Scientific Studies Toward the Restoration of Clear Lake:

2020 Annual Report of the UC Davis Tahoe Environmental Research Center

Geoffrey Schladow, Alexander Forrest, Steven Sadro, Alicia Cortes, Micah Swann and Ruth Thirkill

November, 2020

1. Barriers to Improving Water Quality at Clear Lake

While lists of water quality challenges can be readily compiled, 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 projects and 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 include:

- *Lake water temperatures* are increasing globally, and is likely the case at Clear Lake too. Aside from the direct effect of higher temperatures on metabolic and 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.
- Episodic *low dissolved oxygen* (DO) events in the deep water are known to occur, producing fish kills, release of nutrients through a phenomenon known as "internal loading", 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 in order to make these solutions feasible and cost-effective.
- Identifying the relative contribution of *nutrient inputs* (both phosphorus and nitrogen, P and N) through both external and internal loading. 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 Clear Lake's eutrophication problem.
- Increasing frequency, biomass, duration and distribution of both algal blooms and *cyanobacterial* blooms. 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 a number of restoration projects. Warming temperatures need to be accounted for in the design of these projects.

- *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 are a range of engineering options for controlling mercury release to the water and the food web.
- 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.

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 2020

3.1. Prediction of low levels of dissolved oxygen (hypoxia) at Clear Lake

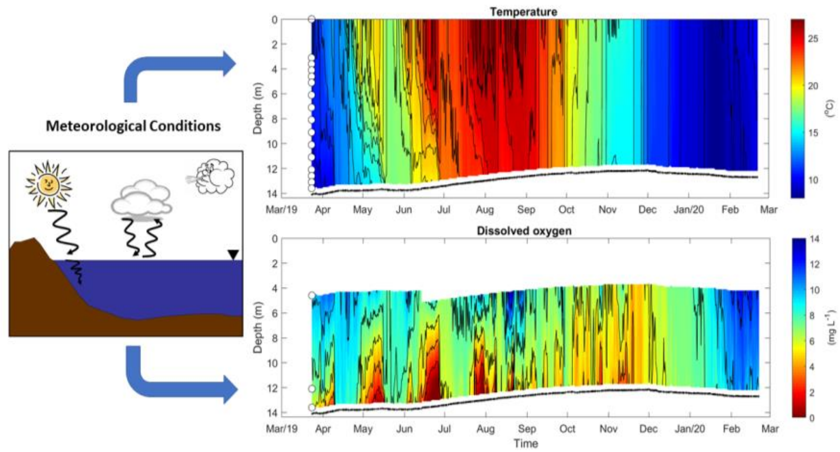

Figure 1. Cartoon summarizing our method to predict hypoxia in Clear Lake

Dissolved oxygen (DO) is essential for maintaining healthy aquatic ecosystems. DO is consumed by multiple biogeochemical processes both in the water column and by the sediments. However, when the water column develops temperature gradients in depth (i.e. becomes *thermally stratified*), DO levels next to the sediments are potentially depleted to the point of hypoxia. Using the in-lake surface temperature and DO data we have collected in all three basins, and a meteorological conditions in the proximity of the lake, we have developed a new, simplified tool for predicting hypoxia (Figure 1). This tool can be a cost-effective decision-making tool for management actions when hypoxia is a concern. We have submitted a manuscript describing this method to the peer-reviewed journal *Water Resources Research*.

This tool has widespread application beyond Clear Lake. The results were presented at the 2020 California Lake Management Society Conference in October 2020, and we are now working with the Santa Ana Regional Water Quality Control Board on adapting it for use in Southern California.

3.2. First measurements of nutrient fluxes from the sediments

Under low DO levels, nutrients accumulated in the sediments (particularly phosphorus in the form of orthophosphate) can be released and returned to the water column, representing a threat for the lake water quality through internal loading. We conducted a laboratory experiment using lake sediment cores during fall 2019/winter 2020 to quantify the rate of phosphorus release from the sediments under low DO levels (Figure 2). In September 2020 we conducted a second set of laboratory experiments to measure the rate of phosphorus release from the sediments under low dissolved oxygen levels and elevated temperatures, more

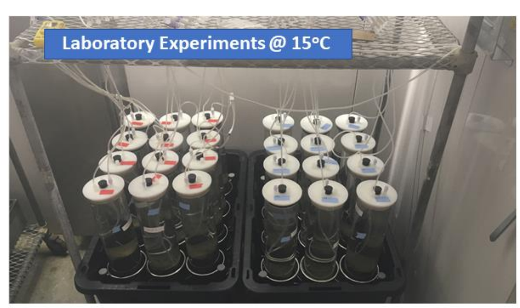

Figure 2. Nutrient release from the sediment laboratory experiment in fall 2019/winter 2020

typical of those encountered at Clear Lake during summer periods.

Results from these experiments have provided the first direct estimates of the annual internal load of phosphorous in Clear Lake. We estimated that phosphorous release from the sediments represents ~40-60% of the total phosphorus annual load in Clear Lake assuming cold lake temperatures. Once fully analyzed, the summer 2020 experiment will validate and quantify our hypothesis about the importance of internal loading in Clear Lake under warm lake temperatures. Other studies suggest temperature controls on sediment P-flux are large, and we estimate that warm temperatures could increase the nutrient release rates up to ~60% of the total phosphorus annual load in Clear Lake. Preliminary analysis of data from the incubation experiment we carried out during Summer 2020 show lower phosphorus flux rates from sediments than we predicted; however, interpretation of these results are complicated by antecedent periods of anoxia in Clear lake and sediment P-fluxes that occurred during the summer that reduced pools of available P in sediments at the time of our incubations (Figure 3). Cores had considerably high starting concentrations of phosphorus—roughly equal to concentrations encountered after 5 days of incubation in our previous experiment at 15°C. As watershed loading is low during this time of year, internal loading is the likely source. We plan to quantify sediment concentrations of P from our summer incubations to confirm this hypothesis. These results demonstrate that internal loading events earlier in the summer may have the greatest contributions of phosphorus to the lake since they occur before available phosphorus is depleted in sediments, and emphasize the need to take into account sediment P-pools in addition to flux rates when modeling total fluxes on an annual basis.

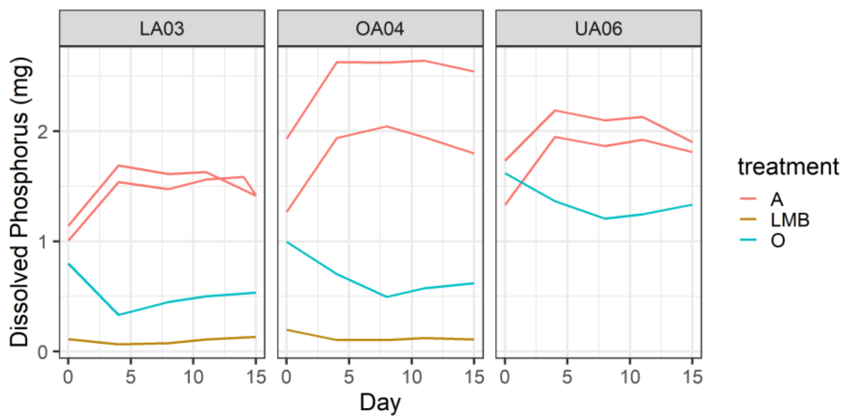

Figure 3. Graph showing the observed phosphsorus flux from sediments in cores incubated over 15 days during September 2020. Anoxic cores (red lines) showed highest flux rates and cores with lanthanum-modified bentonite (LMB) showed the lowest phosphorus flux.

We also conducted a pilot study to evaluate the effectiveness of Lanthanum-modified bentonite (LMB, SePRO, www.sepro.com) to reduce the anoxic release of phosphorus accumulated in the sediments, and subsequent eutrophication in Clear Lake. Results have proved this substance completely blocks the release of orthophosphate from the sediments under anoxic conditions.

3.3. Validating a remote sensing tool for monitoring cyanobacteria in Clear Lake

DO is also relevant for cyanobacterial growth. In collaboration with the California State Water Resources Control Board we have used different sampling techniques to quantify the spatial variability of cyanobacterial blooms in Clear Lake at finer spatial scales than available remote sensing tools (https://fhab.sfei.org/). In summer/fall 2019 we deployed an autonomous underwater vehicle (AUV), a drone, a radiometer, and completed intensive, coordinated sampling and multiple locations around Clear Lake (Figure 4) on three different dates. In 2020 we have been comparing the results to a satellite algorithm aimed at detecting cyanobacteria blooms. The acquired data are being used to quantify critical scales of variability of cyanobacterial blooms and ground-truth satellite data. This work was sent for publication to the peer-reviewed journal *Remote Sensing, Special Issue Remote Sensing of Coastal and Inland Waters* in fall 2020.

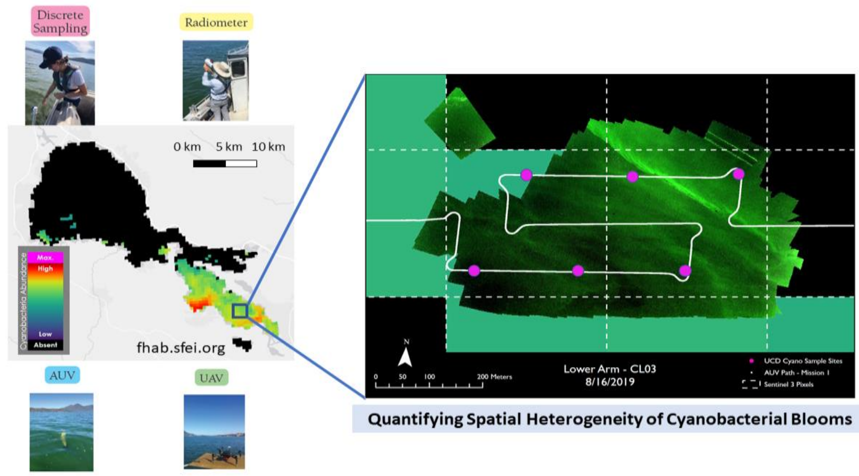

Figure 4. Diagram showing the different instrumentation used in TERC cyanobacterial studies to explore the variability of cyanobacterial blooms and validate remote sensing algorithms available at Clear Lake

We are also collaborating with the Big Valley Band of Pomo Indians and their scientific team to better understand the relationships between hypoxia, cyanobacterial blooms and fish kills.

3.4. NASA Fellowship for the detection of cyanobacteria in Clear Lake

One of our Graduate Students, Samantha Sharp, has received a 3-year NASA Fellowship for her HAB research at Clear Lake. There are only 25 of these awarded annually in the entire country. The monetary value is approximately $270,000. This Fellowship will aid in the effort of validation of the remote sensing tools for the detection of cyanobacteria in Clear Lake, and other lakes in California.

3.5. Impact of hypoxia on fish habitat in Clear Lake

DO is also essential for fish health. Graduate student Drew Stang has used echo-sounding in combination with the data that TERC's monitoring buoys have been collecting, to quantify fish biomass underwater and under different conditions as part of his MS Thesis. He found that during low DO (or stratified periods), fish migrated vertically upwards to shallower depths. Thus, fish are changing their vertical distribution under hypoxic conditions (Figure 5). If hypoxia becomes more intense in the future, this could stress and eventually threaten fish species (native and non-native) further.

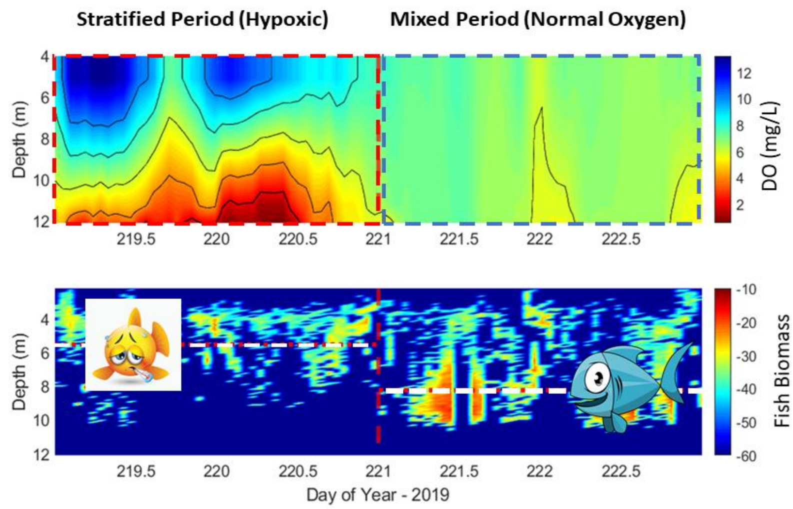

Figure 5. Time series of lake dissolved oxygen concentrations and fish biomass during three days in summer 2019 at Clear Lake. The white-red dashed line in the bottom panel shows the average depth where fish are located under hypoxic and normal-oxygen conditions

3.6. High-resolution data for streams, meteorology, and lake

During 2020, despite the limitations imposed by COVID-19 on our ability to safely conduct fieldwork and laboratory analysis, 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 (seven permanent water quality stations). The field effort was led by graduate students Micah Swann, Ruth Thirkill, Nick Framsted and Drew Stang, together with assistance from other graduate and undergraduate students. All of these data are critical for the ongoing development of the numerical models of physical transport in the lake and in better understanding the range of solutions that may be applied in the future.

3.7. USGS collaboration to find a surrogate for mercury for water quality monitoring

Mercury contamination is a long-standing issue in Clear Lake, particularly in the Oaks Arm. Traditionally, we have to conduct intensive sampling campaigns and time-consuming laboratory analysis to quantify the amount of mercury in the water. As a result, we are collaborating with the US Geological Survey to find a surrogate for mercury, which we can more easily monitor continuously using high-resolution sensors. We deployed two YSI-EXO probes (https://www.ysi.com/EXO2?EXO2-Water-Quality-Sonde-90) in our permanent water quality station in the Oaks Arm in spring 2020 to develop regressions between time series of chromophoric dissolved organic matter (CDOM) and mercury.

3.8. Lake bio-geochemistry

We evaluated the impact of nutrient loads on the lake water quality by measuring multiple constituents throughout the water column and across the lake 5-6 times during the year. We collected water samples to quantify dissolved and particulate forms of nitrogen, phosphorus, and carbon, chlorophyll, and particle size distribution. For example, our long-term records show a direct relationship between soluble reactive phosphorous (SRP) and chlorophyll-a at the end of the summer, when creeks are barely running into the lake and the lake bottom was hypoxic. This observation suggested hypoxia is likely to increase the internal SRP loading from the sediments. The laboratory filtering and chemical analysis was led by Anne Liston, Steven Sesma, Lindsay Vaughn and Tina Hammel, with assistance from graduate and undergraduate students.

3.9. Public data portal

TERC has made our data 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. We have also been collaborating with the County of Lake to provide content for their community Facebook posts.

3.10. Numerical Modeling – Calibration and simulation of particle transport in the lake

The field and laboratory measurements are essential to build, calibrate, and validate a three dimensional (3-D) numerical lake model. A numerical lake model is a computer model that uses sets of mathematical equations to reproduce the different processes which are occurring in the lake (warming, mixing, stratification, inter-basin transport). The model is 3-D because it takes into account changes both in the horizontal and vertical directions. 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*). We are currently working on the calibration/validation of the hydrodynamic model. The *calibration* process is a trial and error process in which we adjust parameters of the mathematical equations to reduce the error between field observations and lake model results. During the *validation*, we use a different set of field data without changing any parameters, and we expect a good agreement between observations and model results. Once the validation is completed, we are expecting to use the model to explore different questions regarding lake water quality (e.g. dissolved oxygen enhancement techniques, the fate of streams, and culvert loads).

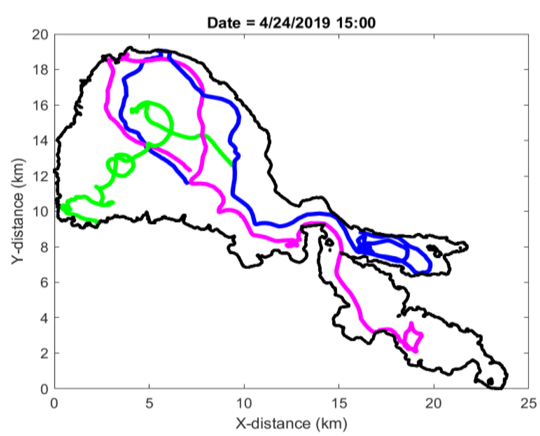

Figure 6. Three-dimensional lake model results of possible pathways for particles. We used a different color to trace the path of each particle

This lake model can also help us to better understand the transport of particles and dissolved constituents in the lake. The particles could be algae, phosphorus-rich sediment, or particulate mercury). Figure 6 shows the lake model results of the paths of three particles released in the Upper Arm. Each particle followed a completely different pathway, which highlights the complexity of the hydrodynamics or water movement in this system. Our field sampling plan is focused on improving our understanding of what are the factors affecting the different pathways.

4. UC Davis (TERC) Next Steps

The activities listed below are contingent on the extension of funding as recommended by the Blue Ribbon Committee. In some cases additional funding from other sources, as indicated, will be utilized to greatly enhance these activities.

4.1. Continue Cyanobacterial studies

We are continuing our collaboration with the California State Water Resources Control Board for the validation of satellite imagery detection algorithms of HABs in California. This validation exercise will allow us to focus on specific areas of research, such as (1) species-specific relationships with remote sensing outputs, (2) effects of spatial variability of the bloom within a pixel, and (3) the impact of atmospheric conditions on the detection algorithms. We have also broadened this collaboration by engaging with scientists at NASA through the NASA Fellowship (see above). Funding from the NASA Fellowship will greatly enhance what can be achieved with the requested level of State funding.

4.2. WQ Modeling and scenario development

A water quality module is coupled to the hydrodynamic model to simulate the evolution of different constituents, such as dissolved oxygen, nitrogen species, phosphorus species, phytoplankton, and suspended solids. This module needs the same type of calibration/validation described for the hydrodynamic module. We are planning to complete this task in 2021.

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. This may result in changes to our monitoring, or possibly specific experiments to understand important phenomena better. Eventually, 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
- Model exploration of the fate of stream and culvert loads
- Model controls on cyanobacteria
- Model climate change impacts
- Model sediment capping

4.3. Adapt 3-D model to provide daily hazard assessment and lake conditions

Models are typically used to provide predictions of future conditions to enable assessments of management actions months, years or even decades into the future. However, it is a relatively straightforward step to adapt the model 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
- Assisting law enforcement in the location and recovery of drowning victims who's bodies may be carried by the lake's complex currents
- Providing data on the spread, concentration and breakdown of accidental toxic releases to the lake

4.4. Link 3-D model to mercury model (USGS) – subject to availability of federal funding

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.

4.5. Wildfire Smoke Impacts on Clear Lake

TERC was recently (November 2020) awarded an NSF RAPID grant to measure the impacts of wildfire smoke and particulates on the productivity of lakes in the western US. Due to the existing mooring stations we have in Clear Lake we were able to include Clear Lake in this study. This will allow for the deployment of an autonomous underwater Slocum glider in Clear Lake to gather lake data continuously for up to three weeks. It will provide additional resources for the analysis of data that have already been collected. This serves as an important example of how the establishment of the research program at Clear Lake has the potential to leverage additional resources beyond those being invested by the State.

4.6. Keck Pre-proposal

The project team has submitted a pre-proposal to establish a Keck Foundation Center focused on the study of improved detection of HABs. Although at an early stage, if successful this will provide $1M of additional funding that will build on our efforts at Clear Lake. The degree of focus of the Center on Clear Lake will be contingent on the continuation of the monitoring program.

4.7. Decommissioning of Lake Moorings, Meteorological Stations, Stream Sampling stations and ending of water quality monitoring

UC Davis funding currently extends through June 2021. Without an extension of funds, we will be forced to commence removing our installations in Spring 2021. This is typically a critical time at Clear Lake, as it is when thermal stratification becomes established and the water quality issues become greatly enhanced.

4.8. Bathymetric Survey

Subject to funding as per the Blue Ribbon Committee request, the bathymetric survey of Clear Lake will commence in winter 2021. The boat and necessary equipment are currently reserved for this effort. We have been negotiating with various sections of the USGS to provide additional funding for this effort, to increase the scope of the survey data.