2021 Annual Research Update for the Blue Ribbon Committee

UC Davis Tahoe Environmental Research Center

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1. Barriers to Improving Water Quality at Clear Lake

Clear Lake faces numerous water quality challenges, but the greatest barrier to improvement is the absence of quantitative data on the response of the system to investments in specific restoration projects. Acquiring quantitative data requires completing four fundamental tasks:

1) Quantifying the processes that contribute to poor water quality, i.e. data collection;
2) Accurately predicting the lake response to environmental forcings, including the extent of the current water quality challenges, i.e. model development;
3) Quantitatively evaluating the impacts, the costs, and unintended consequences of implementing particular restoration projects or strategies, i.e. scenario development; and,
4) Quantitatively evaluating the consequences and costs of the "no action" alternative, with the inclusion of the likely impacts of climate change, i.e. future forecasting.

Past research, together with the experiences of residents and stakeholders at Clear Lake, has made it possible to identify many of the challenges facing the lake that these four tasks will address. These challenges include:

- *Increasing Water Temperatures* - Lake water temperatures are increasing globally, and is likely the case at Clear Lake, too. Aside from the direct effect of higher temperatures on community composition, ecosystem metabolic rates, and biogeochemical reaction rates, the most important consequence of this is expected to be an increase in the duration of periods of thermal stratification. Mixing or turnover events may be less effective and frequent. This trend cannot be prevented by local action as it is happening on a regional scale, but all planning needs to explicitly take this into account.

- *Extended Periods of Anoxia* - Low dissolved oxygen (DO) events in the deep water are known to occur episodically, producing fish kills, the release of nutrients through a phenomenon known as "internal loading", the release of heavy metals including mercury to the food web, and the formation of noxious odors. With climate warming, there are likely to be more extended periods of low DO, with a corresponding increase in water quality degradation. There are engineering solutions to addressing low DO, but the extent of the problem needs to be quantified to make these solutions feasible and cost-effective.

- *Climatic Eutrophication* - High concentrations and loading of nutrients (nitrogen and phosphorus) fuel eutrophication and contribute to cyanobacterial blooms. External loading can be increased by agricultural fertilizer addition, grazing, erosion due to poor land management or wildfire, increases in impervious land cover due to population growth, destruction of wetlands, etc. Internal loading is caused by low DO in the lake. Quantifying the sources of nutrients, their seasonal variability, and partitioning the loading rates (both internal and external) are key to selecting the most appropriate solutions to address eutrophication in Clear Lake.

- *Increased Frequency of Harmful Algal Blooms* - Harmful algal blooms and the prevalence of cyanotoxins are dependent in part on many of the other water quality problems listed above. Increasing frequency, biomass, duration, and distribution of both algal blooms and *cyanobacterial* blooms remain critical problems. Cyanobacterial blooms create risks to human and animal health, increase the costs for water treatment, contribute to a negative perception of the region leading to losses in tourism, property values, and business. Factors that may favor the cyanobacterial dominance include:

    - Episodic low DO events in the deep waters, leading to nutrient release and alterations in the food web;

    - Increased nutrient inputs from the watershed; and,

    - Rising water temperatures.

  The first two factors lend themselves to several restoration projects. Warming temperatures need to be accounted for in the design of these projects.

- *Elevated Mercury Levels* - High mercury levels due to both the watershed inputs, the existing sediment load, and potentially ongoing supply input from the Sulphur Bank mercury mine.

Understanding the mercury cycle in the lake is currently an active area of research at Clear Lake by the USGS. There is a range of engineering options for controlling mercury release to the water and the food web.

- *Ecosystem Shifts* - Shift between a *clear state with macrophyte dominance* and *turbid phytoplankton-dominated state*. Native macrophytes stabilize clear-water conditions by reducing resuspension, increasing sedimentation, providing habitat for fish, and suppressing phytoplankton growth (nutrient competition). When the nutrient concentrations in the water are very high, the submerged and emergent native vegetation can be lost and the turbidity of the water increases. As a result, the buffering capacity of the ecosystem to external stressors is reduced. The current state of Clear Lake waters based on the limnological parameters is being assessed.
- *Increasing exposure of lakes to wildfires* – Increasing wildfire activity has dramatically increased in the last years in the Clear Lake watershed, including increases in fire season length and area burned. Very few studies assess wildfire effects in freshwater bodies. Recent efforts have been focused on developing a framework of how wildfires may influence the physical, chemical, and biological properties of aquatic ecosystems such as Clear Lake.

2. Threats to the Wildlife at Clear Lake

The threats to wildlife are intimately linked to the water quality condition of the lake. While some of the threats may be independent of the eutrophic status of the lake, a better understanding of the relations between watershed and lake processes will be essential when addressing these and other threats. Some of the threats include:

- Tule perch loss due to herbicide use;
- Episodic low DO, pH, and NH_3-NH_4, which may cause fish kills;
- Extensive periods of "fish habitat compression", occurring when low DO deep waters and high surface temperatures reduce the fish habitat;
- The dominance of non-native fish and other aquatic invasive species, which may modify nutrient cycling, cause habitat loss and be more dominant in the food chain as compared to non-native species;
- Native fish such as Clear Lake hitch (*Lavinia exilicuada*) loss due to multiple stressors, including loss of spawning habitat, water diversions, and barriers to passage; and,
- The introduction of new aquatic invasive species such as Quagga mussels. While Quagga mussels are not currently in the lake, and all efforts are being taken to prevent their establishment in the lake, the change in a broad suite of factors tends to increasingly disadvantage native species while at the same time creating niches for species that may previously not have survived in Clear Lake.

3. UC Davis TERC Accomplishments in 2021

3.1. Continued data collection for lake, meteorology, and streams

We continued the high-resolution data acquisition for (1) stream properties at three locations (Middle, Scott, and Kelsey Creeks), (2) meteorological data at seven locations around the perimeter of the lake, and (3) lake temperature and dissolved oxygen at multiple depths and locations across the lake (six permanent water quality stations). In addition, we made measurements of particle size in the water during each of the routine monitoring events as part of our ongoing research on the impact of wildfire smoke on lakes. We also measured nutrient concentrations throughout the water column and across all three lake basins during seven sampling events in 2021. The water samples were analyzed for dissolved and particulate forms of nitrogen, phosphorus, and carbon; chlorophyll; and particle size distribution. The field effort was led by graduate students Micah Swann, Ruth Thirkill, Samantha Sharp, and Kanarat Pinkanjananavee, together with assistance from undergraduate students. The laboratory chemical analysis was led by Anne Liston, Steven Sesma, Lindsay Vaughn, and Tina Hammel, with assistance from graduate and undergraduate students. All of these data are critical for the ongoing development of the numerical models of physical transport and lake production and in better understanding the range of solutions that may be applied in the future. Samples were also collected for phytoplankton identification and quantification and zooplankton identification. The latter have been preserved and will be analyzed if funds become available. Water samples were also collected for the Big Valley Band of Pomo Indians for their cyanobacteria monitoring program. In the last three months of 2021 data collection has been particularly challenging due to the unprecedented low lake levels and the difficulties this presents in launching research vessels. We are particularly grateful for the assistance provided by Lake County.

We also continue our collaboration with the US Geological Survey (USGS) to find a surrogate for mercury that can be monitored continuously using high-resolution sensors, such as the YSI-EXO probes. These instruments have been installed since spring 2020 in our permanent water quality station in the Oaks Arm to develop regressions between time series of chromophoric dissolved organic matter (CDOM) and mercury.

All data are publicly available via the following website: https://terc-clearlake.wixsite.com/cldashboard. This website also includes a brief description of our field monitoring plan, displays data interactively, shows field observation animations, stores photos and publications, and posts updates on a blog.

3.2. Watershed monitoring: USGS-TERC-Lake County

In addition to the in-lake monitoring, we are collaborating with USGS and Lake County to conduct a 3-year upper watershed monitoring study as part of the 2021 BRC-recommended funding. Data collection successfully commenced in fall 2021. Flow permitting, we are planning to sample up to 15 tributaries (natural creeks and culverts) up to 12 times a year. USGS and DWR will be responsible for the sampling. The analytical constituents will vary depending on the sample, but they can be filtered and unfiltered nutrients (N and P), mercury species, and metals. Analyses will be run both at USGS and TERC's labs.

3.3. Interactions with Clear Lake tribes and stakeholders

Interactions with Clear Lake tribes and other stakeholders continue to be a high priority. In 2021, in addition to the previously mentioned cyanobacteria sample collection, we have interacted with Big Valley Rancheria and their consultants to provide advice for the installation of real-time sensors for the monitoring of in-lake dissolved oxygen required for their fish kill project. We have also offered to train tribal members to be able to work with us on ongoing data collection. We are working with Lake County to set up a filtering station for the stream water samples collected during the watershed monitoring program. Our graduate student Kanarat Pinkanjananavee is collaborating with Buckingham Park Water District to analyze disinfection by-products. Geoff Schladow has been collaborating with Clear Lake tribe members and other stakeholders on the goals for future education programs.

3.4. Quantifying external and internal phosphorus loading in Clear Lake

Fueled by excessive nutrient concentrations, principally phosphorus (P), harmful cyanobacteria blooms (HABs) occur across much of Clear Lake during the summer and fall each year. Phosphorus is derived from both external sources (i.e., runoff from agricultural and urban areas conveyed into the lake via streamflows and urban flows) and internal sources (i.e., recycling of legacy phosphorus pools released from lake sediments). Internal loading of phosphorus can be caused by anoxic conditions in the sediment, benthic bioturbation, and mechanical resuspension. While significant mitigation and restoration efforts have been implemented to reduce external, watershed inputs of P, limiting the contribution of internal loading has received far less attention. To investigate the timing and relative contribution of each loading source to the lake's phosphorus budget, our graduate student Micah Swann has quantified external and internal phosphorus loads to Clear Lake for a two-year period (2019-2020).

Watershed phosphorus loads were calculated utilizing streamflow data and stream-specific linear regressions relating discharge to total phosphorus (TP) concentration. Integrating over a stream's hydrograph, a total mass of phosphorus loaded into the lake from each stream was quantified and then a cumulative load from all sub-watersheds was estimated. Internal phosphorus loading was calculated using two different methods. Anoxic and oxic sediment P release rates were quantified by laboratory chamber experiments while the spatial and temporal extent of anoxia was measured by moored hypolimnion dissolved oxygen sensors throughout Clear Lake's three arms.

A preliminary whole-lake mass balance for 2019-2020, depicting monthly estimates of external and internal loads, is shown in Figure 1. In both years, the cumulative external load from the previous water year (~183 tons in 2019 and 20.5 tons in 2020) was significantly smaller than the net observed internal load, 384 and 616 tons in 2019 and 2020 respectively and thus internal recycling of phosphorus accounted for 75-95% of the annual phosphorus load during the period, with the relative magnitude of internal loading increasing dramatically under drought conditions. The magnitude of the internal load highlights the need to focus restoration strategies on mitigating internal sources in addition to controlling watershed inputs.

Modeled internal loads released via diffusion from anoxic sediments closely agreed with the observed increase in water column TP in the lake's two deeper arms (Oaks and Lower). However, in the large and shallow Upper Arm, theoretical estimates significantly unpredicted the observed increase of TP. The discrepancy between observed and theoretical internal P load estimates in the

Upper Arm is a current research focus. This research highlights that while external load reductions are necessary to rehabilitate lake water quality in the long term, understanding the mechanisms and timing of internal loading will be necessary to effectively manage Clear Lake in the future.

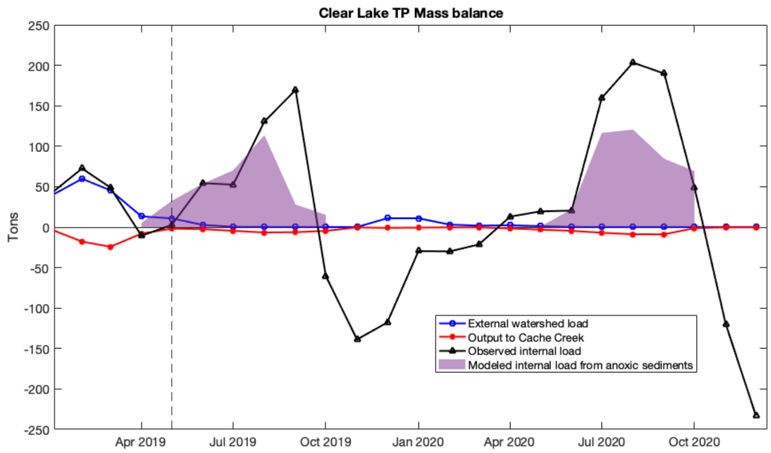

Figure 1 – Total phosphorus mass balance for Clear Lake (2019-2020). Dashed vertical line indicates the start of the UC Davis Lake monitoring program.

3.5. Measurement of cyanobacteria blooms

We have continued our efforts to measure cyanobacteria blooms in Clear Lake using a variety of remote sensing methods. The work from the 2019 study was published this past year in Frontiers in Environmental Science by our graduate student Samantha Sharp (https://www.frontiersin.org/articles/10.3389/fenvs.2021.612934/full). This work included the measurement of cyanobacteria blooms in Clear Lake across scales of multiplatform remote sensing tools. These tools included measurement by discrete sampling, autonomous underwater vehicles (AUV), unmanned aerial vehicles (UAV) or drones, and satellite-based sampling and calculation of the Cyanobacteria Index (CI). Sampling across scales allowed us to gain a synoptic view of the cyanobacteria bloom and quantify its spatial variability (Figure 2). We identified two shortcomings of these methods in this study: (1) daytime fluorometer measurements (such as those on the AUV) are impacted by a process known as non-photochemical quenching (NPQ), and (2) a limitation of the CI remote sensing algorithm is that it tells you a relative abundance of cyanobacteria and not the specific species present and whether those species are toxin-producing cyanobacteria.

These are the focus of two new research efforts commenced in 2021 by Samantha Sharp, through her graduate student fellowship with NASA.

1. The first project will develop a correction method for NPQ-impacts to fluorometer measurements. This project includes data collection at Clear Lake and Lake Tahoe to develop a correction method based on solar radiation.
2. The second project is to evaluate the use of hyperspectral data to determine cyanobacteria bloom types based on the dominant species present. Hyperspectral data is a measurement of reflectance across hundreds of wavelengths, which contrasts to the tens of wavelengths measured by multispectral sensors, such as the OLCI sensor on Sentinel-3 used in the CI algorithm. Hyperspectral data is currently not readily available. However, there are satellite missions planned for the near future that would collect routine hyperspectral data, such as

NASA's Surface, Biology, and Geology (SBG, https://sbg.jpl.nasa.gov/) mission. For this project, we are collecting routine boat-based hyperspectral measurements during our water quality monitoring program, similar to those that will be measured in future satellite missions. This data will be analyzed along with concurrent data characterizing the cyanobacteria bloom type to determine a method to identify the dominant species present from hyperspectral data.

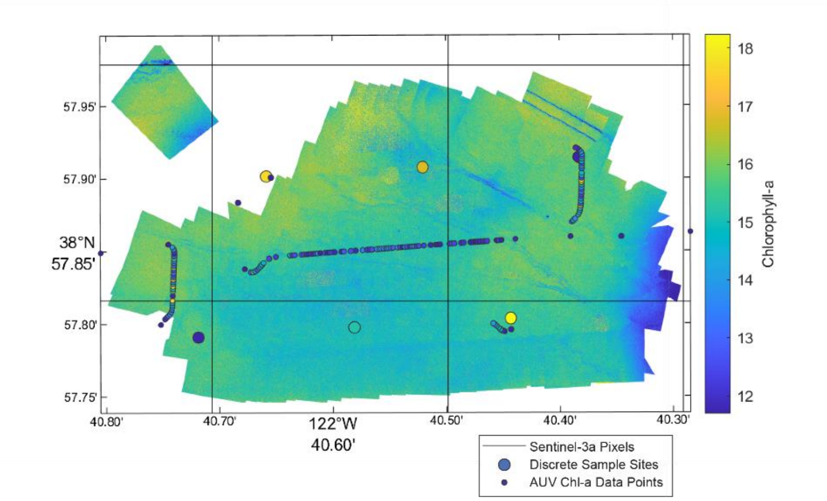

Figure 2. Multiplatform remote sensing measurements of cyanobacteria blooms in the Lower Arm, Clear Lake on August 16, 2019. UAV-derived chlorophyll-a show as background image with discrete sample and AUV measurements. Sentinel-3 satellite pixel outlines are also shown.

3.6. Developing in-situ cyanobacteria sensors and studying the impacts on treated water during HABs

Graduate student Kanarat Pinkanjananavee is leading two applied projects related to HABs:

1- *Development of in-situ cyanobacteria sensor: In situ* monitoring of HABs is limited by the high cost. This has prompted the need for the development of a low-cost *in situ* cyanobacteria sensor. The sensor is developed using the Arduino Mega as the mainboard for computing and software development, a Hamamatsu C12880MA mini spectrophotometer, and a 250nm UV-LED for the cyanobacteria excitation as shown in

2- .

The software development of the sensor itself is now completed, and trial deployments are planned at Clear Lake.

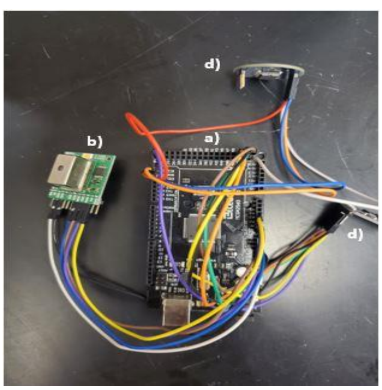

Figure 3. In situ cyanobacteria sensor hardware a) Arduino MEGA b) Hamamatsu C12880-MA spectrophotometer c) ChronoDot RTC d) SD card reader

3- *A plant-scale study on the potential impacts on treated water quality of recycling dewatered sludge supernatant during HABs:* Although the conventional treatment method of coagulation-flocculation and sedimentation is considered effective in removing cyanobacteria cells, the process only neutralizes the charges on the surface of the cells but does not deactivate cellular functions. Thus, cells that were not removed by the sedimentation could repopulate in downstream filtration media and negatively impact treated water quality when the water is recycled in the treatment process. The goal of this study is to investigate the possible effects of cyanobacteria blooms and the recycling of dewatered supernatant during bloom conditions.

The sampling site of this research is at the Buckingham Park Water District (BPWD), which is one of the better-instrumented drinking water treatment plants using the water from Clear Lake. The samples collected from the plant were analyzed for the disinfection by-products (DBPs), cyanotoxins, and species identification and quantification with qPCR. The results for the DBPs are shown in

Figure . Our results show the treatment system of BPWD was able to remove the DBPs that were created through the elimination of cyanobacteria from the final drinking water produced out of the treatment plant.

The water quality analysis for this project is still ongoing every month. Also, a 48-hour experiment to investigate the effects of the recycling process is planned for Winter 2022.

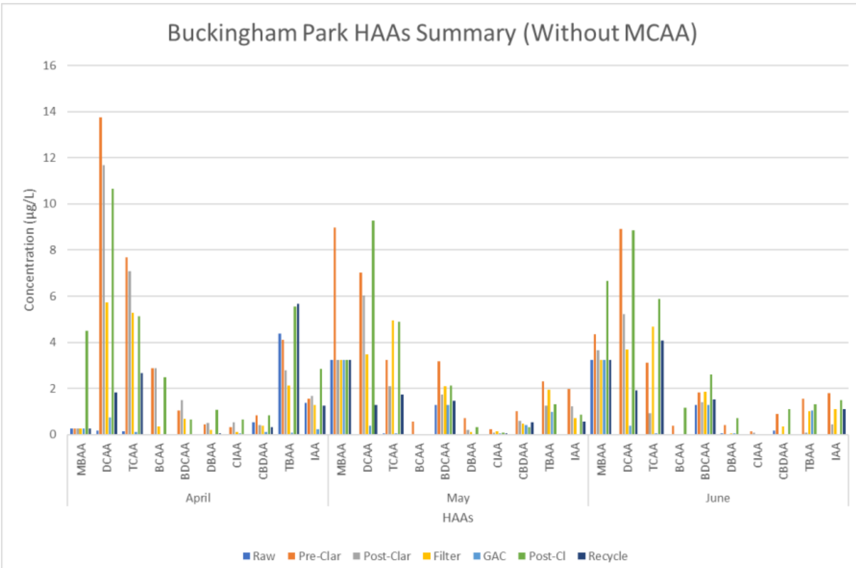

Figure 4. Comparison of HAAs concentration between samples with preservatives and samples without preservative (No NH_4 label)

3.7. Trends in nitrogen and phosphorus across the decades in Clear Lake

In 2006, the Central Valley Regional Water Quality Control Board (CVRWQCB) implemented a phosphorus Total Maximum Daily Load (TMDL) to decrease the nutrient load into the lake as a treatment method towards reducing the occurrence of HABs. Winder et al. (2010) analyzed water quality parameters in addition to biological variables to develop a conceptual model to account for the long-term behavior of Clear Lake. Graduate student Ruth Thirkill has produced an updated version of this data report looking at the entire period when data are available (1970 through 2021).

The data analysis revealed high interannual variability. The nitrogen variables showed a general downward trend across the entire historical record whereas phosphorus values had increasing trends. For the period 2000-2021 dissolved Kjeldahl nitrogen (DKN), nitrate, and nitrite concentrations either trended upwards or had no trend for the first ten years and trended downwards for the second ten years. Ammonium, by contrast, continued to rise over both decades though at a decreasing rate from 2011 to 2021 (Table 1).

The historical analysis of nitrogen and phosphorus data from Clear Lake indicates that the lake continues to suffer from excessive phosphorus loading even though the TMDL has required a reduction in external inputs.

Table 1. Trend direction of depth-averaged concentration for each arm and the whole lake during the period of record, as well as the statistical significance of each trend. Downward trends are indicated by a negative number and upward trends by a positive number. Significance of trends shown by color (see bottom of table for color description). [NO3+NO2, nitrate and nitrite concentration; NH4, ammonium concentration; DKN, dissolved Kjedahl nitrogen concentration; SRP, orthophosphate concentration; TP, total phosphorus concentration; NT, no statistically significant trend.]

Analyte	Lower Arm	Oaks Arm	Upper Arm	Whole Lake
NO3+NO2 1970 – 2021	0.08	-0.12	-0.17	**NT**
NO3+NO2 2000 – 2010	NT	NT	0.24	**0.13**
NO3+NO2 2011 – 2021	NT	NT	-0.27	**-0.16**
NH4 1970 – 2021	-0.12	-0.07	-0.07	**0.07**
NH4 2000 – 2010	0.42	0.30	NT	**0.28**
NH4 2011 – 2021	NT	0.15	0.20	**0.11**
DKN 1970 – 2021	-0.34	-0.28	-0.20	**-0.24**
DKN 2000 – 2010	NT	NT	NT	**NT**
DKN 2011 – 2021	-0.32	-0.33	0.11	**-0.18**
SRP 1970 – 2021	0.30	0.27	0.27	**0.39**
SRP 2000 – 2010	0.46	0.44	0.38	**0.50**
SRP 2011 – 2021	0.17	NT	NT	**NT**
TP 1970 – 2021	0.20	0.20	0.14	**0.25**
TP 2000 – 2010	0.16	0.18	0.19	**0.23**
TP 2011 - 2021	0.16	NT	NT	**NT**

Range of p-values	Color	Color Explanation
p < 0.01	(yellow)	Highly Significant
0.01 < p < 0.05	(blue)	Significant
0.05 < p < 0.1	(green)	Marginally Significant

3.8. Numerical modeling: Fully calibrated and validated hydrodynamic model. Water quality model under development

The field and laboratory measurements are essential to build, calibrate, and validate a three-dimensional (3-D) numerical lake model. The processes the model simulates are organized into two groups: those that characterize how the water moves (i.e. *hydrodynamic*) and those that modify nutrients and algae in the lake (i.e. *water quality*). In 2021 we completed the calibration and validation of the hydrodynamic model. Root mean square errors for temperature are less than 1°C between modeled and observed lake temperatures for a two-year simulation in all Clear Lake basins (Figure 5).

We are concurrently developing a water quality or biogeochemical model to simulate the evolution of different constituents, such as dissolved oxygen, nitrogen species, phosphorus species, phytoplankton, and suspended solids. This model will include cyanobacteria as one of the phytoplankton groups. This module needs the same type of calibration/ validation described for the hydrodynamic module. We are planning to complete this task in 2022.

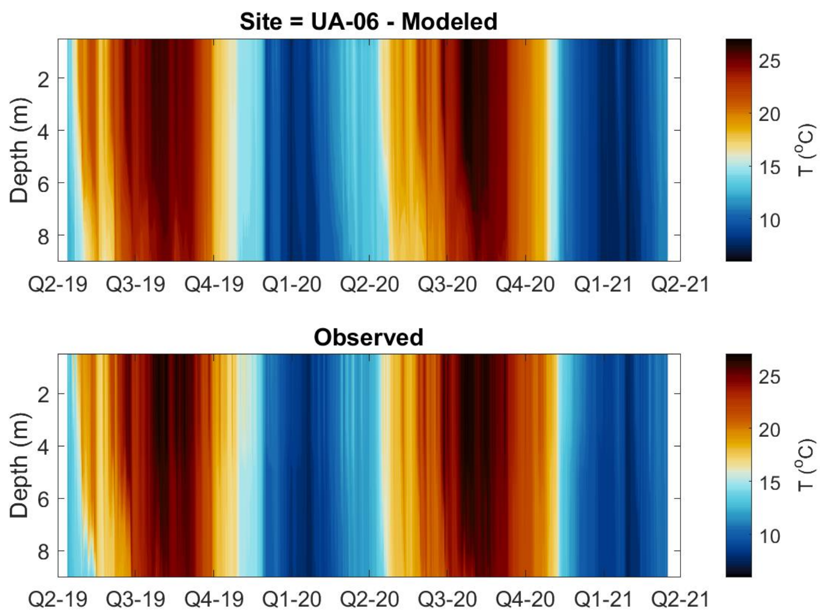

Figure 5. Comparison of modeled (top) and observed (bottom) lake water temperatures between spring 2019 and spring 2021 in the Upper Arm (UA-06)

4. UC Davis TERC Next Steps in 2022

In 2022 we will continue with the monitoring of the lake and the watershed as detailed in the Scope of Work with the California Natural Resources Agency. In addition, we will undertake the following:

4.1. Bathymetry survey

Existing bathymetric data lack the horizontal and vertical spatial resolution necessary to drive our hydrodynamic models, posing a severe constraint on predictive in-lake modeling. A new lake bathymetric survey will be conducted in 2022 and include a combined bathymetry and side-scan sonar survey of all three arms of the lake. This work would have commenced in 2021, but low lake levels prevented the launching of the research boat after September. A new project technician has been hired for this project and is set to start early in the new year.

We are collaborating with the USGS Volcanology Center to use the bathymetric data to better understand volcanic formations that are believed to exist below the lake's surface. This work will be focused on Soda Bay. The USGS is providing additional funding for the bathymetry survey to allow this work to proceed.

4.2. Modeling: Scenario development

Once the 3-D numerical model reproduces previous lake conditions, we will use it to better understand the physical and biogeochemical processes occurring within Clear Lake. The model will be used to explore future management scenarios and to evaluate the effects of different restoration projects on the water quality challenges of Clear Lake. These could include:

- Model exploration of DO enhancement techniques. For example, testing the use of hypolimnetic oxygenation and identifying the location in the lake where we should install this system to mitigate cyanobacteria blooms.
- Model exploration of the fate of stream and culvert loads
- Model controls on cyanobacteria: We are aiming to model the onset, duration, location of the blooms and their movement due to lake currents.
- Model climate change impacts
- Model sediment capping

4.3. Modeling: Daily hazard assessment and lake conditions

Models can be used to provide daily assessments of hazards and lake conditions for the public, lake managers, and a broad range of stakeholders. Examples of how such a tool could be used include:

- Daily forecast of lake temperatures, dissolved oxygen, and currents
- Daily forecast of HAB hotspots across the lake to provide warnings to water companies and the recreational public
- Forecast of areas with high fish-kill potential
- Providing data on the spread, concentration, and breakdown of accidental toxic releases to the lake

4.4. New collaboration with the University of Southern California, USC (Biology department)

Recent conversations between TERC and USC have led to a commitment to work together in 2022 to understand the succession of the cyanobacteria blooms in Clear Lake. That will inform TERC's 3-D transport and water quality model. TERC has also offered the possibility of collecting water samples for USC metagenomics analyses in 2022. Both groups are working to identify periods when multiple platforms were measuring data to help us understand the succession of cyanobacteria blooms in Clear Lake.

4.5. Link 3-D model to mercury model (USGS)

We have been in discussions with the USGS to collaborate on the implementation of a mercury module in the 3-D lake model. Such an addition will provide projections of mercury levels throughout the lake and would be the basis of developing a complete food web model for predicting mercury levels (and other contaminants) in fish. This work is subject to the availability of federal funding (EPA).

4.6. On-going project about wildfire smoke impacts

In fall 2020, TERC was awarded an NSF RAPID grant to measure the impacts of wildfire smoke and particulates on the productivity of lakes in the western US. During the numerous and large wildfires that occurred in our region in 2021, we have continued our post-fire sampling to investigate the smoke impacts in Clear Lake and other lakes such as Lake Tahoe affected by the wildfires.

4.7. Design of a hypolimnetic oxygenation pilot project

Depending on the confirmation with modeling, the use of hypolimnetic oxygenation is considered to be one of the more likely rehabilitation strategies. This is a capital-intensive investment and one that should be preceded by a pilot-scale project. In 2022, using the validated model, we will scope out a pilot-scale project.