TAHOE: STATE OF THE LAKE REPORT 2024

SCIENCE TO SAVE LAKES

UC DAVIS
Tahoe Environmental
Research Center

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Introduction

Lake Tahoe's iconic beauty and clarity are in danger. Challenges presented by aquatic invasive species, an increase in particle and nutrient introduction, changes in phytoplankton and zooplankton populations, and the overlying effects of climate change put the lake under constant shifting pressure. This report aims to explain how these factors affect the lake and to give hope that it is not too late. Everyone who loves the lake can take action to improve the outlook for Lake Tahoe and beyond.

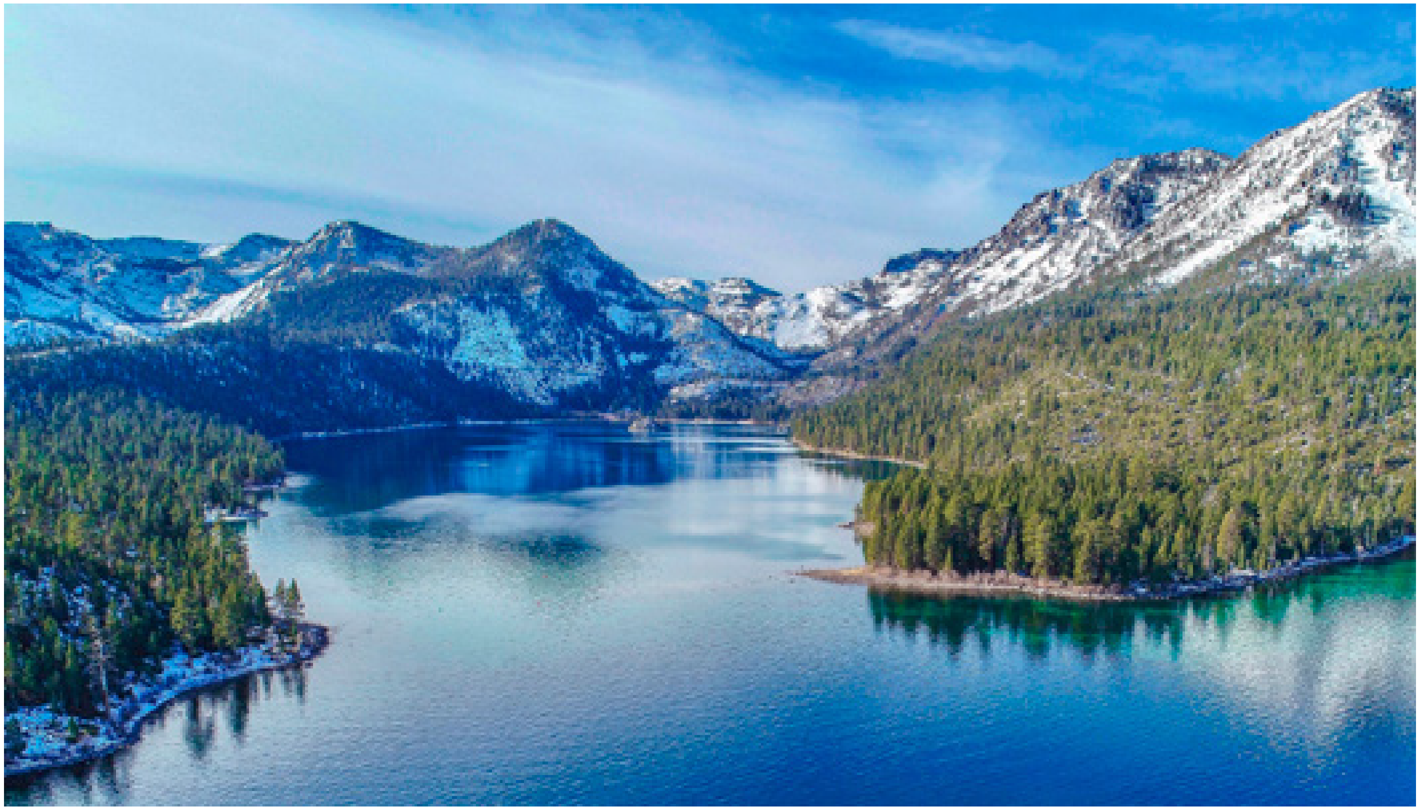
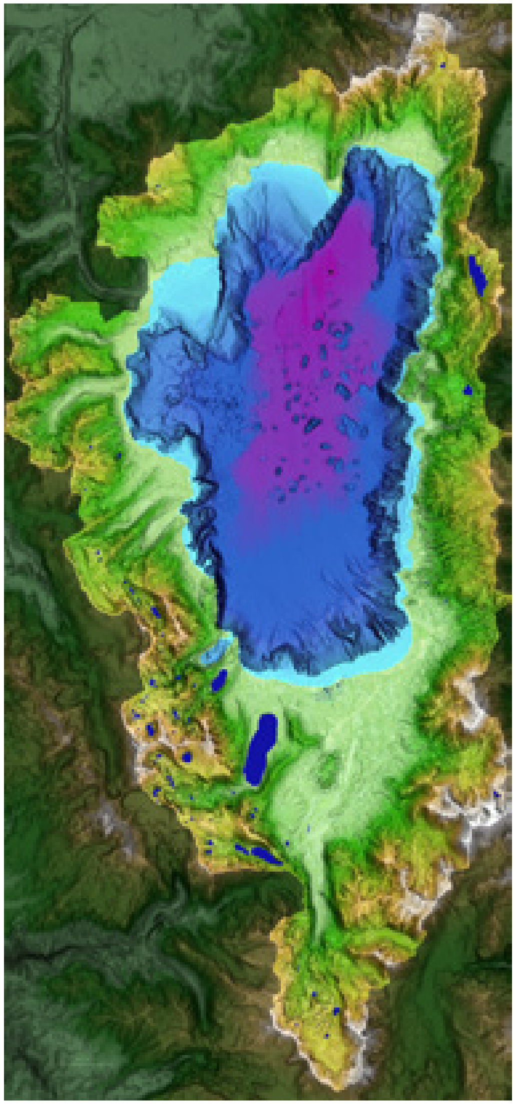


Figure 1. Emerald Bay and the surrounding peaks, the morning after a light dusting of snow (Brandon Berry, UC Davis TERC).

Climate Change has no Borders

Rachel Carson's classic book *Silent Spring* (1962) was a call to arms for a generation to protect our waterways. It led to better stewardship of our lakes and rivers by point source reduction of nutrients and contaminants. More than sixty years later, we continue to face similar challenges she described but are also faced with the ever-growing pressures that climate change presents. From wildfire smoke blowing south last summer from Northern Canada to regional heat waves breaking new records this year to harmful algal blooms (HABs) affecting lakes and rivers across the country, the problems we face today cross state and national boundaries.

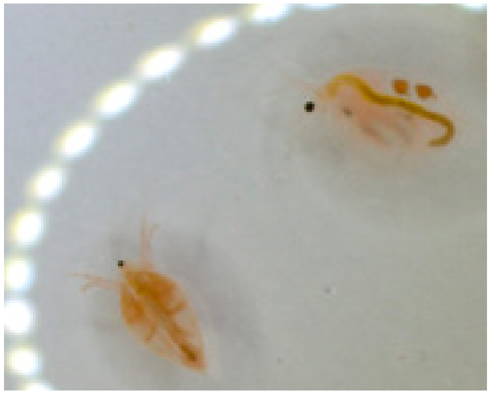
Lake Tahoe (Fig. 2-4) is subject to these same local, regional, and international climatic shifts, which researchers from Tahoe Environmental Research Center (TERC) see in the long-term records curated by TERC since 1968. These changes affect all aquatic, terrestrial, and atmospheric ecosystems, from warming waters to impacted forests to changing rain on snow events. However, people's passion and engagement for the lake and its watershed means it is also a flagship for stewardship and engagement. The lessons and tools we develop through our research at TERC can be widely applied to help protect freshwater across the Sierras, the State, nationally and internationally.



(Clockwise from Top Left) Figure 2. A bird's eye view of the Tahoe watershed and lake bathymetry (Steven McQuinn); Figure 3. Wildfire smoke causes a bright red sunset in Tahoe Vista (Alison Toy, UC Davis TERC); Figure 4. Thick layer of metaphyton washes up on a Lake Tahoe Beach (Katie Senft, UC Davis TERC).

How Does Climate Change Drive Ecosystem Shifts?

Warming water and air temperatures, changes to watershed hydrological patterns, and different chemical conditions are all examples of climate change-driven shifts happening within the lake and watershed. Every ecosystem is in balance, and these shifts will transition the ecosystem to a new balance. An example of this is the proliferation of harmful algal blooms (HABs) (Fig. 5) across California, with Lake Tahoe experiencing its first documented HAB in 2021. These shifts are occurring at all trophic levels in the lake, from the smaller cyanobacteria to the chlorophyll-producing algae (both considered as different forms of phytoplankton) to the zooplankton that include cladocerans (Fig. 6)and copepods (Fig. 7) that graze on the phytoplankton. As these tiny creatures sit at the base of the lake's food web, any significant shifts in population composition and diversity can have wide-ranging ripple effects on the rest of the lake's ecosystem.



Clockwise from Top Left: Figure 5. Surface expression of a HAB event in Clear Lake, CA (UC Davis TERC archives); Figure 6. Daphnia a native cladoceran (UC Davis Tahoe Science Center); Figure 7. Diaptomus a native copepod (UC Davis Tahoe Science Center).

How Does Climate Change Drive Ecosystem Shifts?

Cyanobacteria

Algae or phytoplankton are a naturally occurring simple plant that makes up the base of Tahoe's (and any lake's) aquatic food web. In 2021 and 2022, there was a shift in Tahoe's algae composition, with cyanobacteria dominating algae collected from sampling locations around the lake. Though cyanobacteria are a normal part of most lakes' algae, under some circumstances, some species form HABs that contain toxins that can harm humans and animals. Toxins that these blooms could produce include microcystins, neurotoxins, and hepatotoxins, which could produce reactions such as rashes, severe respiratory distress, or even decreased liver or brain function.

As HAB events are so rare in Lake Tahoe, they are not currently being studied locally by TERC. However, TERC is engaged in a multi-year research study at Clear Lake, CA where HAB events occur annually (Fig. 5, 8-9). This study is focused on understanding the dominant processes in the Clear Lake watershed and within the lake itself that are negatively impacting the rehabilitation of lake water quality and ecosystem health. Since December 2018, TERC researchers have collected monitoring data throughout the Clear Lake watershed to better understand the dominant physical, chemical, and biological processes controlling lake water quality. More information can be found at https://clearlakerehabilitation.ucdavis.edu/.

Figure 8. A TERC researcher samples a HAB event in Clear Lake, CA, with a kayak (UC Davis TERC).

Figure 9. Surface expression of a HAB event in Clear Lake, CA (UC Davis TERC).

How Does Climate Change Drive Ecosystem Shifts?

Phytoplankton

In addition to the infrequent occurrence of HABs, Lake Tahoe has also been witness to changes in the phytoplankton assemblage (the distribution of the dominant species). Since 2017, there has been a significant shift in the dominant phytoplankton species (Fig. 10). While *Cyclotella*, known to impact clarity, are still present, there has been a notable increase in the *Synedra* population. Researchers are trying to understand the drivers of these shifting population dynamics. While these diatoms are significantly larger (40 – 100 µm) than *Cyclotella* (5 – 7 µm), they may be playing a role in the continued reduction in clarity during the summer months by changing the optical properties of the water when they grow.

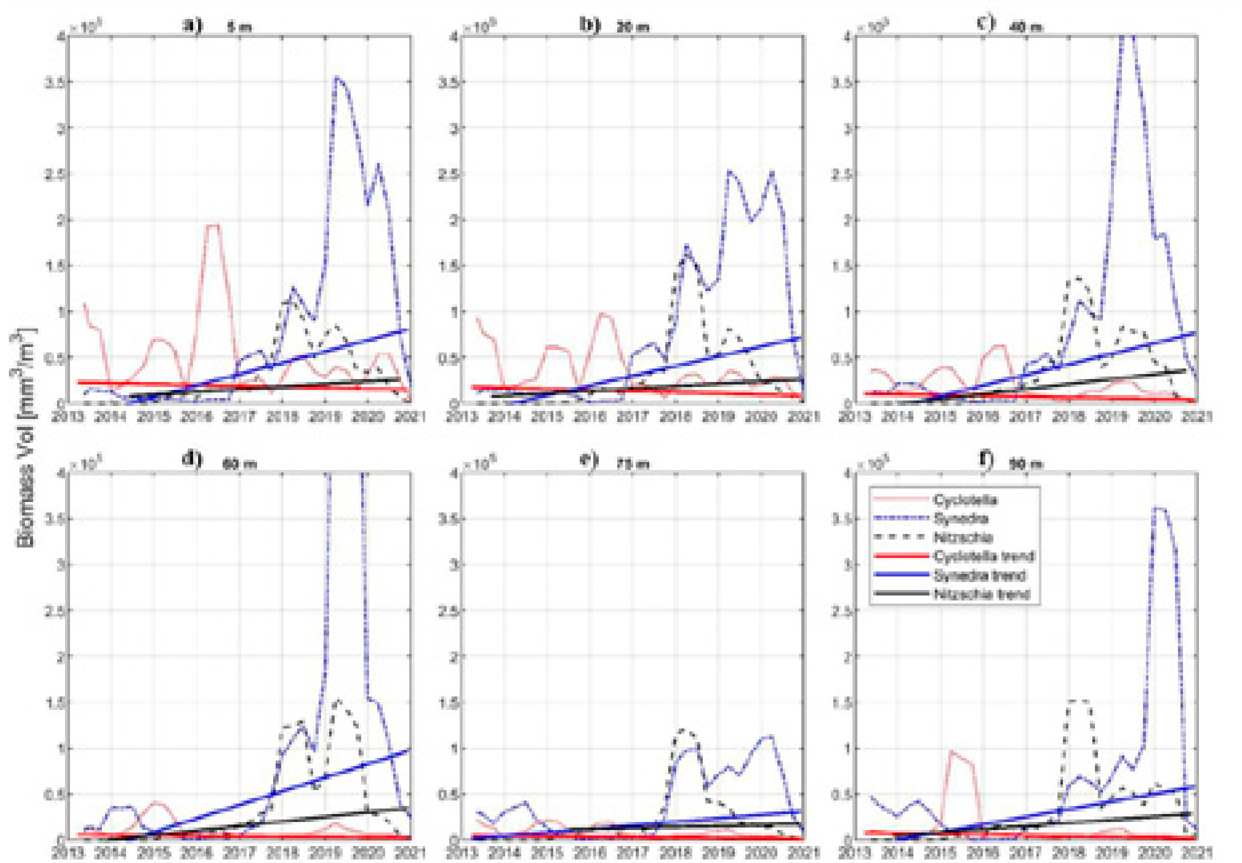


Figure 10. Biomass volume (from cell counts) of dominant genus Cyclotella (red), Synedra (blue), and Nitzschia (black), at a) 5 m, b) 20 m, c) 40 m, d) 60 m, e) 75 m, and f) 90 m. (McInerney, 2024).

How Does Climate Change Drive Ecosystem Shifts?

Nearshore Algae: Metaphyton and Periphyton

Nearshore algal blooms are increasing in freshwater bodies around the world, worsened by the impacts of climate change, nutrient pollution, and the introduction of non-native species. Warming waters enable algae to grow faster, and increased nutrient inputs from a lake's watershed can further fuel algae growth. Invasive species such as Asian clams, which will be discussed on page 6.13, are now established in sandy areas of Tahoe's shoreline and excrete nutrients that can also exacerbate algae growth. In recent years there has been concern that the growth of attached algae (periphyton) and floating algae (metaphyton) are increasing along Lake Tahoe's shoreline, but quantifying changes in nearshore algae is difficult due to its patchiness in space and time. Periphyton along Tahoe's nearshore has been monitored by TERC for decades by snorkeling or SCUBA diving at fixed locations (Fig. 11-12). Monitoring metaphyton has been challenging due to the mobility of the species. Current monitoring has not been sufficient to quantify the changes in metaphyton. TERC's new comprehensive nearshore algae monitoring plan seeks to fill this gap in knowledge.

Figure 11. TERC diver sampling metaphyton in Lake Tahoe (Brant Allen, UC Davis TERC).

Figure 12. Periphyton sampling in Lake Tahoe by TERC research divers (Katie Senft, UC Davis TERC).

How Does Climate Change Drive Ecosystem Shifts?

Nearshore Algae: Metaphyton and Periphyton

In 2023 and 2024, TERC researchers augmented the historical nearshore algae monitoring program by adding aerial monitoring techniques to identify where, when, and how much algae is growing along Tahoe's shoreline. Aerial imagery was collected approximately monthly from 15 shoreline areas using an aerial drone (UAV) and from the entire Tahoe shoreline via helicopter. Images were then used to estimate the spatial areas covered in algae using machine learning models (Fig. 13-14). When combined with ground-truthing and sample collection for algal species composition and biomass, this integrated approach improves monitoring nearshore algae in Tahoe and other clear-water lakes worldwide.

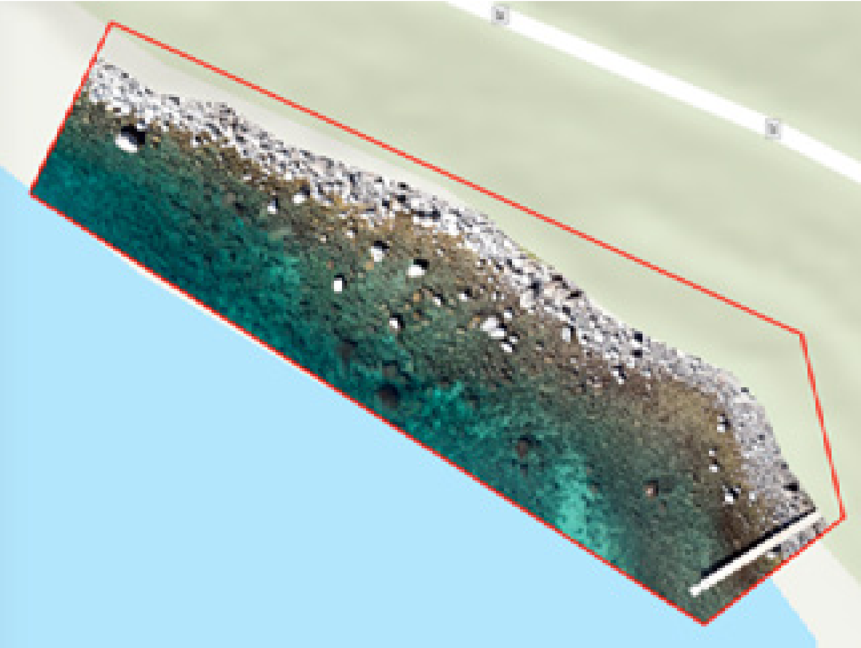


Figure 13. A sample of collected drone imagery of the Lake Tahoe nearshore (Brandon, Berry, UC Davis TERC).

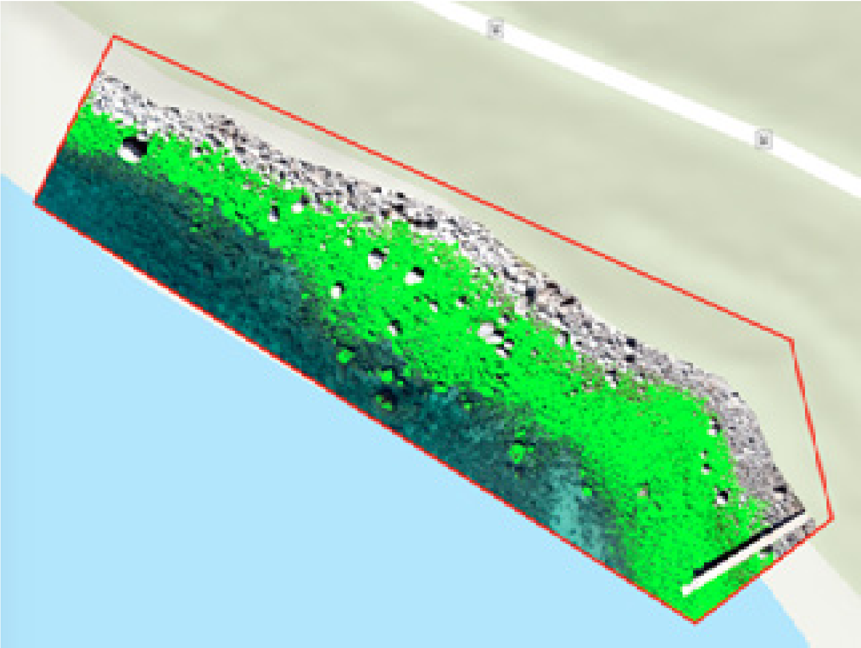


Figure 14. A sample of classified drone imagery of the Lake Tahoe nearshore delineating the presence of periphyton (Brandon, Berry, UC Davis TERC).

How Does Climate Change Drive Ecosystem Shifts?

Zooplankton

In recent years, much attention has been paid to the role of *Mysis* shrimp and their potential impact on the clarity of Lake Tahoe. The decline in the population numbers seen and reported in 2022 has since showed a slight recovery beginning in 2023. There also appears to be shifts in other zooplankton numbers. There have been spikes in the populations of native cladocerans (e.g. *Daphnia* or *Bosmina*) and copepods (e.g. *Diaptomus* or *Epischura*; Fig. 15) that have not been seen in the last decade. Similar to the shifts in phytoplankton numbers, the drivers of these dynamics, such as the reduction in *Mysis* numbers in 2022, are unclear, but each change has a ripple effect through the complex ecosystem of the lake. These changes to the central trophic levels of the ecosystem will require continued monitoring to quantify the long-term impacts on lake water quality.

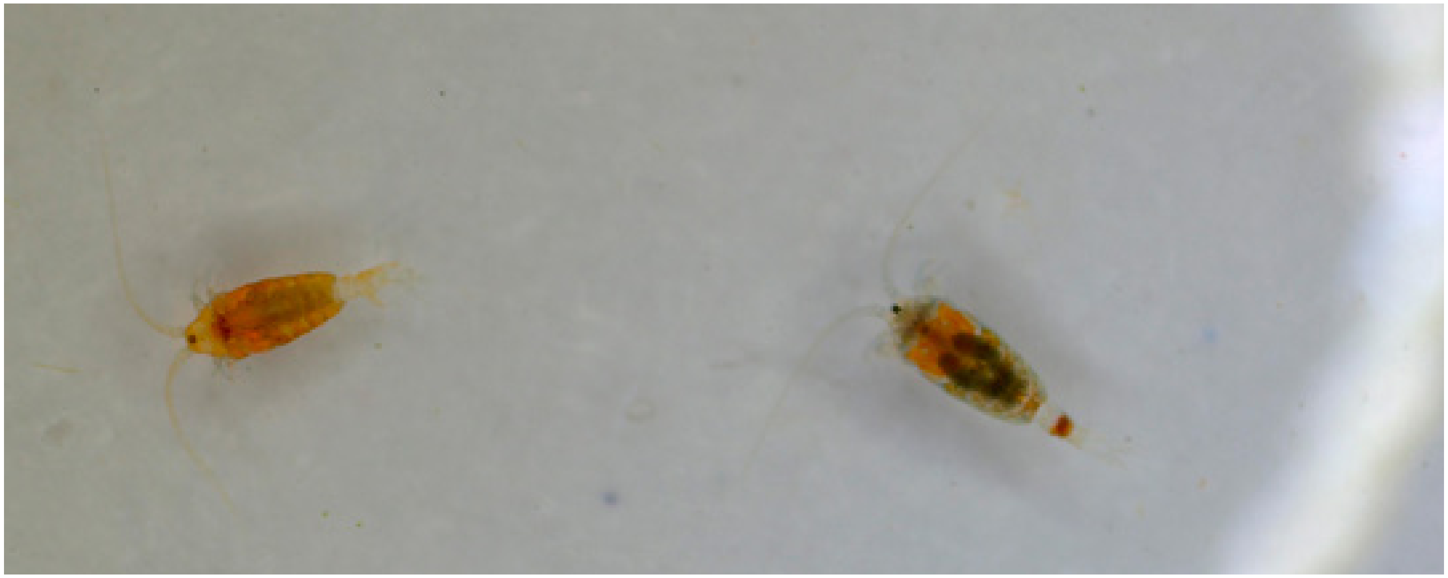


Figure 15. Two native copepods are found in Lake Tahoe, Diaptomus (left) are bright orange and Epischura (right) are opaque grey (UC Davis Tahoe Science Center).

How Does Climate Change Drive Ecosystem Shifts?

Zooplankton

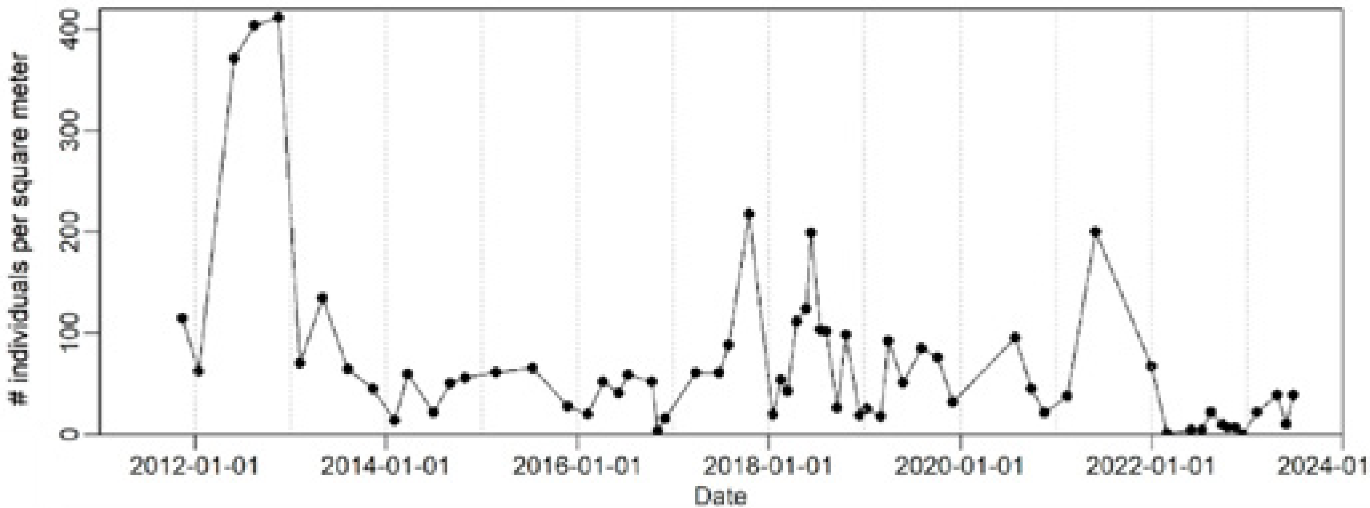


Figure 16. Mysis density in Lake Tahoe from December 2012 to June 2023. The presence of Mysis shrimp, which are a non-native species that were originally intentionally introduced to the lake in the 1960s, has been associated with a reduction in lake clarity due to their negative impact on the native food web.

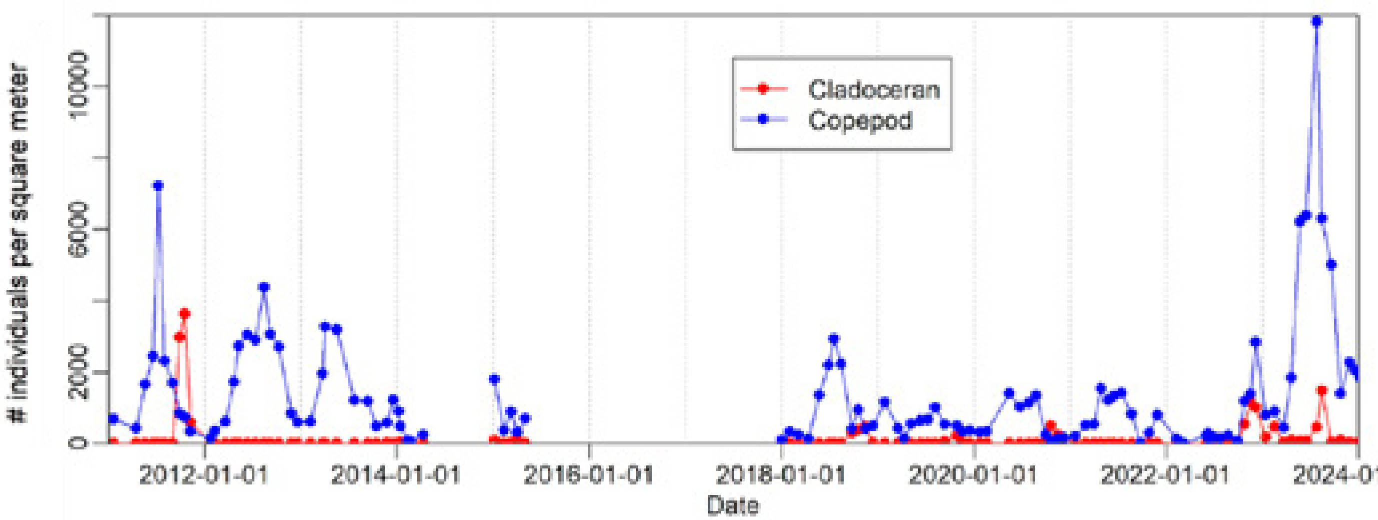


Figure 17. Cladoceran and copepod densities in Lake Tahoe from December 2012 to December 2023. The recent spike in populations indicates that fundamental changes are occurring in the lake, and more research is required to understand the cause and long-term implications.

2023 Lake Clarity

Clarity is measured as the depth to which a 10-inch white disk, called a Secchi disk (Fig.18), remains visible when lowered into the water. These measurements have occurred regularly since 1968, providing a long-term record of change. In 2023, UC Davis scientists took 25 readings at Lake Tahoe's long-term index station (LTP station) and 13 readings from the mid-lake index station (MLTP) that were deemed acceptable (See Appendix 11.1). View the historic clarity readings from 1968-2023 at https://portal.edirepository.org/nis/mapbrowse?scope=edi&identifier=1340.

More than 80 organizations, including government agencies, nonprofits, and research institutions, are working in collaboration with scientists to improve Lake Tahoe's water clarity and ecological health under the Lake Tahoe Environmental Improvement Program, or EIP, which is one of the most comprehensive, landscape-scale restoration programs in the nation. EIP partners are helping meet Total Maximum Daily Load (TMDL) reduction targets of fine-sediment particles and nutrients by reducing pollution through improved roadway maintenance and erosion control on roadways and private properties.

Observations of lake clarity for the 2023 calendar year show the continuing trends of improving clarity conditions during the winter (December through March) months (10th highest in the historical record and highest since 1983) and deteriorating conditions during the summer (June through September) months (5th lowest in the historical record). The annual average decreased from 71.8 ft. (21.9 m) in 2022 to 68.2 ft (20.8 m) in 2023, making it the 10th lowest observed annual average in the historical record. However, the value appears level as a long-term average.

Figure 18. The Secchi disk begins it's descent down the water column for a clarity reading (Brandon Berry, UC Davis TERC).

Figure 19. Winter months show an improving clarity of Lake Tahoe (Katie Senft, UC Davis TERC).

How Does Climate Change Affect Clarity?

Winter Clarity

The observed high winter clarity of 91.8 ft (28.0 m) in 2023 is partly the result of complete lake mixing (turnover). Deep water mixing plays a critical role in winter clarity as clearer bottom waters are mixed in with surface waters. The highest reading of 123 ft (37.5 m) on March 2, 2023, is the twelfth highest in the historical record and the second highest in the last 20 years. Full turnover occurred around February 26, 2023.

As the lake's ability to mix is a crucial component to the improved winter clarity measurements, this is one of the ways that climate change can negatively impact the long-term clarity of Lake Tahoe. Historical data shows that climate change is increasing air temperatures around Lake Tahoe. Increased air temperatures lead to increased temperatures in the lake's surface waters. The difference between the temperatures of the surface water and the deep water creates stratification in the lake. This means that the colder, clearer waters at the bottom of the lake cannot mix with the warmer, shallow waters. Climate change could make this stratification period longer every year, eventually preventing mixing altogether. This would have a devastating impact on the long-term clarity of Lake Tahoe's surface water.

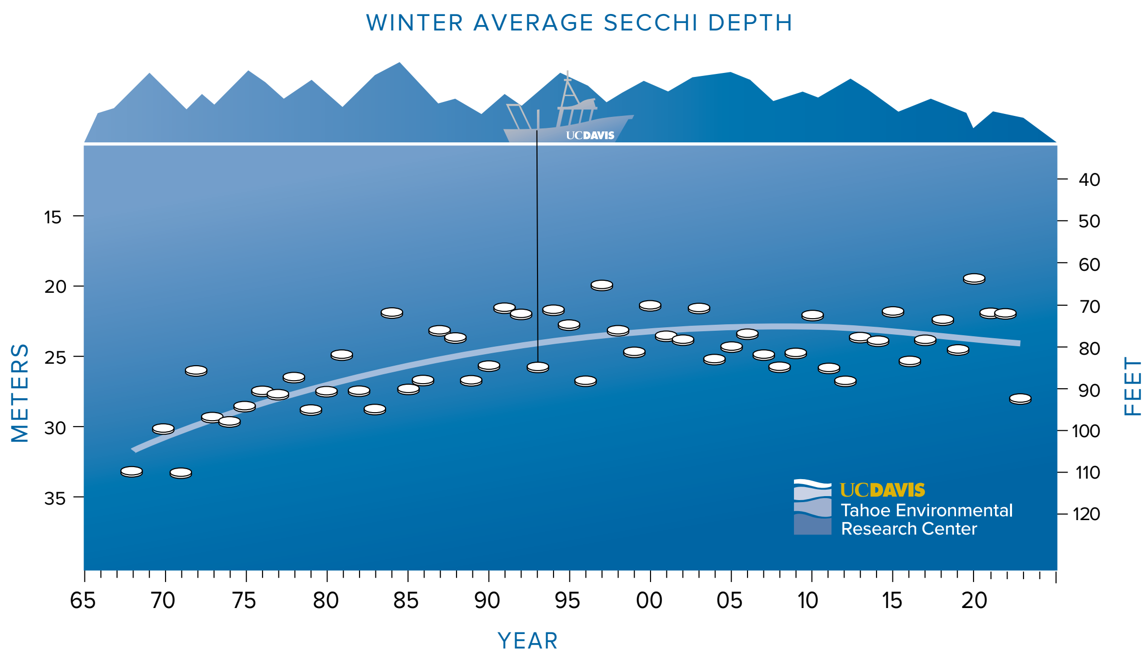


Figure 20. Winter (December – March) average Secchi depth as a measurement of lake clarity (UC Davis TERC).

How Does Climate Change Affect Clarity?

Summer Clarity

Low summer clarity of 53.5 ft (16.3 m) in 2023 primarily results from an increased number of particles in the surface waters. These particles are being discharged from the watershed following the melting of the large snowpack received in 2023. This is exemplified by the rapid decrease in clarity in May 2023, when stream discharge from the watershed neared the maximum. Fine particles (1-6.73 µm in size) in streams around the basin correlate with observed turbidity measurements.

There are factors outside of air and water temperature that are potentially impacting clarity. Future research on lake clarity should focus on understanding the processes associated with short- and long-term trends. Observed changes over the last decade in the zooplankton and phytoplankton communities (e.g. algal growth) are potentially playing a role in clarity. Particles resulting from microplastics may also result in changes in water optical properties but are poorly understood at small sizes (e.g., <5 µm) in Lake Tahoe. The relative contributions of each of these factors are the focus of ongoing research.

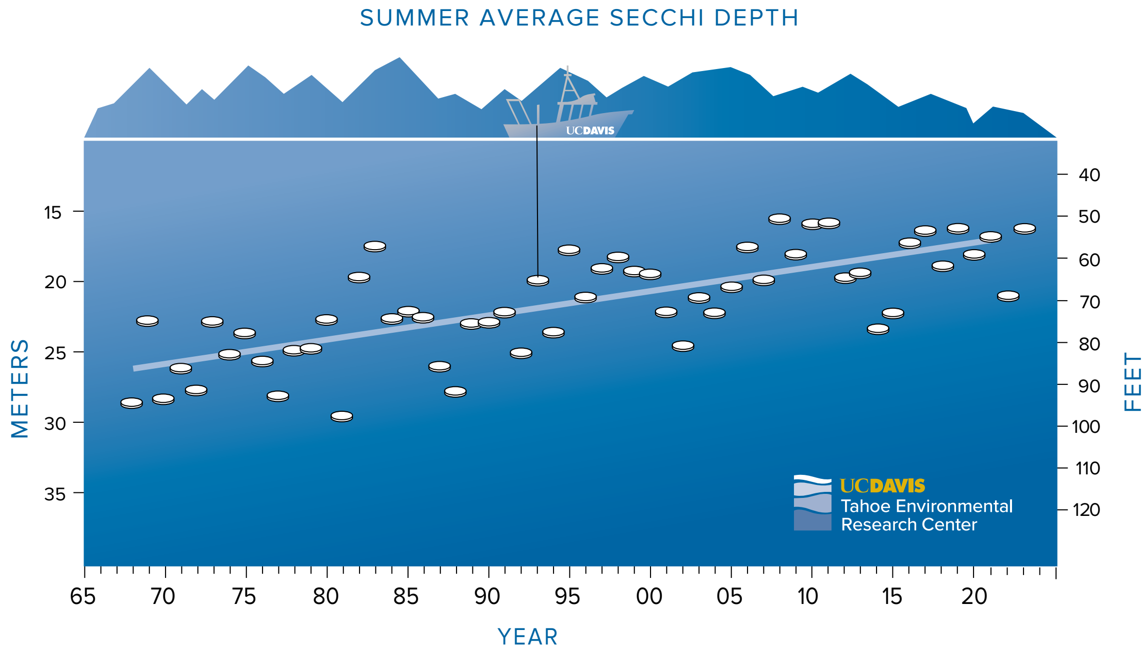


Figure 21. Summer (June – August) average Secchi depth as a measurement of lake clarity (UC Davis TERC).

What Role Does Climate Change Play with Aquatic Invasive Species?

Aquatic Invasive Species (AIS) are non-native species, plants, or animals, that can have devastating environmental, recreational, and economic impacts and potentially affect human health. AIS populations can result from accidental or intentional introduction and ecological shifts in aquatic ecosystems.

TERC is concerned with any invasive species in Lake Tahoe and the surrounding watershed, and examples of both animals and plants will be discussed below. However, before discussing any individual species, it is important to understand that changing lake conditions allow new species to establish themselves that might not have previously been able to. Warmer water makes it increasingly easier for AIS to establish themselves in Tahoe.

The best methodology to prevent the spread of AIS is thoroughly cleaning, draining, and drying all gear that touches the water, including boats, kayaks, inflatables, and fishing gear, before it is put into the lake. Boat inspection and vigilance are necessary to avoid AIS spreading around and between water bodies.

The Asian clam (*Corbicula fluminea*) is identified as an AIS that is well-established in Lake Tahoe. First recorded in Lake Tahoe in 2002, Asian clam densities of up to 5,000 individuals per square meter have since been reported, and its range has expanded substantially throughout much of the Lake's southeastern area. Asian clams have continued to spread to the north end of the lake, transported through currents in the lake and other vectors such as boat traffic. The Asian clam often dominates the benthos (aka life on the lake floor), where it occurs in Lake Tahoe. It is associated with, but not necessarily the cause of, filamentous algal blooms and the deposition of clam shells in the nearshore, which is considered a degradation of the aesthetic conditions in Lake Tahoe.

Figure 22. Examples of adult Asian Clams (Corbicula fluminea) (Marion Wittmann, UC Davis TERC, 2012).

Figure 23. Sediment in Marla Bay circa 1980 (Brant Allen, UC Davis TERC).

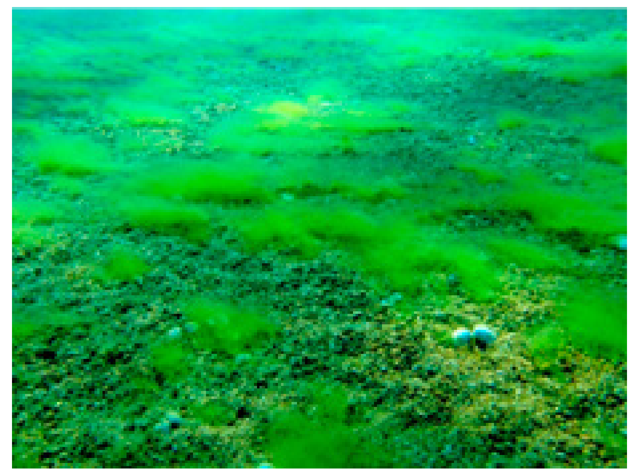


Figure 24. Sediment in Marla Bay circa 2010. Filamentous algae blooms often occur near established populations of Asian clams as a result of excreted nutrients from these animals (Brant Allen, UC Davis TERC).

What Role Does Climate Change Play with Aquatic Invasive Species?

The newest identified species in Lake Tahoe is the New Zealand mudsnail (*Potamopyrgus antipodarum*; NZMS), an AIS well-known for its ability to rapidly spread throughout water systems that were detected in Lake Tahoe in September 2023. In North America, the NZMS was likely introduced in the Great Lakes in the 1990s, and since then, it has rapidly expanded its range to cover most of the Great Lakes region and the American West. NZMS have multiple known ecosystem impacts that may threaten the Lake Tahoe basin. NZMS have the potential of directly affecting the water quality of Lake Tahoe. NZMS can increase nutrient (nitrogen) fixation rates by changing algae communities through grazing behaviors. This change in nutrient dynamics may eventually increase the likelihood of future filamentous algal blooms throughout the lake. Additionally, because of their high biomass (e.g. dense populations), NZMS can intake the majority of gross primary production in streams and dominate nitrogen and carbon cycling through grazing and excretion. NZMS can also be a threat to native macroinvertebrates, such as the native pea clam (Fig. 25) potentially altering the food web in Lake Tahoe.

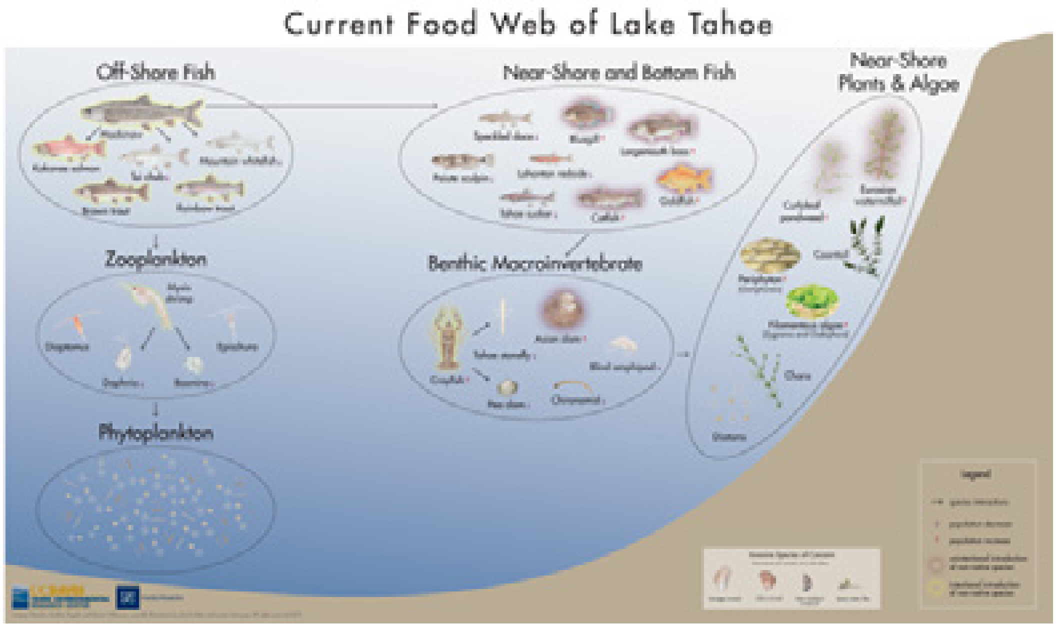


Figure 25. Ecological food web of Lake Tahoe (UC Davis TERC archive) The presence of the NZMS has the potential to disrupt the delicate balance of the established food web, potentially causing long-term and irreparable damage to the lake's ecosystems.

What Role Does Climate Change Play with Aquatic Invasive Species?

Advantageous reproductive cloning strategies allow for the secondary production of NZMS to be exceptionally high. Because they reproduce by cloning, it only takes one NZMS to establish a whole new population, so the species is easily spread and can easily monopolize resources in new waterbodies.

Early detection and monitoring of NZMS is vital for the effective management of populations by water managers (e.g. the Tahoe Regional Planning Agency; TRPA), but available sampling and analysis methods lack the resolution needed to reliably identify their presence in the water. Highly sensitive detection of NZMS environmental DNA (eDNA) from filtered water samples offers a potentially reliable means to detect the species' presence early and simultaneously monitor for other AIS. eDNA encompasses genetic material released into the environment through feces, skin, mucus, and gametes (reproductive cells). Studies utilizing eDNA have demonstrated lower false-negative detection rates compared to traditional survey methods, making it effective for detecting species present in low abundance, such as recently introduced AIS. eDNA is an emerging technique that TERC, in partnership with collaborators across campus, is working on developing the application of at Lake Tahoe.

Figure 26. Full-grown New Zealand mudsnails with a dime to scale, the newest invasive species in Tahoe, was found in the fall of 2023. The tiny species is easily spread on gear and equipment used in infected lakes. It can only take one NZMS to start a new population, so ensuring all equipment that touches the water is cleaned, drained, and dried before going to another water body is crucial to prevent their spread (U.S. Geological Survey).

What Role Does Climate Change Play with Aquatic Invasive Species?

Figure 27. A TERC research diver sampling Curlyleaf pondweed in Lake Tahoe (Brant Allen, UC Davis TERC).

Not all AIS are animals like the Asian clam or the NZMS; instead, they are plants or aquatic invasive weeds. The two most common in Lake Tahoe are Eurasian watermilfoil and Curlyleaf pondweed, which were initially introduced into the Tahoe Keys and have spread to many locations around the lake. Both plants produce dense growth that can crowd out native species, disrupt recreationalists, and increase algae growth. One of the challenges with trying to control these species is their manner of reproduction. For example, the Curlyleaf pondweed undergoes asexual reproduction by producing vegetative shoots called turions. When these turions are established in a new zone, they can seed new plant growth that will quickly colonize an area. Eurasian watermilfoil spreads easily because all it takes is a single fragment of the stem to start a new colony.

Monitoring and rapid response are critical for controlling the spread of these plants. In Emerald Bay, ongoing efforts by the TRPA and its partners are working to control Eurasian watermilfoil through annual diver surveys and rapid treatment and removal as soon as new plant growth is detected. This surveillance and treatment method is costly and labor intensive but necessary as boats can bring in fragments of these plants from other parts of the lake. In the Tahoe Keys, multiple methodologies are being tested to control the population of invasive plants and prevent their spread, including treatment with herbicides and ultraviolet light to kill the plants and deployment of bubble curtains to prevent the spread of turions and stem fragments outside of the marina area. Exploration of all these methods are part of ongoing research and management strategies around the Basin.

How does Climate Change Affect Atmospheric Deposition and Nutrient Levels?

Wildfire season in California and beyond is becoming longer and more intense due to the effects of climate change. As a result, Lake Tahoe is impacted by increased atmospheric deposition of ash and smoke from regional, national, and sometimes international fires. Scientists, including those from UC Davis studying the effects of wildfire on lakes, recently published a paper (https://doi.org/10.1111/gcb.17367) where they explored the effects of atmospheric deposition from wildfire smoke on the physical, chemical, and biological properties of lakes. In this work, they introduced the concept of the 'lake smoke-day,' or the number of days a given lake is exposed to smoke in a fire season, as a metric to evaluate the exposure of water bodies to changing conditions. It was discovered that 98.9% of lakes in North America experienced at least 10 lake smoke days per year during the study period (Fig. 28).

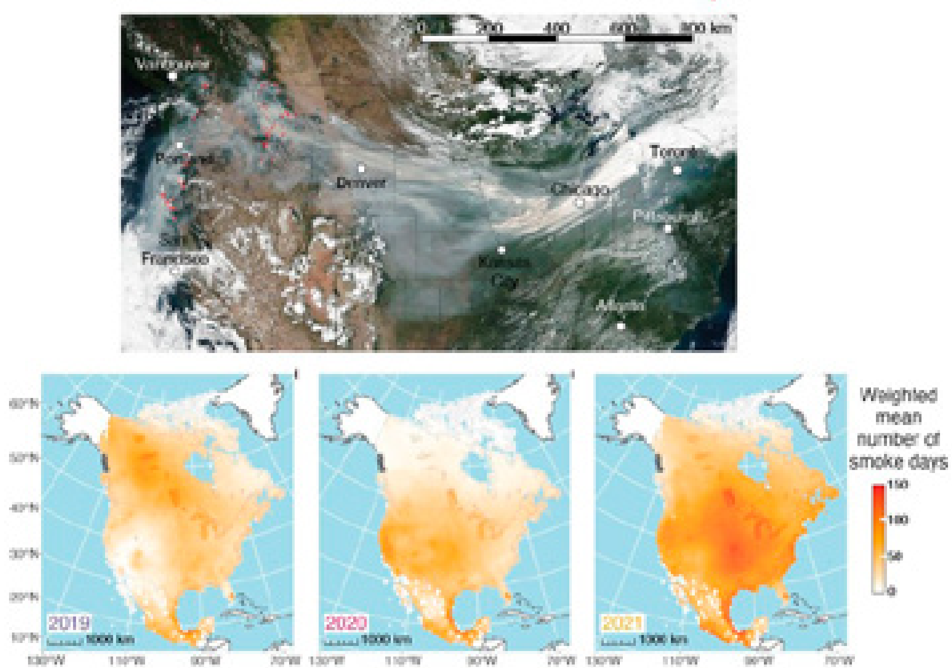


Figure 28. The weighted mean of the number of smoke days experienced across North America for 2019–2021 (Brahney et. al., 2024).

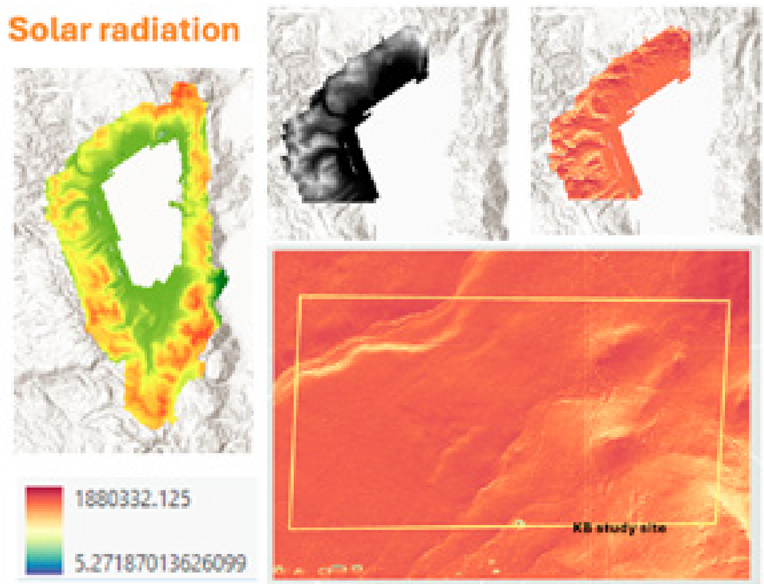
How does Climate Change Affect Atmospheric Deposition and Nutrient Levels?

Many of us recall the recent Caldor Fire (2021), Mosquito Fire (2023), or Royal Fire (2024). Wildfire is part of the reality within the Lake Tahoe watershed. Whether directly in the basin or brought in from afar, the deposition of this ash and smoke causes increases in both phosphorus and nitrogen levels. Research during 2021 and 2022 (Fig. 29), which were impacted by the Caldor and Mosquito fires, respectively, saw phosphorus and nitrogen levels spike at the time of the fires. It is well-established that increased phosphorus and nitrogen levels in Lake Tahoe lead to algae growth and decreased water clarity.

Figure 29. Sampling on Lake Tahoe during the Caldor wildfire event (Shohei Watanabe, UC Davis TERC)

How Does Climate Change Affect Forest Health?

Climate change impacts in the Tahoe Basin are not limited to the lake. The surrounding forest faces pressures from increased temperatures, wildfires, and drought, making the trees more susceptible to pine beetle infestations and fungal pathogens. To combat these trends TERC's Forest and Conservation Biology lab has conducted ecological and genetic studies to develop resilient reforestation strategies for the sugar pine and other 5-needled white pines endemic to the basin. TERC researchers have teamed up with GIS experts and specialists to develop restoration approaches steered by remote sensing technologies and advanced algorithms to develop models to select appropriate microsites for planting locally sourced and diverse seed material to give them the best chance of survival. These integrated approaches can equip land managers with effective adaptive ecosystem restoration tools to respond to extraordinary changes in forested landscapes resulting from climate change, amplify forest resiliency, and facilitate ecosystem recovery.



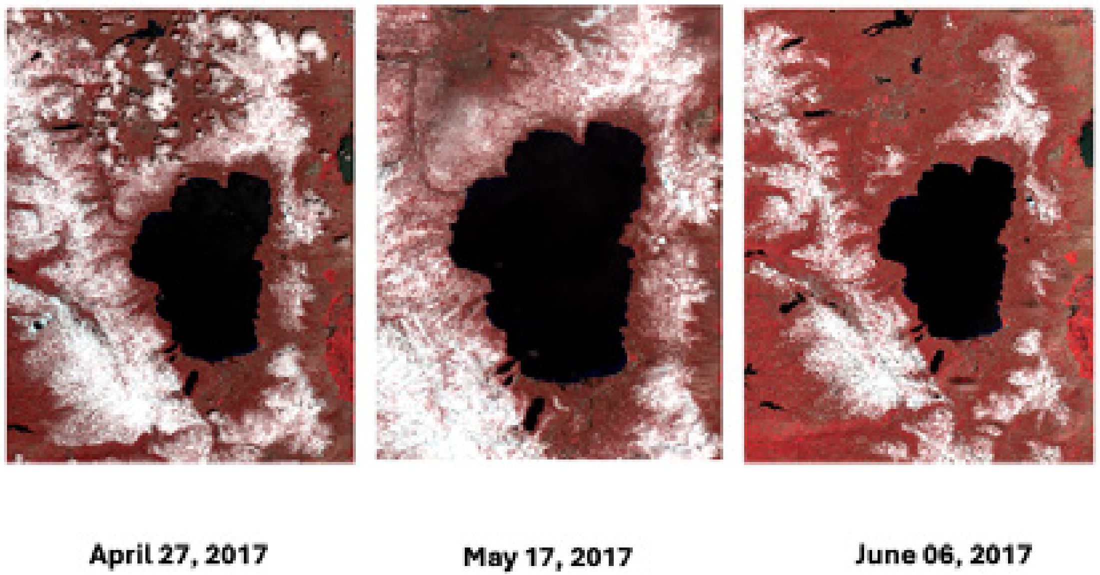


Figure 30. Remote sensing, geospatial data, and mapping products that include solar radiation (left) and late-lying snow (right) (Mui Lay, UC Davis).

How Does Climate Change Affect Forest Health?

This project also establishes a pipeline that recruits and integrates a diverse and equitable workforce into conservation and forest health-related careers by giving California Conservation Corps (CCC) members applied experience in STEM (e.g., restoration, geographic information systems science, plant sciences, and drone technology). Such pipelines are vital to improving our field and training the next generation of forest conservation experts. We will build upon past work and improve project outcomes by strengthening our existing partnership with the CCC, with the goal of fostering a diverse workforce around forestry, restoration, and climate change initiative as we improve restoration strategies. UC Davis and the California Conservation Corps (CCC) are planting trees at Colorado Hill (Monitor Pass area) and Kings Beach on the north shore of Lake Tahoe.

Figure 31. TERC field researcher oversees CCC members planting and watering seedlings at Colorado Hill in the Monitor Pass area (Camille Jensen, UC Davis TERC).

Figure 32. The CCC prepping a planting location in Kings Beach,CA on the north shore of Lake Tahoe (Aaron Vanderpool, UC Davis TERC).

How Does Climate Change Affect Pollinators?

Bees are important pollinators worldwide and in the ecosystems surrounding Lake Tahoe. Dr. Rachel Vannette is Chancellor's Fellow with the UC Davis Department of Entomology and Nematology researching solitary and social bees and their basic biology and life history. The common bees of the Tahoe Basin utilize adaptations to live in this climate including using local flowering plants and specific nesting requirements. Changing management and climate in the Tahoe basin may influence bee-flower interactions. Wildfire and other management practices influence bee communities and their effects on plants.

Dr. Vannette's lab is studying the bacteria and fungi that associate with developing stages of bees. They examine how these microbial communities change as bees develop, and their potential contributions to preservation of bee food (nectar + pollen), bee development, and pathogen protection. There is a great diversity of bee species and not all bee species are social (e.g. living in colonies). Native bees (not honey bees) are most important for maintaining wildflower diversity in Tahoe and some of the bacteria and fungi that live with bees can benefit them and be a source of novel chemistry.

Figure 33. A bumble bee (Bombus) on currant flowers (Rachel Vannette, UC Davis).

Figure 34. A ball of stored pollen that was constructed by a solitary bee (Diadasia) (Rachel Vannette, UC Davis)

Figure 35. A healthy developing larvae in its brood cell, with fungal hyphae lining the cell (S. Christensen, UC Davis).

What New Technologies Can Be Used to Study Climate Change?

One of the strengths of the research at Lake Tahoe is the long-term monitoring observations we've had since 1968. This is one of the longest continuous lake datasets in North America and is required to understand decadal-scale changes in the lake's chemical, biological, and physical conditions.

In an era of rapid technological development, TERC remains at the forefront of developing and applying new technologies to advance our understanding of Lake Tahoe and beyond. In 2020, the Center for Information Technology Research in the Interest of Society (CITRIS) Environmental Robotics Lab @ Tahoe was established. While this group is still relatively small, there is abundant growth potential for collaborations and travel. Core to this initiative has been the use of Autonomous Underwater Vehicles (AUVs) and underwater gliders (Fig. 36). These platforms have been used in Lake Tahoe to understand the dynamics of internal waves (i.e. waves propagating along the thermocline in the lake), aggregation processes of particles, and the horizontal and vertical variability of water quality properties within the lake.

One of the newest technologies funded through philanthropy for work on Lake Tahoe is a new 'wirewalker' system that is planned to be installed in the lake by the end of 2024 (Fig. 37). The principle of operation of this system is that an anchor is tethered to a surface buoy that moves as waves pass by. The resulting wave action causes the positively buoyant profiling platform to winch its way down the line to the specified depth before it releases from the line and profiles back to the surface. The use of wave energy in this way allows for continuous observations throughout the entire water column that will allow TERC researchers to better understand the dynamics of the lake.

Figure 36. TERC PhD student Kenneth Larrieu readying the underwater glider Storm Petrel to study particle dynamics (Sierra Phillips, UC Davis).

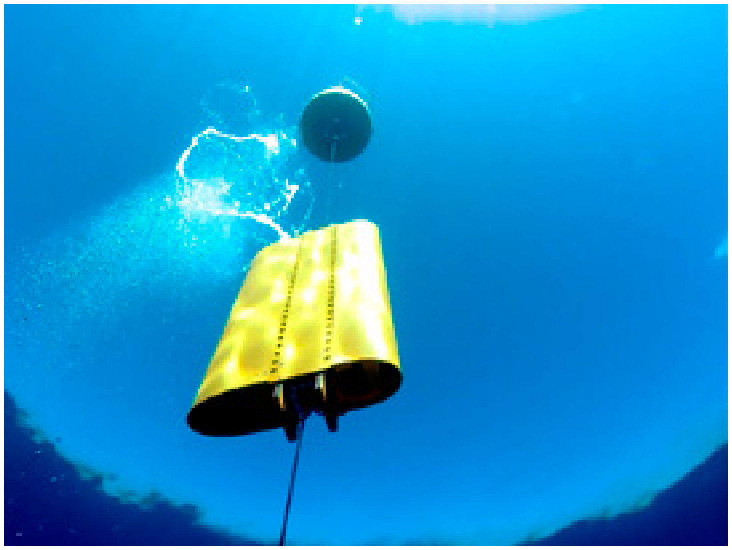


Figure 37. An underwater view of a wirewalker platform mid-profile (Del Mar Oceanographic).

What New Technologies Can Be Used to Study Climate Change?

From new observation platforms in the lake to new instruments in the lab, TERC must constantly innovate how we observe our world. Walter Munk was a physical oceanographer at the Scripps Research Institute who coined the phrase 'a century of undersampling' describing physical oceanography in the 20th century. He went on to say, "Advances in oceanography are dependent basically upon new kinds of instrumentation, the future of our science will be sterile unless we can continually find new things to observe and new ways to measure them." TERC and other scientific research organizations must follow this advice to advance the understanding of how systems, such as Lake Tahoe, are evolving in a changing climate.

Figure 38. TERC scientist Steven Sesma making measurements of water quality aboard the UC Davis research vessel (Steven Sesma, UC Davis TERC).

Figure 39. One of five buoys that calibrate NASA satellites and provide real-time data to the TERC Lake Conditions webpage (Alison Toy, UC Davis TERC).

How Can Lake Tahoe Be Used to Study Climate Change Outside of the Basin?

Studying Climate Change Across the Sierras

Although it is unique, Lake Tahoe is only one of tens of thousands of mountain lakes scattered across the mountains of California. While long term datasets like those collected on Lake Tahoe are vital to answering questions about environmental change through time, understanding how and why ecosystems are changing regionally requires a spatial network of lakes. Two smaller lakes within the Tahoe Basin are part of the California Mountain Lake Network (CaMoLaN), a network of 15 lakes scattered throughout the mountains of California established in 2017 by TERC scientist Dr. Adrianne Smits and Professor Steven Sadro. By selecting lakes that span gradients in size, depth, elevation, and latitude, the network provides a broad regional context in which to explore how climate change and other anthropogenic (human-created) processes affect lakes (Fig. 40).

Every year an undergraduate or graduate student field crew backpacks to each lake, spending 2-3 days sampling water chemistry and downloading data from instruments. Each lake contains a mooring anchored at the deepest location with instruments attached at intervals from the surface to the bottom, measuring temperature, dissolved oxygen, conductivity, light, and lake level. High-frequency monitoring data and short-term experiments from the CaMoLaN network lakes help scientists understand how the effects of climate warming, drought, and smoke from wildfires alter lake thermal dynamics, influence rates of lake productivity, cause algal or periphyton blooms, or affect lake food webs. Data from the network has provided vital information about fundamental lake function during the winter when most of these lakes are covered by 3 to 15 feet of ice and snow and how lake productivity is affected by smoke from wildfires, which can blanket the landscape for months at a time. The CaMoLaN network will help scientists understand the extent to which California's mountain lakes are sensitive to environmental change and help develop a predictive understanding that informs lake management.

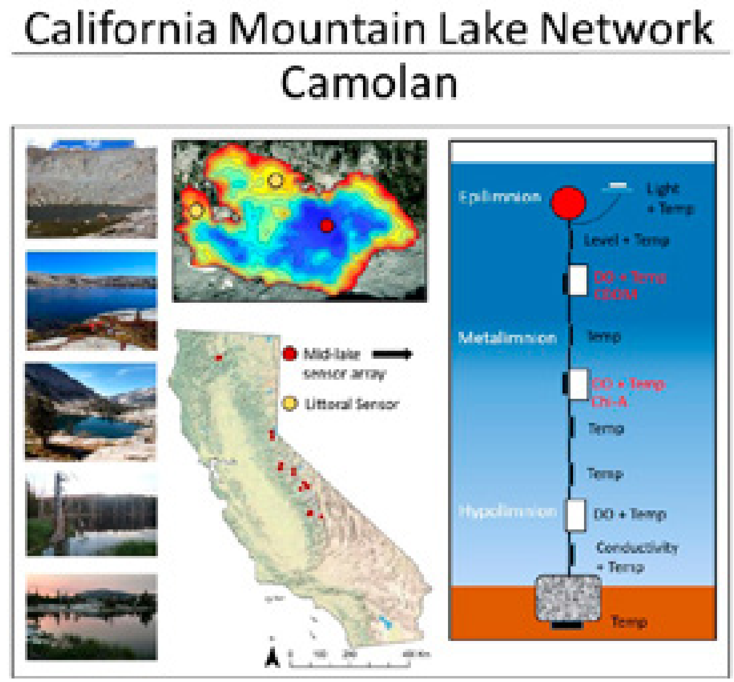


Figure 40. The California Mountain Lake Network provides high-frequency measurements of temperature, oxygen, conductivity, and lake level to characterize fundamental aspects of lake function (Steve Sadro, UC Davis TERC).

Figure 41. Field technician Mike Gomez inflates the research pack-raft before sampling (Steven Sadro, UC Davis TERC).

How Can Lake Tahoe Be Used to Study Climate Change Outside of the Basin?

Studying Climate Change in the Arctic

Lake Tahoe is an amazing natural laboratory to develop tools to study climate change outside of the Basin. Examples of this include collaborations with NASA for work on their Surface Biology and Geology (SBG) mission examining HABs in freshwater systems and the National Oceanic and Atmospheric Association (NOAA) for glider development for work in the Southern Ocean. Since 2016, TERC has been working with the Korean Polar Research Institute and other partners to develop underwater gliders to understand melting rates and stability of ice shelves (Fig. 42) in Antarctica, with several successful deployments in 2017, 2019, and 2022 in the Amundsen and Ross Seas.

Unfortunately, these environments are extremely high-risk. In 2024, after the previous year of preparation in Lake Tahoe, the glider was lost at sea during the deployment at the Thwaites Glacier (sometimes referred to as the Doomsday Glacier because of the potential impact of its melting on sea level rise). While this is a setback for ongoing work, this is the reality of these environments.

Tahoe as a natural laboratory, can be used to develop instrumentation in addition to observation platforms. In 2023, TERC welcomed a postdoctoral scientist from Switzerland who is using new sensors on gliders to understand the role of turbulence. Turbulence control how well things are mixed in the lake on the scale of the smallest organisms within the lake and the aggregation processes controlling the fate of particles. This work has direct application in Lake Tahoe but is also being used to study epishelf lakes (lakes dammed behind ice shelves) in the Canadian High Arctic (Fig. 43).

Figure 42. UC Davis PhD students participated in helicopter surveys of the Thwaites Glacier located in west Antarctica (Kenneth Larrieu, UC Davis TERC).

Figure 43. The frozen surface of the Milne epishelf lake and glacier on Ellesmere Island, Nunavut, Canadian High Arctic (Alex Forrest, UC Davis TERC).

Impacts Beyond Climate: Litter and Microplastics

Lake Tahoe's challenges are not limited to climate. With approximately 55,000 full-time residents and 15 million visitors annually, the lake also faces the impacts of human-generated litter and microplastics.

Since 2014, the nonprofit League to Save Lake Tahoe has been conducting beach cleanups and documenting the materials it collects. In just over 2,000 cleanups on beaches around the Tahoe basin, volunteers have removed 102,507 pounds of litter. Since 2020, the nonprofit Clean Up The Lake, which performs SCUBA-assisted litter cleanups along the shoreline, has removed over 40,000 pounds of litter from beneath Lake Tahoe's surface. In addition to creating a visual blight on the beautiful landscapes of the Tahoe basin, if left in the environment, the litter can breakdown and create negative impacts on the soils and water quality around the lake. While the impacts of litter breakdown on Lake Tahoe have not yet been studied or quantified, it is a cause for concern that needs to be addressed.

Another recently discovered concern for Lake Tahoe and other freshwater lakes around the world is microplastics. Plastic does not decompose. Instead, it breaks down into progressively smaller pieces. When these pieces become less than 5 mm in size, they are classified as microplastics. A recent study conducted by a coalition of researchers discovered that Lake Tahoe has the third-highest amount of microplastics among 38 freshwater reservoirs and lakes around the globe. Research is ongoing into the source and impacts of microplastics so that researchers can make science-informed recommendations to protect the lake in the long-term. Breaking down the composition of the plastic types sampled resulted in observations of three main classes (polyethylene, polypropylene, and polyesters; Fig. 44)

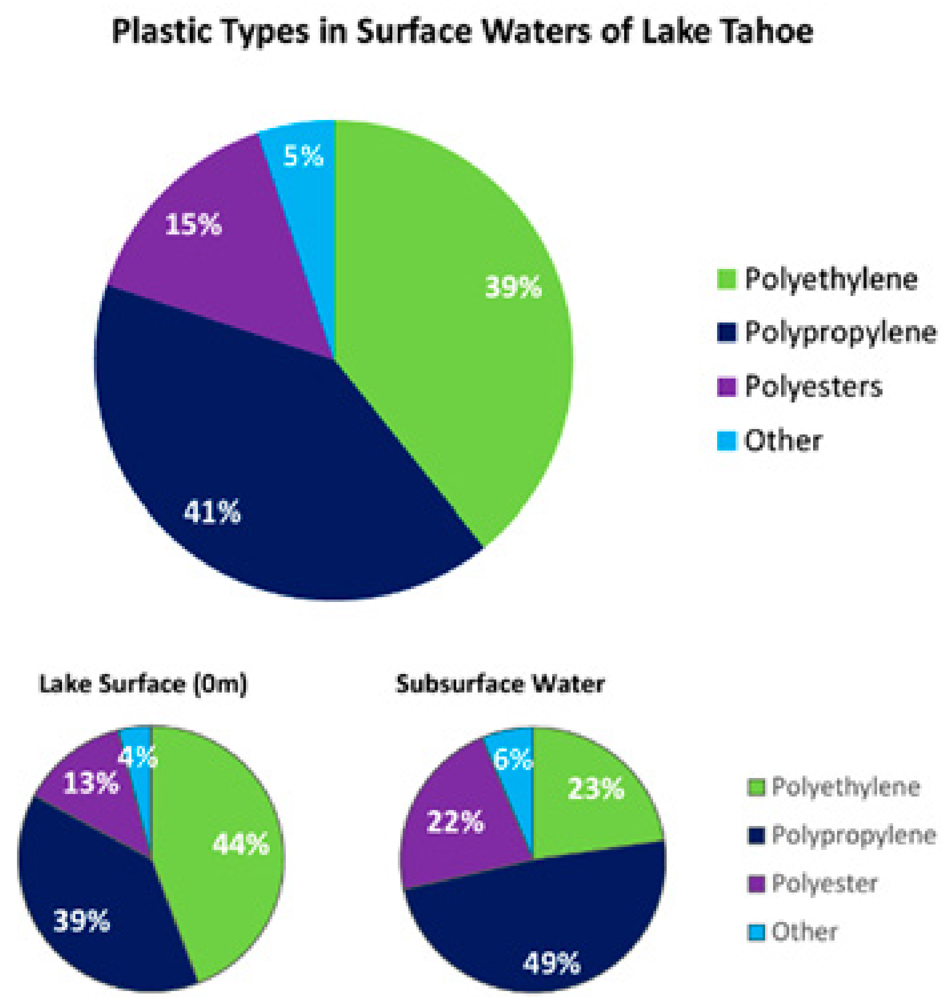


Figure 44. Synthetic polymer (plastic) types of confirmed microplastic particles collected from surface and subsurface waters of Lake Tahoe (Gjeltema et al., 2023).

How Can We Train the Next Generation to Help Mitigate the Impacts of Climate Change?

The Importance of Stewardship Education

Through our education and outreach programs, discussed in the next section, the goal is to provide science-based information about the Lake Tahoe region in order to foster responsible action and stewardship. We provide engaging exhibits, and interactive hands-on educational activities and conduct effective outreach to draw student groups, residents, and visitors to our facilities. Our education programs inspire an interest in environmental sciences, stimulate curiosity, and motivate active conservation and preservation of freshwater resources. We invite broad participation in planetary health solutions by providing evidence-based messaging, exhibits, programs, and other public engagement tools.

In 2023, the UC Davis TERC education team reached 12,988 total visitor contacts through tours, field trips, lectures, and community events. This represents a 46% increase in interactions, and this increasing trend of TERC education is expected to continue with the development of more innovative and exciting exhibits placed in new locations around the basin, including the Tahoe City Visitor Center and Kings Beach Visitor Center.

Science centers, museums, and other public engagement networks are institutions with expertise, community relationships, and platforms for conversations about climate change, biodiversity loss, and pollution. We work to share key messages to support informed, inclusive action that promotes community and planetary health. And our combined voices can be powerful. "Americans who hear others talk about global warming at least once a month have higher levels of perceived collective political efficacy than those who hear others talk about global warming less often – 54% versus 39%," found the Yale Program on Climate Change Communication. Together we can make a difference.

Figure 45. TERC Education team debuts a new extension of the Tahoe Science Center in Tahoe City (Madonna Dunbar, Incline Village General Improvement District).

Figure 46. Education and Outreach Director Heather Segale joins in the excitement of the 2024 Science Expo (Alison Toy, UC Davis TERC).

Figure 47. Summer Intern Meera Putz discusses summer project with TERC education associate Logan Witt (Alison Toy, UC Davis TERC).

There is Hope, and you can Help Mitigate the Impacts of Climate Change

After reading this report, it is easy to be concerned about Lake Tahoe's future. But despite the many challenges, Tahoe is actually in a good position, and TERC scientists are seeing some long-term negative trends begin to reverse.

Resources for Education

The number one thing that anyone who loves the lake and wants to protect it can do is get educated on all the challenges that the lake is facing. To facilitate this, TERC offers a variety of Lake Tahoe-focused education programs for the public, K-12 students, teachers, and other groups. TERC's education programs include:

- Exhibits: Engaging exhibits at the Tahoe Science Center in Incline Village, NV, and Eriksson Education Center in Tahoe City, CA, let individuals get a hands-on understanding of what makes Lake Tahoe unique and highlights the challenges it is facing.
- Outreach: Programs specially designed for student groups, residents, and visitors to the UC Davis Tahoe Science Center
- Tours: Public tours at the UC Davis Tahoe Science Center
- Community events: Lectures and presentations on ongoing research and vital information about the lake and other events like gardening and composting in the basin.
- Field Trips and Workshops: Programs for K-12 students and educators
- Summer Tahoe Teacher Institute: A STEM education program for teachers in partnership with school districts

No time for a visit to TERC? No problem. Sign up to receive TERC newsletters by visiting: https://tahoe.ucdavis.edu/newsletters. These newsletters contain information on TERC research and staff and share the schedule for our TERC talks, which are another great way to find out what is going on with Lake Tahoe.

When residents and visitors educate themselves on the challenges facing Lake Tahoe, they can then educate their friends and neighbors, advocate for the lake in their town, and become protectors of the lake. If all the residents of the Tahoe Basin had the information they needed to become dedicated stewards of the lake, the future would indeed be bright.

Monitored and Studied

TERC's mission is to communicate science-informed solutions to help preserve Lake Tahoe's ecological health and beauty for future generations. As such, TERC has been monitoring Lake Tahoe's health since 1968. This long-term dataset helps researchers understand how the lake's ecosystems function and how they have changed over time. This has allowed TERC researchers to recommend policy changes around the basin and in two states that protect the lake's long-term health. Currently, TERC is adding to this long-term data set by actively monitoring the lake with multiple sensor networks, including:

- Nearshore monitoring networks to track turbidity, algal concentration, and dissolved organic matter concentrations;
- Remote sensing from satellites, aerial drones, and helicopters;
- Autonomous underwater vehicles to collect real-time measurements from around the entire lake; and,
- Installed instrumentation to understand deep lake oxygen dynamics year-round.

All of this work is executed with the purpose of understanding Lake Tahoe so that its beauty can be sustained for future generations to enjoy.

There is Hope, and you can Help Mitigate the Impacts of Climate Change

Collaborations with Scientists and Policy Makers

TERC is not the only group of researchers working to understand and protect the lake. UC Davis works with researchers from other scientific organizations, such as the University of Nevada at Reno and the Desert Research Institute, in part through the Tahoe Science Advisory Council (TSAC).

The Tahoe Science Advisory Council was established in 2015 by a memorandum of understanding (MOU) between the States of California and Nevada. The Council is an independent group of scientists who work collaboratively to advise policymakers to promote, enhance, and maintain the ecological integrity of Lake Tahoe and its watershed. The Council utilizes the best available scientific information on matters of interest to both the states to preserve Lake Tahoe. By bringing together representatives from academic institutions and government agencies tasked with protecting the environment, the Council aims to leverage efforts and maximize resources, streamline and bridge research and restoration activities from watershed to lake.

Collaborations with Citizen Scientists

The Tahoe Basin is a large geographic area with diverse and complex ecosystems that need to be monitored. Even the largest research teams have difficulty covering the entire area and certainly can't do it 24-7. This is why contributions from Citizen Scientists are so valuable. It might seem intimidating but all you need to do is visit citizensciencetahoe.org and select the survey you wish to complete, and you will be guided on how to submit your observations straight to TERC. Citizen Scientists can report observations on algae, invasive species, litter, water quality, and ashfall from wildfires. By increasing the number of observations of these issues all around the lake, residents and visitors can play an active role in protecting the lake.

Citizen Science Tahoe was developed by the UC Davis Tahoe Environmental Research Center (TERC) in collaboration with the Desert Research Institute (DRI) and League to Save Lake Tahoe (Keep Tahoe Blue).

If that is not enough for our engaged residents, TERC welcomes you to become a volunteer docent at the Tahoe Environmental Research Center's Education Center in Incline Village. Volunteer docents are trained to share information about what makes Lake Tahoe unique, environmental issues, how science and research are used to better understand them, and what can be done to protect and preserve our beautiful lake.

Reversing Negative Trends

Though the clarity story is complicated, the fact that water clarity in the winter is improving shows that actions taken to limit the input of fine sediment particles and nutrients are working. The investments made in roadway improvements, erosion controls, and watershed restoration are having a positive effect on the lake. This shows that policies informed by science and research can protect the lake in the long-term.

Actions you can take from anywhere - Donate to Fund our Research

TERC's advancements and achievements are possible because a community of philanthropically minded individuals is committed to making a difference in Lake Tahoe's future. Their vision and generosity support a world-class center for research and education. Private support is essential to continuing TERC's groundbreaking work to restore and sustain Lake Tahoe for future generations. Donations support TERC's research and monitoring efforts, education and outreach programs, undergraduate and graduate students, and the capital projects that make real-time monitoring of the lake possible.

On climate, our goal isn't to have the world paralyzed by anxiety but rather galvanized for action. And for that, we need hope; not false hope that all will be well (it won't be, if we don't act) but hope based on the conviction that if we do something, it WILL make a difference.

- Katharine Hayhoe, Nature Conservancy

Figure 48. Sunrise from Cascade Falls over Emerald Bay (Brant Allen, UC Davis TERC).