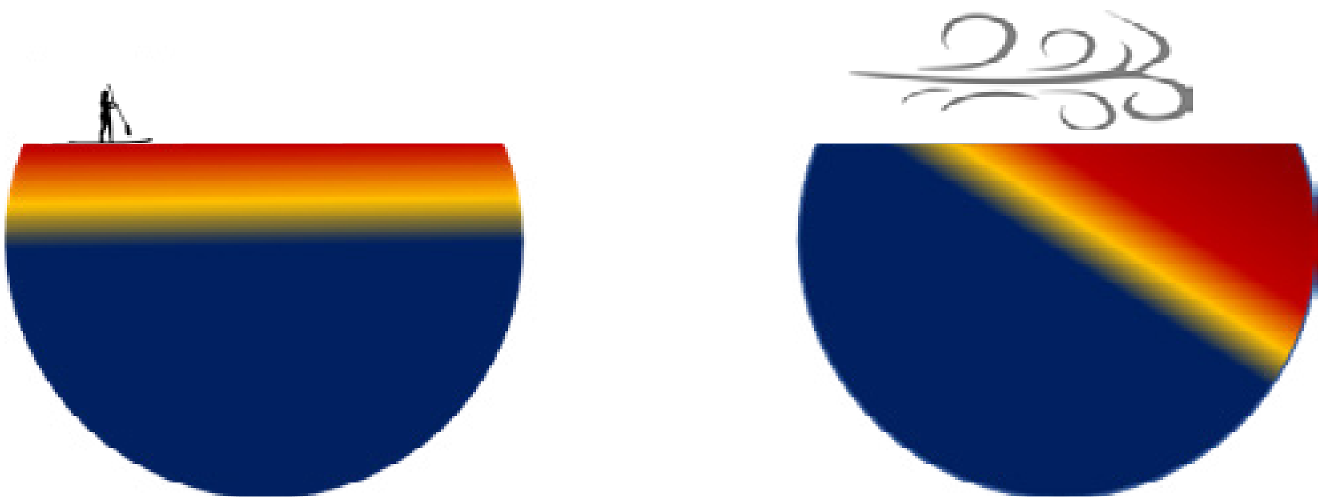
Docent Christie James continues to volunteer at TERC programs, reading to students in the science literacy program. Photos: A. Toy

The Perils of Paddleboarding

Stand up paddleboarding is a wonderful form of recreation and exercise. It is especially wonderful in Lake Tahoe on crystal clear waters, surrounded by beautiful forests and mountains, and in absence of creatures swimming below who might be tempted to eat you. But things are not as idyllic as they seem and serious danger may lurk below, albeit without teeth.

When strong and sustained winds blow at Lake Tahoe and other large lakes, an "upwelling" is produced. Warm surface waters get pushed downwind, and cold water rises (or upwells) from the depths below on the upwind shore. The figure (left) indicates a calm day when paddleboarding is a relaxing, enjoyable experience. Compare this with the figure on the right during a wind event where the effect of the upwelling on the lake is evident. Few people would care to go paddleboarding on such a windy day. The true danger lurks on the following day when the wind has died down, but the lake has not.

Typically, upwellings can occur almost weekly in the spring, but are possible throughout summer and fall. This work was motivated by previous field measurements of temperatures and currents where strong southern currents on the west shore after upwelling events were first observed.

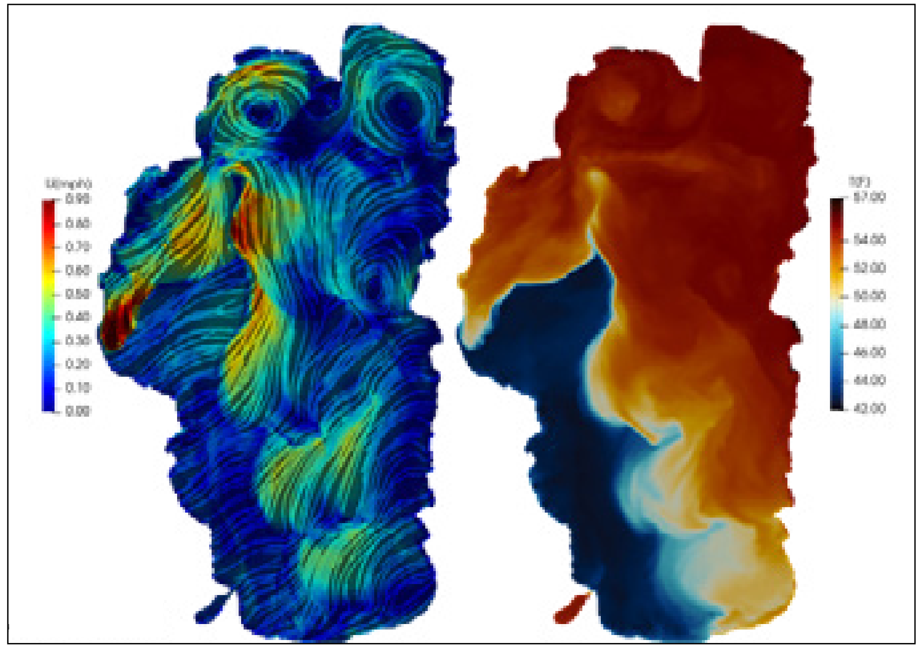


Using a 3-D hydrodynamic model, PhD student Sergio Valbuena has been examining what happens to Lake Tahoe after an upwelling has occurred.

The Perils of Paddleboarding, continued

The figures to the right are from a computer simulation and show lake surface conditions at 3:00 p.m. on June 10, 2018. This was 15 hours after the wind had dropped below 11 mph and 9 hours after the wind had dropped below 4 mph. After the warm water accumulated on the east shore, it flowed across the lake from east to west and then down the west shore, driven in part by the rotation of the Earth (seriously!). The figure on the right shows the surface water temperature with most of the warm water on the east side of the lake. While most of the lake is a brisk 55 ºF, the water in the south-west quadrant is a hypothermia-inducing 42 ºF. As if that isn't enough, the figure on the left shows the surface current patterns occurring at the same time. The red coloration, evident near Tahoma, indicates currents of over 1 mph. That may not seem very fast, but imagine falling off your paddleboard into frigid 42 ºF water. While you are catching your breath, you may or may not notice your paddleboard being carried away at 2 feet per second.

The solution is not to give up paddleboarding, but be aware of complex conditions that prevail at Lake Tahoe. Be wary of the day after strong wind events, as there may be icy water on the side of the lake where the wind came from. There may also be unexpectedly strong currents. Take proper safety precautions by wearing a life preserver and keeping yourself tethered to your board.

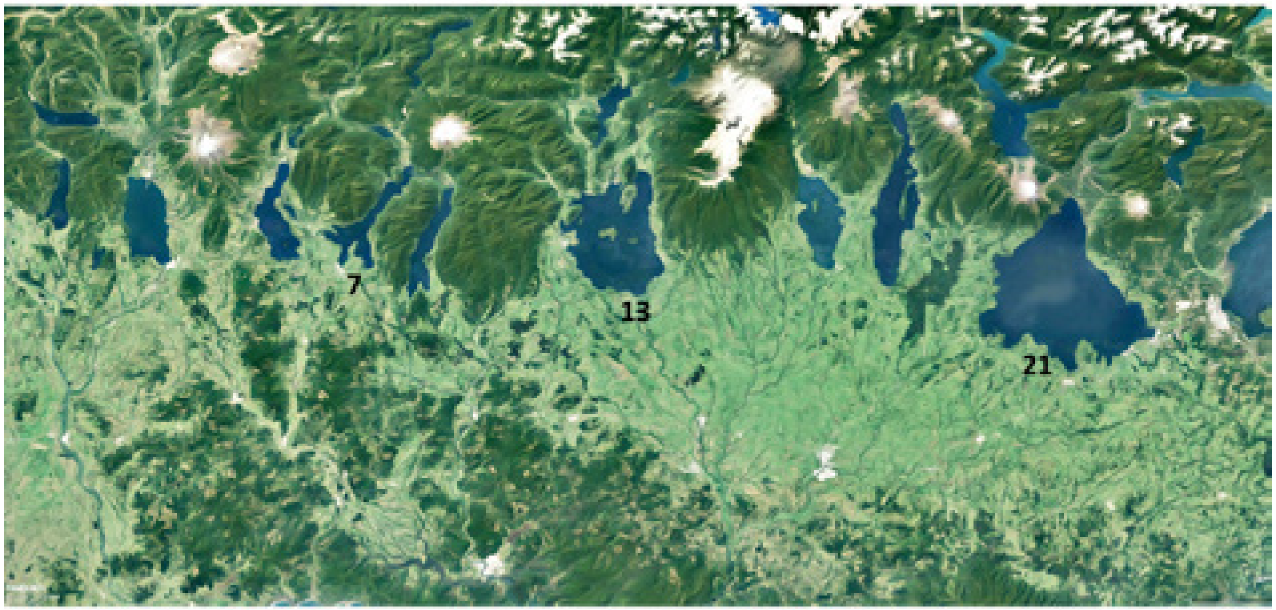


While everyone in this group of paddleboarders is wearing personal protective equipment, very few of them are tethered to their board. Photo: A. Toy

Lake Tahoe's Sister Lakes in Patagonia

A special relationship has been growing between the northern Patagonia lakes of Chile and Lake Tahoe. Why? For one thing, they are both beautiful and iconic regions. Like Tahoe, Patagonia's lakes are deep, near-pristine, offer boundless recreation and eco-tourism potential, and are highly valued by its residents and visitors. There are differences too. Lake Tahoe, known for snowy winter conditions, is perched at over 6,000 feet and is surrounded by the Sierra Nevada, while the Patagonian lakes are snow free at only a few hundred feet above sea level, but with the backdrop of the snow-covered Andes rising precipitously to over 10,000 feet.

Another connection between the lakes is the environmental threats they share. At Lake Tahoe, we have been aware of threats such as over-development, climate change, and poor land-use decisions for over 50 years. In that time, a sophisticated system of management actions and stakeholder engagement was developed to minimize threats and to balance human activities with environmental protection. These actions have usually been predicated on guidance provided by science.

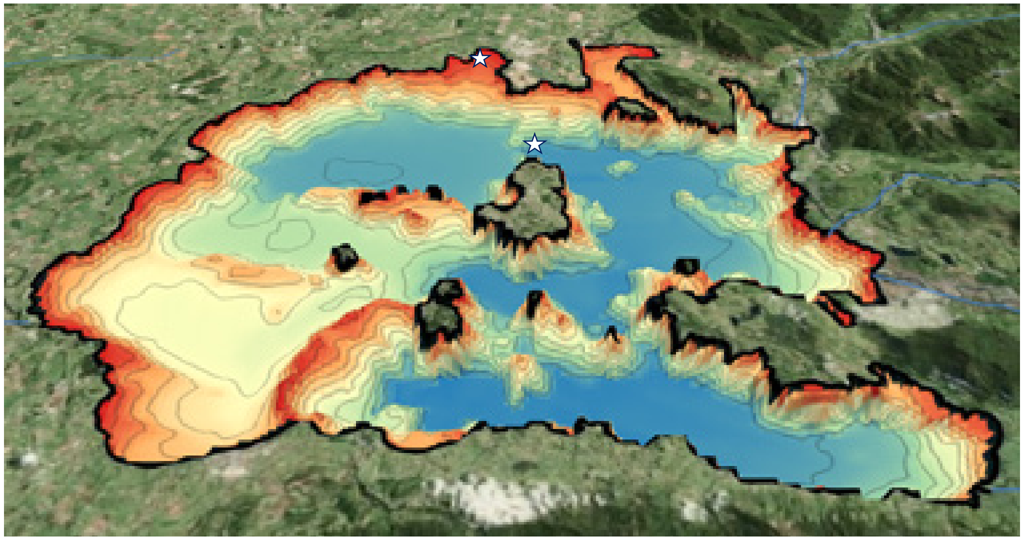


The 23 major lakes of the Northern Patagonia Region. The white areas at the top of the image are the permanently glaciated volcanos of the region. The numbers 7, 13 and 21 indicate the instrumented lakes: 7-Lago Panguipulli, 13-Lago Ranco and, 21-Lago LLanquihue. Image: Land Architects

Lake Tahoe's Sister Lakes in Patagonia, continued

Chile, in contrast, is at a far earlier stage of development and protection but is looking to Lake Tahoe for both inspiration and guidance. As Chile's economy grows, there is increasing pressure for holiday homes, tourism growth, and agriculture. All of these can greatly impact lake water quality if not located in the appropriate parts of the watershed, or in some cases are simply incompatible with maintaining a pristine lake. Investments in more benign options such as ecotourism, sustainable agriculture, and renewable energy can readily be explored to minimize impacts.

TERC has been working with Fundación Chile Lagos Limpios (ChLL), or Chile Clean Lakes, to bring the "Tahoe Process" to Chile. Starting with the installation of water quality instruments in Lago Panguipulli and Lago Ranco, high frequency water quality data are being collected to provide new information on these lakes. With a volume almost identical to Lake Tahoe, the largest lake in the region, Lago Llanquihue has a more ambitious monitoring plan. Through a new partnership with the second largest salmon production company in the world, AquaChile, and the Chilean technology company Innovex, 12 real-time monitoring stations will be installed in this giant lake.



The complex bathymetry (underwater topography) of Lago Ranco. The two TERC instrument stations are indicated by the white stars on the north side of the lake. For scale, the lake is 17 miles from north to south. Image: M. Swann

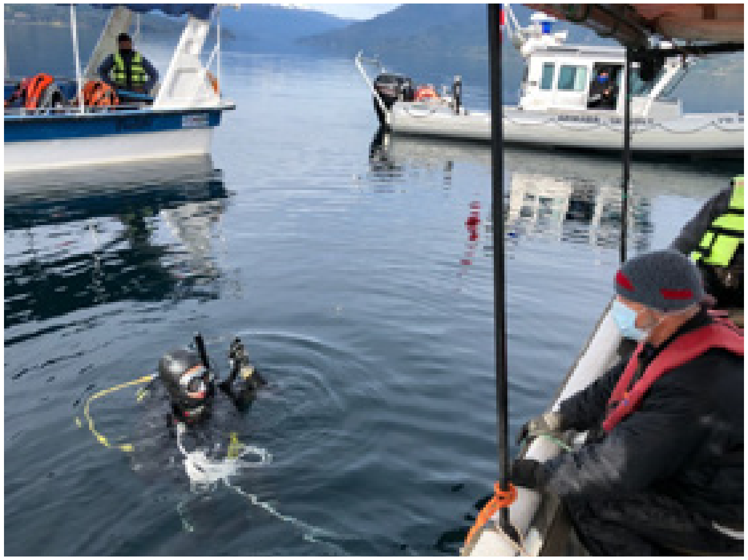
CHILE LAGOS LIMPIOS FUNDACIÓN

Lake Tahoe's Sister Lakes in Patagonia, continued

The data collected will be used to calibrate three-dimensional lake models that will explore the possible changes from combinations of climate change, future land-use options, and evolving government regulations. The development of these models and the lake data analysis will be part of the doctoral research of UC Davis graduate student Micah Swann. Climate modeling, hydrology modeling, as well as lake sampling will be done through an extensive set of collaborations with Chilean universities, private consultants, and government agencies.

As part of this project, a California delegation is scheduled to visit government representatives in Northern Patagonia in January 2021. In a reciprocal visit funded by the U.S. Embassy, a Chilean delegation will visit Lake Tahoe in June 2021. Funding for this project comes primarily from local stakeholder groups and Chilean foundations.

Lago Panguipulli, with the active Villarrica Volcano in the background. Photo: Guy Welborne Photography



Divers recovering a thermistor chain in Lake Panguipulli, Chile. Photo: G. Schladow

TAHOE:
STATE
OF THE
LAKE
REPORT
2020

METEOROLOGY

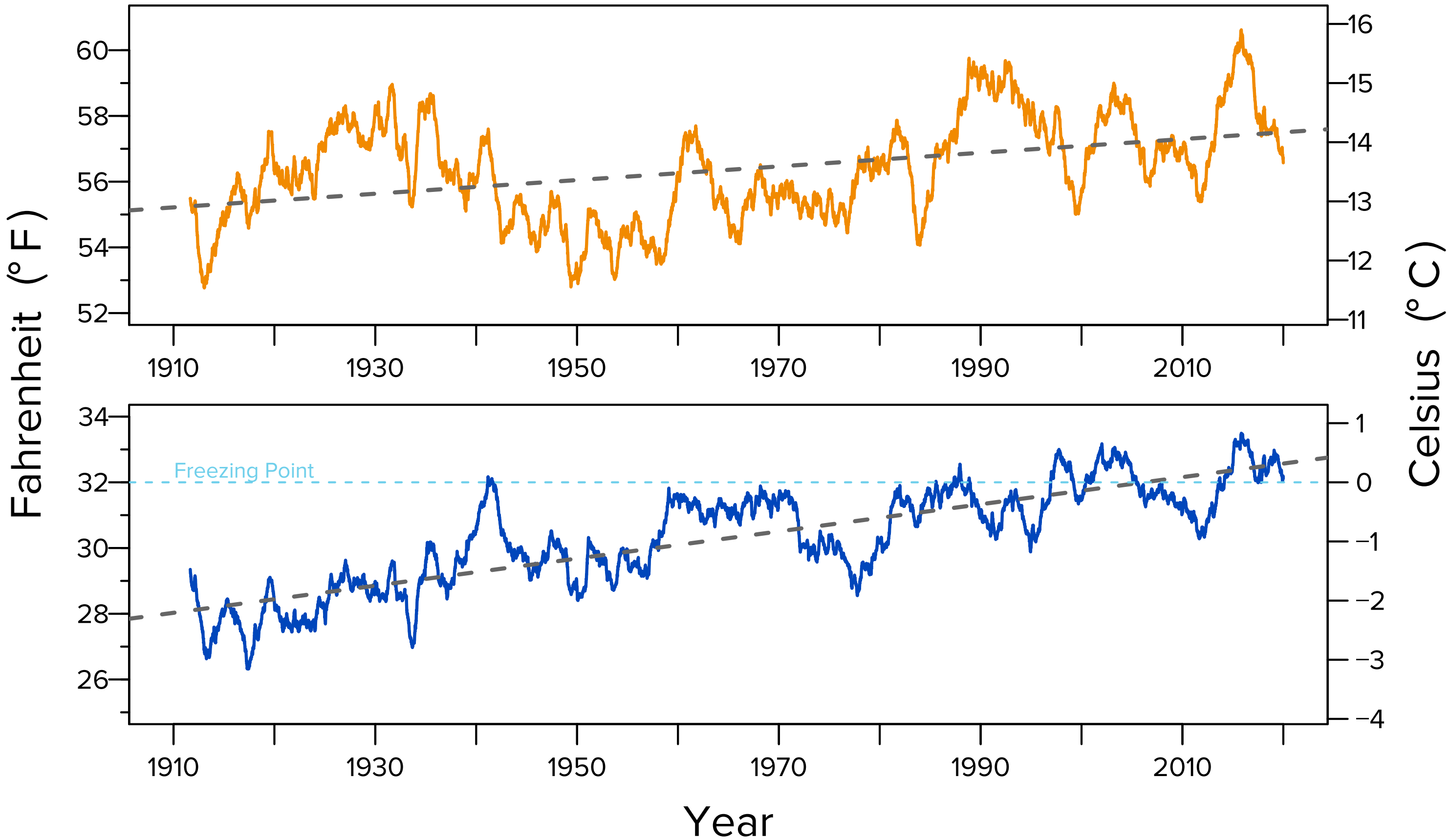
UC DAVIS
Tahoe Environmental
Research Center

Air temperature - smoothed daily maximum and minimum

Daily since 1911

Over the last 108 years, daily air temperatures measured at Tahoe City have increased. The long-term trend in average daily minimum temperature (bottom figure) has increased by 4.47 °F (2.48 °C) and the long-term trend in average daily maximum temperature (upper figure) has risen by 2.25 °F (1.25 °C). The trend line for the minimum air temperature now exceeds the freezing temperature of water, which is 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 temperature data set.

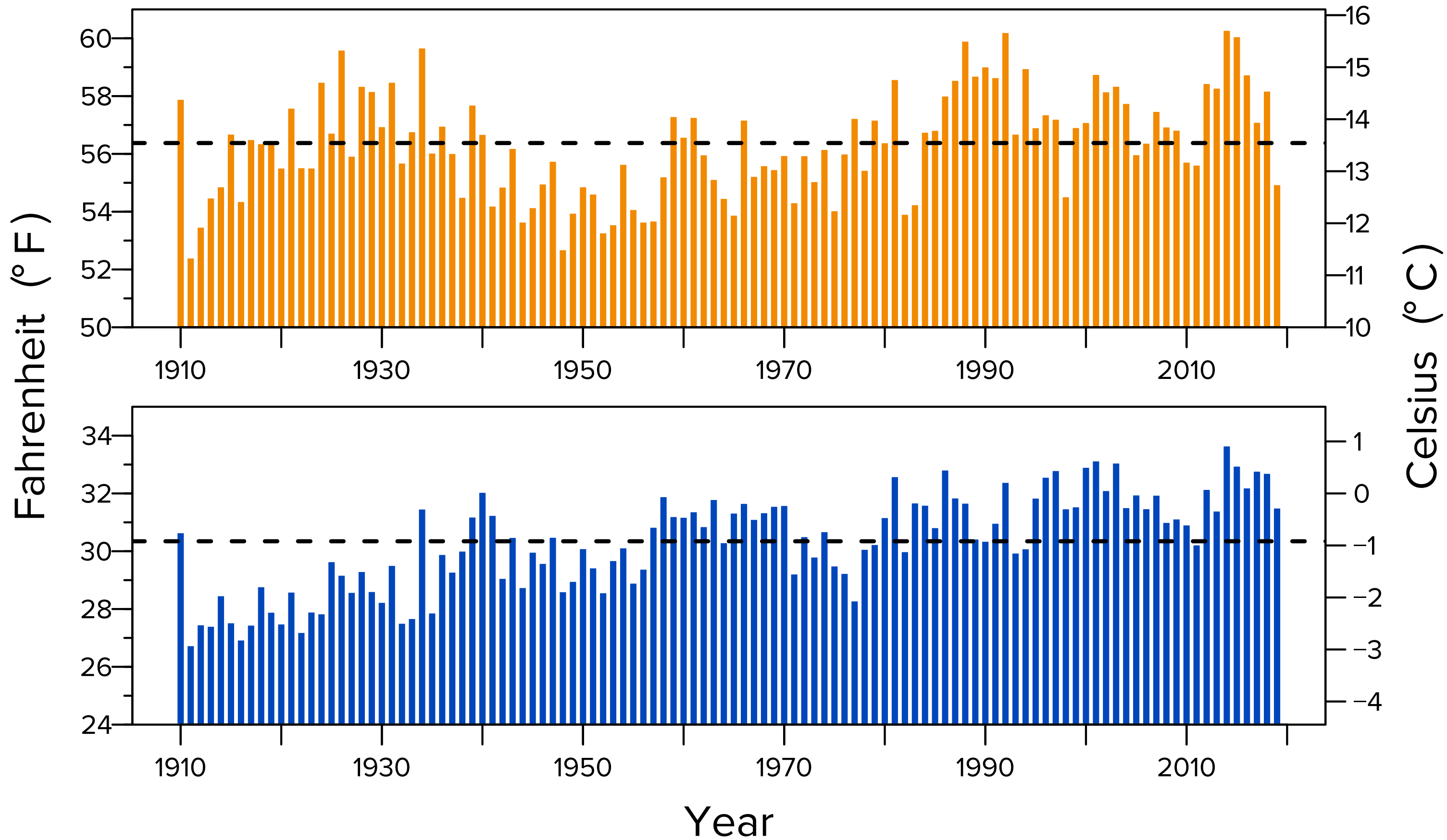


Air temperature - annual average maximum and minimum

Since 1910

Annual average maximum (upper figure) and minimum (lower figure) air temperatures in 2019 were cooler than the previous year. The 2019 annual average maximum air temperature was below the long-term average (dashed line) temperature. The maximum temperature was 54.95 °F (12.8°C), a decrease of 3.2 °F from the previous year. The 2019 annual average minimum was 31.5 °F (-0.3 °C), slightly lower than the previous year, but still above the long-term average temperature. The long-term means for the maximum and the minimum are 56.4 °F (13.6 °C) and 30.3 °F (-0.96 °C), respectively.

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



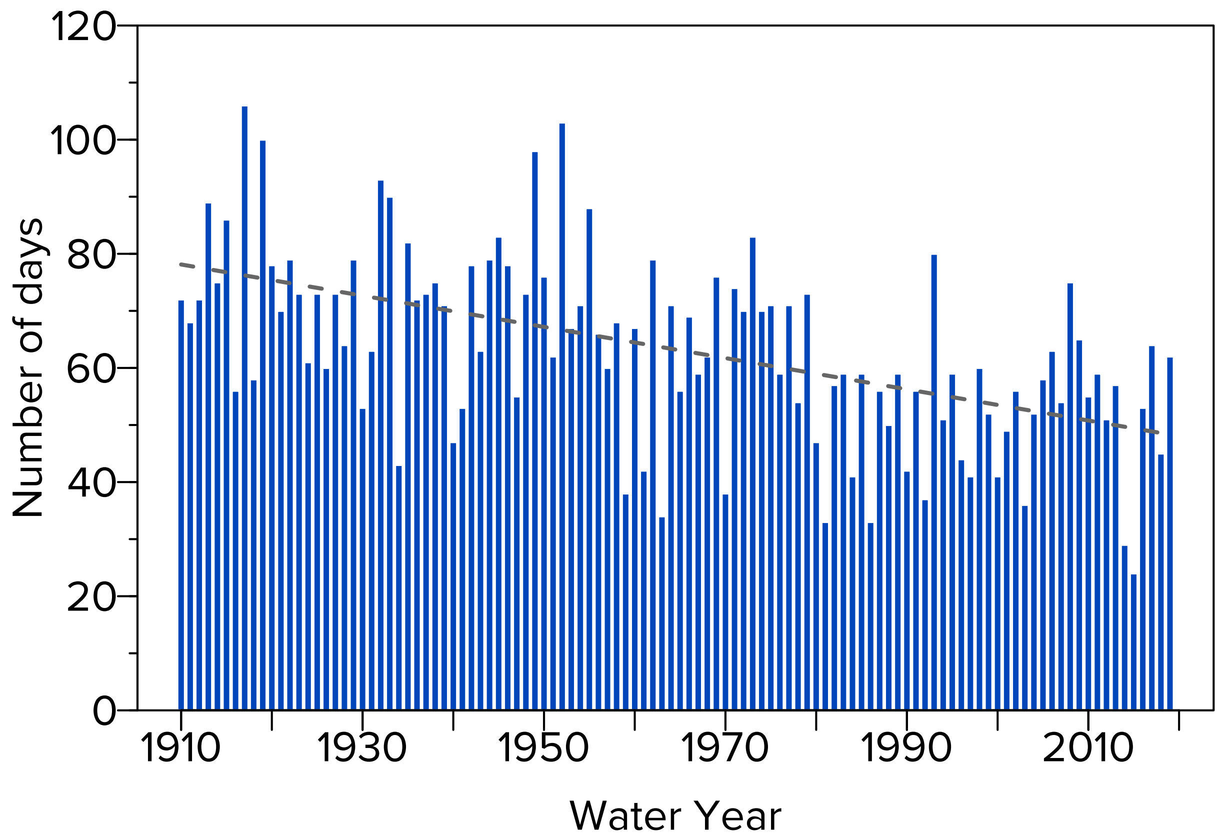
Below-freezing air temperatures

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 2019, the number of freezing days was 62, well above the declining long-term trend-line. This is consistent with the lower air temperatures in 2019.

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.

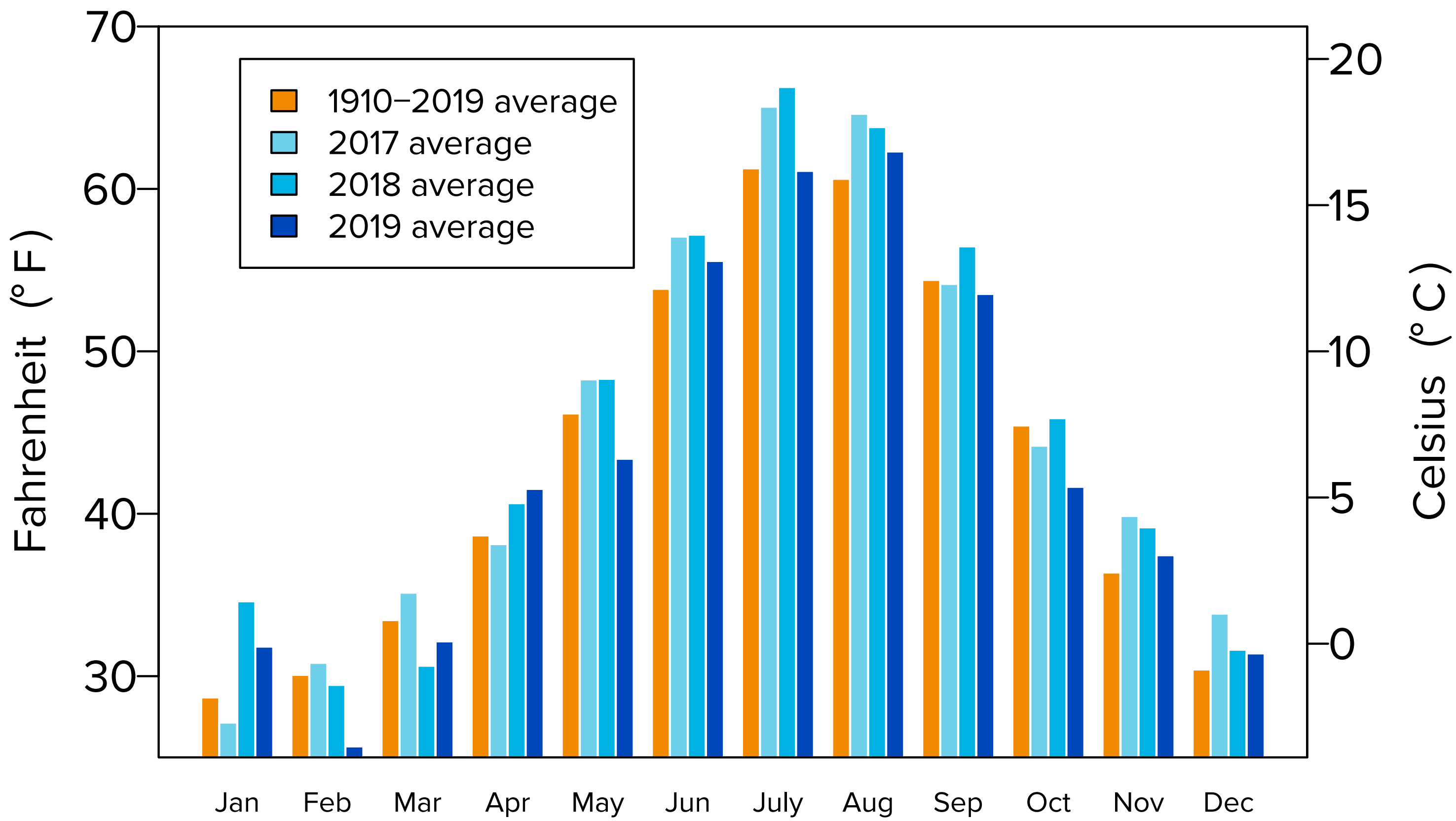


Monthly air temperature

2017. 2018, 2019, and 1910 to 2019

In 2019, monthly air temperatures were colder in every month of the year except April compared to 2017 and 2018. February was particularly cold with the 2019 monthly air temperature being 4.4 °F below the long term average. This was the coldest February since 1956, and the eighth coldest on record.

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

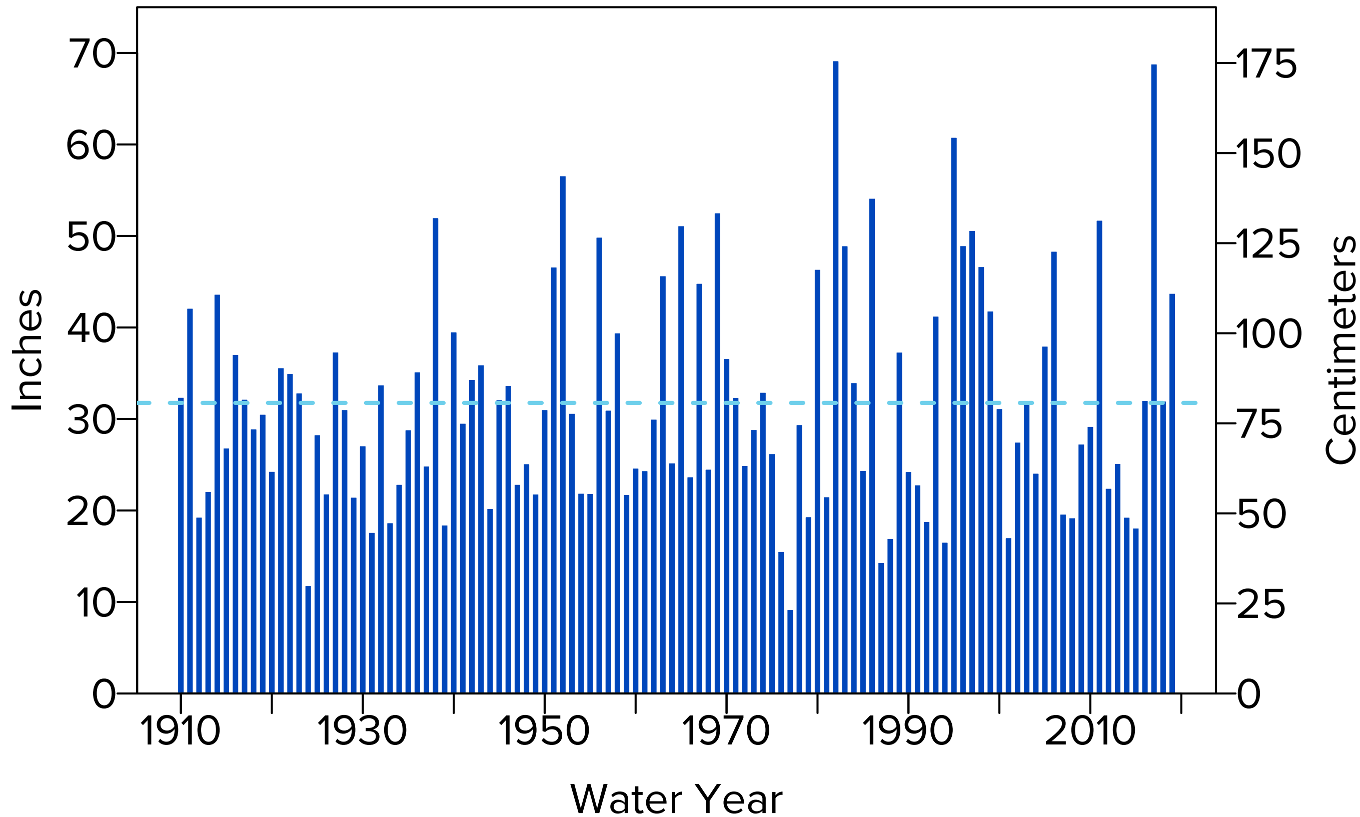


Annual precipitation

Yearly since 1910

From 1910 to 2019, average annual precipitation (water equivalent of rain and snow) at Tahoe City was 31.8 inches. The maximum recorded was 69.2 inches in 1982. The minimum recorded was 9.2 inches in 1977. At 43.8 inches, 2019 was above the long-term average. The long-term average is shown by the dashed line. Generally, there is a gradient in precipitation from west to east across Lake Tahoe, with almost twice as much precipitation falling on the west side of the lake. Precipitation is summed over the water year, which extends from October 1 through September 30.

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

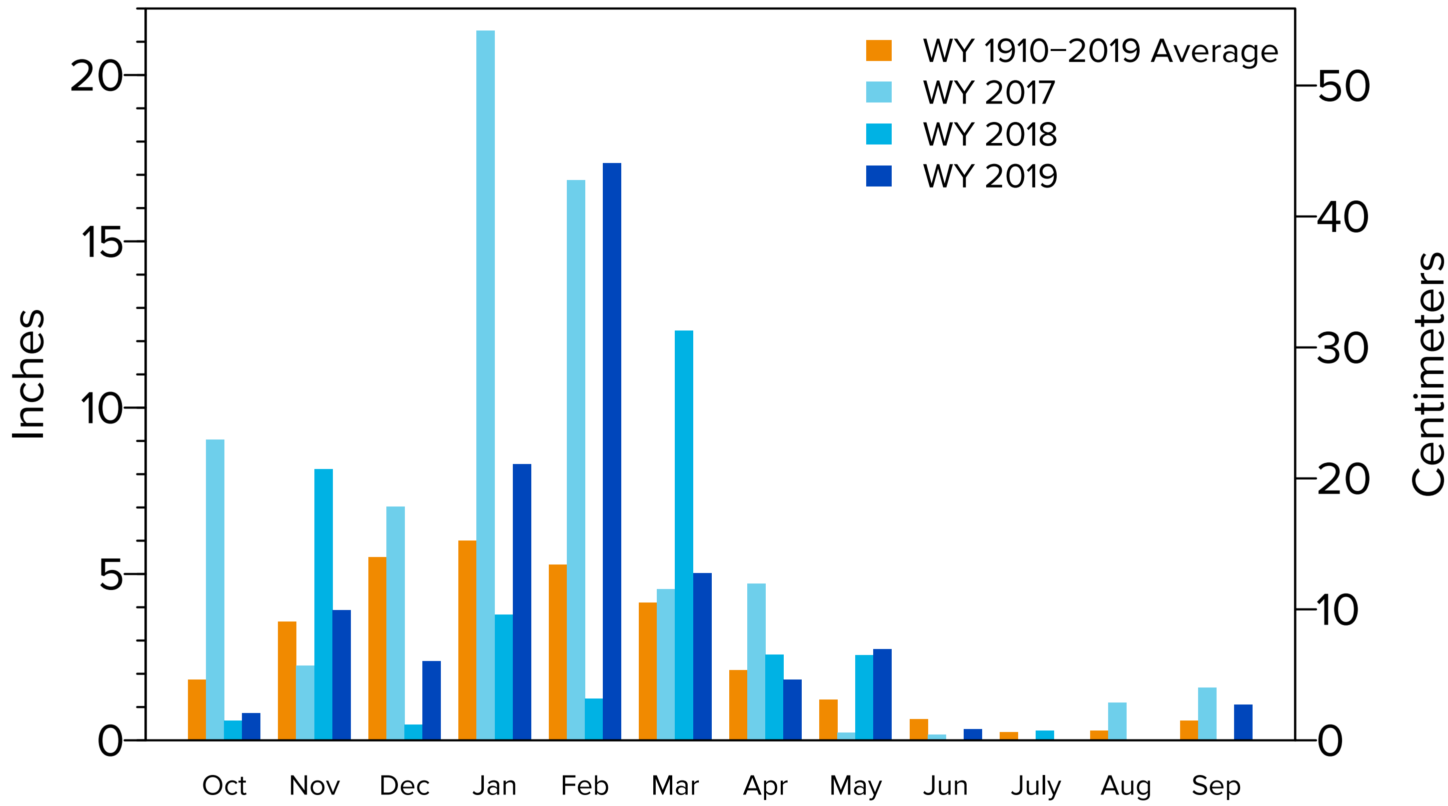


Monthly precipitation

2017, 2018, 2019 and 1910 to 2019

The 2019 water year was well above the long-term average in total precipitation at 43.8 inches compared with the long-term average of 31.5 inches. Precipitation in the month of February, at 17.4 inches, represented 40 percent of the annual total. The 2019 water year extended from October 1 through September 30.

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



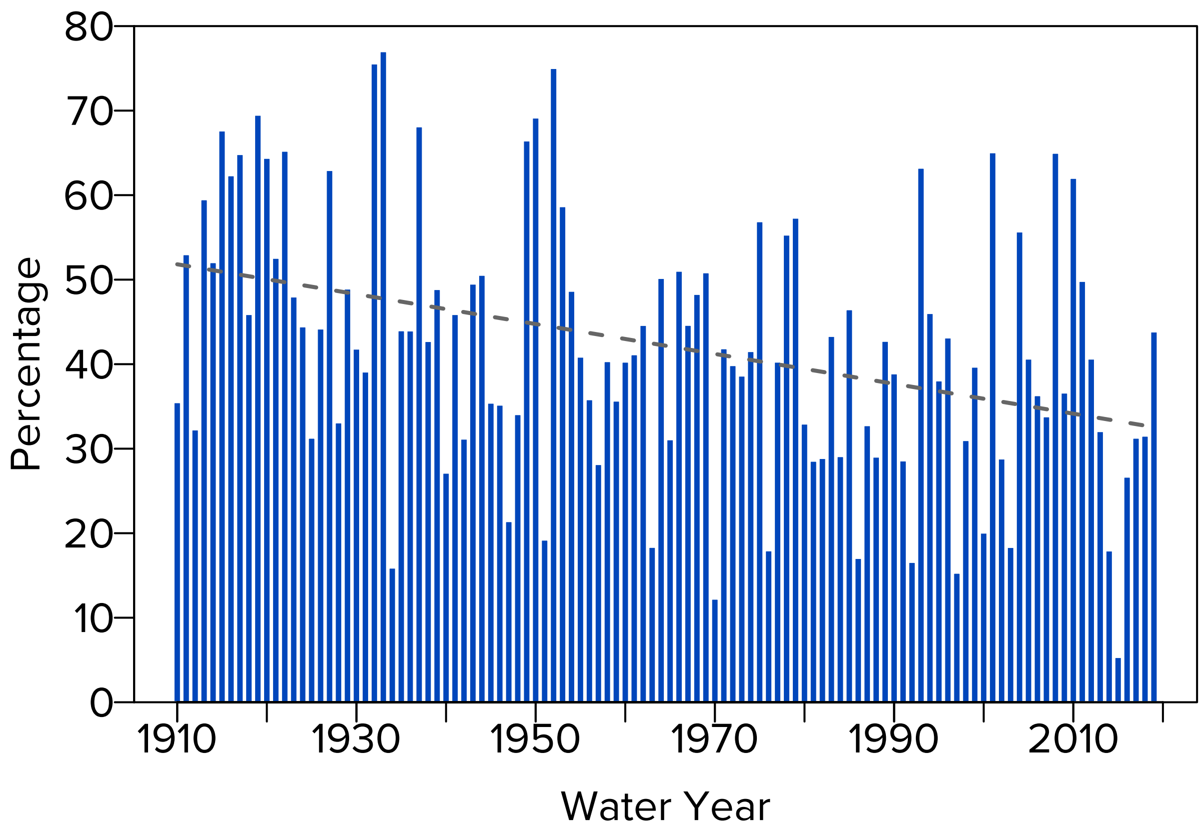
Snow as a fraction of annual precipitation

Yearly since 1910

Snow has declined as a fraction of total precipitation, from an average of 52 percent in 1910 to 32.6 percent, according to the line of best fit. In Tahoe City, snow represented 43.9 percent of the 2019 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.



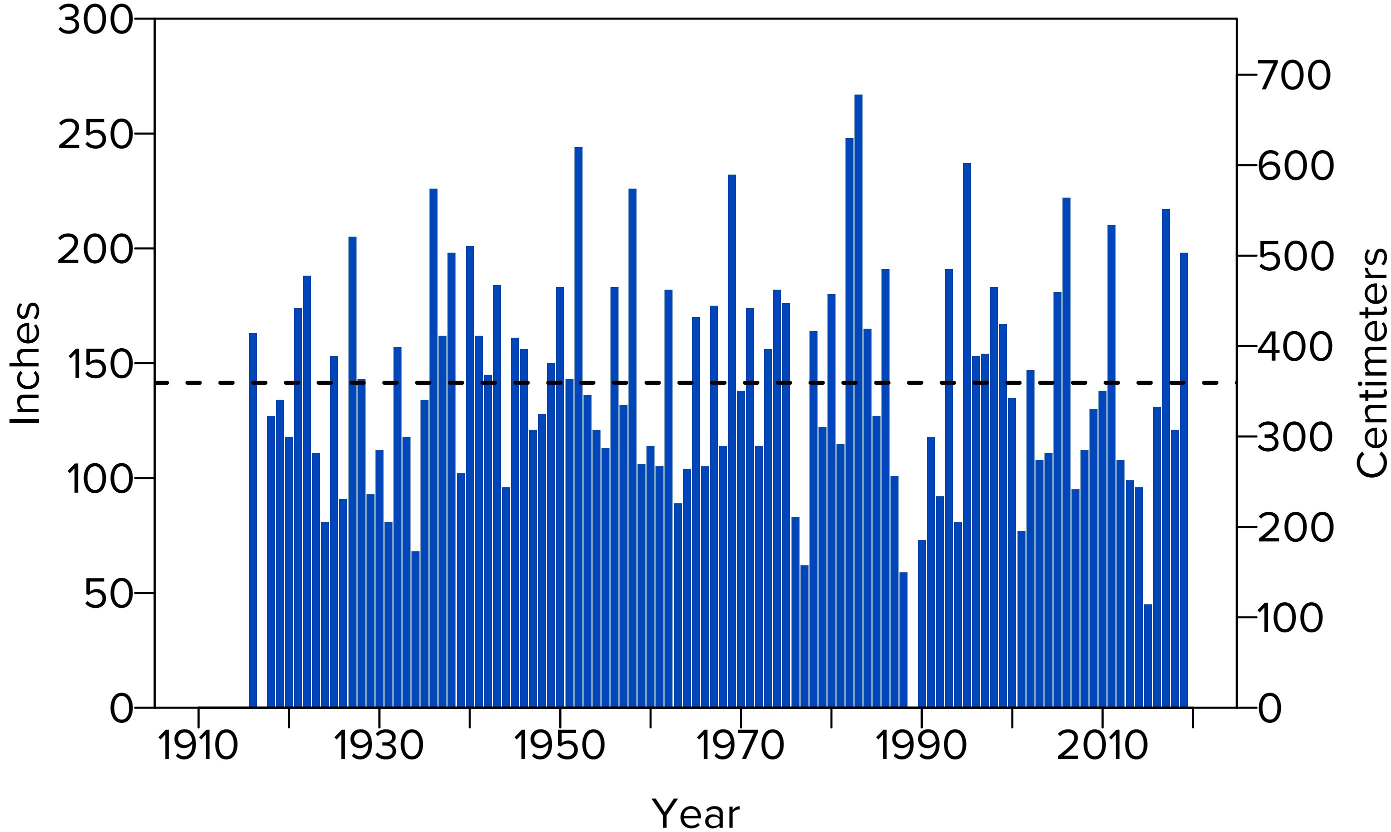
April snowpack

Since 1916

The depth of the snowpack is measured at multiple locations throughout the Sierra over the year. 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. The snow depth on March 29, 2019 was 198 inches, indicative of a wet and cold winter. The largest amount on record was 267 inches on April 5, 1983. The average snow depth over the period 1916-2019 was 142.9 inches.

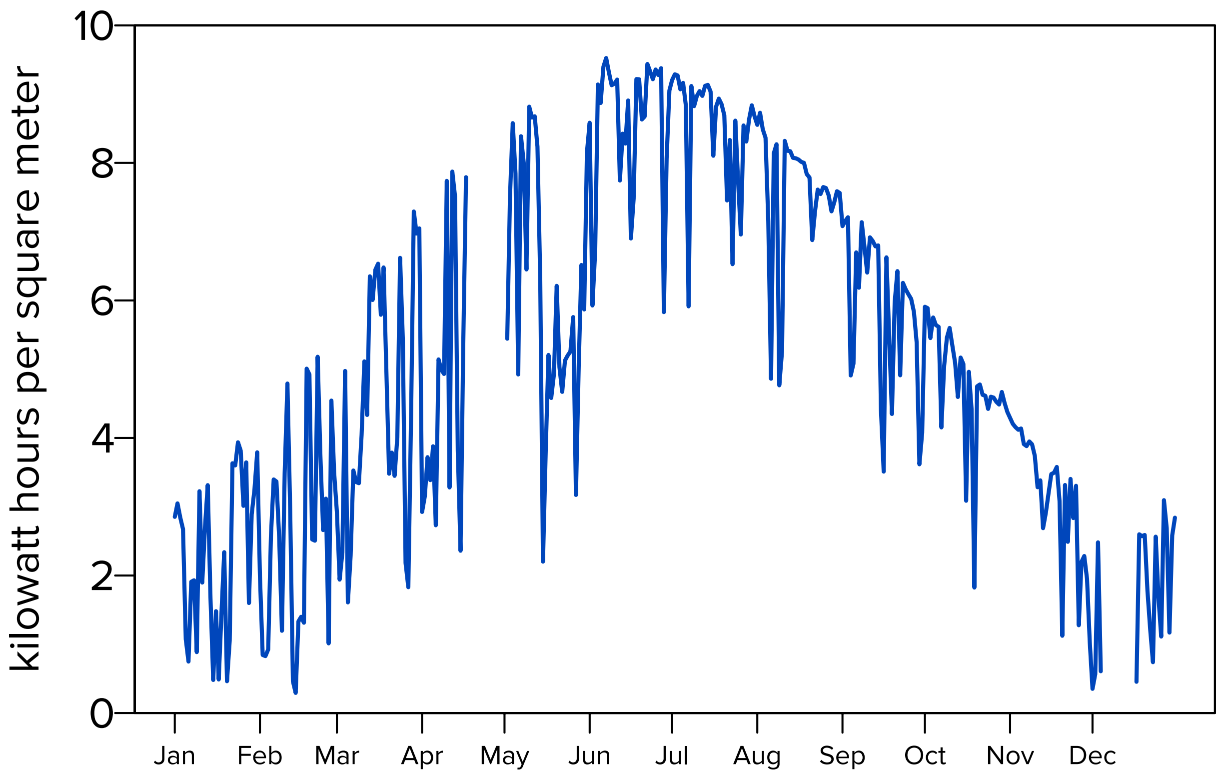
Data source: USDA Natural Resources Conservation Service, California Monthly Snow Data.



Daily solar radiation

In 2019

Solar radiation showed the typical annual pattern of increasing and decreasing sunlight, peaking at the summer solstice on June 21 or 22. Dips in daily solar radiation are primarily due to cloud cover. 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. 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 2020

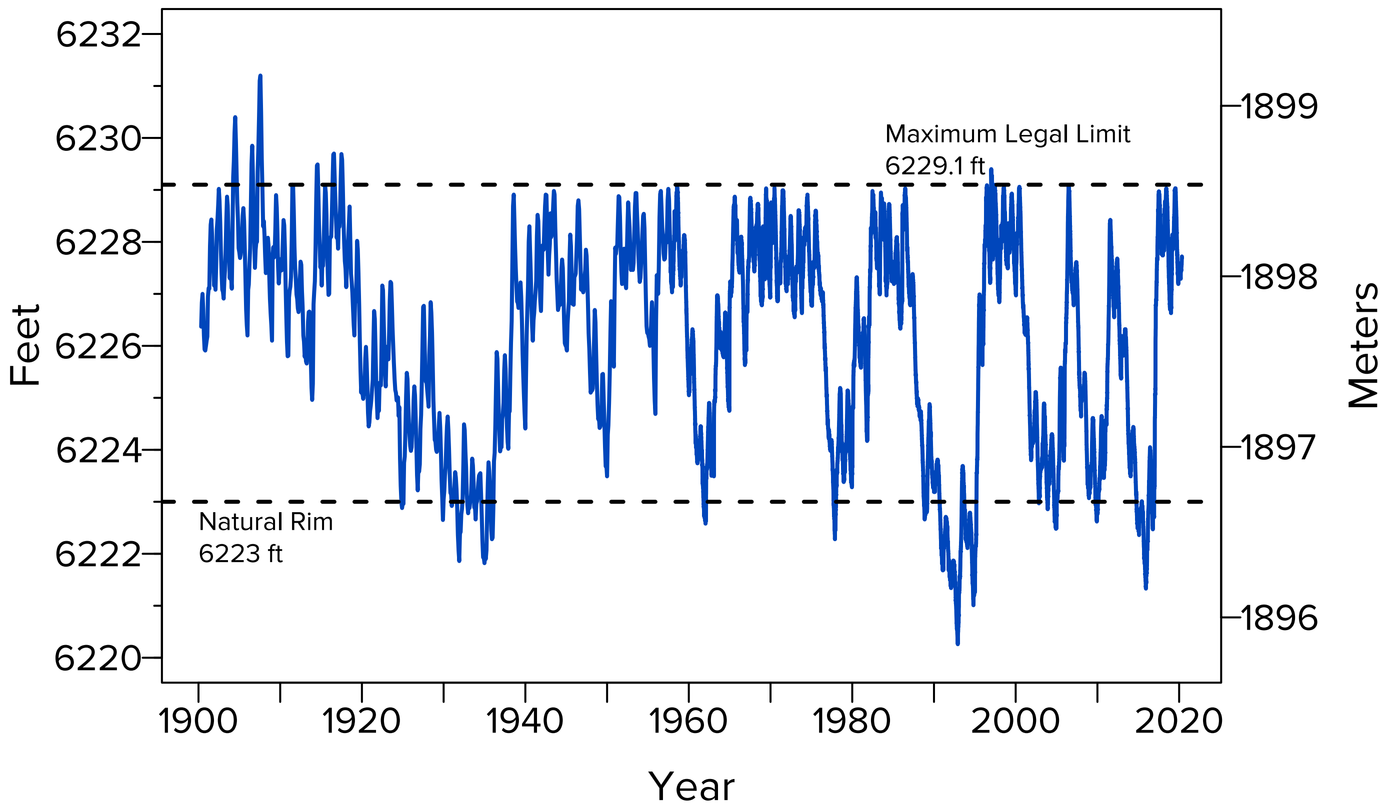
PHYSICAL PROPERTIES

Lake surface level

Daily since 1900

Lake surface level varies throughout the year. Lake level rises 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 outflow via the Truckee River at Tahoe City.

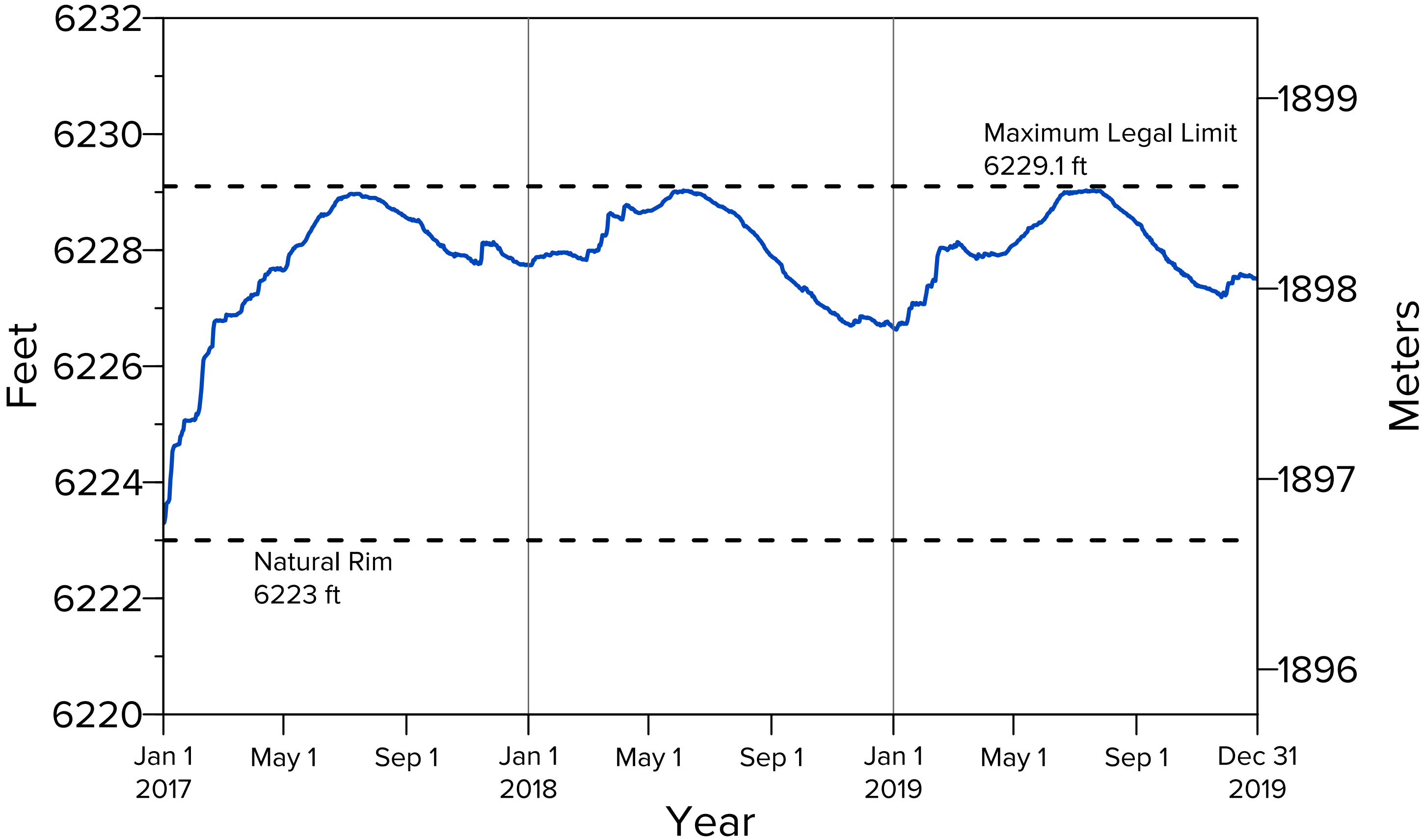
The highest lake level in 2019 was 6229.03 feet on July 1, and the lowest was 6226.63 feet on January 4. The natural rim of the lake is at an elevation of 6223 feet. Lake Tahoe was above its rim for the entire year. When the lake is below its rim, outflow via the Truckee River ceases. Several episodes of lake level falling below the natural rim are evident in the last 114 years. The frequency of such episodes appears to be increasing. The lowest lake level on record is 6220.26 feet on November 30, 1992. Data source: U.S. Geological Survey level recorder in Tahoe City.



Lake surface level

Daily since 2017

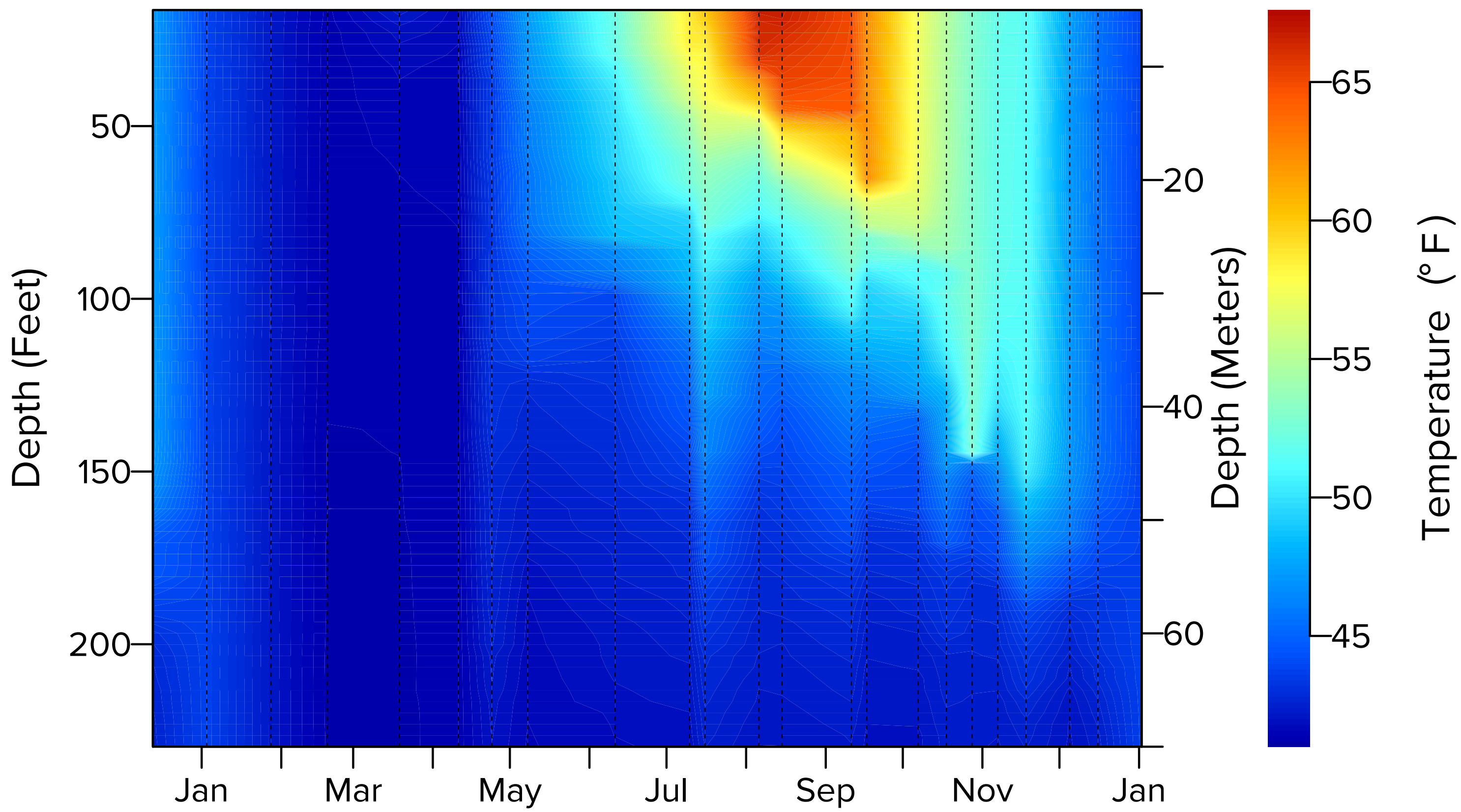
Displayed below is a subset of lake surface data extracted from the same data as in Fig. 8.1 for the most recent three years from 2017-2019. This more time restricted presentation of recent lake level data allows us to see the annual patterns of rising and falling lake level in greater detail. In each of the last three years, Lake Tahoe has come close to its maximum level. Typically, the lake is at its highest level in early summer and reaches its lowest level in early winter. From January through December 2019, lake level rose 10.2 inches.



Water temperature profile

In 2019

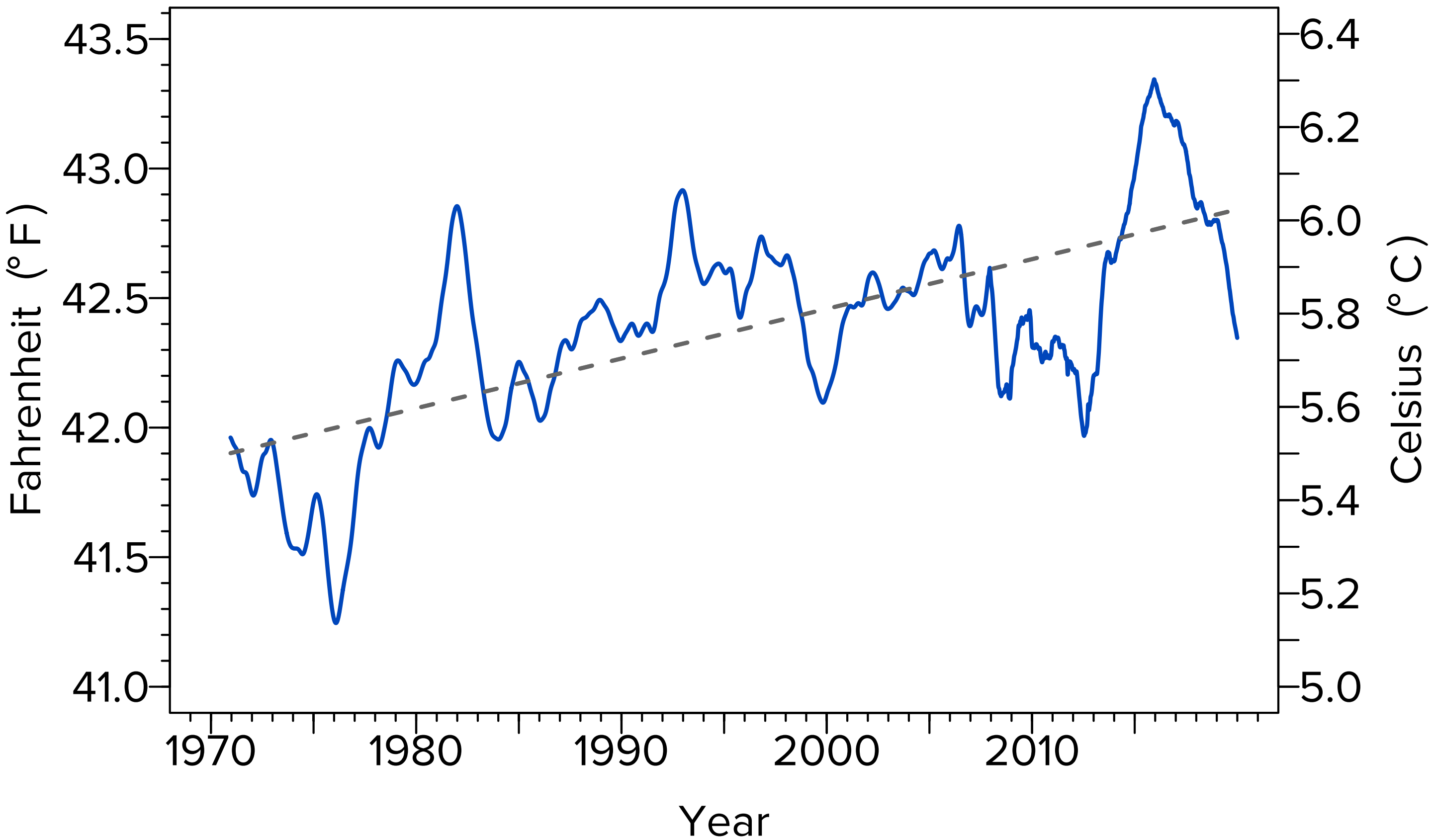
Water temperature profiles are measured in the lake using a Seabird CTD (conductivity, temperature, depth) profiler at the times indicated by the dashed vertical lines. The temperature is accurate to within 0.005 °F. The vertical distribution of water temperature is important, as it represents lake density, 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 2019, the lake temperature followed a typical seasonal pattern. In February-March, the lake surface was at its coldest, while it was at its warmest in August. The thickening of the warm water zone toward the end of the year is the result of winter mixing, a process that is important in bringing oxygen to the deeper parts of the lake.



Average water temperature

Since 1970

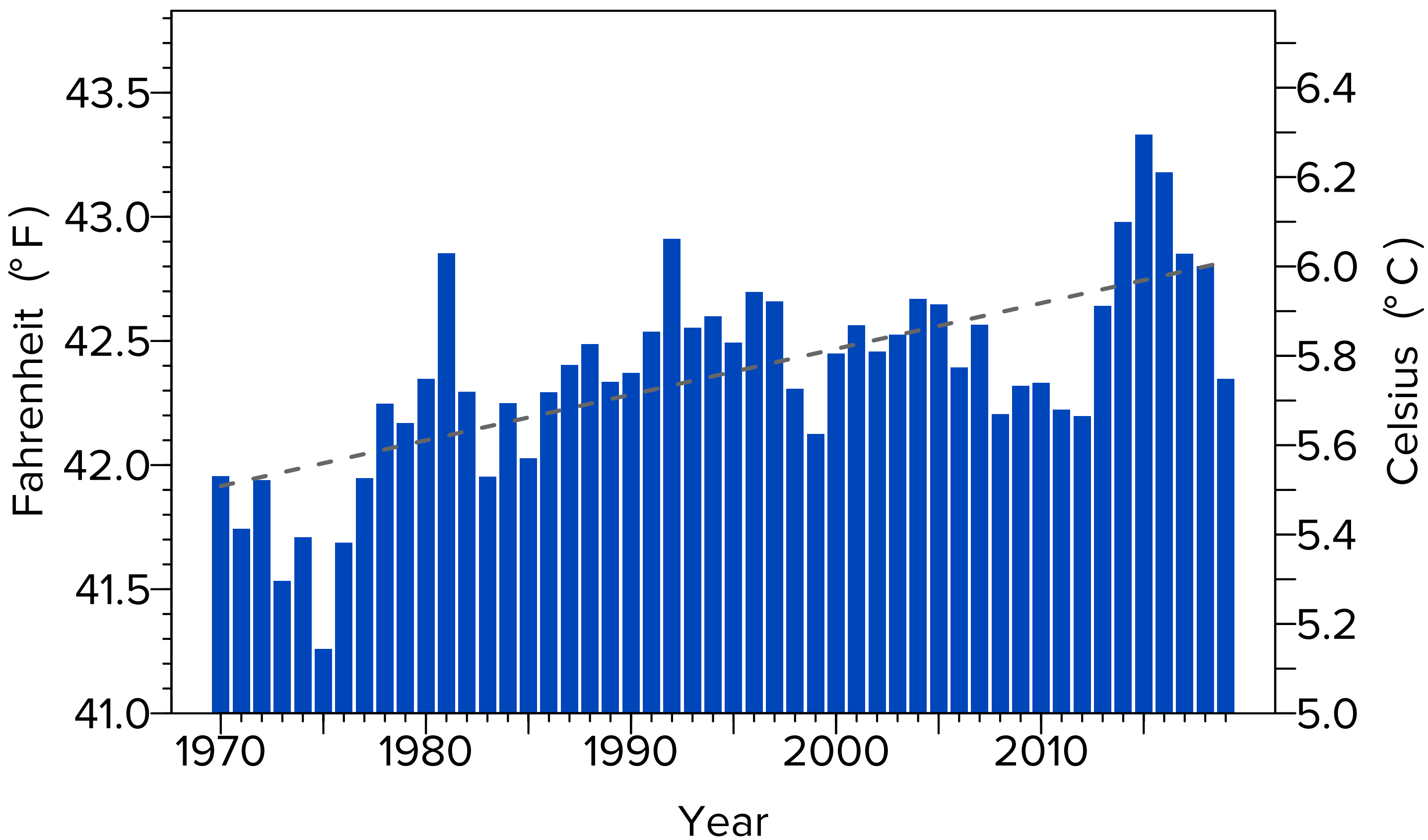
The linear trend in the average temperature of all the water in Lake Tahoe (dashed line) has increased by approximately 0.94 °F since 1970. The annual rate of warming is 0.19 °F/decade (0.011 °C/decade). The monthly temperature profile data from the top to the bottom of the lake has been smoothed and seasonal influences removed to best show the long-term trend. Up until the late 1990s, the warming rate was high. However, a high number of deep mixing years between 1997 and 2011, plus deep mixing in 2019. caused the average lake temperature to cool.



Annual average water temperature

Since 1970

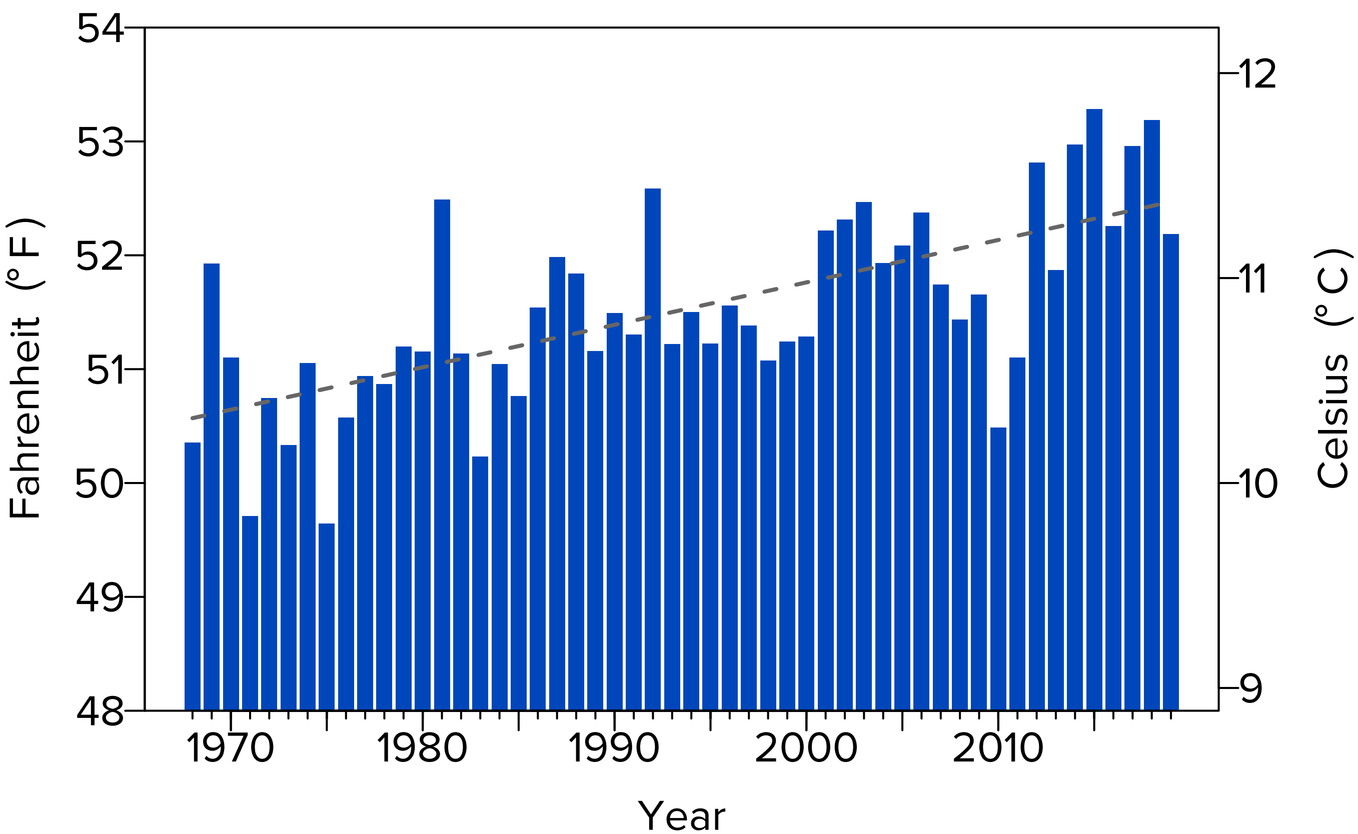
The volume-averaged temperature of the lake for each year since 1970 is shown. In 2019, the volume-averaged temperature decreased by 0.5 °F (0.2 °C) over the previous year. In the last four years, the lake has cooled slightly from its record warmest year in 2015. Since 1970, the trend in annual temperature rise (dashed line) has increased by 0.94 °F.



Annual surface water temperature

Yearly since 1968

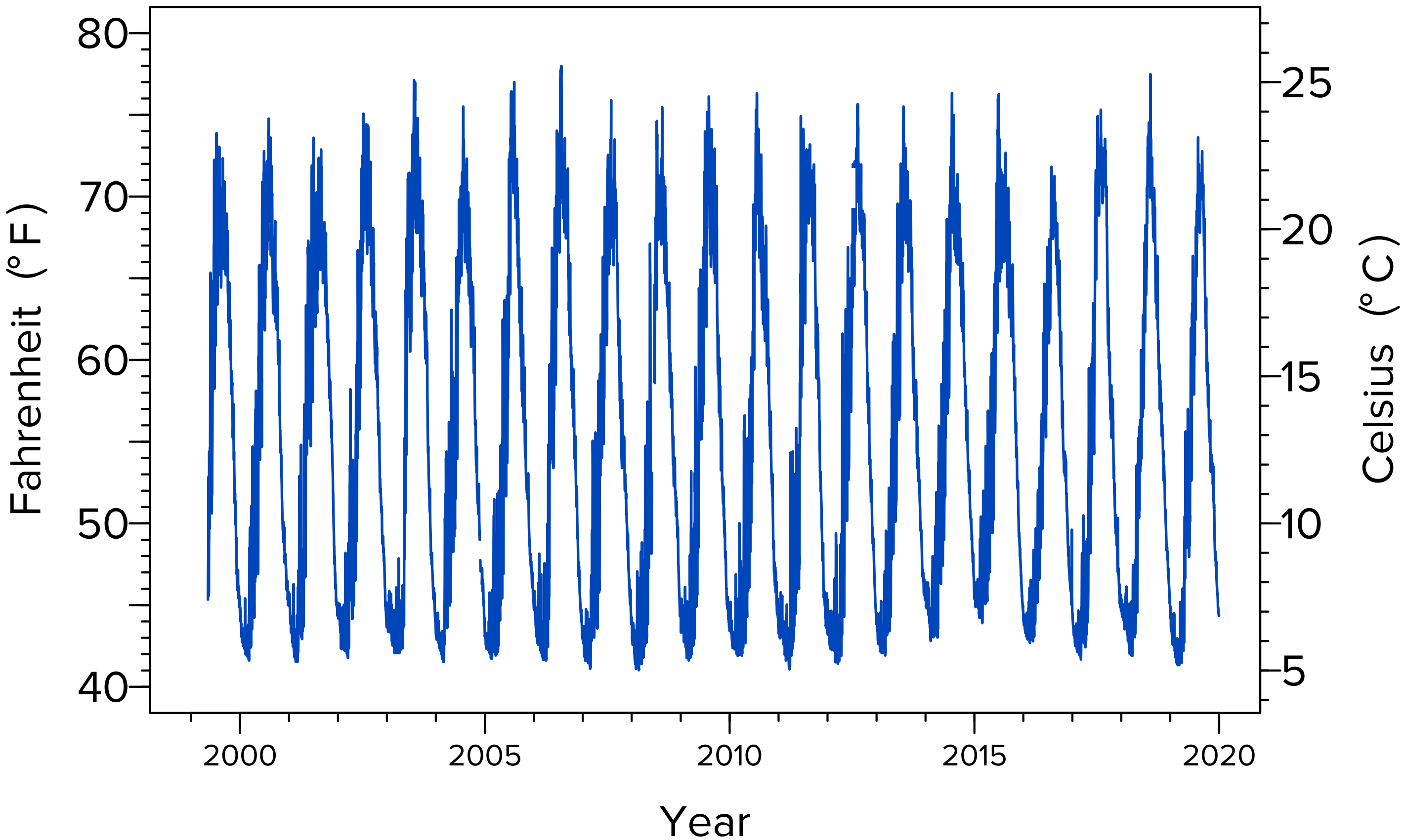
Surface water temperatures have been recorded monthly at the Mid-lake and Index stations since 1968 from the R/V John LeConte and the R/V Bob Richards. Despite year-to-year variability, the annual average surface water temperatures show an increasing trend. The average temperature in 1968 was 50.4 °F (10.2 °C). For 2019, the average surface water temperature was 52.2 °F (11.2 °C), slightly cooler than 2018. The overall rate of warming of the lake surface is 0.37 °F (0.21 °C) per decade.



Maximum daily surface water temperature

Surface temperature measured since 1999 every 2 minutes

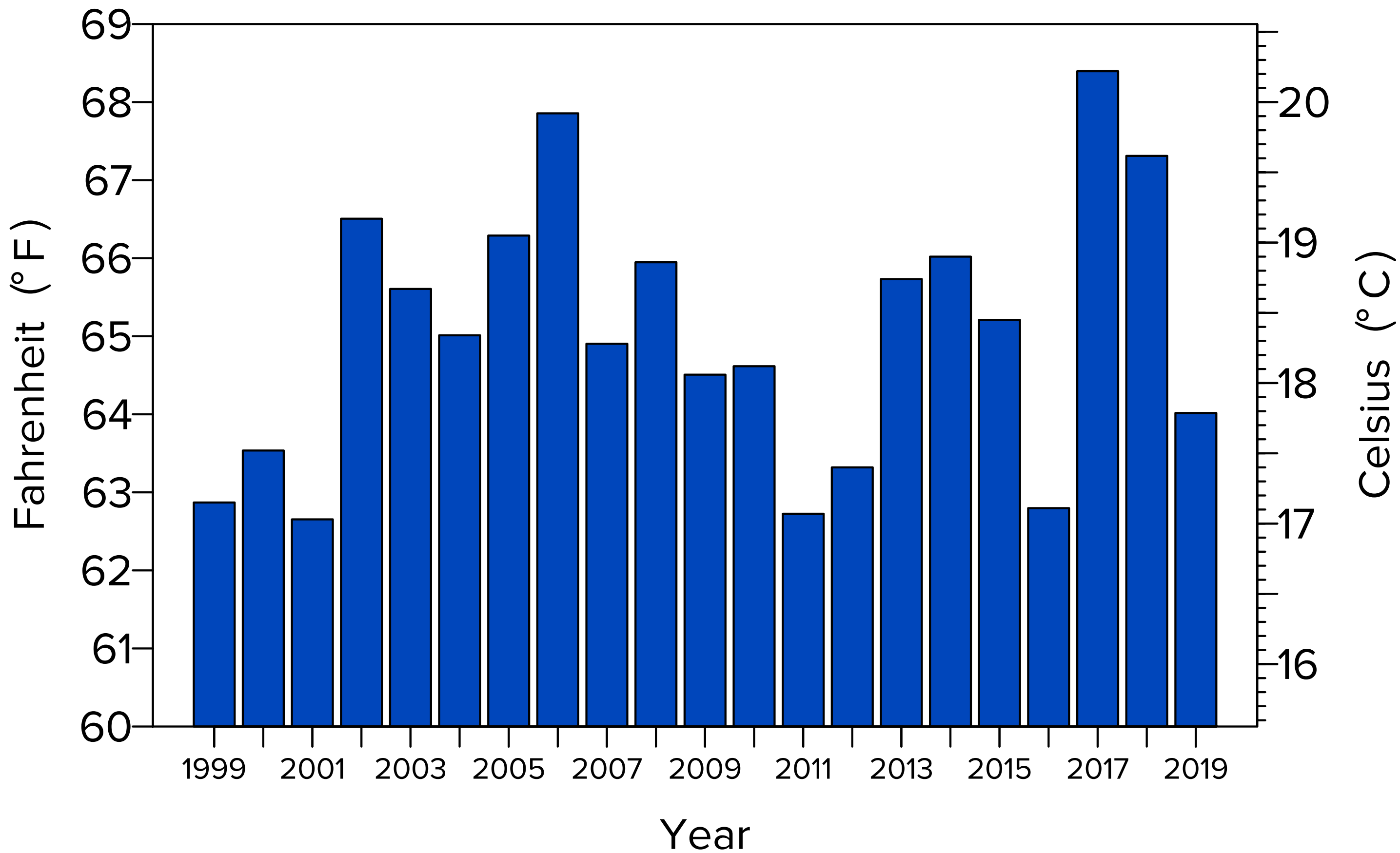
The maximum daily summer surface water temperature in 2019 was the second coolest since continuous data collection commenced in 1999. The highest maximum daily surface water temperature (summer) was 73.6 °F (23.1 °C), recorded on July 28, 2019, 3.9 °F cooler than the previous year. The lowest maximum daily surface water temperature (winter) was 41.3 °F (5.18 °C), which was recorded on February 26, 2019. These data are collected in real-time by NASA-JPL and UC Davis from four buoys located over the deepest parts of the lake.



July average surface water temperature

Measured since 1999 every 2 minutes

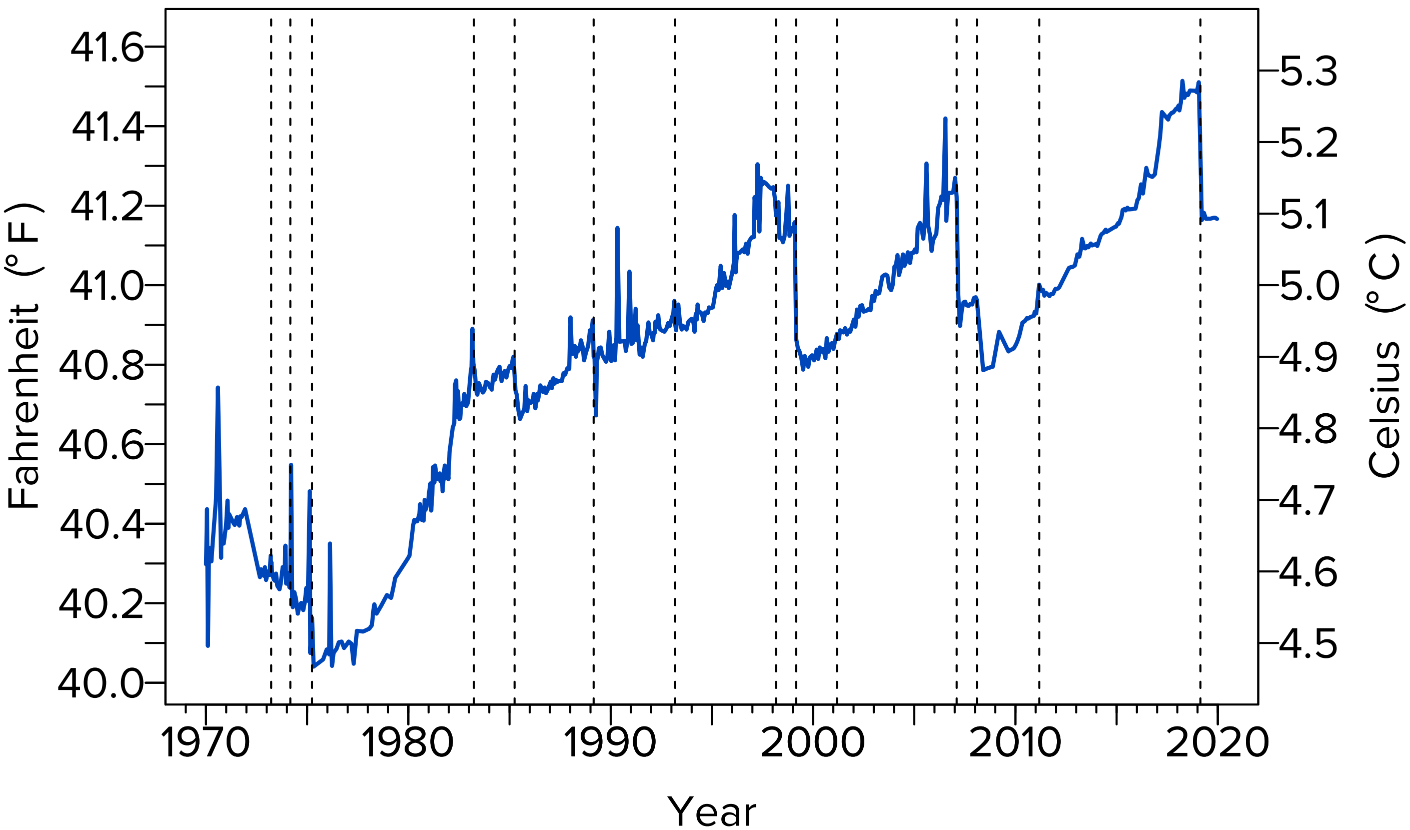
Surface water temperature has been continuously recorded since 1999 from four NASA/UC Davis buoys in the center of the lake. Shown here are 21 years of average surface water temperatures in the month of July when water temperatures are typically warmest and when the greatest number of people are swimming in the lake. In 2019, July surface water temperature averaged 64.0 °F, one degree below the average for the period of record. The warmest July temperatures were 68.4 °F in 2017. The average July surface water temperature for the 21-year period is 65.0 °F.



Deep water temperature

Monthly since 1970

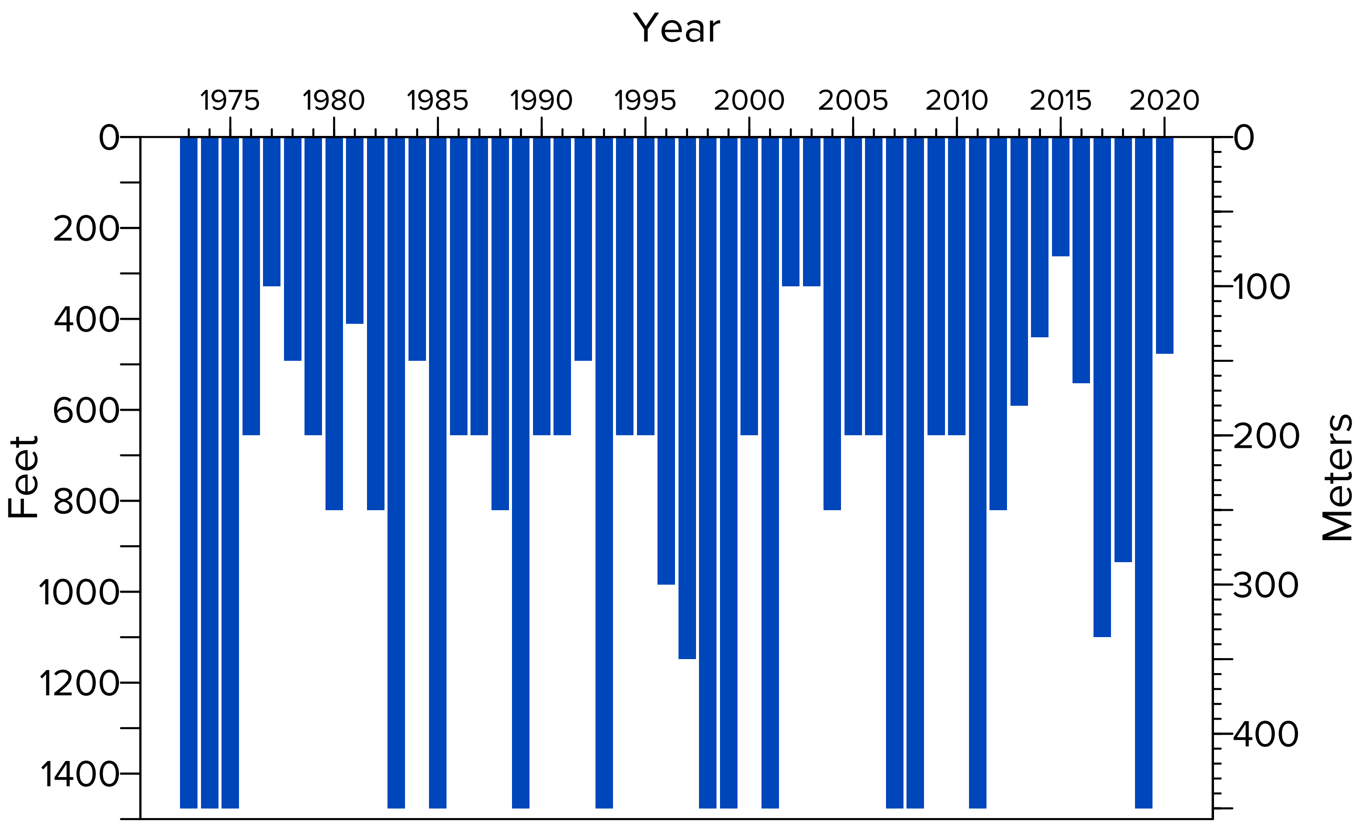
The water temperature at a depth of 1,320 feet (400 m) is indicative of conditions in the deeper waters (hypolimnion) of Lake Tahoe. The deep-water temperatures show a complex pattern of warming and sudden cooling. Warming occurs when the lake does not mix deeply. During deep mixing events (shown by the dashed lines), the temperature can drop precipitously over a short period of time. Generally, bottom temperatures are rising. Between the last two deep mixing events in 2011 and 2019, the rate of warming of the deep water 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 are temporary effects caused by the motions of internal waves.



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 22, 2019, Lake Tahoe was observed to have mixed to a depth of 1476 feet (450 m), effectively from top to bottom. This deep mixing likely contributed to the cooler surface temperatures experienced in the following summer. Beginning in 2013, the depth of mixing has been determined with high-resolution temperature profiles rather than nitrate concentration sampled at discrete depths.

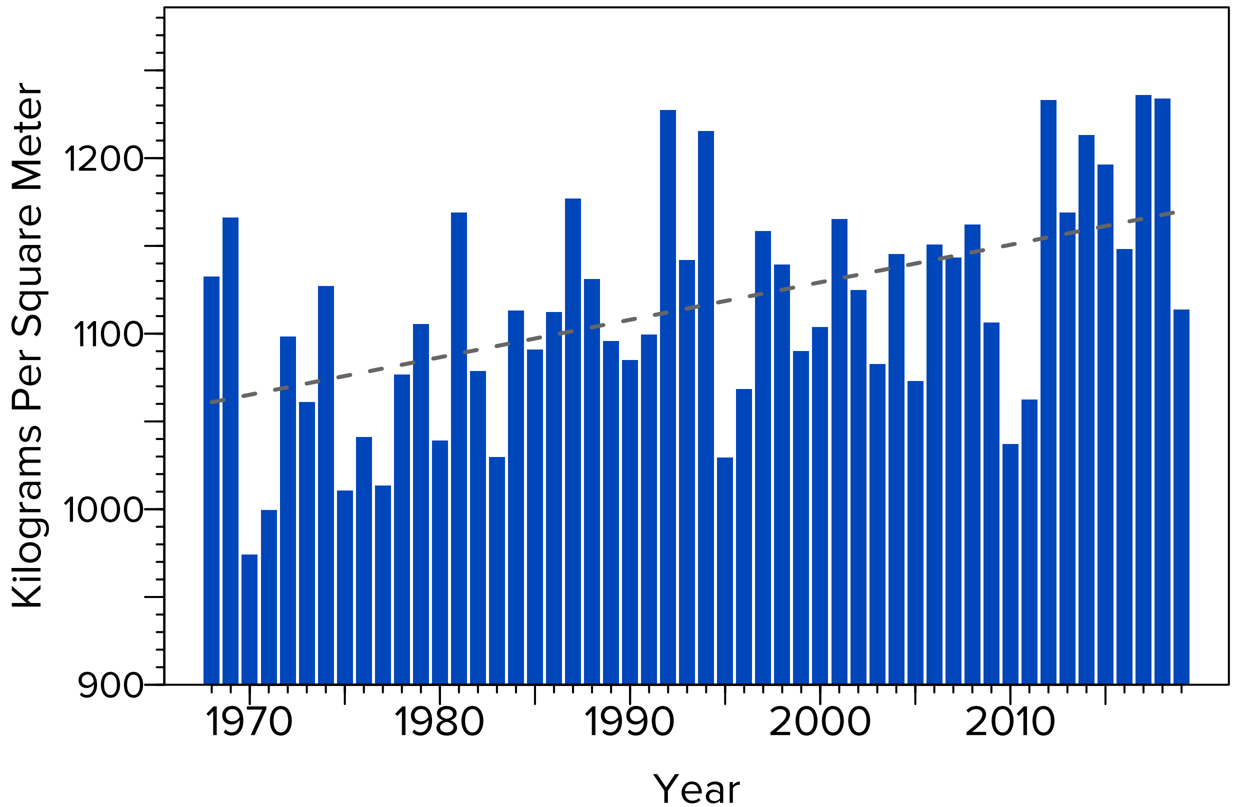


Lake stability

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 at depth. 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 10 percent in the last 51 years.

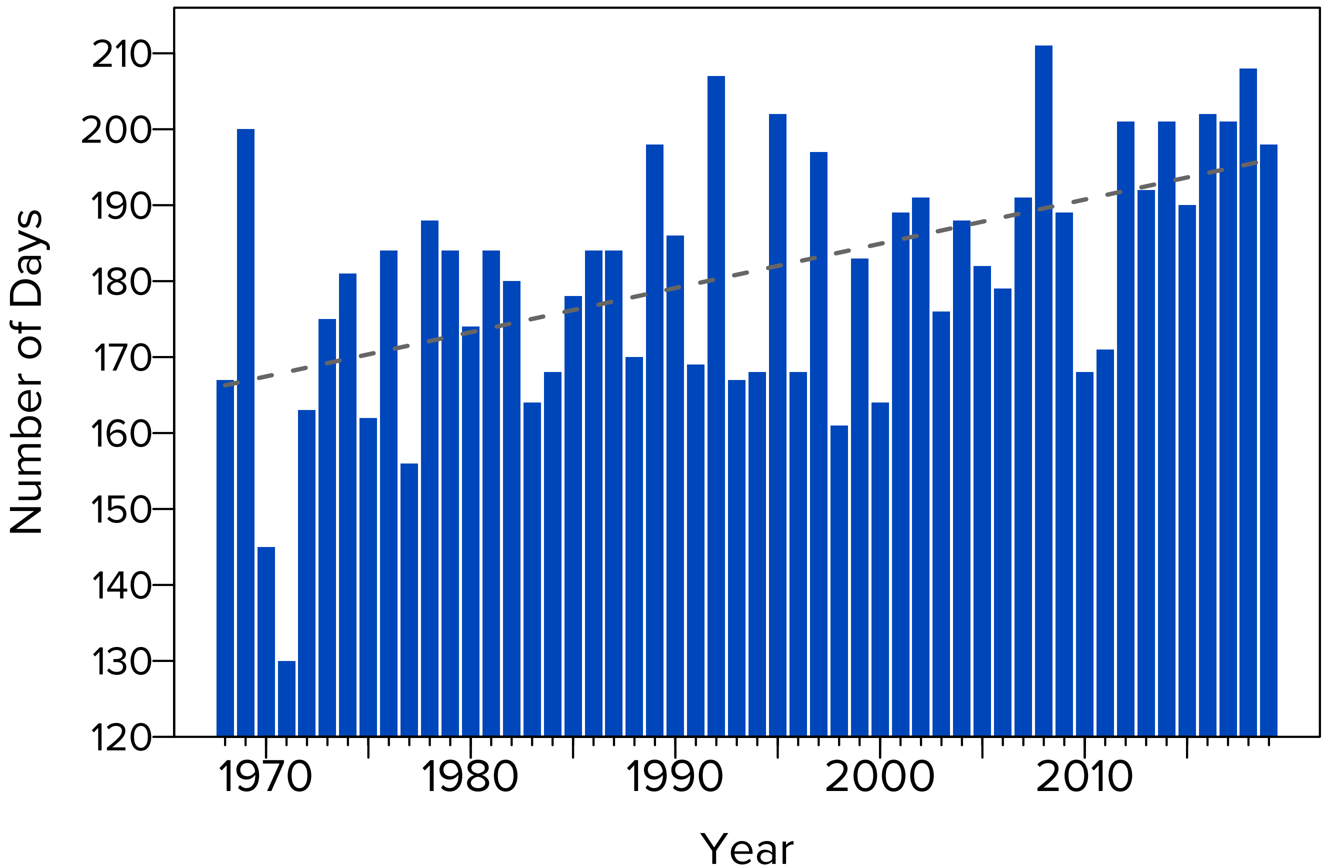
In 2019, the stability of the lake fell below the long-term trend-line, in part due to the cooler surface temperatures.



Stratified season length

Since 1968

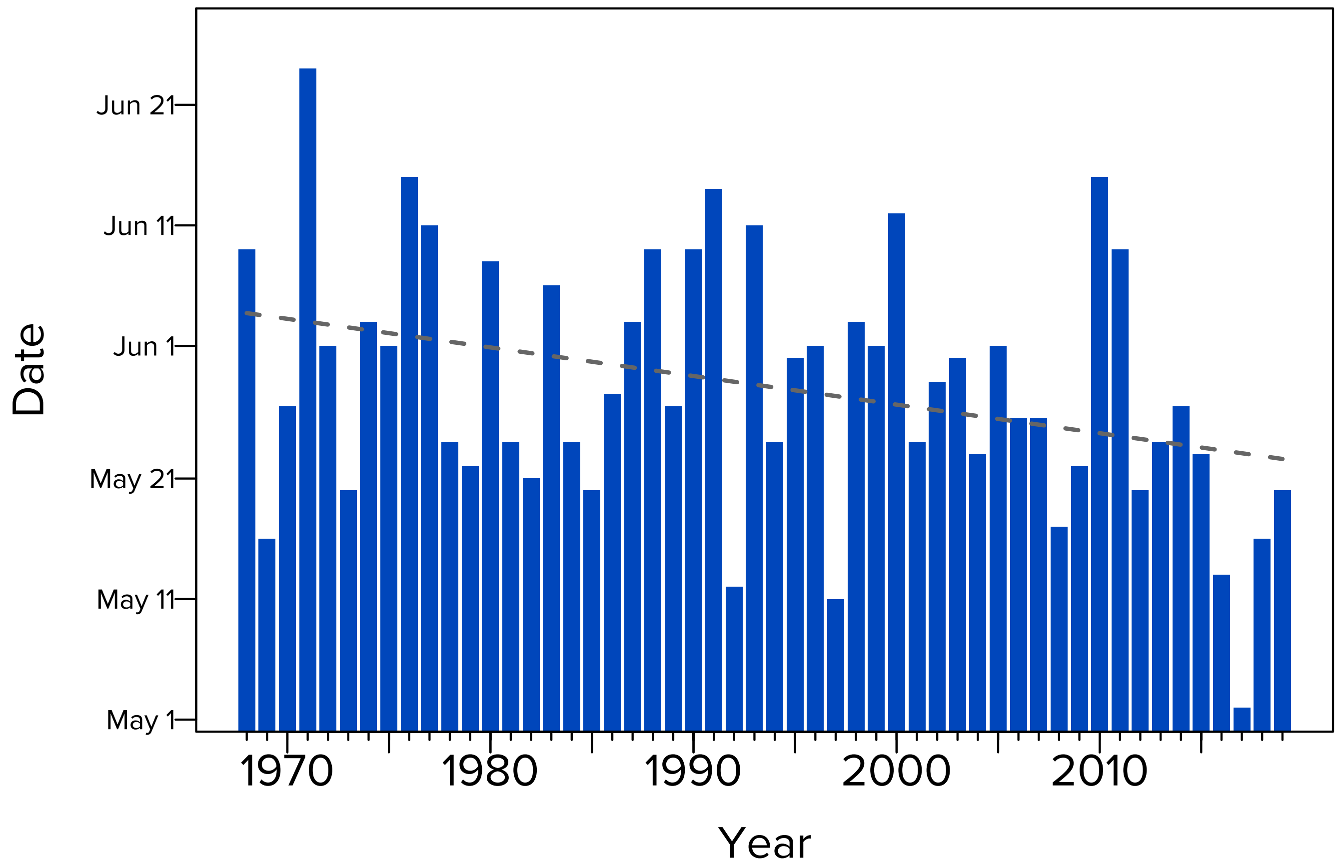
The stability index, a measure of the energy required to mix the lake, can be evaluated for every day of the year. We define the stratification season as the length of time when the stratification index exceeds a value of 600 kilograms per square meter. Since 1968, the length of the stratification season has increased, albeit with considerable year-to-year variation. Overall, the stratification season has lengthened by 30 days since 1968. In 2019, the length of the stratified season was 198 days.



Beginning of the stratification season

Since 1968

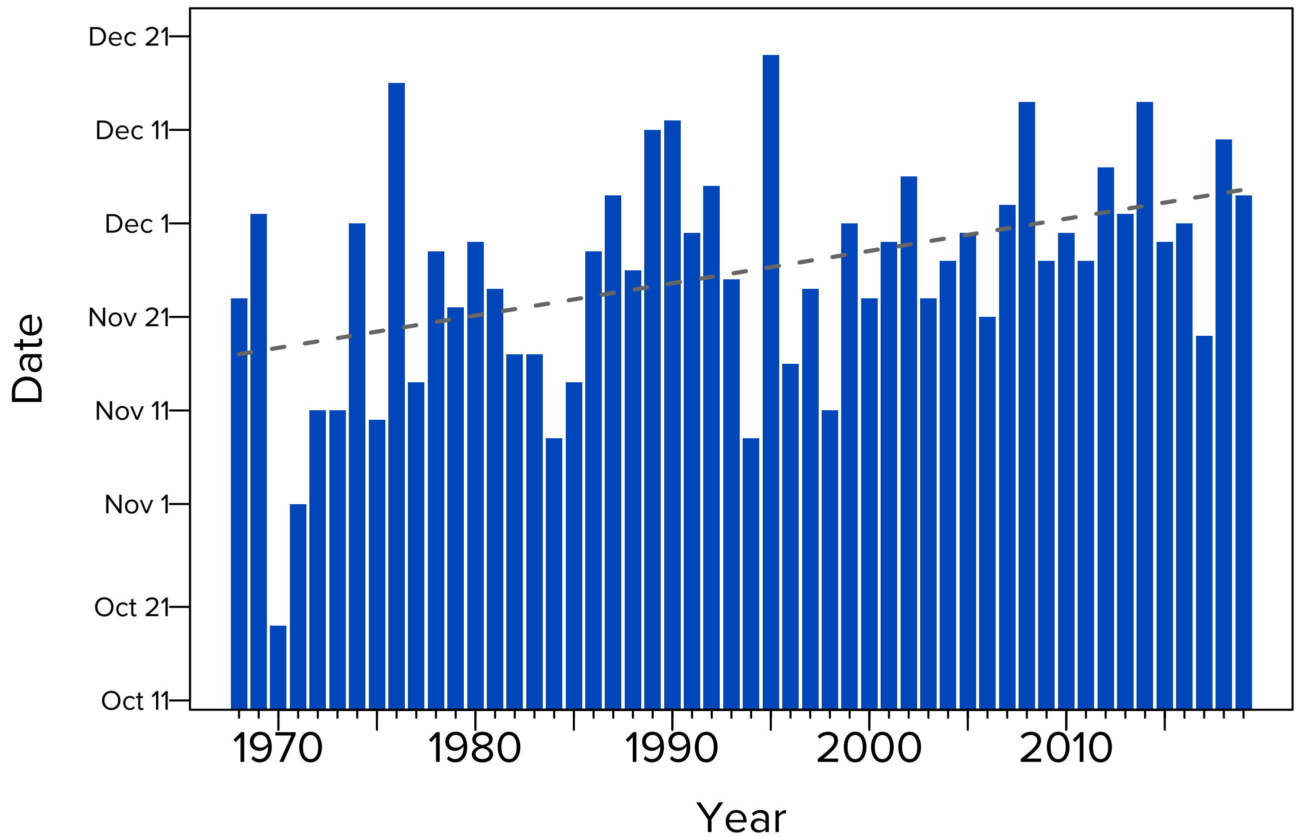
The amount of time that Lake Tahoe is stratified has been lengthening since 1968. One reason for this is the increasingly early arrival of spring as evidenced by the earlier commencement of stratification. Stratification occurs approximately 12 days earlier than it did in 1968. The commencement of the stratification season is typically in late May or early June. In 2019, stratification began on May 20 (Day 140).



End of stratification season

Since 1968

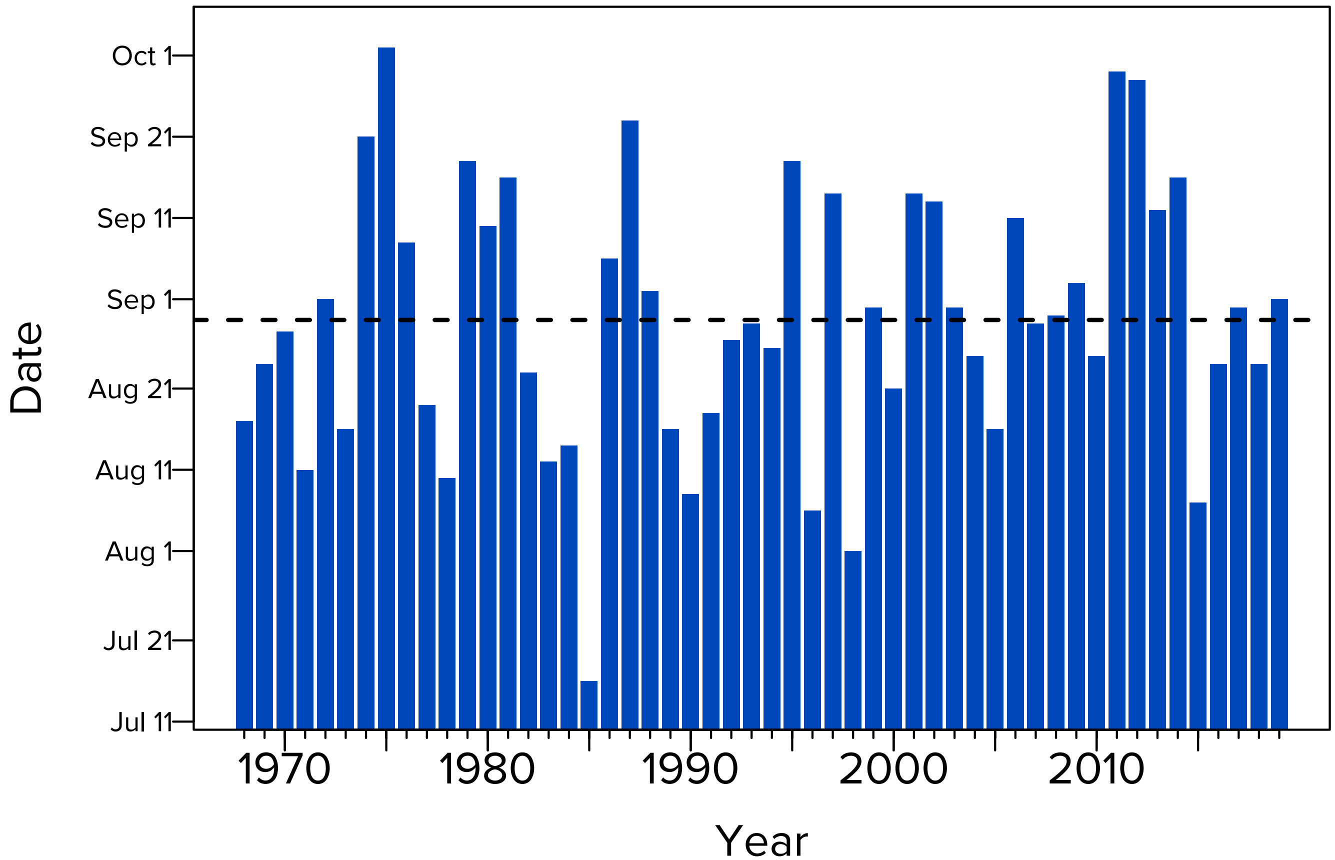
The amount of time that Lake Tahoe is stratified has lengthened by a month since 1968. The end of stratification appears to have been extended by 18 days on average. In other words, the fall season for the lake has been extended. In the late 1960s, stratification ended in mid-November. Now it often ends in December. In 2019, stratification ended on December 4 (Day 338). This can have important implications for lake mixing and water quality, such as the buildup of nitrate at the bottom of the lake.



Peak of stratification season

Since 1968

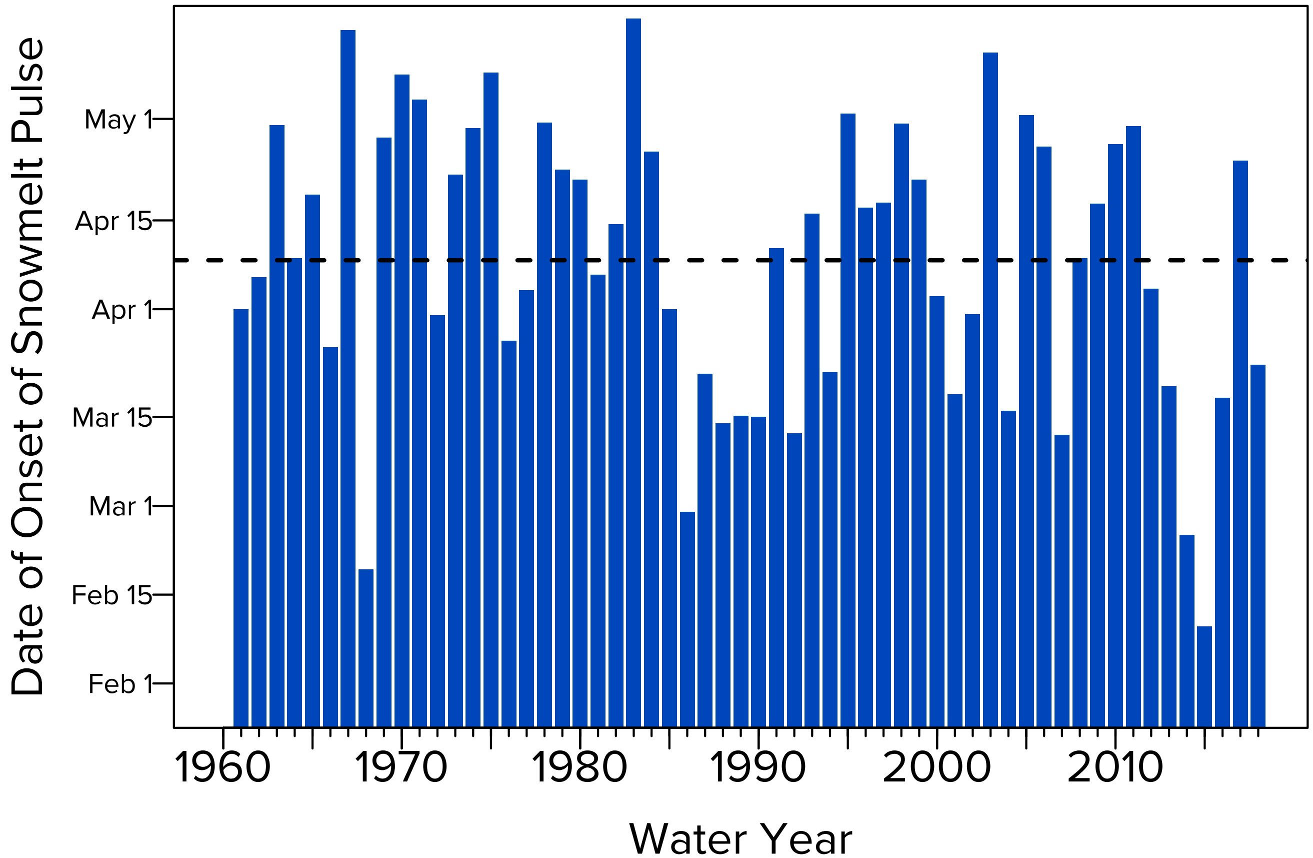
The day of the year when lake stratification reaches its maximum value has been plotted. There is considerable year-to-year variation, but over time there has been little change in when the peak occurs. In 2019, the peak occurred on September 19, very close to the long-term average (dashed line).



Onset of snowmelt pulse

Yearly since 1961

Although the date on which onset of the snowmelt commences varies from year to year, since 1961 it has shifted earlier an average of almost 18 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 2019, the onset occurred on April 8, slightly later than the long-term average. In the 34 years since 1985, the onset of the snowmelt peak has occurred earlier than the long-term average on 20 occasions. 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.



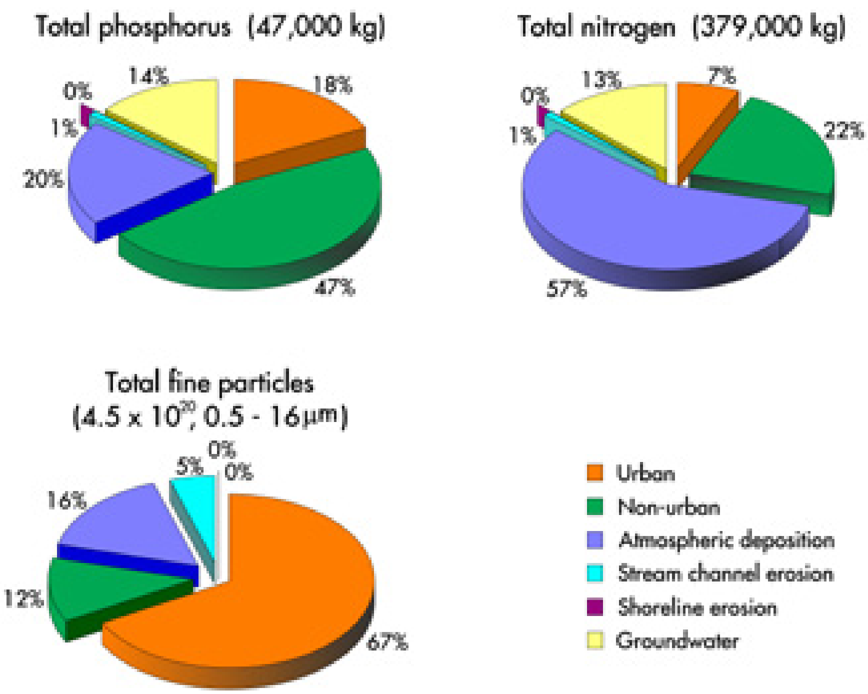
TAHOE:
STATE
OF THE
LAKE
REPORT
2020

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 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 agencies including the Lahontan Regional Water Quality Control Board, the Nevada Division of Environmental Protection, and the Tahoe Regional Planning Agency. Data were originally generated for the Lake Tahoe TMDL Program. These results are revised from the original estimates as they are based on a longer time series of monitoring data.

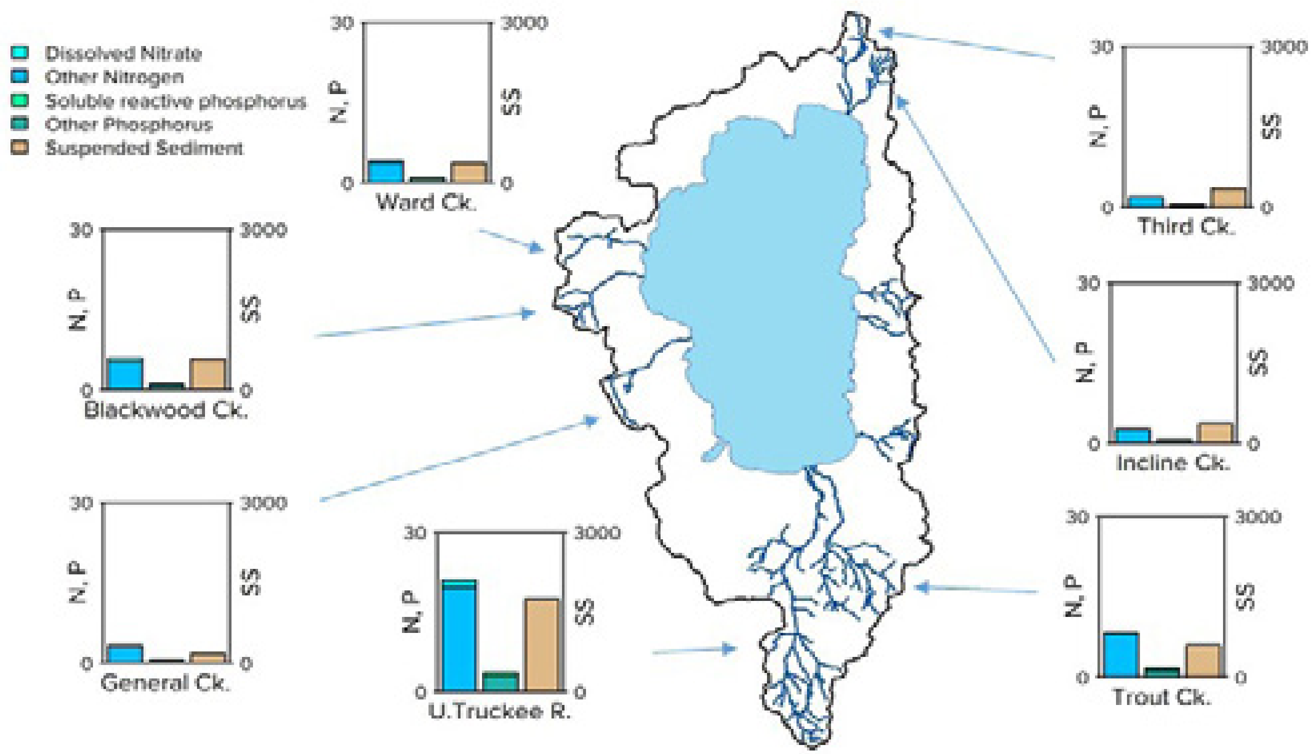


Pollutant loads from seven watersheds

In 2019

The Lake Tahoe Interagency Monitoring Program (LTIMP) measures nutrient and sediment input from seven of the 63 watershed streams. The watersheds are the Upper Truckee River, Trout Creek, Incline Creek, Third Creek, Ward Creek, Blackwood Creek, and General Creek. In 2019, 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 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.

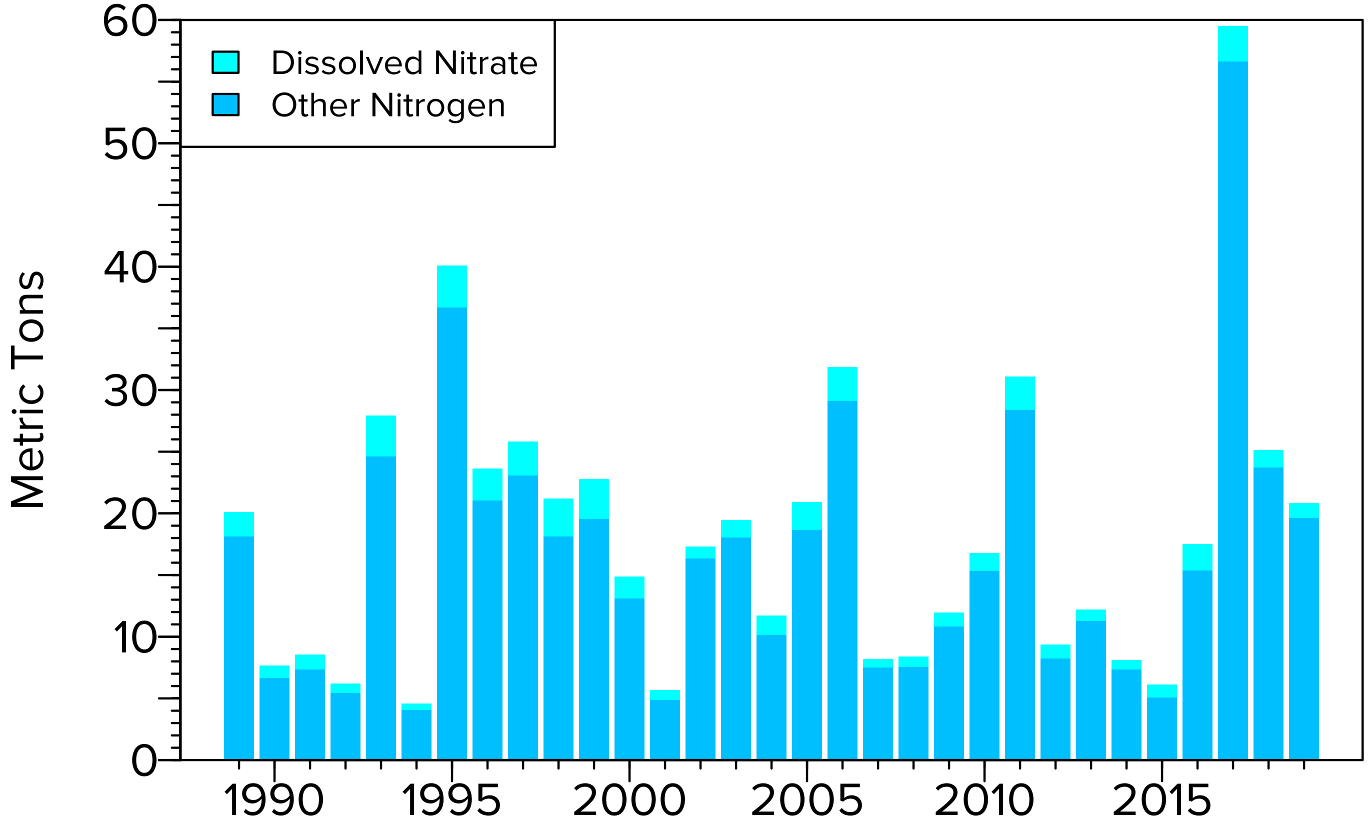


Nitrogen contribution by Upper Truckee River

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 only 16.6 inches of precipitation and a low total nitrogen load of 4.6 MT, while 2017 had 68.9 inches of precipitation and a record high total nitrogen load of 59.5 MT. In 2019, there was an above average 43.8 inches of precipitation, and an above average total nitrogen load of 20.9 MT. The long-term mean annual total nitrogen load is 18.2 MT/yr.

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

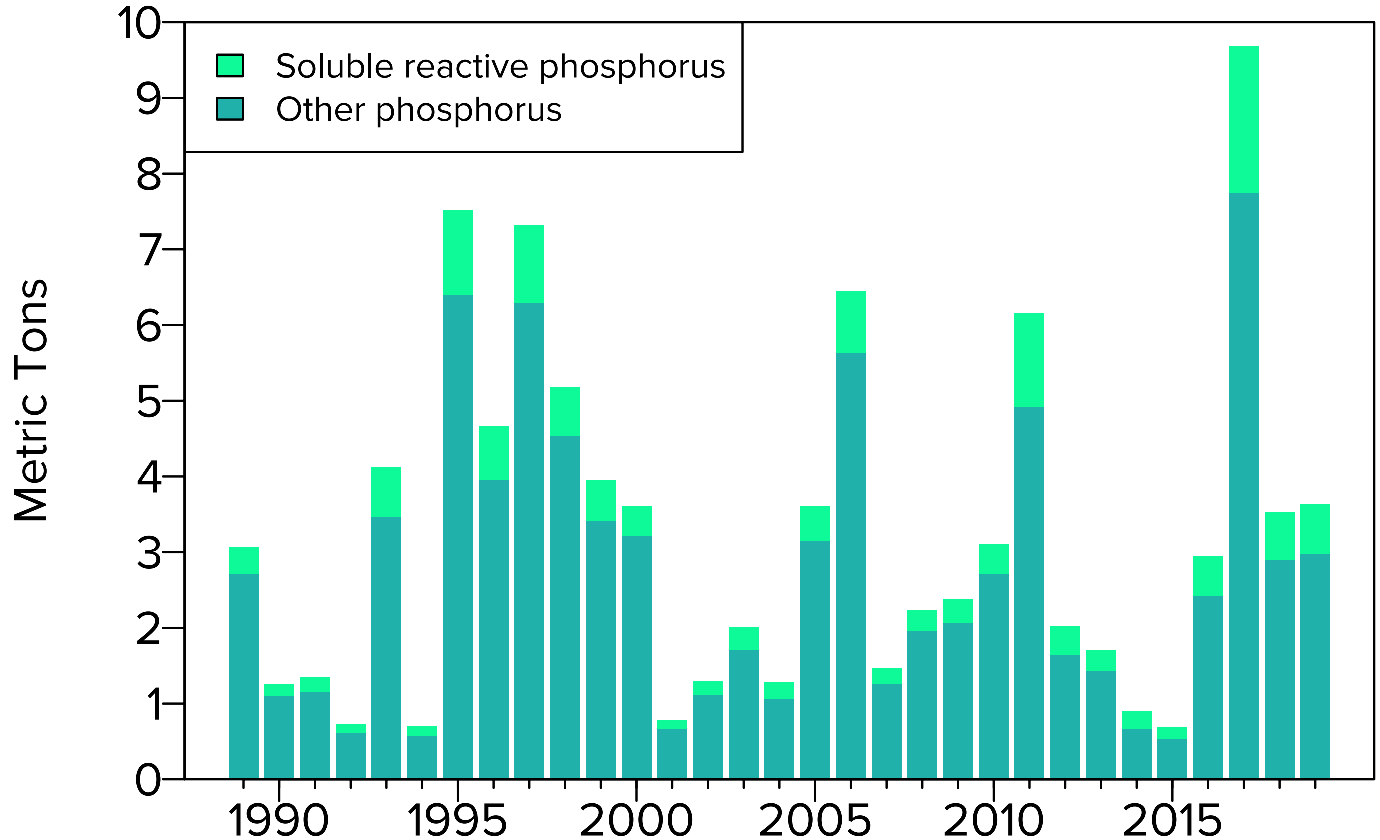


Phosphorus contribution by Upper Truckee River

Yearly since 1989

Soluble reactive phosphorus (SRP) is the fraction of 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. Above average precipitation in 2019 resulted in a total phosphorus level of 3.6 MT and SRP load of 0.65 MT. These compare with the long-term averages of 3.2 and 0.49 MT respectively. Decreasing nutrient inputs is 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.

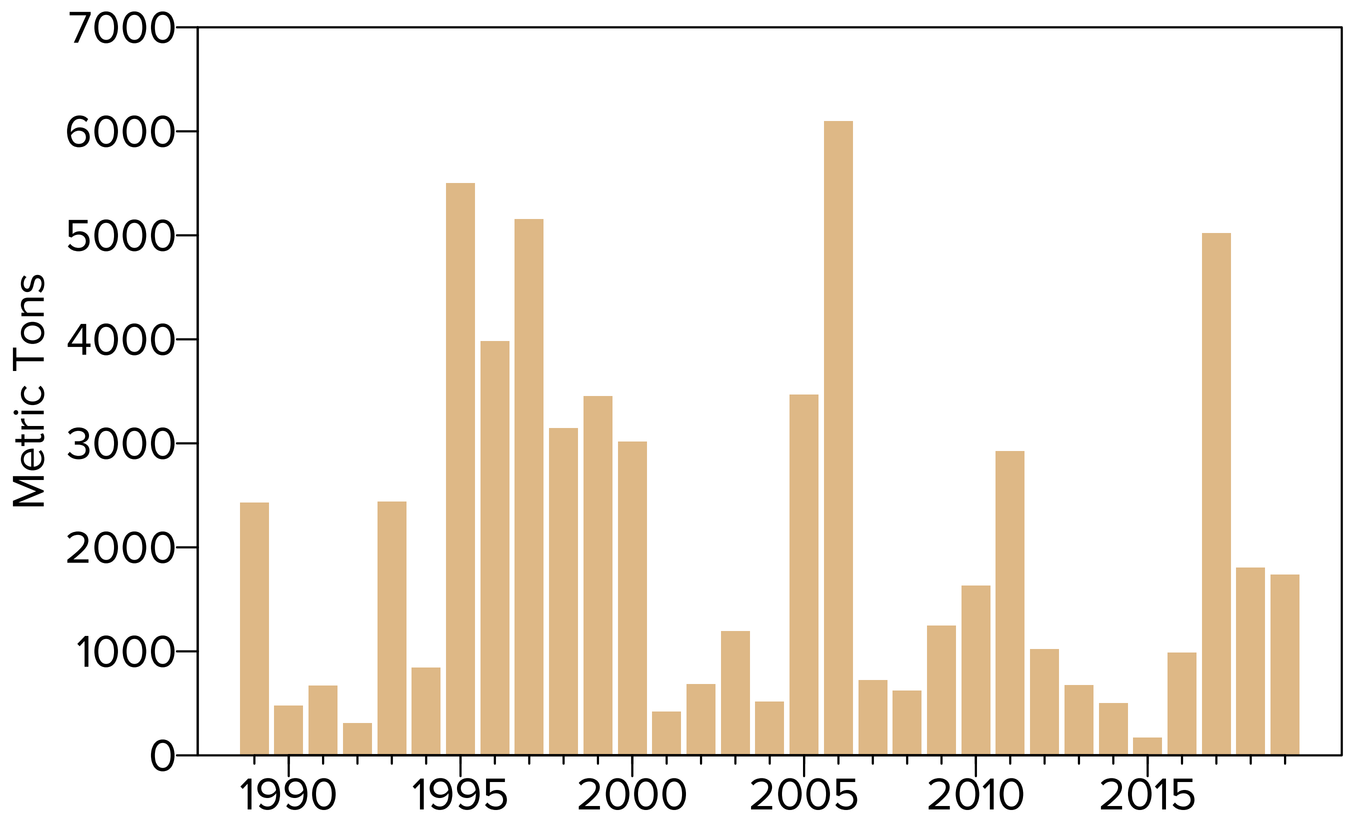
One metric ton (MT) = 2,205 pounds.



Suspended sediment contribution by Upper Truckee River

Yearly since 1989

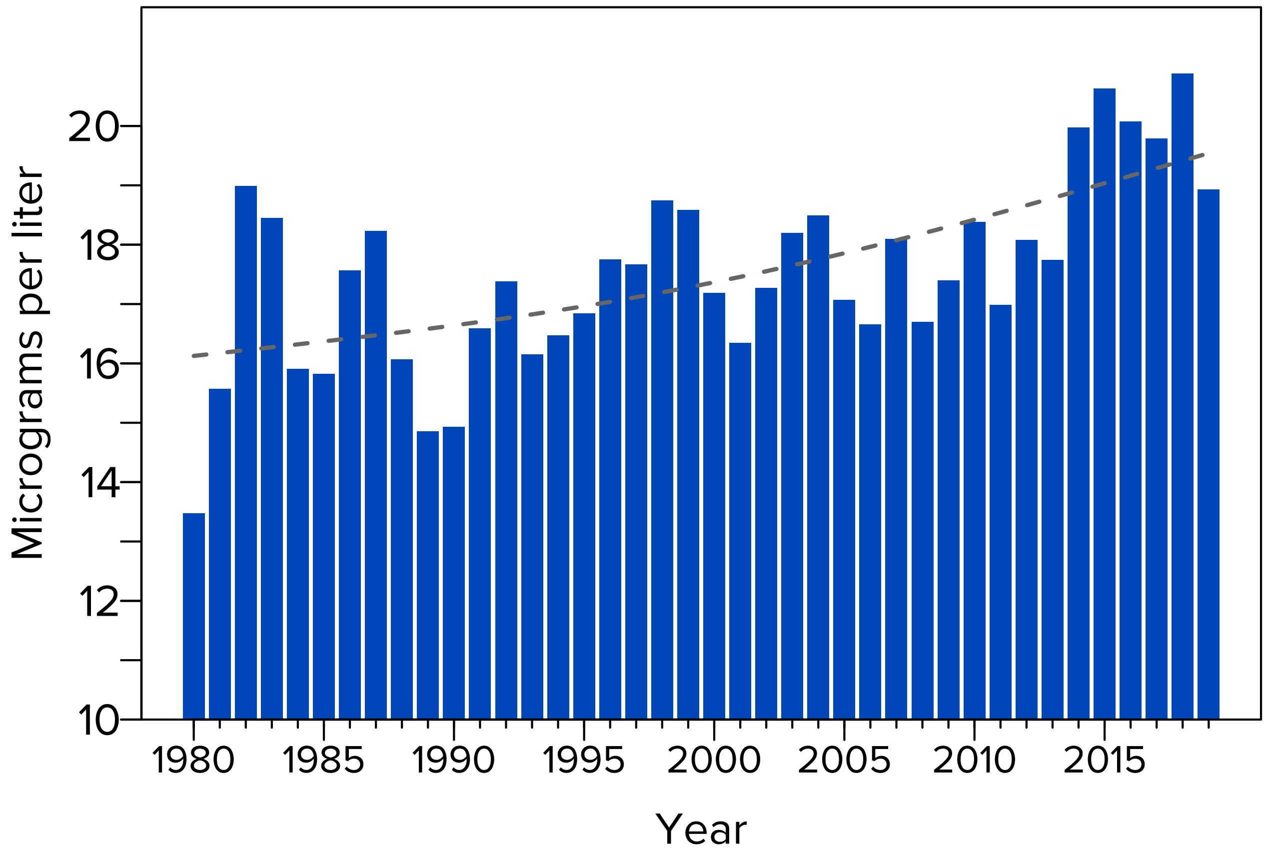
The load of total suspended sediment delivered to the lake by the Upper Truckee River is related to landscape condition and erosion as well as to precipitation and stream flow. Inter-annual variation in sediment load over shorter time scales is more related to the latter. Plans to restore lake clarity emphasize reducing loads of very fine suspended sediment (less than 20 microns in diameter) from urbanized areas. Efforts to restore natural stream function and watershed condition focus on reducing loads of total sediment regardless of size, as well as restoration of habitat for plants and wildlife. In 2019, the suspended sediment load from the Upper Truckee River was 1,739 MT. The highest load ever recorded was 6,100 MT in 2006. The average annual load is 2,028 MT.



Lake nitrate concentration

Yearly since 1980

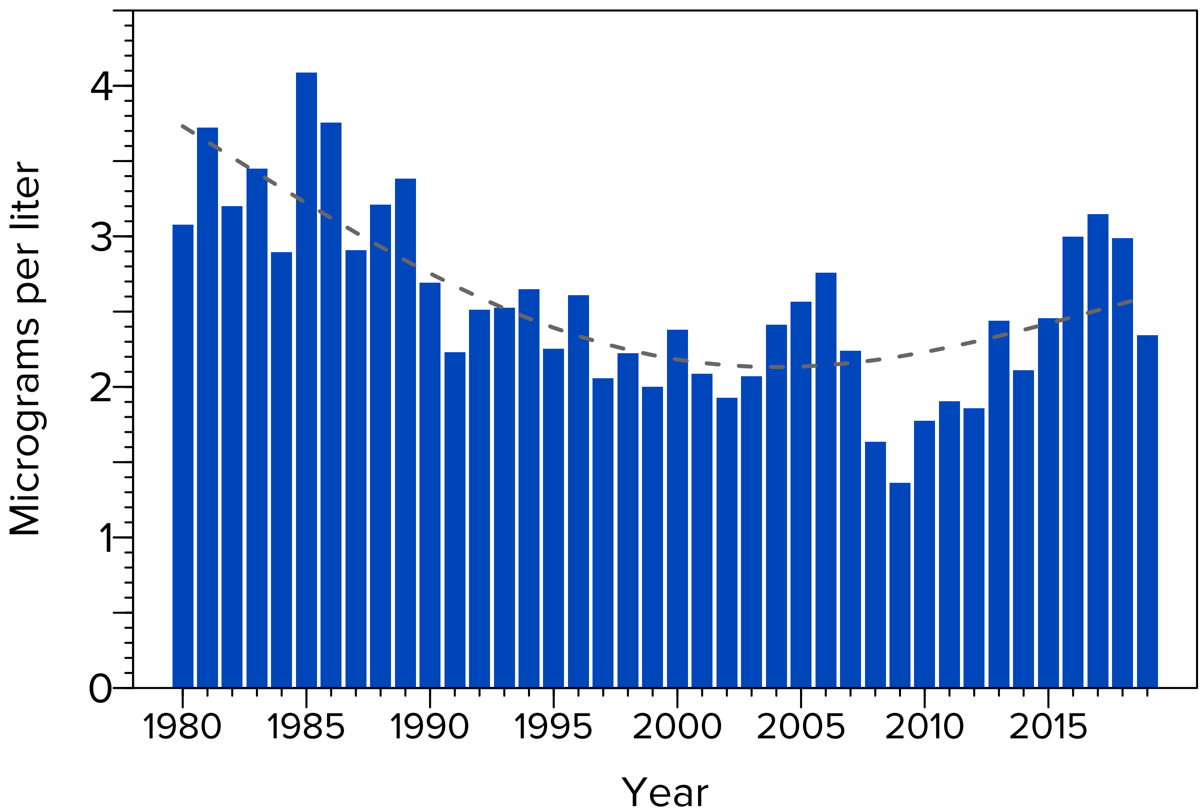
Until 2012, the volume-weighted annual average concentration of nitrate-nitrogen had remained relatively constant, ranging between 13 and 19 micrograms per liter. Since that time, however, the lake's nitrate concentration has been increasing, as evident in the trend line produced with a Generalized Additive Model. In 2019, the volume-weighted annual average concentration of nitrate-nitrogen was 18.9 micrograms per liter. The reduction in concentration was due to the deep mixing that occurred early in 2019 and that redistributed the nitrate that had been accumulating at the bottom of the lake for the previous eight years. This nitrate was subsequently made available for algal uptake, accounting for the increase in algal abundance in 2019 (see Fig. 10.2). The average annual nitrate concentration is 17.5 micrograms per liter. 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 hydrolyzable phosphorus, or 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 15 years the values have been stabilizing or possibly increasing. In 2019, the volume-weighted annual average concentration of THP was 2.34 micrograms per liter, compared to the long-term average value of 2.57 micrograms per liter. Water samples are taken at the MLTP (mid-lake) station at 13 depths from the surface to 1,480 feet.



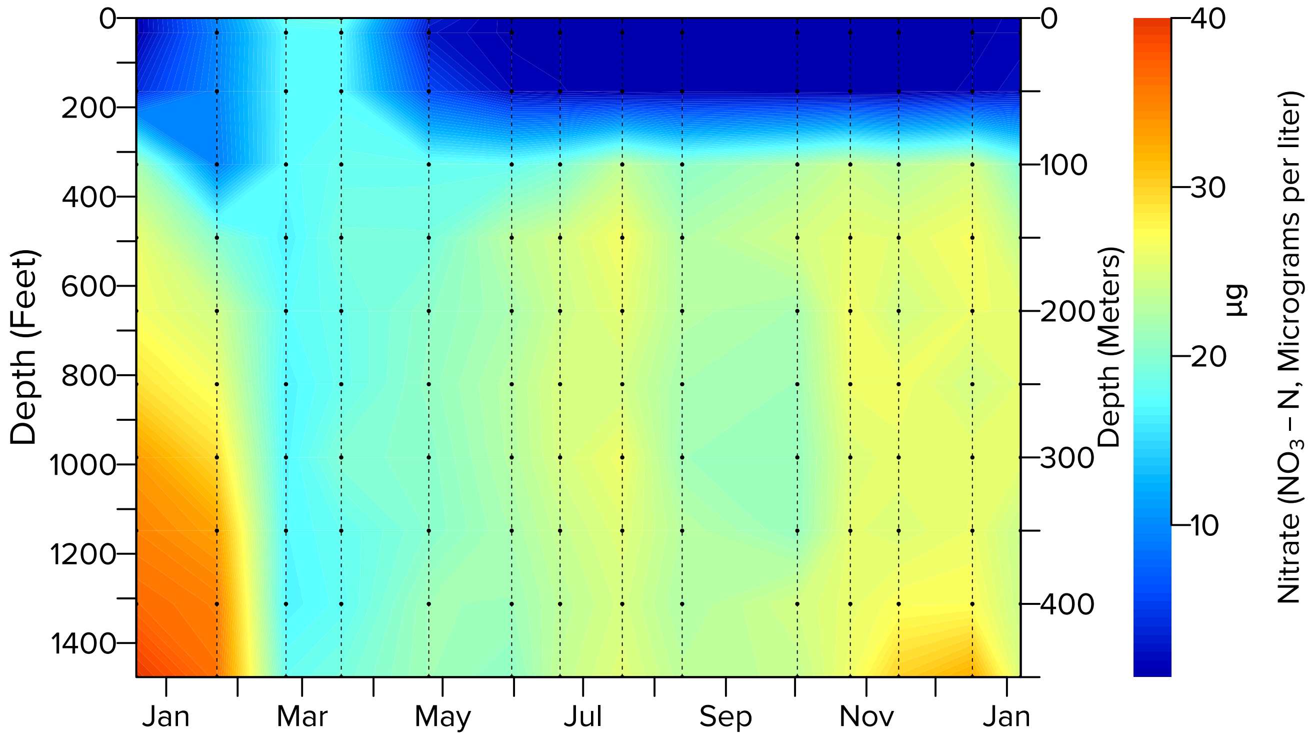
Nitrate distribution

In 2019

Water samples are collected approximately every month (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) at the middle of the lake, 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 disappearance of the high nitrate region in the bottom half of the lake with deep mixing in February. Initially nitrate was uniformly distributed, but by April the surface of the lake was being depleted and a sharp "nitricline" is evident at a depth of 250 feet.

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.

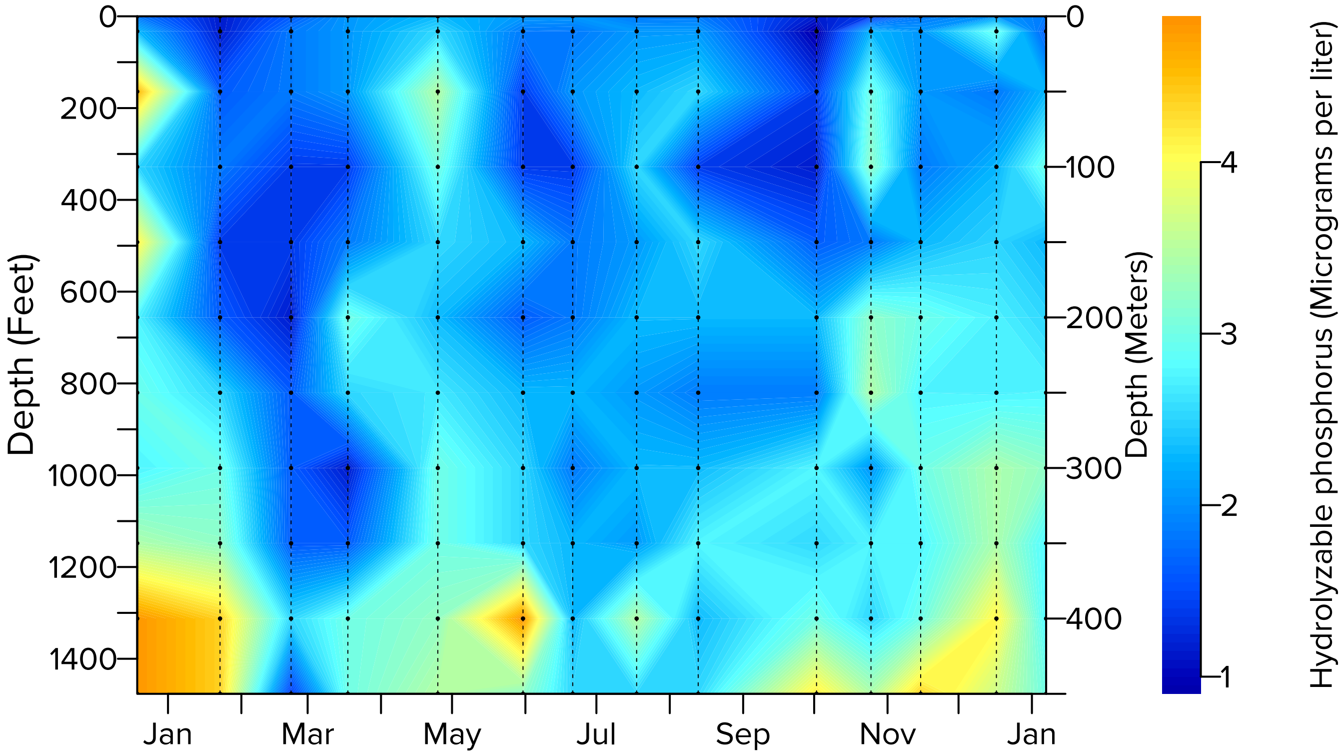


Total hydrolyzable phosphorus distribution

In 2019

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

Phosphorus mainly enters the lake in association with fine particles during runoff events in April and May. The higher values near the surface in spring and summer suggest that in 2019, nitrogen was the nutrient that limited algal growth, rather than phosphorus. The high concentrations of phosphorus deep in the lake during January were the result of the previous eight years of no deep mixing. With deep mixing in February, the high phosphorus levels were rapidly diluted through the entire water column.

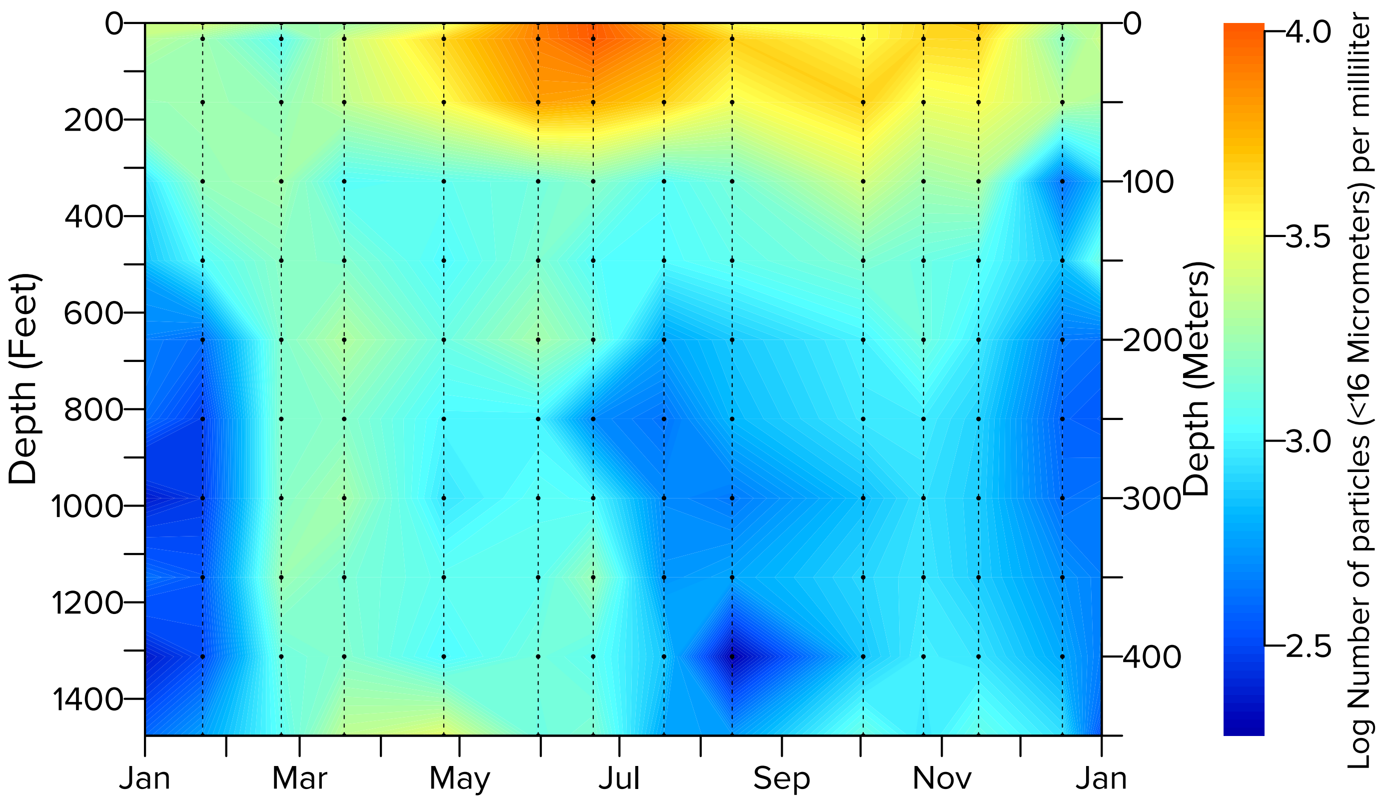


Fine particle distribution

In 2019

Water samples are collected approximately monthly (on dates indicated by the dashed lines) at 13 depths (indicated by the dots) at the middle of the lake, and analyzed in the TERC laboratory for the concentration of fine particles in 15 different bin sizes. Here the distributions of the finest particles (in the size range of 1.0 to 8 microns) are shown in the form of color contours. Particles here 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 during January. With deep mixing, however, surface particles are mixed throughout the lake during February. Later in the year the fine particles are largely concentrated in the upper part of the lake (above 200 feet in depth). May and June, when the fine particles in this upper layer are highest, the clarity was lowest. 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) and that allows them to more rapidly settle to the lake sediments at the bottom.



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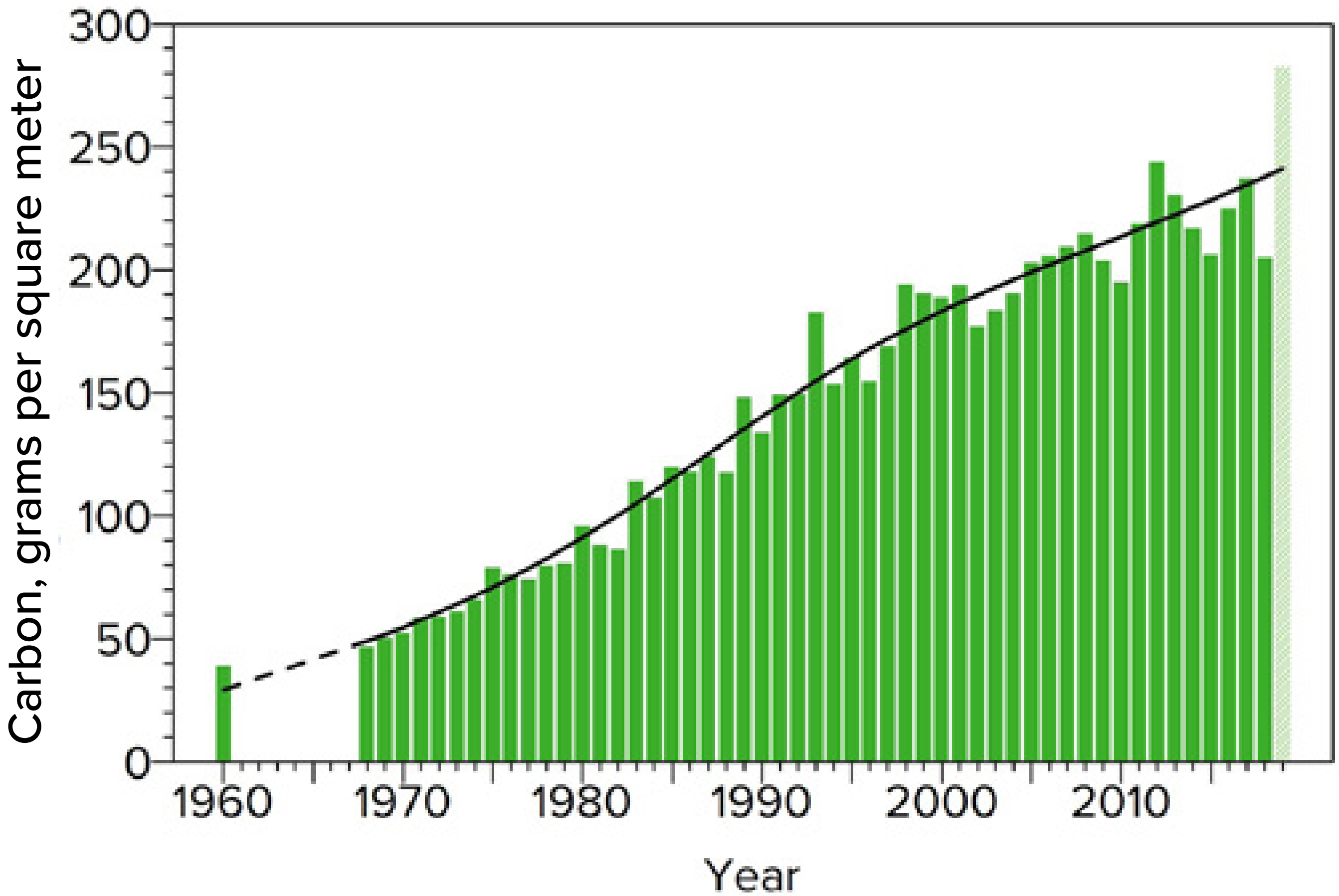
BIOLOGY

UC DAVIS
Tahoe Environmental
Research Center

Algae growth (primary productivity)

Yearly since 1959

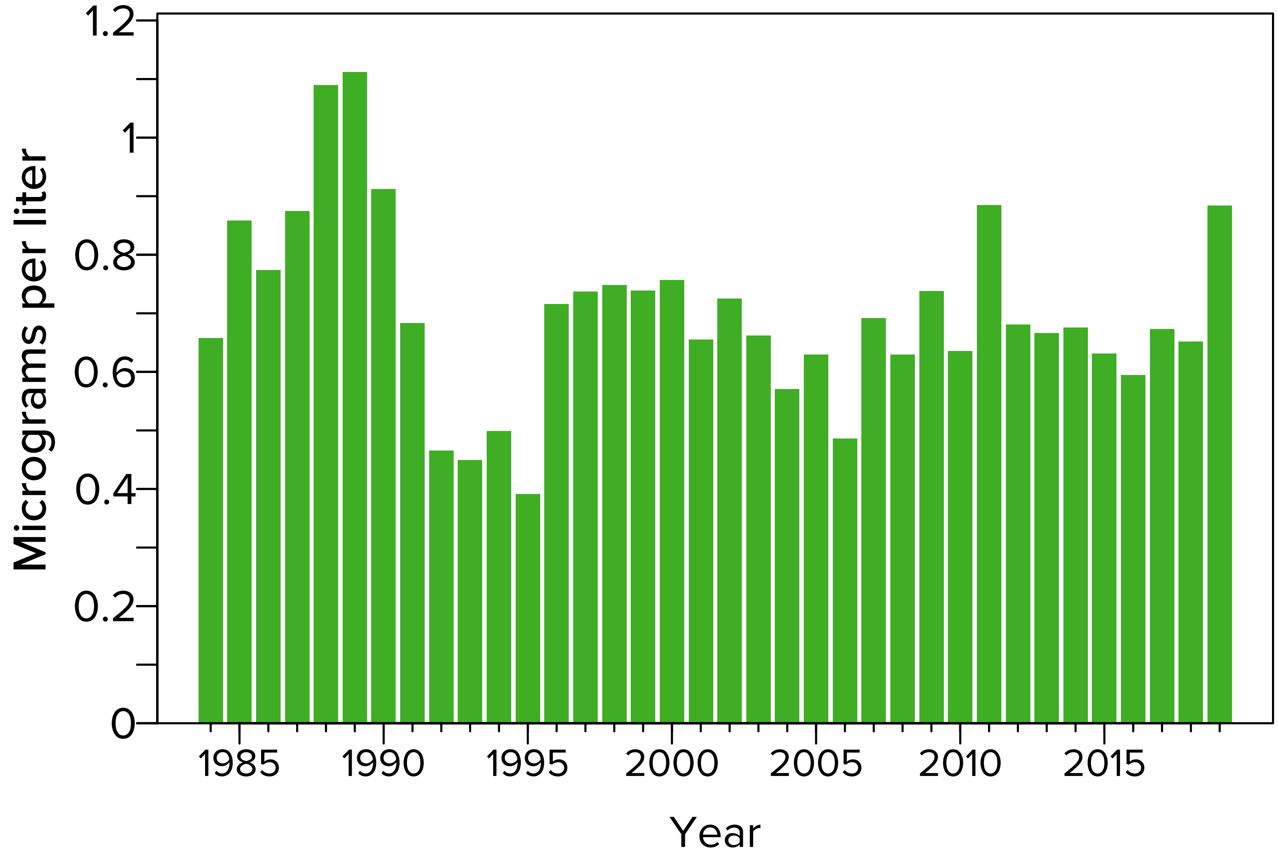
Primary productivity is a measure of the rate at which algae produce biomass through photosynthesis, and is measured at a number of depths at monthly intervals. It was first measured at Lake Tahoe in 1959 and the annual average value has been continuously measured since 1968. Supported by nutrient loading 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 data displayed an unusually large increase in the rate of primary production. The data are currently being reviewed and the 2019 value (shown cross-hatched) should be considered provisional.



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 (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 2019 was 0.88 micrograms per liter. For the period of 1984-2019 the average annual chlorophyll-*a* concentration in Lake Tahoe was 0.70 micrograms per liter. The 35 percent increase in 2019 over the previous years is believed to be due to the infusion of nitrate as a result of deep mixing. A similar observation was made in 2011 following a deep mixing event.

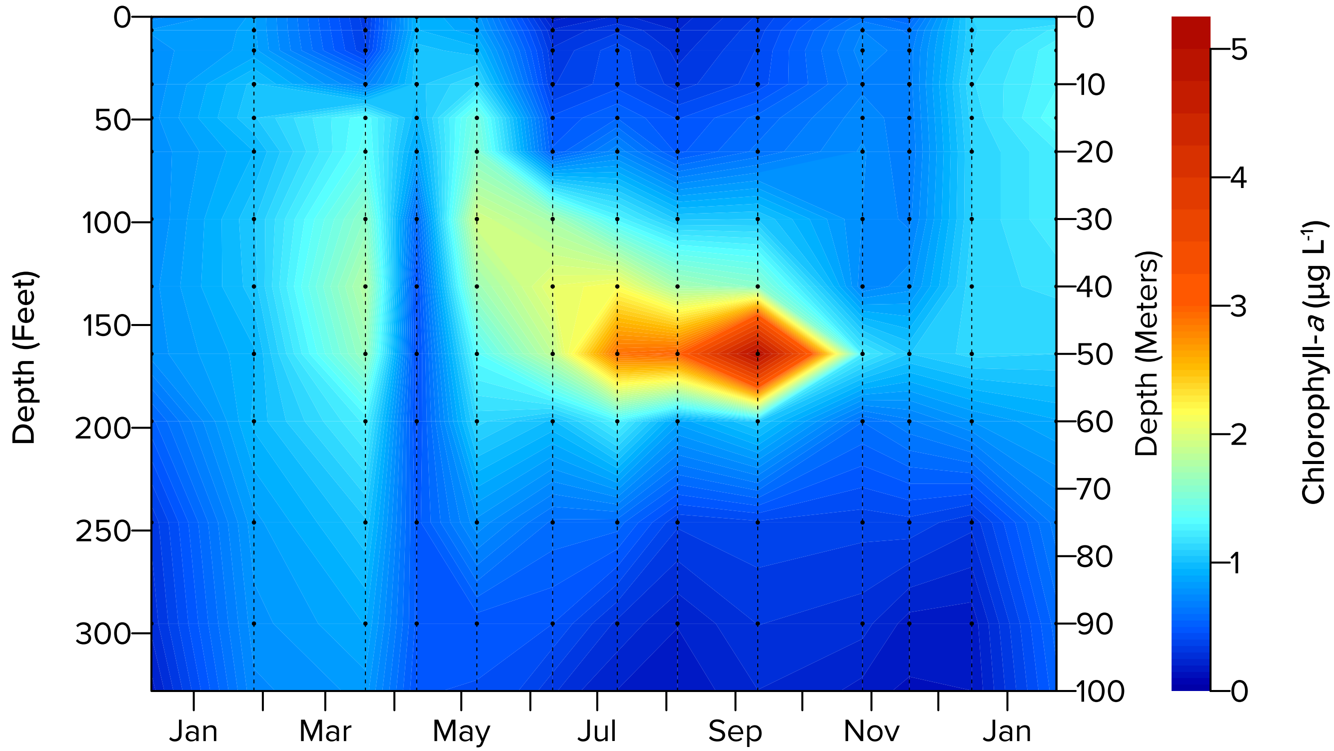


Chlorophyll-*a* distribution

In 2019

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.

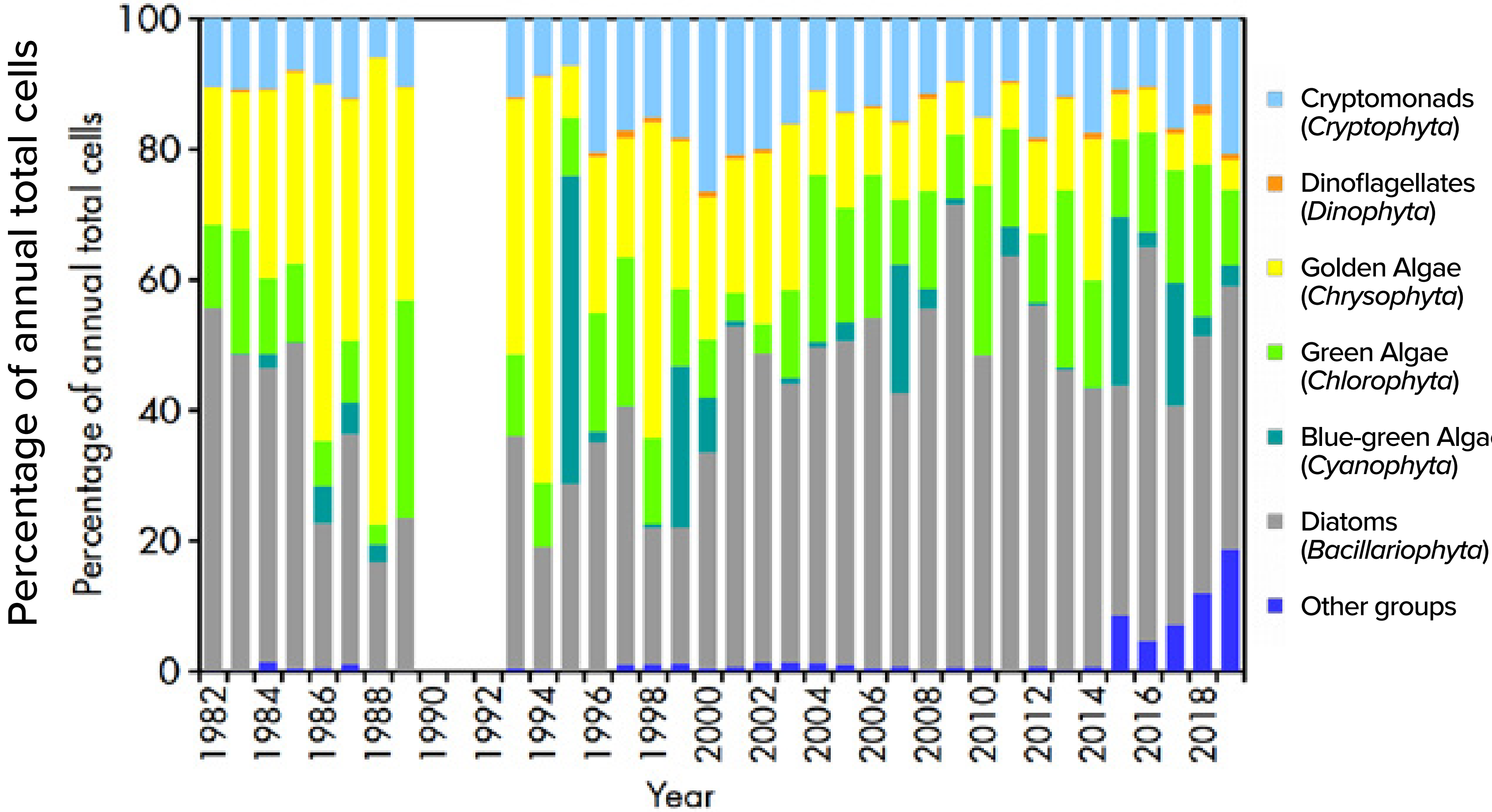
With the onset of thermal stratification in spring, the majority of the high chlorophyll-*a* algae were confined to a discrete band. The time of maximum chlorophyll-*a* concentration was during late June, and centered at a depth of 150-200 feet. Later in the year concentrations decreased as nutrients were depleted. In November and December, the commencement of mixing again redistributed the algae over a broader range of depth. Note that small *Cyclotella* cells at the surface have a very small chlorophyll-*a* expression. However, the large number of these tiny cells have a major impact on clarity.



Annual distribution of algal groups

Yearly since 1982

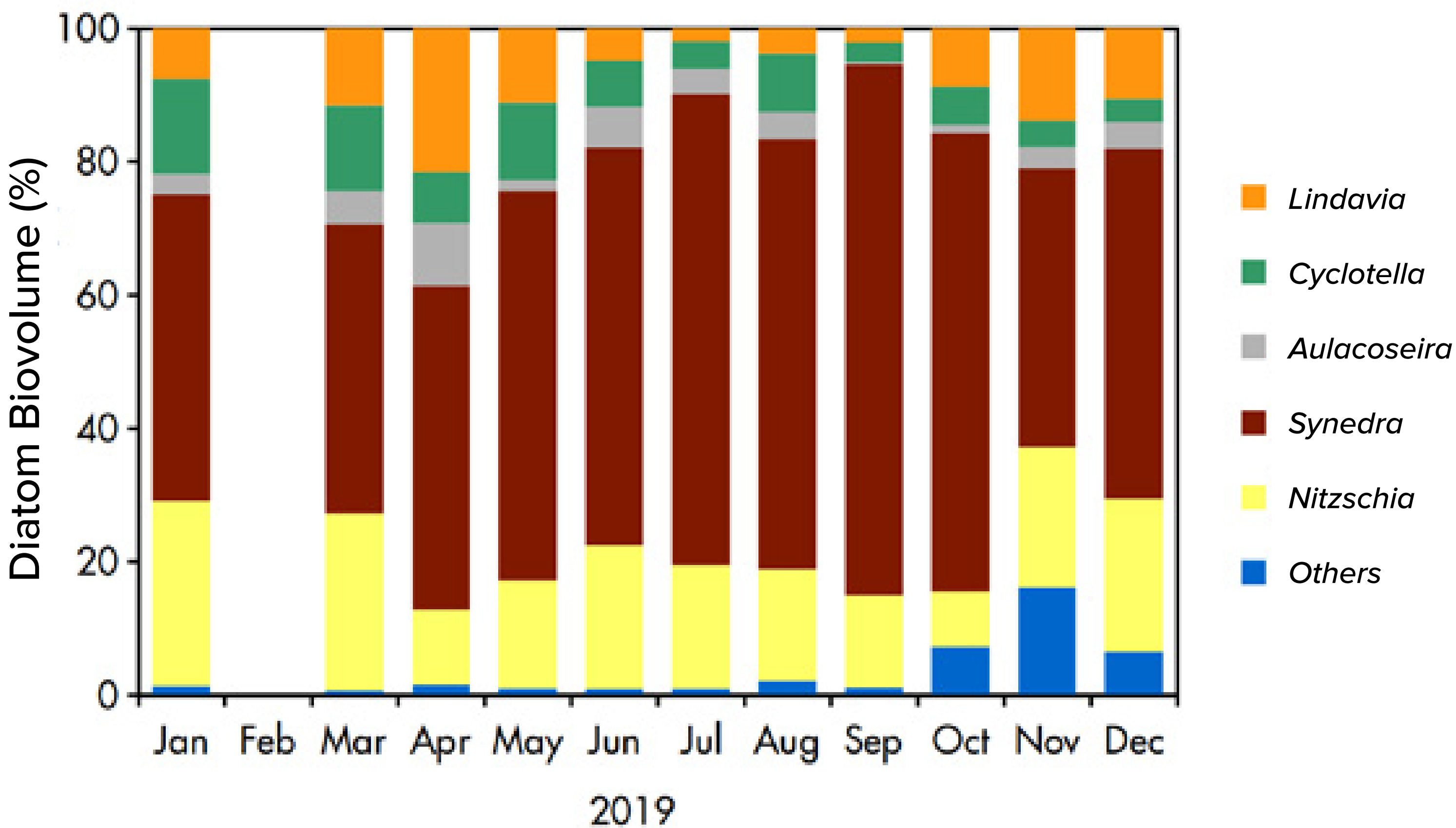
The amount of algal cells from different groups varies from year to year. Diatoms are the most common type of alga, comprising approximately 50 percent of the total abundance of algal cells and Chrysophytes are next, each comprising less than 15 percent of the total. Interestingly, over the last five years, there has been an increasing trend 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 2019

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 2019 are shown below. Large variations in the relative composition are evident by month. *Synedra* and *Nitzschia* were again the dominant diatom species during every month of the year, forming over 80% of the diatoms during summer. Although *Cyclotella* was a relatively low fraction of the percentage of biovolume of diatoms in 2019, it still had a large impact on clarity. Its very small size means that its biovolume can be small, but the actual number of light scattering cells can be extremely large. February sampling could not occur on account of the weather.

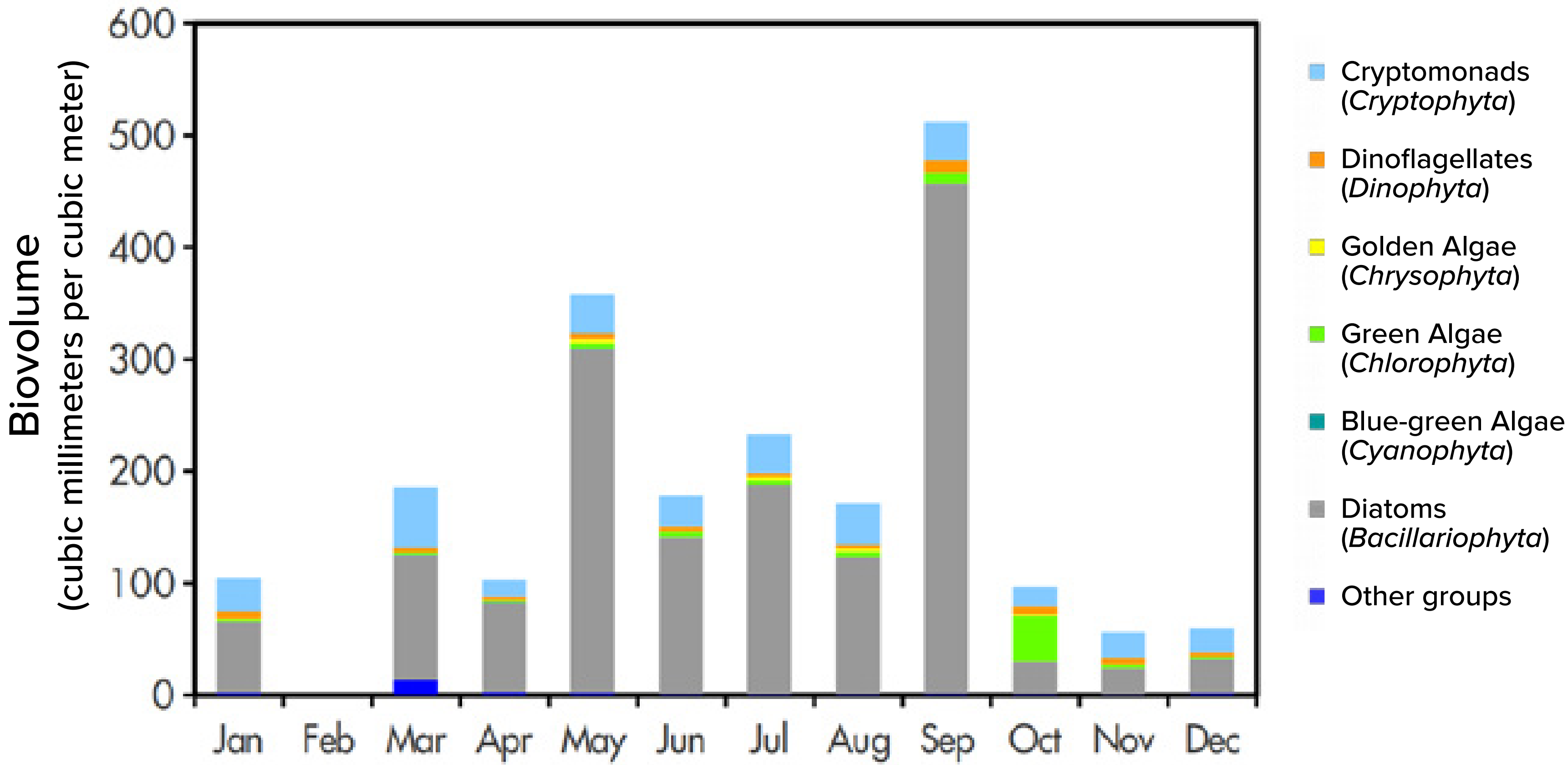


Algal groups as a fraction of total biovolume

Monthly in 2019

The biovolume of algal populations vary month to month, as well as year to year. In 2019, diatoms again dominated the biovolume of the phytoplankton community in every month, with the exception of October, when green algae seem to dominate most years. Peaks in the biovolume occurred in May and September in 2019. The "spring bloom" in May is a common occurrence at Lake Tahoe, but the magnitude of the late "summer bloom" was unusually high.

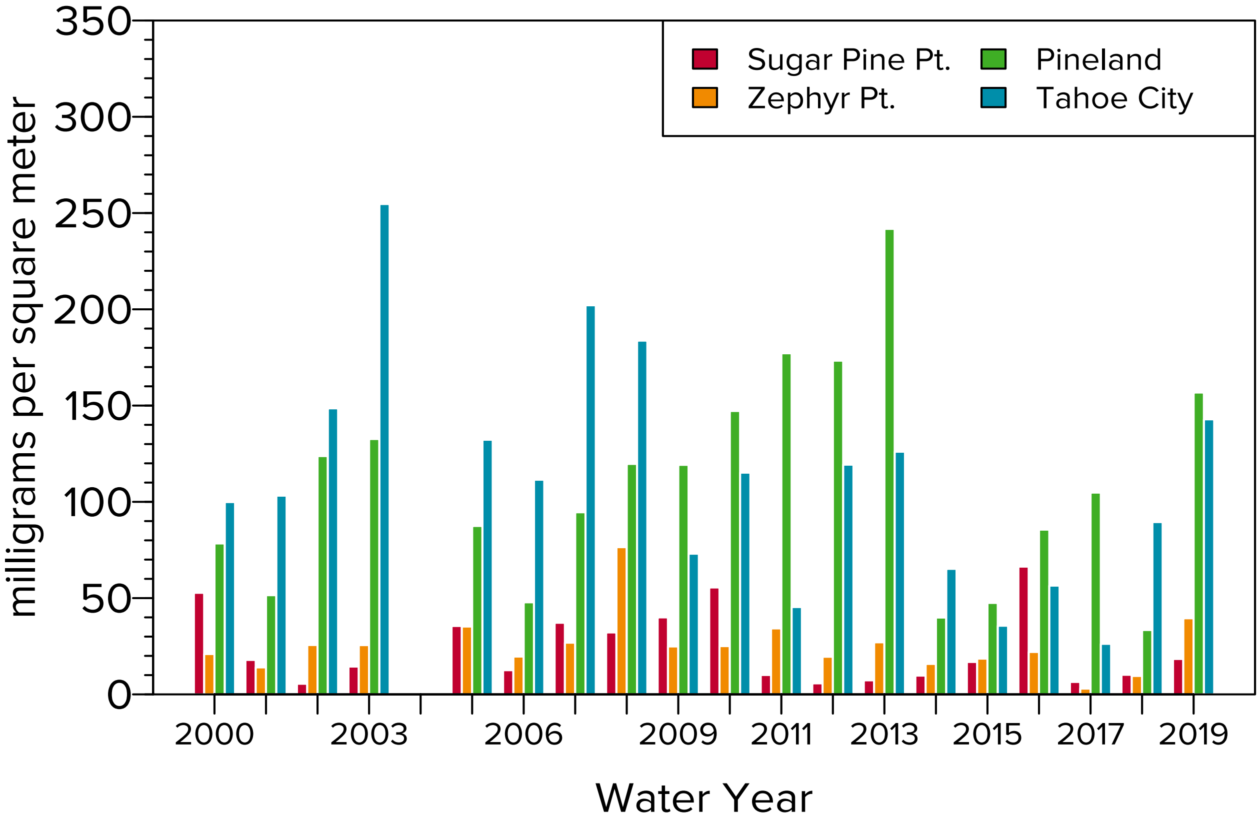
The peak biovolume in 2019 was 500 cubic millimeters per cubic meter, almost three times greater than the biovolume of recent years, a reflection of the increase of *Synedra* and *Nitzschia*.



Peak shoreline algae concentrations

Yearly since 2000

Periphyton, or attached algae, makes rocks around the shoreline of Lake Tahoe green and slimy, or sometimes like a very plush white carpet after they have been sun-bleached. Periphyton is measured five to eight times each year, and this graph shows the maximum biomass measured 1.5 feet (0.5 m) below the surface at four sites from January to June. In 2019, concentrations at the four sites shown were above their long-term average. One of the most urbanized sites, Pineland, historically one of the heaviest periphyton locations, was again heavily impacted by periphyton, compared to its record low level last year. Zephyr Point, though seemingly low, had its second highest value on record in 2019. Monitoring periphyton is an important indicator of near-shore health, but it is very challenging to characterize it on account of both the temporal and spatial variability inherent in the system.



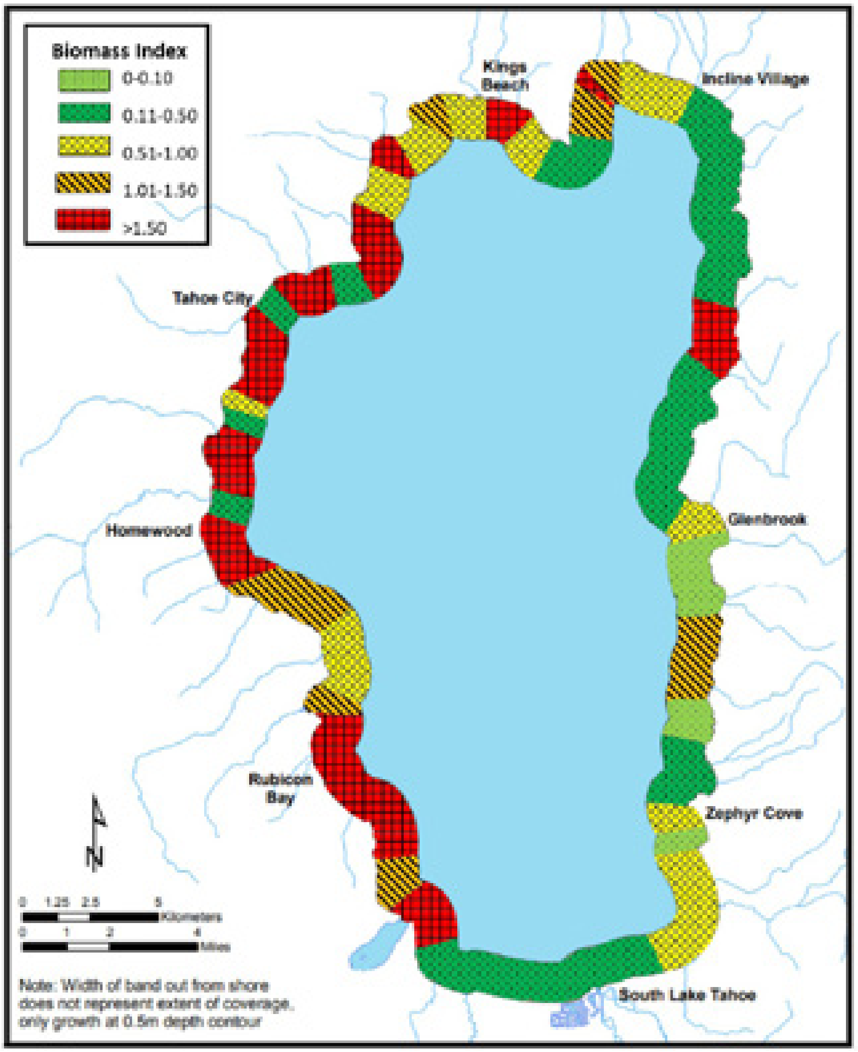
Shoreline algae distribution

In 2019

Periphyton biomass was surveyed around the lake over a three-week period during the spring of 2019, when it was estimated to be at its annual maximum. 54 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 rapidly 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. A large number of sites had high PBI in 2019 (i.e. about half of the sites had PBI > 1.5 indicated by red-shaded sections of shoreline in the map). The majority of these sites were on the California side. Compared to previous years, this is considered to be a relatively heavy periphyton year, although specific measurements of chlorophyll concentration at four sites (Fig. 10.7) would suggest otherwise. Most of the east shore has 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 2019



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CLARITY

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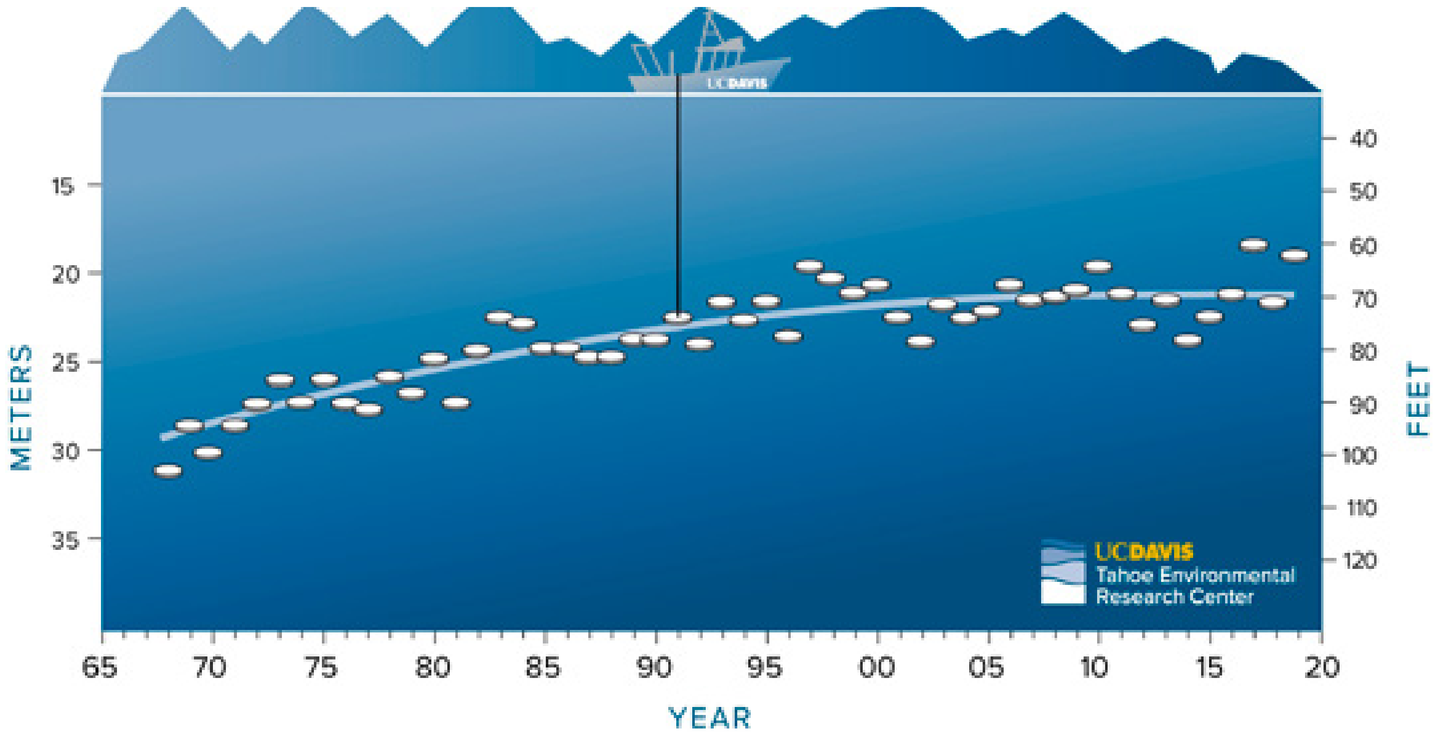
Annual average Secchi depth

Yearly since 1968

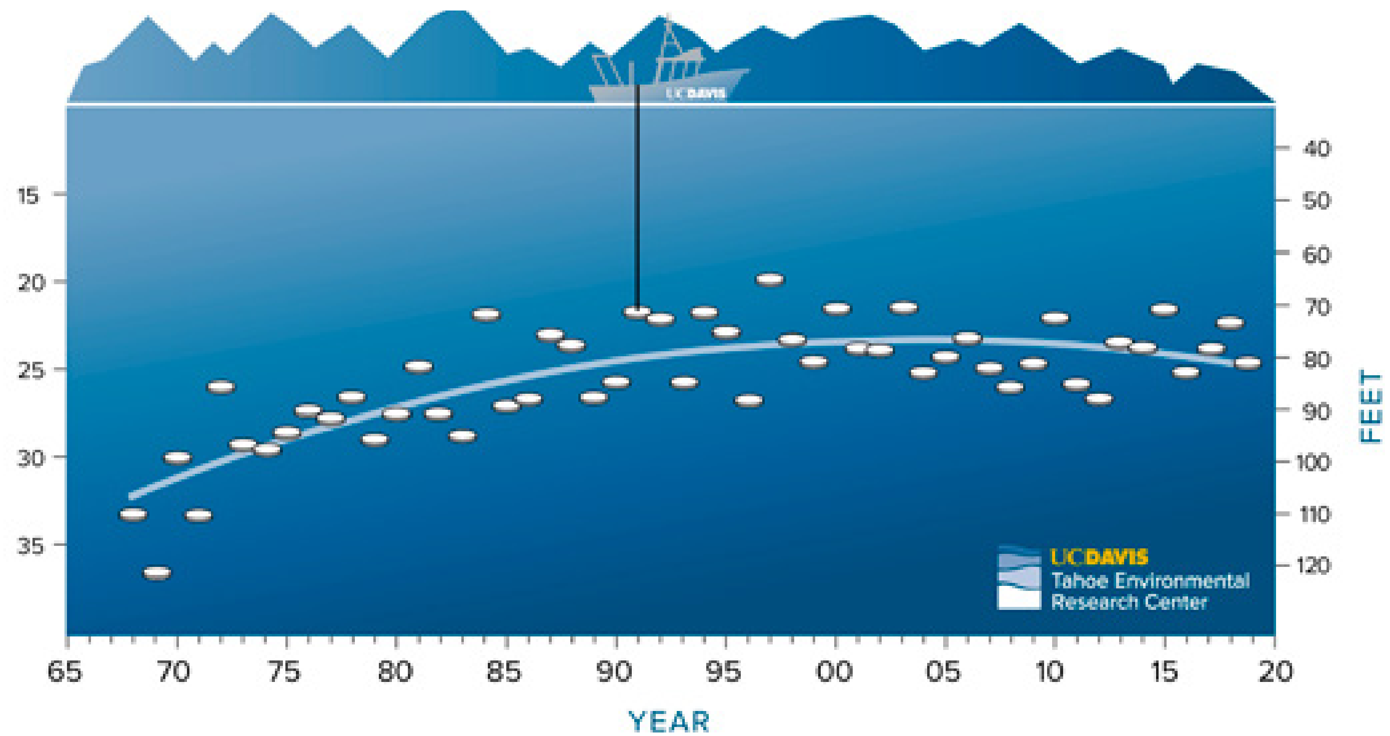
The Secchi depth is the depth at which a 10-inch white disk, called a Secchi disk, remains visible when lowered into the water. In 2019, the annual average Secchi depth was 62.7 feet (19.1 m), an 8.2-foot decrease over the previous year. The highest individual value recorded in 2019 was 112.0 feet (34.0 m) on February 19, coinciding approximately with the complete vertical mixing of the lake. The lowest was 36.1 feet (11.0 m) on May 8, coinciding with a bloom of the tiny algal cell *Cyclotella*. The decrease in clarity in 2019 was the result of a combination of factors including the 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 preceding 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

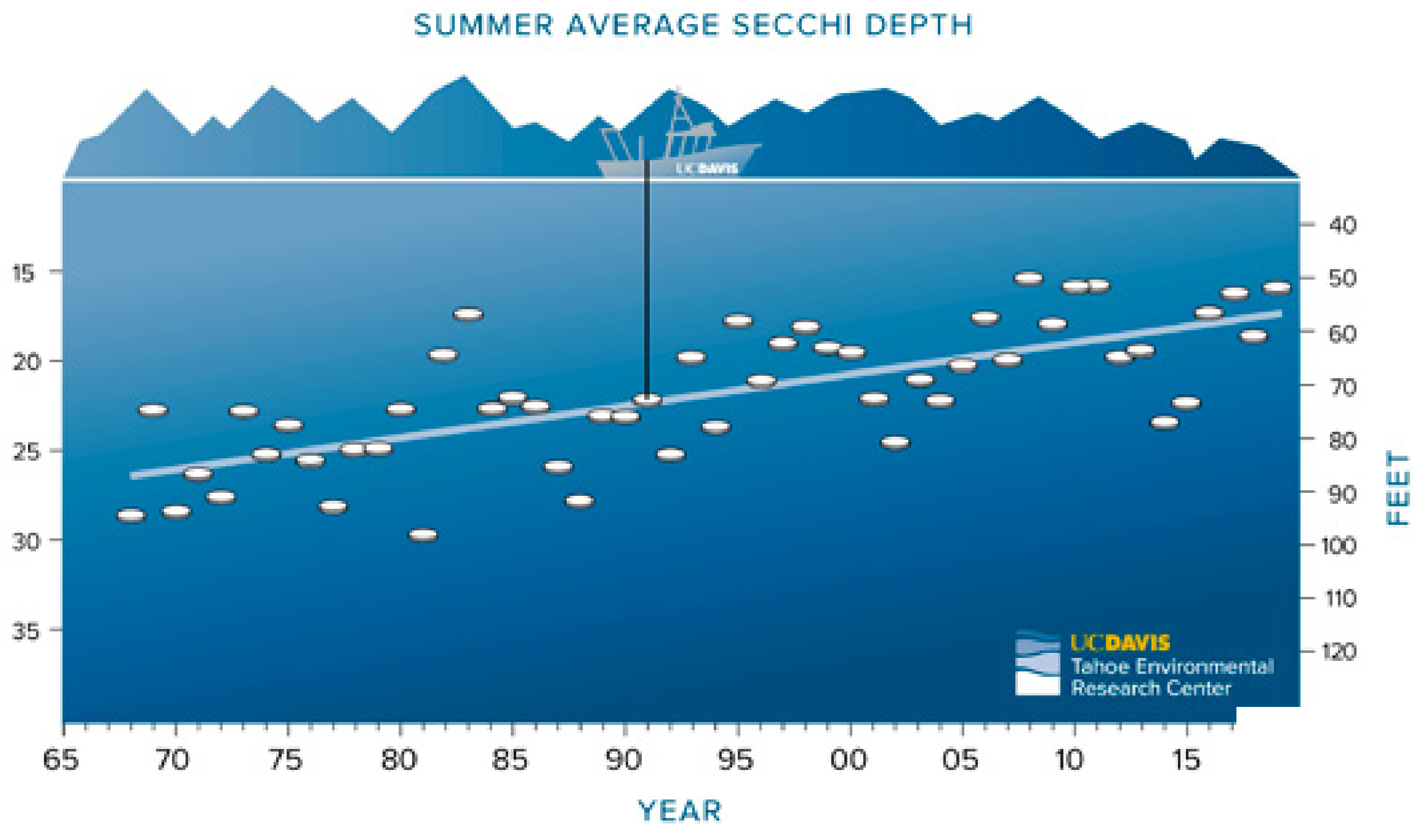
Average winter Secchi depth was 81 feet, based on eight readings between December 2018 and March 2019. This is only slightly below the long-term mean of 84 feet. The winter clarity increased by 7.5 feet over the previous year. The winter, clarity was well above the worst winter average, 65.6 feet (20.0 m), seen in 1997. Winter precipitation in 2019 was above the long-term average, and is believed to be one of the contributing factors to inputs of particles from urban areas surrounding the lake.



Summer Secchi depth

Yearly since 1968

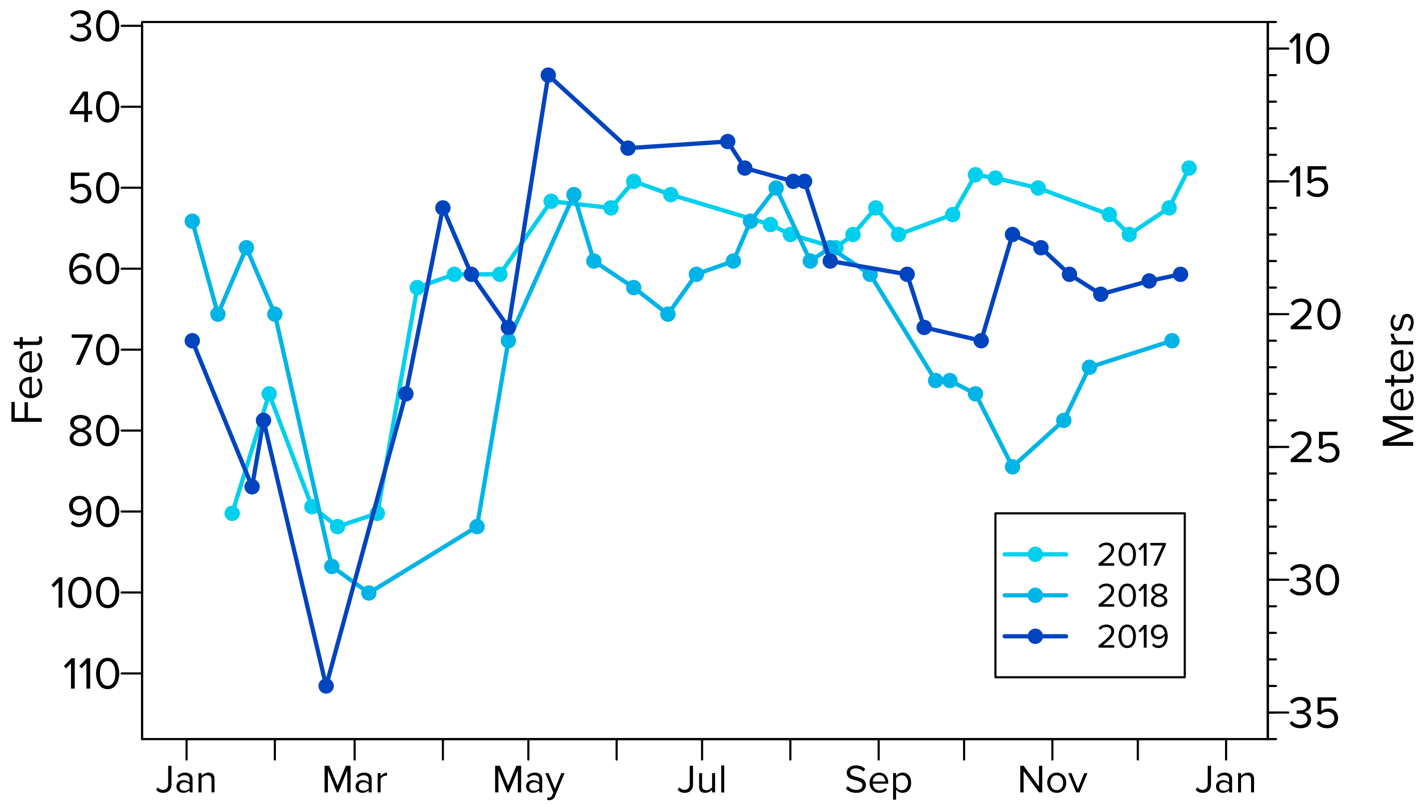
Summer (June-September) clarity in Lake Tahoe in 2019 was 53 feet (16.2 m). This is the fourth lowest summer value, with 2008 being 51 feet, and 2010 and 2011 being 52 feet. Summer is typically the season of poorest clarity. The long-term summer trend is dominated by a consistent degradation. In the 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 are believed to play an important role.



Individual Secchi depths

2017, 2018, 2019

Here, the individual Secchi depth readings from the Index station on the west side of the lake for 2017, 2018, and 2019 are plotted. Secchi values can be seen to sometimes vary considerably over short time intervals. This figure makes clear the abnormal summer conditions for 2019 that contributed to the low annual clarity value.



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EDUCATION AND OUTREACH

UCDAVIS
Tahoe Environmental
Research Center

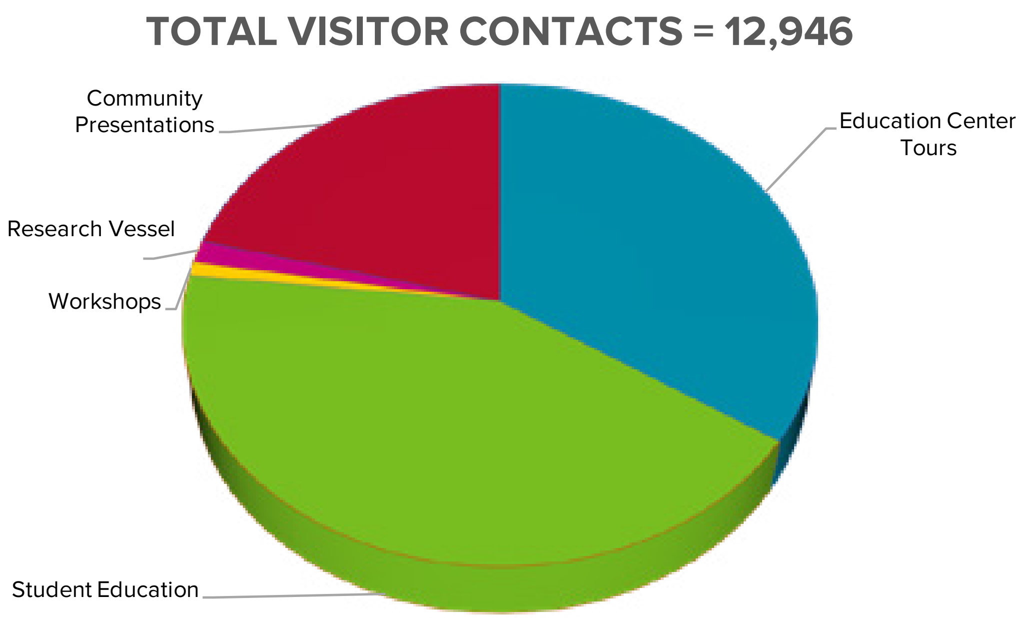
TERC education and outreach

In 2019

As part of our mission to achieve healthy aquatic and terrestrial ecosystem conditions, TERC incorporates education and outreach to benefit the community locally and globally. Our education programs are designed to provide science-based information about the Lake Tahoe basin to people of all ages and backgrounds and to foster responsible action and stewardship.

In 2019, TERC interacted with nearly 13,000 visitors through tours, field trips, and events. Student field trips and public tours accounted for a little over 67% of these interactions. TERC also reached the public through monthly public lectures, events, workshops, and presentations to community organizations. Our events in 2019 included Science Expos in both North Lake Tahoe and South Lake Tahoe, Trout in the Classroom teacher training program, Project WET workshops, High Elevation Garden workshops, Weird Wednesdays at the Incline Village Library, the Science of Cocktails fundraiser, Boys and Girls Club Gardening program, and volunteer docent training program.

TERC also partners with numerous organizations to deliver environmental science education and complete interpretive projects in the Tahoe Basin. In 2019, we partnered with the Sierra Nevada AmeriCorps Partnership, Boys and Girls Club, California Tahoe Conservancy, Desert Research Institute, Incline Village General Improvement District, Lake Tahoe Outreach Committee, League to Save Lake Tahoe, North Tahoe Environmental Education Coalition, Sierra Nevada University, Sierra Watershed Education Partnerships, South Tahoe Environmental Education Coalition, Take Care Tahoe, Tahoe Institute for Natural Sciences, Tahoe Public Art, and many others.



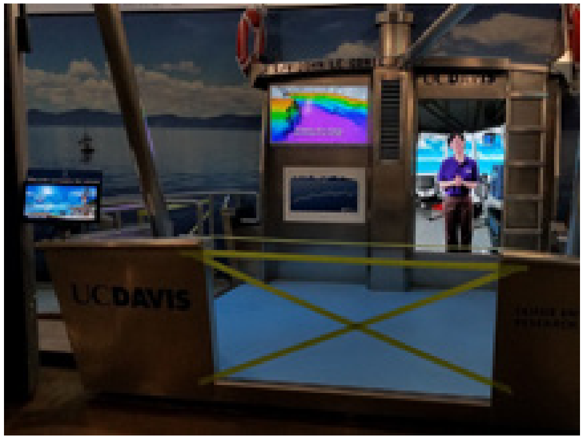
TERC educational exhibits

In 2019

Continuing the goal of heightening and enriching the experience of all Tahoe visitors, TERC has expanded educational offerings available inside and outside of the UC Davis Tahoe Science Center.

Our educators are working with Tahoe Public Art and the California Tahoe Conservancy (CTC) to develop an Environmental Art Master Plan for CTC lands in the Tahoe Basin.

We upgraded and remodeled the equipment driving our iconic virtual research vessel and laboratory exhibits, that were originally installed in 2006. We are continuing to work towards the next step of updating video content to feature the newest research findings. Through the creation and improvement of engaging hands-on educational activities we are making a real contribution to transferring knowledge and understanding of Lake Tahoe to an ever-widening audience.



The virtual research vessel exhibit was updated with new technology and now includes a touchscreen. Upgrades were funded by support from private donors and the Parasol Tahoe Community Foundation.
Photo: A. Toy

The virtual laboratory exhibit was also updated with new technology and now includes a touchscreen. Upgrades were funded by support from private donors and the Parasol Tahoe Community Foundation.
Photo: A. Toy

A 360-virtual reality exhibit and video was developed in partnership with the UC Davis Office of Strategic Communications for the Tahoe Federal Summit and showcased at the Capital Public Radio "Tahoe Land" special event.
Photo: A. Toy

TERC outreach

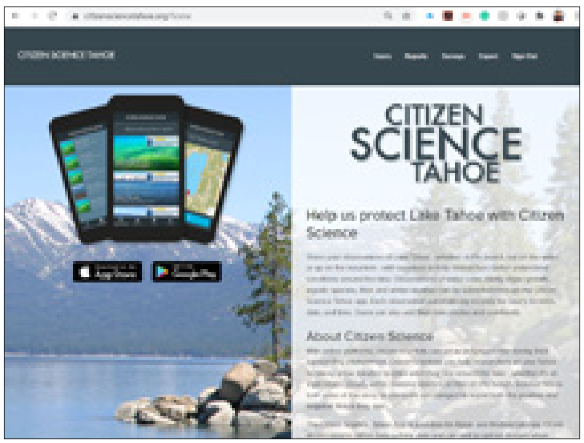
In 2019

TERC continues to promote the "Citizen Science Tahoe" mobile app. Citizen scientists help lake researchers collect observations by simply taking a few minutes to enter the conditions they observe around the Tahoe Basin.

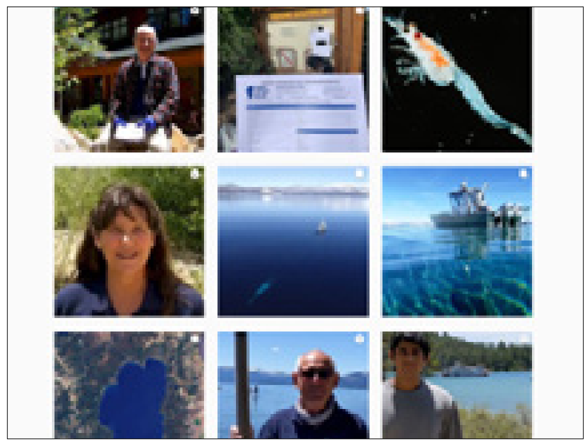
Promotion of all TERC education and research efforts continue and grow through various virtual methods including our website, Instagram (@UCDavisTahoe), Facebook, YouTube Channel, and more. We have pushed for greater consistency and themes in our content and posts. Our Instagram account now has 1,495 followers which is nearly a 50% increase from last year. Combined with Facebook and Twitter, there is now a total of over 4,200 members in our social media community.

Find the UC Davis Tahoe Environmental Research Center through various methods including:

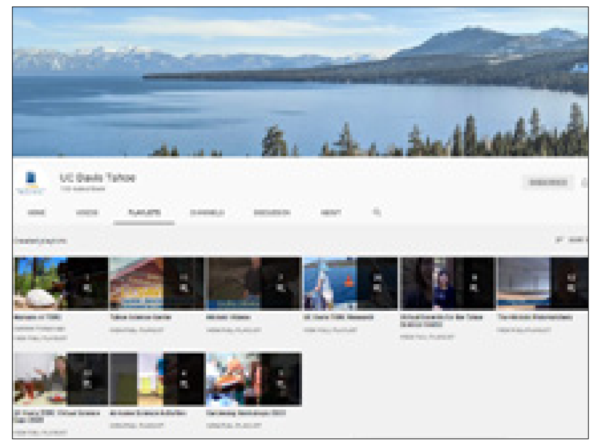
- Website (https://tahoe.ucdavis.edu),
- Instagram (https://www.instagram.com/UCDavisTahoe),
- Facebook (https://www.facebook.com/UCDavisTahoe),
- Twitter (https://twitter.com/UCDavisTahoe), and
- YouTube (https://www.youtube.com/c/UCDavisTahoe).



After a total overhaul of the Citizen Science Tahoe mobile app, version 3.0.2 became available in spring 2019. This completely new version of the app for citizen scientists in our region helps us gather information and images about algae, water quality, litter, aquatic invasive species, stormwater pollution, and meterology.



The @UCDavisTahoe Instagram now includes "virtual docent" interviews, humans of TERC, quizzes, and increased content to share with the broader audience at Lake Tahoe and beyond.



The new YouTube Channel @UCDavisTahoe includes playlists such as research, historic videos, Tahoe Science Center videos, virtual docent videos, humans of TERC, and more.

TERC educational programs

In 2019

TERC provides educational programs for the general public, K-12 students, teachers, and volunteers. Public programs include science center tours, monthly lecture series, citizen science programs, and garden workshops.

K-12 education efforts include school field trips, Trout in the Classroom, Science Expo, in-classroom presentations, and outdoor education programs. In 2019, the education team provided informal science education to 4,358 third- through twelfth-grade students. The average interaction time with each student was 4.25 hours.

Science activities and thematic field trips continued to be modified and updated annually. Of the students surveyed, 93 percent had a 25 percent or more increase in knowledge. Responding teachers indicated that they were satisfied with their overall field trip experience and that the activities presented were appropriate for the grade level being taught.

Our engaging Earth System Science field trip (concept developed by Dr. Art Sussman, WestEd) includes a simple three-part play with students in costumes acting out the scientific processes of photosynthesis and the carbon cycle as the roles of sun, flower, and cow.
Photo: B. Goodwin

AmeriCorps member Baylee Goodwin teaches about weather and cloud formation at Science Expo with fun activities.
Photo: A. Graham

Our field trip activities are continually improved with the goal of increasing student engagement and linking learning goals to the NGSS science standards. The Environmental Detectives field trip presents a mystery for students to solve.
Photo: B. Goodwin

TERC educational programs, continued

In 2019

During the summer months, UC Davis TERC and Lake Tahoe Master Gardeners hosted the High Elevation Gardening workshop series at the Tahoe City Field Station and provided guidance on lake-friendly practices for growing fruits and vegetables in the challenging Tahoe climate.

Additionally, in 2019 TERC assumed the management of the North Tahoe Demonstration Garden in collaboration with the Incline Village General Improvement District and Sierra Nevada University. This outdoor space is an extension to tours and content of the Tahoe Science Center and allows for outdoor education programming in summer and fall with the local Boys and Girls Club and other summer camp programs.

Another popular program was the outdoor education presented at the Junior Waterman's camp in Carnelian Bay. Hosted by Waterman's founders Jay and Anik Wild, our education team members had the opportunity to incorporate science and stewardship into this outdoor program.

Each year, new volunteer docents participate in a multi-day docent training workshop. The docents become local experts, lead public tours at our science centers, help maintain the Tahoe City Field Station's native plant demonstration garden as a beautiful community resource, and assist us with many events and activities throughout the year.

The High Elevation Gardening workshops at the Tahoe City Field Station and native plant demonstration garden were highly attended. Following a discussion of growing techniques and cultural anthropology, participants take home a selection of seedlings.
Photo: A. Toy

The TERC education team teaches fun and engaging outdoor activities to the Junior Waterman's camp over the course of three weeks. Topics included Citizen Science, watersheds, stream monitoring, and benthic macroinvertebrates.
Photo: A. Toy

The annual docent training program includes an in-depth presentation about TERC's research and monitoring programs on Lake Tahoe with boat captain Brant Allen aboard the UC Davis Research Vessel John LeConte.
Photo: A. Toy

TERC special events

In 2019

TERC hosts monthly lectures throughout the year on various environmental issues, new scientific research, and related regional topics of interest. One special lecture in partnership with Classical Tahoe was presented by University of California President and former Director of Homeland Security Janet Napolitano.

This year, TERC hosted three special film screenings. "The Human Element" highlighted Americans on the front lines of climate change and featured director Matthew Testa for a virtual question and answer session. The award-winning "Screenagers" documentary explored bringing up children in the digital era and included a post-film discussion. The third movie, "Wilder than Wild," dealt with fire suppression and how the combined effects with climate change have exposed our forest and communities to large, high-severity wildfires. Following the screening a panel of experts discussed the direct effects of wildfire to the Tahoe Basin.

In 2019 we partnered with the Tahoe Film Fest to support TERC research and education. This festival showcased and celebrated American independent films, new films from Latin America, and a filmmaker tribute. A series of environmental films were shown to educate audiences and celebrate the efforts of everyone who helps to maintain the beauty of the Lake Tahoe basin and the Sierra Nevada. The festival brought actors, directors, and producers to mingle with Tahoe locals, creating an unforgettable experience that we are excited to be a part of in future years.

Classical Tahoe and TERC combined efforts to host "A Conversation with Janet Napolitano: How Safe Are We?" on July 25, 2019 in the Classical Tahoe Pavilion. Photo: H. Segale

Tahoe Film Fest and TERC hosted "The Human Element" film screening on August 16, 2019 in the Crystal Bay Club Crown Room with a virtual discussion with Director Matthew Testa. Photo: H. Segale

Heather Segale welcomes attendees to opening night of the 5th annual Tahoe Film Fest hosted at multiple venues including Incline Cinemas (shown here), Crystal Bay Club, and Northstar Theaters during December 5-8 for a selection of award-winning films. Photo: R. Roussel