# Science to Action Planning, Project Briefing and Science Vision for Lake Tahoe, 2019

**Tahoe Science Advisory Council Report | August 2019**

TSAC
TAHOE SCIENCE ADVISORY COUNCIL

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Tahoe Science Advisory Council (TSAC)

**Science for Action, Executive Summary and Project Briefing 2019**

The effects of climate change are becoming increasingly evident throughout the Sierra Nevada (Dettinger et al. 2018) with long-term warming trends, decreasing snowpack, more extreme annual fluctuations in precipitation, and corresponding changes in stream hydrology. These effects are increasingly translating into stresses on ecological conditions and function of natural processes inherent to both the lake and terrestrial environments. At the same time, demographic pressures are increasing due to growing populations and increasing tourist demand for access to environmental assets in mountain environments (CTC 2019). Ultimately, the social, economic and ecological vitality of the Lake Tahoe Basin will depend on the development of sustainable management strategies that are based on scientific understanding of the likely changes to come and the identification of opportunities to enhance system resilience to impacts.

Conditions in Lake Tahoe are already transforming due to the changing climate. The signs of this are unmistakable in the data record, with air temperatures (measured since 1910) and water temperatures (measured since 1968) rising at an accelerating rate (State of the Lake Report, 2019). These changes appear to be contributing to profound impacts, including:

1. An unabated decline in summer clarity;
2. Strengthening of the lake's thermal stratification for longer periods, which has reduced lake mixing while increasing the concurrent threat of deep-water hypoxia (i.e. dead zones) in Lake Tahoe;
3. A transition toward a rain-based hydrology driving earlier peak streamflow runoff, with the potential for increased pollutant loading and disruption to spawning patterns of native fish; and
4. Changes to ecological communities at all trophic levels, including opportunities and niches for new invasive species and harmful algal blooms.

These changes, and Lake Tahoe's response, could influence the future success of basin-wide management initiatives such as the Lake Tahoe Total Maximum Daily Load (TMDL) Program and the Environmental Improvement Program (EIP). While these programs have shown significant progress at slowing annual average clarity loss, the long-term lake clarity and other important characteristics of lake function and condition are at greater risk from climate change than when the TDML science effort was initiated almost twenty years ago. Investment is needed now to enhance existing science tools and data collection programs at Lake Tahoe to better understand how the changing climate is affecting the Lake and its watershed, and to ensure that current and proposed management actions are appropriate and scientifically defensible. The development and application of modernized approaches to modeling, data analysis and interpretation will provide the scientific context and understanding needed to address management questions as agencies adaptively manage against adverse impacts on the unique resources of Lake Tahoe.

Three priority issues for Science to Action development are to:

- quantify the impacts of future climate change on the aquatic environment – existing monitoring has established several climate driven trends, but the full extent of future changes will need to be adequately anticipated to inform planning decisions.
- determine the causes of divergence in summer and winter clarity trends – while winter clarity improves, likely reflecting the success of past TMDL and EIP initiatives, summer clarity continues to decline.
- assess current and future management decisions in response to both climate change and the evolving drivers of lake clarity.

The Tahoe Science Advisory Council (hereafter "Council") proposes a set of recommendations to guide the investment of immediately available funding, with the overall objective of providing decision-relevant science that informs policy and that anticipates critical emerging issues relevant to lake water quality and ecosystem health. Implementation will require close coordination with resource agencies to develop the funding resources needed to sustain this objective over the long term.

At present the Council has secured funding from two new sources. The first is a $400k grant from the federal SNPLMA program focused on Hydrologic Connections Between Forest Health and the Health of the Lake. This project will evaluate the potential effects of large, landscape-scale changes and vegetation management work on the lake by quantifying hydrologic and nutrient fluxes through the heavily forested west side of Lake Tahoe and their fate in both the nearshore and offshore regions of the lake. The second source will support a $500k project from State of California funds to commence evaluation of future climate change impacts on water quality and lake conditions, to reassess the drivers of Lake Tahoe's clarity, and to recommend actions for addressing these issues. Over the next two years, the Council will initiate four priority projects to address changing conditions in Lake Tahoe and provide recommendations for the data and tools needed to anticipate impacts and test management scenarios for building system resilience:

1) Conduct a broad assessment of available data to articulate and test the hypotheses for why summer and winter clarity are diverging.
2) Review and update existing tools for evaluation of clarity, lake and nearshore responses to changing climate and lake conditions. This includes the identification and filling of critical data gaps needed for enhanced model calibration and application that represent changes (e.g., meteorological data, hydrodynamic data, storm water data, food web interactions, etc.)
3) Evaluate fluxes of water and nutrients along transect(s) in the Lake Tahoe West watershed(s) and model their fate in nearshore and offshore regions of Lake Tahoe.

4) Initiate data synthesis and early assessment briefing workshops hosted by the Council to analyze ongoing data collection efforts and to develop statistical products relevant to modeling and for representation of status and trends of selected variables.

*Project descriptions for these four priority near-term tasks have been included in materials immediately following this executive summary, along with a representation of the Council science vision that will inform longer-term application of science for action in the Tahoe Basin, as described below. The objective is to provide decision-relevant science that informs policy and that will anticipate critical or emerging issues relevant to lake water quality and ecosystem health.*

**Long term science framework**

Resource management agencies have numerous questions related to lake ecological health, and the dominant hypotheses associated with them (Exhibit 1). The TSAC believes that the four projects and modeling tools described above will provide new insights into many of these important questions.

To address other current and future management priorities, the TSAC recommends implementing a Climate Response Action Framework for Tahoe (CRAFT) to guide development of the tools needed to anticipate longer-term climate change impacts. As recommended by the Lahontan Water Board and NDEP in the 2018 *Findings and Program Recommendations Memo* for the Tahoe Total Maximum Daily Load (TMDL) Program, this effort must be aligned with the TMDL program along with ongoing efforts to address nearshore water quality, and must be aligned with other priorities of the EIP, including forest health management. Ultimately, this framework will enhance and integrate various lake and watershed model components to address climate change impacts on the lake and its watersheds at sufficient spatiotemporal resolution to be relevant for scenario assessment of management options (science for the mid-term). Ultimately, the development and implementation of this formal, coordinated, science-based Climate Response Action Framework for Tahoe (CRAFT) will provide an integrated, sustainable program for understanding and communicating the health of the lake and its watershed (science for the long-term).

*A description of the Climate Response Action Framework for Tahoe (CRAFT) research vision that informs longer-term application of science for action in the Tahoe Basin is described after the priority project descriptions below. These derive from the Science to Action document (January 24, 2019), which was developed in response to a list of ten questions (June 12, 2018) addressed to the Council by Secretary Laird (CA Natural Resources Agency) and Director Crowell (NV Department of Conservation and Natural Resources) as a consequence of the record low annual lake clarity average from 2017.*

**References:**

Dettinger, Michael, Holly Alpert, John Battles, Jonathan Kusel, Hugh Safford, Dorian Fougeres, Clarke Knight, Lauren Miller, Sarah Sawyer. 2018. Sierra Nevada Summary Report. California's Fourth Climate Change Assessment. Publication number: SUM-CCCA4-2018-004.

California Tahoe Conservancy (CTC). 2019. Climate Change Vulnerability Assessment for the Lake Tahoe Basin (Draft). South Lake Tahoe, CA.

UC Davis Tahoe Environmental Research Center. 2019. Tahoe: State of the Lake Report, 2019.

***Exhibit 1.*** *Key Management Questions Document provided to TSAC by representatives of the Tahoe Regional Planning Agency, the Lahontan Regional Water Quality Control Board and the Nevada Division of Environmental Planning (received 4/25/19).*

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**Priority Water Quality Management Questions**

**Clarity**

- What is driving the divergence in summer and winter clarity trends?
- How has ecological change influenced clarity?
- Is the Clarity Model still capable of predicting deep water clarity? If not, what data and information is needed to update and refine the model?

**Algae**

- What are the primary drivers of nearshore algal growth?
- How should metaphyton be monitored?
- How should periphyton be monitored?
- Past analysis of periphyton data has revealed little to no change in periphyton in Lake Tahoe, how confident are we that there hasn't been a change in the last 20 years?
- Is groundwater nutrient delivery an important driver of periphyton growth at the lake-wide scale?
- What are the predominant, specific sources of groundwater nutrients contributing to periphyton growth?

**Climate Change**

- Are increasing temperatures, associated with climate change, altering the nearshore environment?
- How are changing climate condition and lake temperatures influencing watershed hydrology, in-lake ecology, and lake clarity processes?
- Are there alternative management strategies/practices not previously considered that can help offset the impacts of climate change?

***Exhibit 2.*** *Ten questions addressed to the Council by Secretary Laird (CA Natural Resources Agency) and Director Crowell (NV Department of Conservation and Natural Resources) as a consequence of the record low annual lake clarity average from 2017. (The original letter and preliminary science responses to those ten questions are included as part of Attachment 1 in the Linking Science to Action Phase 1 framework included at the end of this document.)*

1. What does the 2017 clarity result tell us about the overall health of the Lake and its watershed? What additional information would enable us to better understand the change in 2017 and the relative impact on the Lake and/or the connection to the Basin's broader ecosystem health?

2. Why was the negative impact on lake clarity in 2017 different from other years with extreme wet weather conditions?

3. How much, if any, did warming of the Lake's surface waters or other impacts from effects of a changing climate influence 2017 clarity?

4. The 2017 annual clarity result was heavily influenced by seasonal data during the Fall of 2017. Are Lake Tahoe's seasonal dynamics changing? If so, why, and what impact may that have on the Lake's long-term ecosystem health?

5. How much worse might clarity be today had investments in the EIP and the TMDL not been made?

6. Do 2017 sources of pollutant load differ from those identified in the TMDL?

7. Once the likely cause(s) of the 2017 clarity decline are identified, how likely are these factors to repeat, persist, or cause a change in trend?

8. Should the annual clarity average report be adjusted to analyze a different time scale to better determine various causes and impacts related to changes in Lake clarity?

9. When assessing the health of the Lake ecosystem and watershed, what other metrics for determining ecosystem health are most important for analyzing in conjunction with Lake clarity?

10. Given the questions above, what local or regional impacts are causing the greatest impact and/or pose the largest threat to protecting the Lake and surrounding Tahoe Basin ecosystem?

**Science to Action Priority Projects**

*The justification section of each project description provides a listing of questions from Exhibit 2 above that will be addressed specifically during development or as products of the project. These are not exclusive, because each project will contribute information relevant to several other questions, but these are the questions most immediately connected to each project.*

## **TSAC S2A, Project 1:** *Assessment and Analysis of Available Data to Evaluate Seasonal and Long-term Summer and Winter Clarity Trends*

**Background**

Lake Tahoe's trends in clarity have shown a continual decline of 0.2 m/yr in summer months with a relatively steady or improving trend for clarity in winter months. In general, the decline in water clarity has been attributed to inorganic fine sediment particles entering the lake from watersheds, which account for roughly two-thirds of the lake's impairment. Sources of fine sediment are urban runoff, forested upland runoff, atmospheric deposition and erosion from stream channels, with degradation or alteration of wetlands, catastrophic fire and landscape disturbance also contributing sediment inputs to Lake Tahoe. The seasonal divergence in lake clarity may be attributable to various factors, including improvements from management activities that have reduced sediment inputs, but data have not been fully evaluated to determine the extent of all potential contributing factors. Other factors that may impact clarity, many of which have a strong climate-related signature, are seasonal inflow changes, lake level changes, changing lake stratification, decreasing frequency of deep mixing, the changing makeup of the lake's phytoplankton, and food web interactions.

**Objective**

The overall objective is to conduct data analysis and quantify the impact of processes that relate to the divergence of seasonal trends. This will be based on analysis of existing data from monitoring activities. Specifically, this project will compile and analyze hydrologic inputs (flow, sediments) along with in-lake data (mixing events, thermal stratification, phytoplankton, zooplankton, etc.) to determine their relative importance during the historic record and potential causes for the continued decline in summer clarity. An evaluation of annual or seasonal drivers of clarity variations will also provide valuable information on management actions that may be attributed to improvements in winter clarity trends.

**Description**

This project will address the following priority water quality management questions as they pertain to clarity: What is driving the divergence in summer and winter clarity trends? How do in-lake physical and ecological drivers influence seasonal and historic trends?

Results from compilation and analysis of the data will be documented to describe the role of in-lake drivers such as the alga *Cyclotella*, thermal stratification, particle and nutrient insertion depths; hydrological drivers such as timing and delivery of material, and extreme climate conditions that result in large changes in seasonal clarity.

**Justification**
The Tahoe Science Advisory Council recently completed a review of the anomalous 2017 Lake Tahoe clarity data and provided responses to ten questions posed in a June 12, 2018 letter from Secretary Laird (CA Natural Resources Agency) and Director Crowell (NV Department of Conservation and Natural Resources), the co-chairs of the Bi-State Executive Committee. The TSAC identified several factors that led to the low 2017 clarity observations. An evaluation of existing data to determine how these factors have changed over time or how they contribute to contribute to the divergence in seasonal clarity is needed. Further, a TSAC survey of priority water quality management questions completed by resource management agency staff listed divergence of clarity and how ecological change influence clarity to be the most important issues regarding clarity that needed to be addressed.

Completed policy briefs will inform resource managers on the relative efficacy of existing pollutant load reduction efforts in the context of summer and winter clarity trends. The briefs are expected to identify potential actions to address declines in summer clarity. Defining data gaps and research needs will guide investment to better inform future management decisions.

This project will help address questions #2, #3, and #4 (see Exhibit 2) with specific data analyses, findings and recommendations related to shifts in summer and winter average clarity conditions.

**TSAC S2A, Project 2:** *Review and Update Existing Tools for Evaluation of Clarity and Lake Responses to Climate Change*

**Background:** Actions to restore the clarity of Lake Tahoe are a central focus of the Environmental Improvement Program. The recent low clarity of 2017 highlighted the need to relook at the predictive modeling framework that underlies the development of the TMDL – the Lake Tahoe Clarity Model (hereafter the Clarity Model). The Clarity Model is in fact an integrated set of linked models, and each part of the model will be examined for its current applicability and upgraded as deemed necessary. Results from updated modeling tools will be compared with results from the existing model.

**Description**
The Clarity Model comprises a nested set of sub-models – a hydrodynamic model, an ecology model, an inorganic particle model and an optical (i.e. clarity) model. It also has a complex set of external inputs. These inputs are meteorology (measured or modeled), loading of particle and nutrients from streams, an atmospheric model, a groundwater model and a hydrology model. Task 1: Each sub-model and data input source will be reviewed for its current applicability/correctness and those that are deemed to be critical for improving predictive ability will be upgraded. Task 2: Upgrade critical sub-models – preliminarily it is considered that those sub-models most urgently requiring upgrades are the hydrodynamic model; the ecology (specifically the introduction of discrete algal functional groups, the change to a carbon-based

model as opposed to a chlorophyll-based model, and explicit modeling of zooplankton and mysis grazing); and the particle model with inclusion of synchronicity in vertical motions.

The deliverables will be (1) Assessment of deficiencies in existing Clarity Model; (2) Assessment of the Deficiencies in the Available Model Inputs; (3) Development of an Improved Clarity Model through upgrade or replacement of sub-models; (4) Comparison Runs of Existing and Improved Models; (5) Running the Improved Model for a Limited Range of Current Conditions and Hypothesized Future Climate Conditions.

**Justification**
Predictive modeling with demonstrated validity is a critical tool for management agencies. Recent findings are increasingly showing that the current modeling framework needs to be updated, as the lake physics and ecology continue to diverge from the conditions that were the norm 20 years ago.

This project will help address questions #1, #3, and #5 (see Exhibit 2) with specific monitoring data, data analyses, modeling enhancements and recommendations.

**TSAC S2A, Project 3:** *Science Support for Management of Landscape Scale Changes on Lake Tahoe: Hydrologic Connections Between Forest Health and the Health of the Lake*

**Background:** Landscape scale changes to the forests surrounding Lake Tahoe will have a large impact on many drivers of lake condition. Examples include the alteration of air temperature patterns, snow cover and duration, soil moisture, stream flows and constituents, stream temperatures, and alteration of future fire frequency and intensity. Individually or combined, such factors can significantly alter the quality of (1) the nearshore environment, (2) the pelagic environment, and (3) conditions that favor native or invasive species.

This project will provide scientific information needed for evaluating the impacts and mitigation strategies on lake condition resulting from landscape-scale forest alterations. By focusing on the west shore of Lake Tahoe, specifically the Ward Creek Watershed, this project will leverage existing information from this intensively studied watershed on landscape characteristics and processes.

The hypothesis is that by taking appropriate measurements to calibrate/validate existing hydrologic models (developed as part of Lake Tahoe West) for the Ward Creek watershed, an estimate of water fluxes and nutrient pools can be determined under current forest conditions can be made. These validated results will increase the confidence with which the model results for future forest conditions can be applied. The fate of the water (and its nutrients) in the nearshore of Lake Tahoe and its transport to the offshore will be examine through a combination of measurements to quantify the plunging of the riverine inflow and incorporation into the upgraded Clarity Model.

**Description**

The existing Lake Tahoe West hydrologic models have had limited opportunity to be calibrated/validated to measured data. Through this task we will measure key component of the hydrology to provide a minimal level of calibration/validation. The components that will be measured include forest water uptake, regolith water content at different elevations, shoreline groundwater fluxes, and plunging inflow dynamics. The components to be modeled included snow/surface water/groundwater interactions, and transport and fate of groundwater and streamwater into the littoral and pelagic zones of the lake.

Using the calibrated/validated models developed for the Ward Creek watershed, estimates will be made for the likely impacts of different forest treatments on Lake Tahoe.

**Justification**

Future forest treatments will need to be undertaken, and the impacts of these on the aquatic resources need to be factored into management agency decisions. Specifically, this project will test the relative impacts of three different forest treatment scenarios on Lake Tahoe.

This project will help address questions #1, #9, and #10 (see Exhibit 2) with specific monitoring data, data analyses, modeling enhancements and recommendations.

**TSAC S2A, Project 4:** *Data Synthesis and Annual Assessment Briefing Workshops*

**Background**

Scientific information has long contributed to informed management decision-making at Lake Tahoe, since the early days of increasing urbanization when lake clarity decline was first documented. More recently, science has informed development of the TMDL program for restoring lake clarity, and is being integrated as part of the EIP process to restore and maintain Tahoe Basin environmental qualities, including air, water and forest health. These environmental qualities are embodied in TRPA threshold standards. While science-based integration across monitoring programs, thresholds and performance measures is in progress, more work is needed, especially in terms of linking EIP performance measures to outcomes and anticipating the interim responses to management actions.

Current projections of the impacts of future climate change show accelerating rates of change for multiple driving variables, all of which will push the lake further from the conditions observed and assumed in development of the TMDL science and EIP efforts. There is a need for more frequent analysis and reporting of hydrologic, climate and lake conditions as they develop, accompanied by near-term forecasts of water clarity and lake conditions for the duration of the year.

**Objective**

The purpose of this project is to provide integrated analyses and executive-level briefings on climate, watershed and lake conditions each year, accompanied by updated statistical models and projections of status and trends in key outcome metrics associated with lake threshold standards and EIP reporting. Further, these workshops will bring the region's top scientists together for assessment of data analytic results, review of projections and interpretations, as well as annual recommendations for adjustments to data collection programs, analyses, modeling integration, and reporting.

**Description**

This project will coordinate data synthesis and annual assessment briefing workshops, hosted by TSAC with participating agency stakeholders, to analyze ongoing data collection efforts and develop statistical products relevant to modeling and representation of status and trends for selected variables. The development and implementation of this project will consist of two related efforts.

1) Quarterly meetings of data collection principals and engaged staff to review progress and products of ongoing monitoring and modeling efforts, to coordinate integration of data collected for modeling or reporting purposes, and to report on preliminary findings as they evolve during the year. A summary progress report will be produced each quarter for abbreviated presentation and discussion at regularly scheduled TSAC meetings, with the intent of engaging Council members and agency stakeholders in assessment and discussion of methods, progress, findings and emerging topics.

2) An annual workshop hosted by TSAC as part of its peer-review process for coordinated science development and implementation. Draft documentation of findings and recommendations, developed from quarterly meetings of the data analysis team and from feedback during discussions at TSAC meetings, will be distributed for external peer-review. These reviews will then be distributed to Council members and to agency stakeholders in advance of a full day workshop that discusses findings, science coordination, recommendations and integration with management programs. The final product of this workshop will be presented and discussed as an annual briefing to the Tahoe Interagency Executives Steering Committee (TIE-SC).

**Justification**

These quarterly data analysis and integration meetings and the annual workshops will bring top scientists together for on-going assessment of data analytic results, review of projections and interpretations, as well as compilation and analysis of historical data and annual recommendations for adjustments to data collection programs, analyses, modeling integration, and reporting. It will also contribute to strategic development of the Climate Response Action Framework for Tahoe (CRAFT), which will help guide development of the tools needed to anticipate longer-term climate change impacts.

We recommend a mid-year briefing, modeled after the successful Winter-Weather Outlook Workshop that the California Department of Water Resources organizes each year, for which it is important to distinguish between sources of annual variability and the underlying causes of longer-term trends. At Tahoe this approach will contribute to development of statistical models and reporting products that anticipate changes associated with annual variability in climate, hydrology and lake conditions. It will also support development and integration of process-based models that work at different scales and provide other types of information.

This will also contribute to the annual Findings and Program Recommendations Memo of the Tahoe Total Maximum Daily Load (TMDL) Program, as well as to ongoing efforts that address nearshore water quality and with other priorities of the EIP. Ultimately, recommendations developed from implementation of this project will support integrating science as part of the EIP process and support associated funding requests designed to address management mandates for best available science in the context of stewardship and accountability.

This project will help address questions #6, #7, and #9 (see Exhibit 2) with specific monitoring data, data analyses, statistical modeling products and recommendations.

Tahoe Science Advisory Council (TSAC)

**Research Vision for Lake Clarity and Health**

Through a series of workshops and meetings, the TSAC has developed a Vision for the direction of research at Lake Tahoe, specifically motivated by questions posed by the California Natural Resources Agency and the Nevada Department of Conservation and Natural Resources. Those questions centered on lake clarity and health. There are in fact numerous other dimensions to Lake Tahoe's health and well-being, but they are not the focus of this document.

For the issues pertaining to lake clarity and other measures of lake health and water quality, the TSAC believes that the primary research focus should be on developing a suite of comprehensive system models for Lake Tahoe that will provide mechanistic, quantitative formulations of scientific understanding that will serve to identify gaps in understanding and in data. While models can be used for predictions, we equally emphasize their heuristic value, or in other words their ability to inform us on how the lake system actually works. Furthermore, models allow and require careful sensitivity and uncertainty analyses, and can simulate various management scenarios and societal behaviors.

Models have the advantage of providing a quantitative way of looking at the impacts of changes in land-use, climate change and the different management actions. The effective use of these models, however, requires monitoring data for their calibration and validation. In the absence of rigorous calibration and validation, model results while appearing to be plausible and compelling, may have little heuristic or predictive value. Beyond calibration and validation, a model may not always include all the relevant mechanistic processes. Through model application the importance of these "missing" processes (physical, biological or chemical) can often be identified. In such a case, models may need to be extended to include the missing processes, something that may require separate measurements and experimentation by disciplinary experts.

*Summary of Previous Lake Modeling at Tahoe*

In a time of rapid climate-change-induced variability, the validity of past models and modeling approaches need to be questioned. In many cases the hydrologic flow regimes and lake stratification regimes are such that the conditions are well outside the range of those that may been expected just 20 years ago. In other cases, scientific knowledge has advanced and the models may need to be updated.

Five physical (or hydrodynamic) lake models that have been used at Lake Tahoe in the last 20 years, albeit for different purposes. These physical models represent the physical responses of the lake to its external "drivers". A different set of models that predict the range of water quality and ecological responses that agencies generally wish to know are described as ancillary models or sub-models to these physical models. They may be embedded within the main physical model, or they may be run separately using the physical model's outputs. As with all models, these models are in continual development and have features that may need enhancement to address the evolving research and management questions at Lake Tahoe. Likewise, new questions are emerging, particularly with respect to climate change impacts.

The physical models that have been used at Lake Tahoe in the last 20 years are as follows.

(1) The Lake Tahoe Clarity model (DLM) and its component sub-models is a public-domain model. This one-dimensional (1-D) model was used as the underpinning of the Lake Tahoe TMDL (see References). It has been used for many Tahoe-related, peer-reviewed publications, and other forms of the model (DYRESM, GLM, CAEDYM) are in wide use around the world. Though the 1-D hydrodynamic underpinnings capture many of the dominant processes that control clarity change, there are other important lake processes that are not represented. At the time of the TMDL research, it was not computationally feasible to use a three-dimensional (3-D) model.

    The largest shortcoming of this model is its one-dimensional assumption, which prevents it from providing information on the horizontal distribution of lake properties (nearshore vs offshore) and impacts of two- and three-dimensional processes. These processes are becoming dominant at Lake Tahoe. In addition, there are lake health issues beyond clarity (for example, periphyton growth in the nearshore, invasive species distribution and control) that cannot be addressed with a one-dimensional model.

(2) Si3D is a public domain, three-dimensional (3-D), time-varying hydrodynamic model, capable of representing lake processes in both the horizontal and vertical directions. It has been used previously at Tahoe (see References) for describing the internal wave dynamics, the spread of invasive species, and the fate of pathogens. It has also been used in a broad range of water bodies of varying size around the world. Its structure allows new or existing sub-models for a range of biogeochemical processes, physical processes (e.g. fine particle fate) and an optical (Secchi model) to be readily incorporated. An initial DO and nutrient cycling model has already been developed (Doyle 2010).

    One of the greatest attributes this model possesses is the ability to use "nested" grids. The model's grid size determines the spatial resolution of processes it can represent. A large grid is computationally efficient, but cannot represent small-scale processes such as occur as a stream enters the lake. On the other hand, using a fine grid that can represent all the small-scale processes will take an exceedingly long time to run (many months) and is impractical for addressing lake management questions. Using nested grids, Si3D utilizes efficient, larger grids over the majority of the domain, but can then nest progressively finer grids in those specific parts of the lake where it is needed. This compromise provides a good balance between speed and accuracy.

(3) ELCOM is a proprietary, three-dimensional model that has been used extensively in lakes around the world. In many ways it is similar to Si3D in terms of its input needs and outputs, but with the biggest difference being its inability to accommodate nested grids.

(4) STWAVE is a two-dimensional) 2-D, steady state, spectral surface wave model used at Lake Tahoe to predict the variation of turbidity around the entire shoreline (Roberts et al. 2019; Reardon et al. 2016). Currently it is being used as part of periphyton modeling to estimate wave-induced sloughing.

(5) SEICHEFEM is a 2-D, steady state finite element model for predicting the natural surface seiche periods and amplitudes in lakes of variable shape (Roberts et al., 2019; Rueda and Schladow 2002).

In many cases, the data needed to "drive" a lake model cannot be provided by measurements alone. Rather, they need to be provided by ancillary models. Examples would include watershed (or hydrology) models (that provide estimates of streamflow, overland flow, nutrient concentration, sediment concentration etc. from the surrounding watershed); groundwater flow models (that provide estimates of groundwater inflow and outflow from the lake); future climate models (that provide estimates of the meteorology that the lake may be subjected to in the coming decades); and atmospheric models (that estimate the loading of atmospheric particulates and nutrients to the lake, as well as estimates of latent heat fluxes). Some of these models exist and have been used in the past (e.g. the watershed model LSPC was used for the TMDL). In general, however, the suitability of any ancillary models should be evaluated on a case-by-case based on the specific needs and questions being asked.

*Future Lake Modeling*

Given the inability of the Lake Clarity Model to represent three-dimensional processes, it is the opinion of the TSAC that the future modeling focus (for both its predictive and heuristic benefits) be directed toward a three-dimensional model. Given the advantages of Si3D over ELCOM (it is a free, public domain model, has a peer-reviewed publication history for Lake Tahoe and other lakes, and it can represent the small-scale processes at the lake boundaries that are important at Lake Tahoe), Si3D should be utilized in the next phase of model use and development at Lake Tahoe.

*Model Data Needs*

While 3-D modeling is clearly the way forward for the Tahoe basin, models require data. These data are of three basic types:

1. Forcing data – these are the data that actually drive and energize the lake, and include meteorological data, stream data, and groundwater data. Without these data, the lake cannot be modeled. On-lake meteorological data, particularly wind data and radiation data, are limited. What data exist, have been provided by research groups on modest budgets. The quality of these data is increasingly uncertain as the equipment ages. The stream data (flow, nutrients, etc.) are currently being collected by the USGS and UC Davis. Though the program has been reduced over the years (currently only 7 of the 63 streams are being monitored) it still represents the most comprehensive data for lake drivers. Groundwater data collection is extremely sparse in the Lake Tahoe basin.

2. Boundary condition data – these are the data that describe the physical shape of the lake basin. A recent lidar survey of the shallow regions of the lake (to a depth of 10 m) is a valuable recent addition. The USGS deep water survey from 1997 has good representation of the deep, flat parts of the lake. The intermediate depth shelves of Lake

Tahoe (depths from 10-100 m) could greatly benefit from a resurvey using current bathymetric survey equipment that could provide accuracy on the scale of centimeters.

Boundary conditions are also required for the hydrology/watershed model. Fortunately, a recent lidar survey provides excellent coverage of the entire watershed.

3. In-lake data – these data are needed for calibration and validation of models. While there is an extensive set of chemical data and some biological data (see Appendix I), physical data such as time series temperature, dissolved oxygen and current velocity data are largely absent. Recent advances in sensor technologies also offer new opportunities for improved measurements.  These new sources of information are extremely valuable and would contribute to future modeling efforts.

Focused experimental data for poorly understood processes may also be required. There are many processes occurring in Lake Tahoe that are poorly understood or not even recognized. Routine monitoring is unlikely to provide understanding of these processes. Rather, time-limited focused experiments are needed to better understand and describe the processes. Once they are understood, they can be incorporated into models or into longer term monitoring if warranted. Examples of such processes include some of the biological and biogeochemical processes that take place in the lake. For example, a complete nutrient balance for the lake does not exist, i.e. establishing that the nutrients entering the lake, are equal to the nutrients exiting the water column As there are many internal processes that recycle nutrients, this is not a trivial exercise. Current research is addressing some of these questions.

*High Priorities*

The Phase 1 document ‘Linking Science to Action: A framework to advance science-based management for Lake Tahoe’ (see Attachment 1), provided a tiered set of recommendations for science needed. These were not intended to represent investments for short or long-term efforts, rather they represented the work that would be required to address questions that will emerge over those time frames. Building upon that report and based upon feedback received from TSAC and Agency representatives at the 5/16/2019 TSAC meeting, the following lists of high science priorities are recommended to be commenced at the earliest possible time.

<u>Level 1</u>

1.1 Enhance whole lake physical modeling using improved models (e.g. Si3D) with particular goals of distinguishing littoral and pelagic temperature differences currently and in the future; allowing tracking of introduced “contaminants”; updating of the sub-model for both fine particles and small algal cells; modification of existing chlorophyll model to be Carbon-based, and to allow a minimum of 3 functional algal groups (including Cyclotella); food web-interactions including vertical migration by Mysids.

1.2 Fund critical forcing data gaps; e.g. on-lake meteorological data.

1.3 Fund critical in-lake data gaps; e.g. time-series temperature and dissolved oxygen data, water current data to enable calibration and validation of model's ability to correctly capture temperature stratification, vertical transport and horizontal transport.

Level 2

2.1 An annual data synthesis and early assessment briefing from workshops hosted by TSAC each year focused on the analysis of ongoing data collection and discussion of findings pertaining to the past year's lake conditions and clarity, and an outlook on the current year's clarity expectation, based on data and forecasts that are available.

Level 3

3.1 Develop and implement a formal, coordinated, science-based Climate Response Action Framework for Tahoe (CRAFT) to provide an integrated, sustainable program for understanding and communicating the health of the lake and its watershed in the context of climate change. This will include developing a mechanistic understanding of how Lake Tahoe will change with a new climate regime, supported by appropriate modeling tools, data acquisition and analyses, and recommendations for management options needed to address lake basin response to climate change.

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## Appendix I: Existing Lake Monitoring

### Deep Water (Pelagic Monitoring)

Deep water monitoring was initiated by UC Davis in 1959, following a brief period when California DWR monitored the lake. Funding precluded regular sampling, so the irregular data from 1959 to 1968 is rarely reported (with the exception of primary productivity). In 1968 regular (monthly or more frequent) sampling was initiated and has largely continued to this day. The funding was initially provided through a combination of TRPA, California State Water Resources Control Board (Lahontan) and UC Davis, although in recent years the Lahontan funding has been redirected increasingly to nearshore monitoring. This 50-year data set represents the longest, most complete long-term data set for a lake in the western US, so as well as having fundamental importance for Tahoe, it is a resource for water resource management in the Sierra and the west.

Modifications to the sampling frequency and variables have been made over time. For example, following rigorous statistical analysis it was concluded that some variables (e.g. primary productivity) were being monitored more frequently than was required to identify the important trends and cost savings could be achieved by decreasing the frequency, There have been several cycles of review over the 50 years of monitoring, and it is considered unlikely that any further substantial savings exist (without compromising the integrity of the data set). By contrast, over time it was found that new variables emerged as being important to monitor. An example of this is fine particle concentrations, which were only identified in 2000 as being the controlling variable for lake clarity at that time. It is possible that changing conditions may call for new variables to be added in the future.

The mid-lake monitoring occurs at two locations – the mid-lake (MLTP) station and the Index (LTP) station. The MLTP is near the deepest part of the lake (500 m) and is on the California-Nevada border. Sampling at this station allows for the entire water column to be sampled. The LTP is 1 km off the lakes western shoreline near Homewood, CA. Despite its proximity to shore, it is still in 125 m of water and experiences little if any littoral influence. Sampling at this station allows for greater spatial resolution to be achieved in the upper part of the water column. Its location was selected as it represented the station that was closest to the spatial mean following a synoptic survey conducted in the 1960s. In general, the two stations give similar result, although the index station displays greater temporal variability due to internal wave impacts. This variability is important to be aware of, and to track into the future as it is likely to change with climate change impacts.

In one of the more recent reviews and reductions of monitoring frequency, it was agreed with TRPA that each site (MLTP and LTP) be monitored monthly in a staggered fashion, so effectively lake water samples are taken every 2 weeks (biweekly). Previously water sampling had taken place every 10 days at the LTP and monthly at the MLTP, The LTP was still monitored using instruments every 10 days, but actual water sampling (and the subsequent laboratory chemistry) was only done monthly.

**Table 1.** Annual sampling at Lake Tahoe Index Station.

| **Index Monitoring Station** | | |
|---|---|---|
| **Parameter** | **Sampling Location in Water Column** | **Sampling frequency** |
| Secchi Depth | - | Bi-weekly (24 readings/year) |
| PAR (Vertical Extinction Coefficient) | Continuous profile, measurements starting > 1m depth | Bi-weekly (24 readings/year) |
| Temperature | Continuous Profile | Bi-weekly (24 readings/year) |
| Specific Electrical Conductance (µmhos per cm at 20° c, sec) | Continuous profile | Bi-weekly (24 readings/year) |
| Dissolved Oxygen | Continuous profile | Bi-weekly (24 readings/year) |
| In situ Fluorescence – relative abundance of phytoplankton algae | Continuous Profile | Bi-weekly (24 readings/year) |
| Turbidity | Continuous Profile | Bi-weekly (24 readings/year) |
| Beam attenuation | Continuous Profile | Bi-weekly (24 readings/year) |
| Nitrate | 13 depths (0, 2, 5, 10, 15, 20, 30, 50, 60, 75, 90, 105m) | Once monthly (12 samples at each depth/year) for a total of 72 samples/year |
| Total Hydrolyzable (soluble) Phosphorus | 13 depths (0, 2, 5, 10, 15, 20, 30, 50, 60, 75, 90, 105m) | Once monthly (12 samples at each depth /year) for a total of 72 samples/year |
| Phytoplankton Chlorophyll *a* | 6 depths (5, 20, 40, 60, 75, 90) and a composite | Once monthly (12 samples at each depth/year). 84 samples/year |
| Primary Productivity | 13 depths (0, 2, 5, 10, 15, 20, 30, 50, 60, 75, 90, 105m) | Once monthly (12 samples at each depth/year) for a total of 156 samples/year. |
| Algal speciation and enumeration | 6 depths (5, 20, 40, 60, 75, 90) and a composite | Once monthly (12 samples at each depth/year). 84 samples/year |
| Particle Enumeration (<16 mic.) | 13 depths (0, 2, 5, 10, 15, 20, 30, 50, 60, 75, 90, 105m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Particle size distribution | Continuous profile to 100 m depth | Monthly (12 profiles/year) |
| Total Inorganic Carbon (TIC) | 13 depths (0, 2, 5, 10, 15, 20, 30, 50, 60, 75, 90, 105m) | Once monthly (12 samples at each depth /year) for a total of 72 samples/year |

**Table 2.** Annual sampling at Lake Tahoe MLTP Station.

| **Midlake Monitoring Station** | | |
|---|---|---|
| **Parameter** | **Sampling location in water column** | **Sampling frequency** |
| Secchi Depth | - | Once monthly (12 readings/year) |
| PAR (Vertical Extinction Coefficient) | Continuous profile, measurements starting > 1m depth | Monthly (12 profiles/year) |
| Temperature | Profile | Once monthly (12 profiles/year) |
| Specific Electrical Conductance (µmhos per cm at 20° c, sec) | Continuous profile | Monthly (12 samples/year) |
| Dissolved Oxygen | Continuous profile | Monthly (12 profiles/year) |
| In situ Fluorescence – relative abundance of phytoplankton algae | Continuous Profile | Once monthly (12 profiles/year) |
| Turbidity | Continuous Profile | Once monthly (12 profiles/year) |
| Beam attenuation | Continuous Profile | Once monthly (12 profiles/year) |
| Total nitrogen | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Nitrate (used to also calculate Dissolved Inorganic Nitrogen) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Ammonium (used to also calculate Dissolved Inorganic Nitrogen) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Kjeldahl Nitrogen (TKN) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Hydrolyzable (soluble) Phosphorus | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Phosphorus | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Particle Enumeration (<16 mic.) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Particle size distribution | Continuous profile to 100 m depth | Monthly (12 profiles/year) |
| Dissolved Phosphorus (DP) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Reactive Phosphorus (TRP) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Carbon Hydrogen Nitrogen (CHN) | 11 depths (0, 10, 50, 100, 150, 200, 250, 300, 350, 400, 450m) | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |

**Atmospheric Modeling**

Limited atmospheric sampling takes place at the MLTP. (Atmospheric sampling had previously taken place at two land stations as well, but those sites were discontinued for lack of funding several years ago.)

**Table 3. Atmospheric Pollutant Deposition Monitoring Data**

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| Dissolved Inorganic Nitrogen | Midlake | Bi-weekly (at least 24 readings/year) |
| Total nitrogen | Midlake | Bi-weekly (at least 24 readings/year) |
| Soluble reactive phosphorus | Midlake | Bi-weekly (at least 24 readings/year) |
| total phosphorus | Midlake | Bi-weekly (at least 24 readings/year) |

**Periphyton Monitoring**

UC Davis has conducted periphyton monitoring in Lake Tahoe since 1982. Monitoring occurred for select periods in the 1980s (1982-85) and 1990s (1989-93). Near-continuous monitoring has occurred since 2000 with a one-year gap in 2004. Periphyton monitoring has primarily focused on measuring levels of algal biomass (as chlorophyll *a*) at six to ten "routine" monitoring sites around the lake. Samples of attached algae for measurement of biomass have been collected from natural rock surfaces at 0.5 m below the water level at the time of sampling. The monitoring frequency has varied from as few as three samples per year to as many as fifteen in a year.

The current (2016-2019) monitoring entails collection of biomass samples five times per year from nine sites with three of the five samplings done during the spring when periphyton biomass typically exhibits a peak. This monitoring provides information on levels of periphyton around the lake. In addition, once each spring an intensive synoptic sampling of approximately 40 additional sites is completed. This synoptic sampling is timed to occur when periphyton biomass is believed to be at its spring peak. This spring synoptic monitoring includes collection of biomass samples (chlorophyll a) at a sub-set of the sites, as well as a rapid assessment method referred to as the periphyton biomass index (PBI). The synoptic monitoring essentially provides a "snapshot" of periphyton distribution at a large number of sites around the lake close to the time of peak annual biomass.

In July 2019 the monitoring will change to sampling at 3 depths, to better characterize the differences between the two distinct population types. Sampling will also be spread out more to capture summer growth as well.

**Table 4. Periphyton (attached algae)**

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| PBI, AFDW, Chlorophyll *a* | Pineland, CA | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Rubicon Pt, CA | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Sugar Pine Pt., CA | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Tahoe City, CA | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Dollar Pt., CA | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Incline West, NV | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Zephyr Pt, NV | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Incline Condo, NV | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Sand Point, NV | 5 times/year |
| PBI, AFDW, Chlorophyll *a* | Deadman Pt., NV | 5 times/year |

**Nearshore Monitoring**

Real-time monitoring of the Nearshore (littoral zones) was commenced by UC Davis in 2014. The project was initiated through funding by private property owners, although two stations have subsequently been funded by the Lahontan Regional Water Quality Control Board.

**Table 5. Nearshore Water Quality Network**

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Tahoe City, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Dollar Point, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Tahoe Vista, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Sand Harbor, NV | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Glenbrook, NV | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Timber Cove, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Camp Richardson, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Rubicon, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Meeks Bay, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Homewood, CA | Continuously (every 30 secs) |
| Water temp., elec. cond., chlorophyll, turbidity, DO, CDOM, wave height | Cascade Lake, CA | Continuously (every 30 secs) |

**Meteorological Monitoring**

Meteorological data at the shoreline of Lake Tahoe or on the lake itself was commenced by UC Davis in 1998. These data are critical for the interpretation of water quality measurement data, the running of numerical models, and public safety. In 2002 NASA/JPL equipped four mid-lake buoys with meteorological sensors. Currently there are 6 dock stations, and 6 buoy stations. Funding is from UC Davis and NASA/JPL. Breaks in funding for significant periods has meant that there are multiple data gaps (due to instrument failure, lack of servicing and calibration etc.). Additionally, the age of many of the instruments is such that they urgently require replacement.

**Table 6. Meteorological Data Network (and near-surface temperature monitoring)**

| Parameter | Sampling Location | Sampling frequency |
| --- | --- | --- |
| Wind speed, wind direction, air temperature, relative humidity, precipitation, SW radiation, LW radiation | USCG Station, Tahoe City, CA | Every 10 minutes |
| Wind speed, wind direction, air temperature, relative humidity, precipitation | Tahoe Vista, CA | Every 10 minutes |
| Wind speed, wind direction, air temperature, relative humidity, precipitation | Sunnyside, CA | Every 10 minutes |
| Wind speed, wind direction, air temperature, relative humidity, precipitation | Cave Rock, NV | Every 10 minutes) |
| Wind speed, wind direction, air temperature, relative humidity, precipitation | Timber Cove, CA | Every 10 minutes |
| Wind speed, wind direction, air temperature, relative humidity, precipitation | Rubicon, CA | Every 10 minutes |
| Wind speed, wind direction, air temperature, relative humidity | Buoy TDR1, CA | Every 2 minutes |
| Wind speed, wind direction, air temperature, relative humidity. | Buoy TDR2, CA | Every 2 minutes |
| Wind speed, wind direction, air temperature, relative humidity. Water temperature at depths 0.5, 1, 1.5, 2, 3.0, 4.0, 5.0, 5.5 m. | Buoy TB1, CA | Every 2 minutes |
| Wind speed, wind direction, air temperature, relative humidity. Water temperature at depths 0.5, 1, 1.5, 2, 3.0, 4.0, 5.0, 5.5 m. | Buoy TB2, CA | Every 2 minutes |
| Wind speed, wind direction, air temperature, relative humidity. Water temperature at depths 0.5, 1, 1.5, 2, 3.0, 4.0, 5.0, 5.5 m. | Buoy TB3, CA | Every 2 minutes |
| Wind speed, wind direction, air temperature, relative humidity. Water temperature at depths 0.5, 1, 1.5, 2, 3.0, 4.0, 5.0, 5.5 m. | Buoy TB4, CA | Every 2 minutes |

## Bottom Dissolved Oxygen Monitoring

A thermistor chain with a bottom dissolved oxygen sensor has been operating in approximately 460 m of water off Glenbrook, NV, since 2010. A real-time thermistor chain and bottom DO sensor has been operating in approximately 120 m of water off Homewood since 2013. Lack of funding has resulted in nearly all the thermistors at Homewood currently being out of operation, although bottom DO and temperature are still being recorded. The Glenbrook thermistor chain is also in need of replacement of several sensors.

**Table 7. Continuous pelagic temperature and DO sampling**

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| 18 hi-accuracy temperature loggers at heights above the bottom of 5, 20, 25, 30, 40, 60, 100, 120, 160, 200, 240, 280, 320, 360, 400, 440, 460 m. Conductivity, temperature, depth, dissolved oxygen sensor at 0 m off the bottom. | Off Glenbrook, NV, in 465 m water depth | Every 30 s for temperature. Every 10 min. for bottom C, T, D, DO |
| 16 hi-accuracy temperature loggers at heights above the bottom of 0, 2, 5, 10, 20, 30, 40, 50, 59, 69, 79, 88, 98, 108, 109, 110 m. Dissolved oxygen sensor at 0 m off the bottom. (Note – most of the temperature sensors are currently non-functional) | Off Homewood, CA, in 115 m water depth | Every 30 s. |

## Stream Monitoring

The LTIMP tributary monitoring program began in 1979 to address the decline in lake clarity for Lake Tahoe. The monitoring program, in its current form, began in 1988 as a cooperative program between the U.S. Geological Survey (USGS), the Tahoe Regional Planning Agency (TRPA), and the University of California, Davis (UCD). It was designed specifically to assess and document the loading contributions of sediment and nutrients (nitrogen and phosphorus) to the lake from its tributaries.

There were originally 7 primary sites and water quality at locations upstream of urban development at 10 secondary sites. Currently, the monitoring program includes just 7 primary streamflow and water quality sites in California and Nevada.

**Table 8. Streamflow measurement**

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Ward Creek, CA | Approximately 25 samplings per year for water quality variables. |
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Blackwood Creek, CA | Approximately 25 samplings per year for water quality variables. |
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | General Creek, CA | Approximately 25 samplings per year for water quality variables. |
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Upper Truckee River, CA | Approximately 25 samplings per year for water quality variables. |
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Trout Creek, CA | Approximately 25 samplings per year for water quality variables. |

| Parameter | Sampling Location | Sampling frequency |
|---|---|---|
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Third Creek, NV | Approximately 25 samplings per year for water quality variables. |
| Continuous streamflow, nutrients (TN, TKN, NO3, NO2, OP, TP), fine sediment, SSC. Continuous turbidity and water temperature | Incline Creek, NV | Approximately 25 samplings per year for water quality variables. |

### Stormwater Monitoring

Stormwater monitoring is currently being conducted by several Agencies. Interactions of Science Institutions with these monitoring activities have been limited.

### Remote sensing

Remote sensing in various forms is being utilized by several institutions, particularly for the conditions of the Nearshore and the watershed. Much of the data collected of Lake Tahoe by satellite platforms (e.g. Landsat, MODIS, ASTER, AVHRR) have not been fully examined.

**Linking Science to Action: A framework to advance science-based management for Lake Tahoe – Phase 1**

January 24, 2019 v3

Prepared by the Science to Action (S2A) subcommittee: Alan Heyvaert (DRI), Geoffrey Schladow (UCD), Michael Dettinger (USGS), Ramon Naranjo (USGS), and Steven Sadro (UCD).

***Note:*** *This document is a subcommittee product for the Tahoe Science Advisory Council (TSAC). It does not represent consensus or endorsement by the full Council. Rather this is intended to inform discussion and continued development toward a science program focused on Lake Tahoe clarity and lake conditions. A broader discussion on budgets, topics and priorities will engage the full TSAC, with agency feedback and external peer-review, during Phase 2 of this science planning effort.*

## Executive Summary

Lake Tahoe is currently undergoing unprecedented change due to a number of driving factors, the largest of which is the changing climate. The signs of this are unmistakable in the data record, with air temperatures (measured since 1910) and water temperatures (measured since 1968) rising at an accelerating rate (State of the Lake Report, 2018). These changes are already producing profound impacts, including:

1. An unabated decline in summer clarity;
2. Lengthening of the lake's thermal stratification period, which has reduced lake mixing while increasing the concurrent threat of deep-water hypoxia (i.e. dead zones) in Lake Tahoe;
3. A reduction of snow accumulation relative to rain along with earlier peak streamflow runoff is contributing to ecological and clarity changes;
4. Opportunities for new invasive species, as well as the loss of native fish and shifts in other aquatic species important for the lake ecology.

The clarity results of 2017, which prompted this review, are a clear signal of these changes. The worst clarity ever recorded was preceded by one of the longest and driest droughts on record, which was ended by an extreme winter. While 2017 may be considered an anomalous year, such anomalies will increasingly become the norm. And while the current lake monitoring program could largely explain the events of 2017, our current tools and models are no longer adequate to help guide future management actions with the necessary confidence.

In fact, according to the initial findings of a multi-institutional vulnerability assessment for the Lake Tahoe basin, both droughts and peak stream flows of this magnitude will become more common in the coming decades (CTC 2019). For example, peak flows may occur as much as five months earlier, and flood flows typical of a 100-yr storm may occur every 5-10 years.

In light of these unprecedented challenges, the Tahoe Science Advisory Council (TSAC) recommends that the basin's scientific and management institutions, through the Bi-State Executive Committee, partner in developing and implementing a new Climate Response Action Framework for Tahoe (CRAFT). As recommended by the Lahontan Water Board and NDEP in the *Draft* 2018 *Findings and Program Recommendations Memo* for the Tahoe Total Maximum Daily Load (TMDL) Program, this effort must be closely aligned with the established TMDL program, and with ongoing efforts to address nearshore water quality.

Towards that end, to support the lake's iconic status and its multi-billion dollar economy, the TSAC recommends three concurrent strategies over three timescales:

**Immediate actions (2019)**: An annual data synthesis and early assessment briefings from workshops hosted by TSAC in March or April of each year focused on the analysis of ongoing data collection and discussion of findings pertaining to lake conditions and clarity.

**Near-term actions (2019–2021):** A comprehensive update of the Lake Clarity Model, as recommended by the *TMDL Recommendations Memo*. This will require a series of focused studies, along with changes in long-term continuous monitoring programs, to develop an informed understanding of the feasibility of meeting the Clarity Challenge by 2026 and maintaining nearshore water quality in the face of rapidly changing environmental conditions. Some aspects of the monitoring initiated during this period may well need to be maintained in the long term.

**Longer-term actions (2020–):** Development and implementation of an integrated, sustainable program for understanding and communicating the health of the lake and its watershed in the context of a formal, coordinated, science-based Climate Response Action Framework for Tahoe (CRAFT). This will include developing a mechanistic understanding of how Lake Tahoe will change with a new climate regime, supported by appropriate modeling tools, data acquisition and analyses, and recommendations for management options needed to address lake basin response to climate change.

## I. Introduction and Summary

The annual average water clarity of Lake Tahoe in 2017 was the lowest on record since standardized Secchi depth measurements began in 1968, despite a run of recent years during which annual Lake clarity had stabilized (Figure 1). This result prompted a request of the Tahoe Science Advisory Council (TSAC) from the Bi-State Executive Committee to review relevant factors that may have contributed to this outcome. The request was framed around ten questions posed in a June 12, 2018 letter from Secretary John Laird (CA Natural Resources Agency) and Director Bradley Crowell (NV Department of Conservation and Natural Resources), co-chairs of the Bi-State Executive Committee.

The TSAC draft response to these ten questions concluded that the available monitoring data could in large part inform relevant factors contributing to the low 2017 clarity observations (see Attachment 1). It was also clear, however, that some specific questions could not be answered with the existing information, such as:

- *How much worse might clarity be today had investments in the EIP and the TMDL not been made?*
- *Do 2017 sources of pollutant loads differ from those identified in the TMDL*?
- *What local or regional impacts are causing the greatest impacts and/or pose the largest threat to protecting the Lake and surrounding Tahoe Basin ecosystem?*

Additional questions also became evident in the context of this review, for example:

- *How should basin planning and management efforts be adapted to account for likely climate change impacts on lake clarity and other ecosystem issues?*
- *What are the linkages between mid-lake clarity changes, nearshore ecosystem changes, and landscape management strategies?*

The Bi-State Executive Committee charged the TSAC to develop recommendations for an applied research and monitoring framework that supports basin planning and management. A Council subcommittee has examined the existing science efforts, evaluated options, and has developed the recommended framework described below. Our objective was to develop an applied science framework that is responsive to shifting conditions and provides "actionable science" information that agencies can use to evaluate and adapt relevant management policies and strategies.

This framework emphasizes factors affecting lake clarity and documents a preferred approach for linking science to management decisions and actions, along with tracking the resulting outcomes. Lake clarity naturally integrates responses to changing conditions across watershed, airshed, climate and lake domains, and it is the longest standing metric of the Tahoe environment. Understanding the factors that affect lake clarity necessarily includes identifying, tracking and evaluating relevant processes and conditions in these other domains, but lake clarity serves as the organizing principle.

Science has historically worked with resource management agencies to identify and help develop solutions for emerging environmental problems at Lake Tahoe (e.g. LRWQCB and NDEP, 2008; Hymanson and Collopy, eds. 2010; Heyvvaert et al., 2013). In an era of potentially unprecedented environmental change from growing climate and demographic stress, we anticipate substantial impacts to lake condition and clarity. If adopted, the recommendations in this document will establish a framework for research, monitoring and communications between science institutions and agency partners that will provide the information and context for a better understanding of the factors driving changes in Lake Tahoe clarity and lake conditions.

This document is issued as Phase 1 recommendations for the Science to Action framework. It is presented for further consideration and feedback prior to commencing onto Phase 2 of this planning effort, which will define the specific actions and identify the resources needed to support these adjustments to current and future programs at Lake Tahoe.

***The Framework for Science to Action***

Expected climate change impacts on the basin and the lake indicate the urgency of a need to change the model for interaction of science and management (CTC 2019). Examples of changes that would elevate management concerns include an anticipated five-month advance in peak stream flow, floods of the magnitude of 1997 becoming the "ten year storm" standard in coming decades, and unprecedented changes in lake warming and mixing. While clarity in 2017 was considered anomalous in our review relative to the general trend (see Attachment 1), these anomalies will soon become more frequent.

This framework describes a three-tiered approach structured to address information needs for multiple purposes operating across a range of spatial and temporal scales. This includes scientific assessment for reporting on status and trends of lake condition, research on the processes and drivers affecting lake conditions, and tracking performance measures that assess outcomes resulting from management actions.

1) Mid-Year Science Synthesis and Briefing
There is a need for more frequent reporting of current hydrologic, climate and lake conditions as they develop and near term forecasts of water clarity and lake condition for the duration of the year. We recommend a mid-year briefing around March or April of each year based on the analysis of ongoing data collection and discussion of findings from a focused workshop hosted by TSAC This would be modeled after the successful Winter-Weather Outlook Workshop that California's Department of Water Resources organizes each fall. This annual mid-year lake condition briefing would communicate developing lake status and trends information to the Tahoe Interagency Executives Steering Committee and the Bi-State Executive Committee.

2) Science for the Near-Term / Clarity Challenge
The Tahoe TMDL program is designed to achieve an interim lake clarity goal by 2026 (the Clarity Challenge). The subcommittee recommends several focused studies along with changes in long-term continuous monitoring programs to develop an informed understanding of the feasibility of meeting the Clarity Challenge in the face of rapidly changing environmental conditions. These science investments would aim to confirm whether current actions are still consistent with lake clarity targets being achieved. This links with the *Draft Lake Tahoe TMDL Program Recommendations Memo* to directly engage with the TSAC to align scientific assessment of Lake Tahoe's clarity condition with the established TMDL program.

3) Science Investments for the Longer Term
The subcommittee recognizes that Lake Tahoe and its watershed will change in significant ways as its climate and hydrology evolve with the climate changes anticipated over the remainder of this century. The large size of the basin and lake, with the long residence time of lake water, and large year-to-year variability of the region's climate and hydrology combine to create response lags that can take can take years or decades to become evident. Further, the change-and-response paradigm is complex, with multiple interactions and potential thresholds. Therefore, the subcommittee recommends specific monitoring and modeling approaches to develop an integrated long-term approach for understanding and communicating the health of the lake and

its watershed. This links with the *Draft Lake Tahoe TMDL Program Recommendations Memo* to revisit the Lake Clarity Model to investigate and inform climate trend impacts on lake clarity.

## II. Background

Scientific information has long contributed to informed management decision-making at Lake Tahoe, since the early days of increasing urbanization when lake clarity decline was first documented following the 1960 Winter Olympics at Squaw Valley (Engineering Science, 1963; Goldman and Carter, 1965). That evidence ultimately led to exporting all sewage from the Tahoe Basin, rather than discharging it into the lake. Subsequent studies demonstrated a shift from nitrogen limitation of algal growth toward a phosphorus limited system, which focused more management efforts on land-use management and erosion control. More recently, science partners worked closely with resource management agencies to develop the TMDL program for restoring lake clarity (LRWQCB and NDEP, 2010).

TMDL research found that an approximate 70% reduction in fine sediment particles (FSP), accompanied by reductions in nitrogen and phosphorus of 10% and 35% respectively, would be necessary to achieve 100 feet of clarity (the current State and TRPA standard). The agencies also identified a 'Clarity Challenge', which is an interim planning milestone of ~80 feet annual average Secchi disk depth to be realized by 2026, and confirmed by continued monitoring over a five-year period as assurance that adequate progress has been achieved. This TDML research, monitoring, and program development took ten years (2001–2010) and cost an estimated $10 million.

Based on TMDL projections, restoring the lake's deep-water transparency to its the State and TRPA standard of 97.4 feet (29.7 meters) is anticipated to take 65 years. The TMDL Management System was developed to coordinate and guide adaptive management of the Lake Tahoe TMDL implementation over the long-term. Several existing monitoring programs support this effort (Appendix A), focused on:

- pelagic (deep-lake) clarity and algal productivity,
- nearshore lake conditions,
- urban runoff and best management practices,
- tributary runoff and pollutant loading to the lake.

The Environmental Improvement Program (EIP) represents capital investments needed to restore and maintain Tahoe Basin environmental qualities, including air, water and forest health, as well as scenic qualities, public access to recreational areas and fish and wildlife conditions. These environmental qualities are embodied in a set of TRPA threshold standards, of which mid-lake clarity is one. However, science-based integration across monitoring programs, thresholds and performance measures is incomplete, especially in terms of linking EIP performance measures to outcomes, leading to a disconnect in our scientific understanding of results from specific actions.

The science to action framework outlined below is designed to contribute timely and relevant information that identifies changing conditions and expected responses to management actions based on updated and contemporary scientific understanding of important processes and functions linked to changing climate conditions.

***Effects from Changing Climate***

The challenges that the EIP and TMDL have been designed to address are substantial and will require ongoing monitoring and adaptive adjustments as understanding of the lake system continues to evolve. However, in addition to these adjustments, climatic, demographic, technological, and resulting lake conditions are already changing significantly from conditions that prevailed at the time of initial TMDL science investment (e.g., Coats et al. 2006) with, for example, water temperatures at depth (400 m) in the Lake about 1ºF warmer, and with almost 10% more precipitation falling as rain rather than snow than in the 1970s (Coats et al. 2013).

Current projections of the impacts of future climate change show accelerating rates of change for multiple driving variables, all of which will drive the lake farther from the conditions observed and assumed in the TMDL science efforts completed in 2010. For example:

- Air temperatures in the basin are projected to warm by between about 4 and 7ºF in this century (Dettinger et al. 2018)
- Water temperatures are also projected to increase, with thermal stratification persisting for longer periods, and reduced deep lake mixing (e.g., Sahoo et al. 2013).
- Winds may decline by up to 10%, which would also affect stratification and mixing.
- Warmer air temperatures are projected to produce about 15 to 30% more precipitation falling as rain rather than snow, and to result in more winter snowmelt episodes and earlier spring snowmelt, so that streamflows will peak and then decline as many as four months earlier in the year.
- Annual precipitation is projected to become more erratic with more extreme droughts, storms and floods, affecting the magnitude, timing, and extremes of stream and groundwater inflows to the lake (Riverson et al. 2013) along with sediment and nutrient loading.
- Nearshore periphyton and metaphyton growth dynamics will respond to changes in groundwater fluxes and elevated water temperatures, affecting primary productivity and grazing rates.
- Warmer nearshore temperatures will also affect the lake's habitability for invasive species.
- Annual areas burned by wildfire in the Sierra Nevada are projected to increase by 40 to 80% (Dettinger et al. 2018).
- The possibility of achieving the Clarity Challenge by 2026 was questioned in one of the earlier climate change impact studies (Sahoo et al. 2013)

All of these changes will impact lake clarity as well as overall health of the lake and the health of the forests and streams, but the most threatening of projected changes will be a decline in the dissolved oxygen concentrations of deep waters in response to reduced deep mixing (Sahoo et al. 2016)

The decline in dissolved oxygen will have direct implications on the health of fish and invertebrates, and for chemical health of the lake. Low dissolved oxygen is known to cause internal loading of nutrients and heavy metals into the water column from bottom sediments. These changes will challenge the lake's clarity, but also extend far beyond clarity to threaten the condition of the total lake environment. In this context, different priorities may need to be given to the various contaminants that enter Lake Tahoe. For example, nutrients, which stimulate algal growth, may become important in ways not considered highly effective for the TMDL at the time of the TMDL science investment. These environmental changes are projected to accelerate in coming years in response to continuing and accelerating climate changes.

## III. Framework for Science to Action Plan

The objective of the proposed framework is to develop sufficient scientific understanding supported by observations and models to adequately predict and explain both near and long term changes in water clarity and lake condition. This framework will inform the selection and tracking of appropriate metrics and performance measures for assessing progress and for making timely adjustments to management actions on several time scales as the system continues to evolve in response to climate, demographic and technological changes.

### 1. Mid-Year Science Synthesis and Briefing

The record low clarity of Lake Tahoe in 2017 broke upon many in the basin as something of a surprise, seemingly bucking decades of efforts to control and reduce sediment and nutrient loads to the lake. This low clarity was almost certainly a reflection of record high precipitation and snowpack that winter, and a record warm summer that followed. Extra-large winter storms, extra-large winter runoff and spring snowmelt, and extra warm summers have in past years been followed by large drops in lake clarity, and all played a role in 2017's outcome. By spring, those large storms and snowpacks had already occurred, so a forecast of the 2017 clarity could already have been anticipated, and indeed was by many scientists.

To reduce surprises in the future, and to provide agency representatives with advance notice to identify meaningful actions, we recommend that TSAC orchestrate at least one mid-year science synthesis and lake briefing for agency representatives and the public each year. This would be modeled after the successful Winter-Weather Outlook Workshop that the California Department of Water Resources organizes each year.

- The annual mid-year lake briefing would be scheduled for March or April to communicate preliminary findings and provide advance notice on projected clarity and lake conditions to the Tahoe Interagency Executives Steering Committee and the TSAC Executive Committee.
- This briefing would focus specifically on provisional data pertaining to basin and in-lake conditions that are likely to affect clarity later that year, building on measurements of precipitation and snowpack that have accumulated by March or April, along with the maximum depth of mixing, patterns of stratification, and preliminary estimates of loading to different strata in the lake.

- In very wet or dry years, these briefings would likely focus on how clarity played out in past years that had reached similar conditions by March.
- In addition to avoiding surprises by providing earlier hydrologic outlooks as the year's clarity develops, it would provide a forum for considering possible agency actions in the current year. Taken together these briefings and deliberations would contribute early information useful in structuring the annual Findings and Program Recommendations Memorandum of the TMDL Management System.
- Multiple year analyses would be evaluated in the context of emerging patterns. For example, 2017 was not the largest percentage decline in lake clarity on record, since both 1982 and 1997 were greater, but the cumulative three-year clarity loss of 18 feet from 2015 through 2017 was unprecedented in the record. Climate change is likely to manifest with these types of patterns, and early briefings on extended changes would help prepare the management and science communities to address these issues in terms of appropriate planning and communication.

To make these synthesis briefings as useful as possible, an annual clarity-outlook workshop of a dozen or so relevant scientists (not unlike the annual Winter-weather Outlook Workshop that California's Department of Water Resources organizes each November) would be conducted a few weeks earlier, to draw in a full range of insights and forecasts regarding what conditions to date tell us about clarity outcomes for the rest of the year, based on findings from ongoing data analyses. Limnologists, hydrologists, and NWS and NRCS forecasters would be drawn into this workshop. These workshops, along with this new demand for more useful briefings to agencies and executives, are expected to drive development and testing of various forecast strategies, tools, and models (statistical and otherwise) in support of improved tracking and anticipation of developing clarity outcomes.

**2. Science for the Near Term and Clarity Challenge**

The Lake Tahoe TMDL program has an interim transparency target, the Clarity Challenge, of 23.5 to 24 meters (77.1–78.7 feet). This goal is to be achieved by 2026, and maintained (on average) through 2031, representing 20 years since the TMDL adoption in 2011.

There are a number of important science actions that should be initiated now to assure state, federal and public stakeholders that the clarity challenge remains attainable, or if not, what has changed to make it less attainable, and what would need to be done to bring it back on track. What distinguishes these proposed actions from those described in "Science for the Long-term" is that these recommendations will guide action over the next 4–8 years of the Clarity Challenge and will inform management issues aligned with the TMDL, such as the nearshore.

The TMDL program was based on the best available science and information at the time it was developed, from 2003–2010. It concluded that (1) fine sediment particles are primarily responsible for clarity loss, and (2) urban stormwater is the largest fine sediment particle source (LRWQCB and NDEP, 2010). Although we expect these conclusions are still valid today, other processes are beginning to change in the lake and the watershed that may shift the relative importance of other factors and the selection of management responses that address them. Most of these are linked to climate change, as precipitation and runoff patterns change, seasonal average temperatures increase, and internal lake dynamics change, although demographic patterns and technological advances will also affect environmental conditions and our ability to evaluate and develop appropriate responses.

Ultimately any changes to the existing program must align with the TMDL Management System and should be framed in the context of the following three questions:

*1) Are management actions focused on the right things?*

*2) Are the right management actions being taken?*

*3) Are the right things being measured to track progress and assess change?*

During its development the TMDL produced a useful table showing the different sources of clarity degrading pollutants, the relative contribution from each source, and a general assessment of the uncertainty associated with each. This TMDL product has been reproduced for reference in Figure 2. Note that these assessments of scientific confidence shown in the table were based on expert judgments at the time. It is common practice to review these types of assessments periodically, even when no change is evident. Qualitative confidence ratings are not scientific measurements or established fact. Rather, they are best professional judgments of that time, and those judgments can change as the science advances and new methods or technologies become available. This is why, for example, the international, national and state climate assessments are redone every five years or so, to reflect the evolution of scientific understanding and qualitative assessments on dominant drivers and projected impacts.

The science underlying the TMDL was conducted 10-20 years ago. Based on subsequent reviews it is generally considered to be as strong a science-based TMDL as any in the country. However, it would be beneficial to revisit the TMDL and the relative importance of the different factors contributing to loss of clarity in the context of ongoing climate change. The recommendations below address areas of specific importance for the Clarity Challenge and for other relevant conditions in the near-term.

1. Update the Lake Clarity model. The existing clarity model, developed as part of the TMDL studies, should be updated and re-applied to evaluate the benefits of past load reduction efforts in the context of the meteorological and hydrological conditions experienced since TMDL adoption in 2011. If the model output agrees with measurements to date, it would be a powerful validation of the model under some very extreme events (i.e., recent droughts and floods). If, on the other hand, the model fails it could indicate where the model assumptions require refinement, or what new processes may be more important now than when the science phase of the TMDL was undertaken. This is an important first step in preparation for reporting on the Clarity Challenge, as it would help to (1) confirm our general understanding of and ability to predict clarity; and (2) justify the recommendations for further data collection, model refinements, and/or management changes.

2. Integrated nearshore assessment. Conditions in the nearshore of Lake Tahoe are of great concern to the public and to resource management agencies. The subcommittee believes

that nearshore (littoral) conditions are particularly sensitive to climate change and that impacts will be greater and will occur more rapidly in the nearshore than in the mid-lake. Further, residents and visitors are in closer proximity to the nearshore than mid-lake areas, so these changes will be more evident. It is also an extremely important interface and filter between the watersheds and hydrology of the basin and the pelagic zone of the mid-lake. Although an increase in monitoring and scientific investigation of the nearshore has occurred over the last ten years, the subcommittee believes that significant gaps still exist in understanding of nearshore processes, particularly the dynamic linkages between the littoral and pelagic zones of the lake, clarity conditions, primary productivity in the nearshore, growth of periphyton and metaphyton, and impacts of aquatic invasive species. Establishment of routine sampling along the littoral zone is needed to improve the understanding of ecological and hydrological connections throughout the lake. This is particularly important as changing patterns in basin hydrology and temperatures are likely to manifest more quickly and evidently in the nearshore. Specifically, we recommend integrated implementation of the Nearshore Monitoring and Evaluation Framework (Heyvaert et al. 2013) combined with development of appropriate data analysis, modeling tools and linkage to mid-lake clarity.

3. Groundwater hydrology and loading update. Groundwater hydrology and nutrient loads were evaluated as part of the TMDL development, but important questions persist regarding the fate of nutrients from urban areas in lacustrine deposits and alluvial soils close to the lakeshore and streams. The TMDL Table 4-67 (Figure 2) shows that 36% of the orthophosphate (as SRP) and 17% of the dissolved inorganic nitrogen (DIN) loading into Lake Tahoe is derived from groundwater. Both of these nutrient species are bioavailable forms quickly taken up by algae, compared to broader categories of total phosphorus and total nitrogen. The TMDL groundwater loading estimates were based on surveys of available data from various studies in the basin available at the time, but most of the data derived from 32 groundwater sites sampled between 1990 to 1992 (Thodal 1997). The U.S. Army Corps of Engineers (2003) issued an assessment of these data along with their modeling results that estimated groundwater flows across five broad regions in the Tahoe Basin. Confidence assessment for these data, based on supporting lines of evidence and best professional judgment, ranged from 5 to 7 (on a scale of 1 to 10, with ten indicating high confidence). This was a moderate level of confidence at that time, but conditions have changed since the 1990s in terms of climate, hydrology and urbanization. Specifically, on-site infiltration and stormwater infiltration basins have become common best management practices (BMPs) for nutrient, pollutant and sediment load reductions to Lake Tahoe. These early studies were not designed to represent the effects from stormwater infiltration and mitigation in close proximity to receiving waters, and very limited fieldwork has been done since that time. A few studies have reported lower concentrations of nutrients in groundwater under stormwater treatment systems than in the up-gradient stormwater and groundwater samples (Green et al., 2008; 2NDNature, 2006), but these data typically represent detention basins or wet basins rather than BMPs designed specifically to function as infiltration systems. Thus, we do not yet know the extent to which stormwater pollutants are transported to the lake via groundwater from infiltration sites, nor whether improved maintenance requirements would ensure continued effectiveness. A study by Naranjo et al. (2019) on the west shore

of Lake Tahoe found that groundwater nutrient concentrations had increased from earlier measurements in the same area and showed that loadings attributable to groundwater discharge correlated to increases in algal biomass. This demonstrates the need to further characterize nutrient sources within the watershed, and the groundwater-surface water interactions and nutrient cycling impacts that may result from urban stormwater management practices and changing climate patterns.

4. Regional Stormwater Monitoring Program (RSWMP) enhancements. This monitoring program for urban stormwater pollutants has been in effect for several years to evaluate stormwater management practices and loading estimates. During this time methods have been developed and sites established to obtain relevant data on urban inputs to the lake, and to estimate the benefits of BMPs in terms of load reductions. This monitoring program provides data critical to validation of the pollutant load reduction model, which underpins the TMDL crediting program (TRCD 2018). The assumption is that these data are representative and appropriate for estimating changes in stormwater loading associated with basin-wide restoration projects and changes in watershed management, which may not be the case given the relatively small number of monitoring sites around the Tahoe Basin. Stormwater monitoring is inherently expensive, requiring durable and sophisticated field equipment for site installations, experienced personnel, and extensive laboratory sample processing and analyses. The certainty levels for TMDL estimates of nutrient loading from urban areas was generally moderate to high (ranging from 6 to 8, see Figure 2), based on a considerable amount of data collected during the TMDL scientific investigations phase, but confidence in estimates of FSP loading from urban and non-urban areas was lower (ranging from 5 to 6), due in part to the limited data set available at the time. We recommend a TSAC project working with RSWMP managers to review the goals of this monitoring program, to ensure the current sampling and evaluation methods meet those goals. It is possible there are opportunities to implement lower cost solutions for data acquisition and analysis. This would allow the program to expand beyond its seven sites currently monitored (eleven instrumented locations) to increase statistical representation and reduce uncertainty. We also recommend developing and evaluating a statistical sampling approach for monitoring culvert outfalls, since there are over 150 of these and they represent direct loading to the lake and the nearshore environment. This would be included as part of the existing RSWMP program, with an emphasis on flow and turbidity monitoring to assess FSP loading in particular. The TSAC Peer Review Committee would then submit the results for independent external review prior to implementation.

5. Statistical lake response assessments. It is anticipated that early-warning metrics derived from annual clarity briefing efforts could be formally embodied in a statistical forecasting tool. This is different from the TMDL Lake Clarity Model, which serves for long-term projections but does not provide annual forecasts. Such a tool would be of great value in its own right, since deviations between yearly forecasts and the actual measured clarity values would be an important indication of changes in lake condition from past states and would contribute to our understanding of system function and assessment of uncertainties.

6. Lake Tahoe tributary site installations. The Lake Tahoe Interagency Monitoring Program (LTIMP) has measured and documented sediment and nutrient (nitrogen and phosphorus) loadings to the lake from Tahoe basin tributaries since 1988. The long-term data set has been particularly useful for evaluating trends in nutrient concentrations and loads, for assessment of stream restoration projects, for post-fire evaluations, and for estimating the effects of intense precipitation and snow-melt runoff events. Over the years, budget constraints have eliminated several LTIMP monitoring stations, including upstream stations, which limits the ability to quantify pollutant loadings from upland areas versus urban areas. This limitation will become evident as extreme climatic and hydrologic conditions begin to occur more frequently under future climate conditions, and the snow-line moves up in altitude. Loading uncertainties associated with upland areas are the same as were determined for urban estimates (Figure 2), but we don't know if climate change effects on snowmelt timing and duration along with stream flows in excess of those used for the TMDL modeling will change the loadings of nutrients and FSP. Therefore, we recommend re-establishing three selected upland LTIMP monitoring stations for paired comparisons to downstream locations to specifically address this issue. Upland gauges should include real-time temperature and turbidity in addition to flow to be consistent with existing monitoring sites. Consideration should also be given to installing meteorological stations at these locations.

7. Annual assessment of progress. The Tahoe TMDL has adopted a science-based adaptive management approach for lake clarity management. Each year Lake Tahoe TMDL Management Agencies request stakeholders' assistance in evaluating TMDL Program operations and performance. When appropriate, the findings are paired with recommendations to adjust the TMDL Program, including management strategies and policies. We recommend an annual collaborative workshop where the monitoring data, annual science synthesis briefings and new research summaries are linked to programmatic and project information for evaluating progress toward achieving the lake quality goals. Together, agency and science representatives would examine overall progress with the crediting system, linkages to actual clarity and performance measures, validation of credits and accounting for climate change. These annual assessments would also provide an opportunity to raise awareness on emerging issues or anomalous patterns, such as enhanced extremes in hydrology or temperature, impacts from atmospheric deposition and wildfires, or changing phytoplankton communities in the lake.

## 3. Science for the Longer-Term

The response of Lake Tahoe to future changes, whether they be changes in how the lake and watershed are managed, or the impacts of changing climate and hydrology on the lake, cannot be confidently evaluated by short-term programs. Short-term programs are inadequate in this regard because of: (1) inherent interannual and multi-year variability of climate and associated hydrology; (2) the size of the system means that "real change" can take years or decades to become evident; (3) the change-and-response paradigm is complex, with intermediate lags and variables separating primary drivers and the ultimate responses; and (4) the lake itself is now undergoing fundamental alterations, meaning that an adaptive monitoring framework may be necessary. Therefore, we recommend development of an integrated program for evaluating and communicating the health of the lake and its watershed in the context of a formal science-based Climate Response Action Framework for Tahoe (CRAFT). This includes developing mechanistic understandings of how Lake Tahoe will change within a new climate regime, supported by the appropriate modeling tools, data acquisition and analyses, along with recommendations for management options needed to address lake basin response to climate change.

The following are new actions needed for understanding and predicting the long-term health of the Lake and its watershed. None of the recommended actions are part of any currently funded monitoring.

(1) Continuous lake profiling. Understanding and tracking the lake mixing processes are fundamental to predicting long-term clarity changes. This could minimally be accomplished with a single station at which the current water temperature profile and dissolved oxygen concentration at multiple depths (incl. bottom) are measured at high frequency (intervals between 1-10 minutes). The water temperature profile is a key indicator of the evolving lake physics and mixing, and the most efficient way to evaluate and understand the types of impacts climate change is having. Measuring pelagic and littoral lake currents is important as it is a direct measure of how the evolving temperature stratification is changing advective processes in the lake. Dissolved oxygen concentration is the one variable that has the potential to trigger a tipping point in the ecology of Lake Tahoe, leading to sudden eutrophication from internal nutrient loading. It will be driven in part by the changes in temperature stratification and advective (current) processes, so it is critical to describe the trends and characteristics of change in these variables. Otherwise, future changes in clarity and lake ecology may be ascribed erroneously to management defects rather than to these climatically driven changes, or vice versa. The information derived would support improved application of the lake clarity model under climate change conditions and interpretation of annual briefings, as well as the development of strategies to prevent lake hypoxia.

(2) Meteorological network for lake and watershed modeling. Modeling the predicted response of Lake Tahoe to changes in climatic drivers is critical for planning future management actions. However, this type of modeling effort involves climate data that is currently not being collected. The most important driving data for the lake clarity model are lake level wind measurements. We recommend developing a program of wind and meteorological data acquisition that augments existing sites and adds new installations as necessary to produce a data field sufficient for running the clarity model in a predictive framework for assessing impacts of climate change. At the same time, the basin-wide meteorological network available for watershed and runoff modeling and assessment should be evaluated for general utility in the face of coming climate changes.

(3) Landscape water budget for the Tahoe Basin. The water budget of the basin influences the health of its forests, streams and meadows, which feeds back to impacts on the basin's water budget. The hydrologic budget is predicted to change under a new climate (longer droughts, less snow/more rain, warmer temperatures, etc.), and with planned management actions (e.g. Lake Tahoe West and similar landscape-scale projects, future wildfires, etc.). As recommended above in the Clarity Challenge monitoring section,

upland stream gauges in key catchments will help to quantify water and nutrient budgets. This will also help anticipate and document climate change impacts across elevations in the Tahoe basin. Additionally, soil moisture, groundwater and nutrient monitoring within urban and upland environments would provide key information for quantifying subsurface changes in water and nutrient budgets. Monitoring of hydrological budget components (runoff, recharge, ET) should be designed to include locations near monitored streams, so that linkages between streamflow and groundwater can be better understood and evaluated with process-based models.

(4) Response to regional climate changes. Global and regional climate modeling is periodically updated and refined. Typically, such modeling upgrades occur at approximately 5-year intervals. It is important that Tahoe-specific downscaled climate models are updated on an equivalent basis, and then used to reevaluate likely changes in basin hydrology and impacts on lake processes through the use of both 1-D and 3-D models. Thus, as climate change continues to modify the system the science community can provide managers guidance on whether historic conditions still provide meaningful insight into current and future conditions, and provide technical updates that encompass the range of conditions as they develop.

(5) Aquatic species audits for Lake Tahoe. We anticipate that sensitive aquatic species will be placed at increasing risk with climate change, while some invasive species will acquire competitive advantages. The Lahontan cutthroat trout is one example of a native species at risk from climate change on which considerable resources are being invested for restoration. Although not directly related to lake clarity, the species shifts that are likely to occur could have peripheral impacts and would affect other aspects of lake condition that may be desirable features supporting the qualities that provide socio-economic benefit for the Basin. Thus, we recommend establishing a regular, systematic lake-wide monitoring program to document the size and distribution of existing populations of aquatic invasive plants, fishes, and clams. Establishing an early detection monitoring program for Lake Tahoe is a logical extension of the existing prevention program. Early detection monitoring would occur as a combination of periodic data evaluation produced by a lake-wide monitoring program, as well as the more targeted and frequent monitoring of high-risk areas (e.g., marinas).

## IV. Citations

California Tahoe Conservancy (CTC). 2019. Lake Tahoe Climate Change Resilience and Adaptation Action Plan. In development

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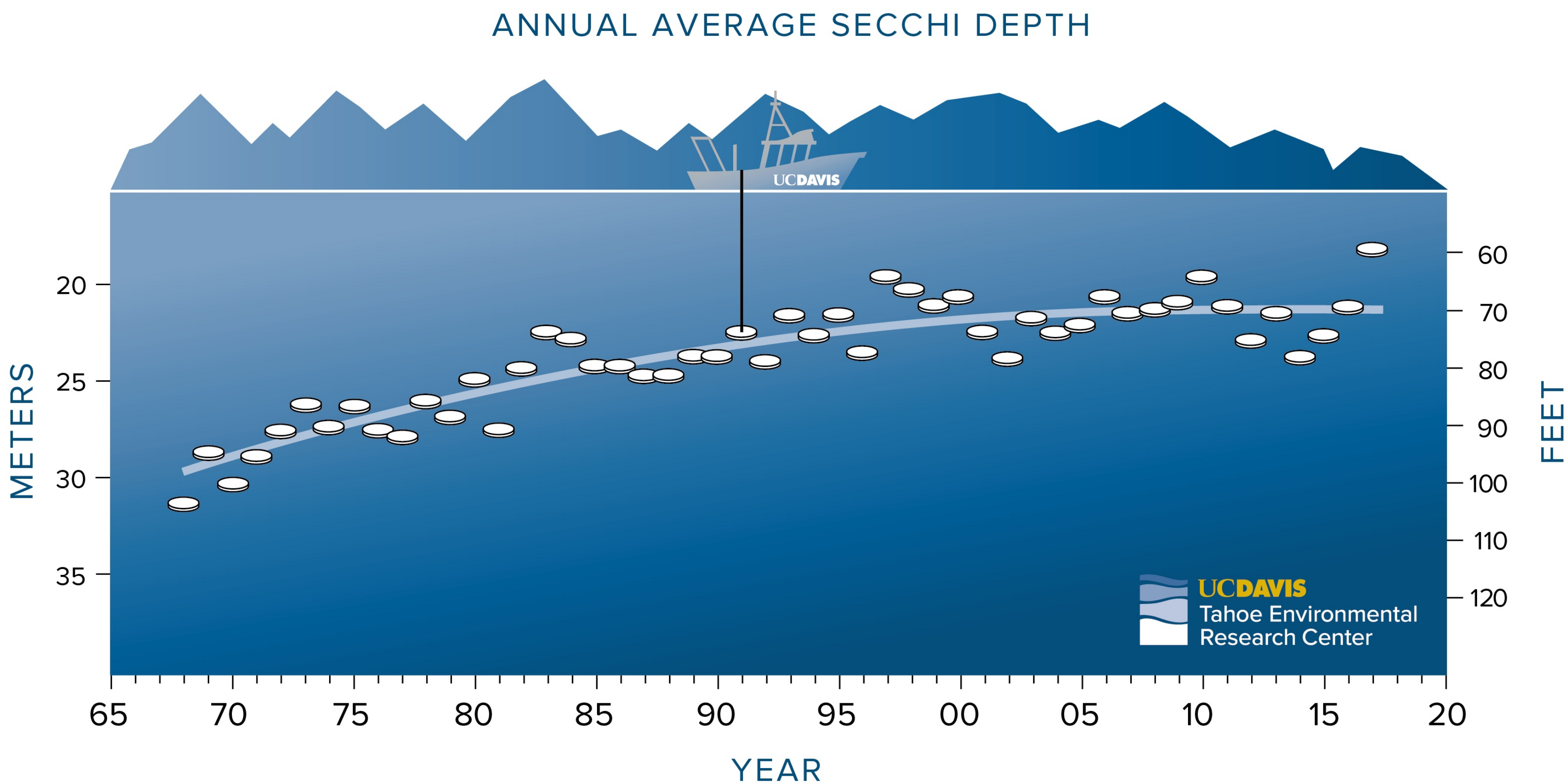



Figure 1. Annual average Lake Tahoe Secchi clarity measurements (TERC, 2018).

**Table 4-67. Nutrient and sediment loading budget for Lake Tahoe based on analyses for the five major sources. Discussion on period of record appears in accompanying text. DIN refers to dissolved inorganic nitrogen ($NO_3^-$, $NO_2^-$ and $NH_4^+$) while SRP refers to soluble reactive phosphorus. Approach used to estimate bioavailable nitrogen and phosphorus is detailed in accompanying text and in Chapter 5. All values (except for particle number) expressed as metric tons (1 metric ton = 1,000 kg) on an average annual basis. Percent values refer to relative portion of total basin-wide load. Numbered, colored boxes represent level of confidence based on supporting lines of evidence and best professional judgment. Red, yellow and green denote low, moderate and high levels of confidence as defined in text. Three numeric values are given for each of the major levels (1, 2, 3 or 4, 5, 6 or 7, 8, 9) depending on confidence within each major classification. Entries with two values (e.g. 6-7) represents a range.**

| | NITROGEN | | | | | | PHOSPHORUS | | | | | | SEDIMENT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DIN | % | | Total N | % | | SRP | % | | Total P | % | | TSS | % | | < 63 µm | % | | Particle # [e] | % | |
| **Upland Runoff** | | | | | | | | | | | | | | | | | | | | | |
| Urban | 8 | 4 | 7 8 | 63 | 16 | 7 8 | 2.3 | 17 | 6 7 | 18 | 39 | 7 8 | 5200 | 17 | 6 7 | 4430 | 31 | 6 7 | $34.80 \times 10^{19}$ | 72 | 5 6 |
| Non-Urban | 4 | 2 | 7 8 | 62 | 16 | 7 8 | 3.8 | 29 | 6 7 | 12 | 26 | 7 8 | 11700 | 40 | 6 7 | 4670 | 33 | 6 7 | $4.11 \times 10^{19}$ | 9 | 5 6 |
| **Stream Channel Erosion** | ND | NA | NA | 2 | <1 | 1 2 | ND | NA | NA | <1 | <1 | 3 4 | 5500 | 19 | 5 6 | 3800 | 27 | 5 | $1.67 \times 10^{19}$ | 4 | 5 |
| **Atmospheric Deposition** | 148 | 77 | 7 | 218 | 55 | 8 | 2.3 | 17 | 6 7 | 7 | 15 | 7 | NA | NA | NA | 750 [a] | 5 | 2 3 | $7.45 \times 10^{19}$ | 15 | 2 3 |
| **Groundwater** | 32 | 17 | 6 7 | 50 | 13 | 6 7 | 4.8 | 36 | 5 | 7 | 15 | 5 6 | NA [c] | NA | NA | NA [c] | NA | NA | NA [c] | NA | NA |
| **Shoreline Erosion** | ND [d] | NA | NA | 2 | <1 | 4 5 | ND [d] | NA | NA | 2 | 4 | 4 5 | 7200 [b] | 24 | 6 7 | 550 [b] | 4 | 5 | $0.11 \times 10^{19}$ | <1 | 4 5 |
| **TOTAL** | 192 | 100 | 7 8 | 397 | 100 | 7 8 | 13.2 | <100 | 6 | 46 | <100 | 7 | 29600 | 100 | 6 | 14200 | 100 | 6 | $48.14 \times 10^{19}$ | 100 | 5 |

ND = No data

NA = Not applicable

[a] Data availability and sampling methodology only allows for the ≤ 30 µm fraction to be included in this estimate.

[b] Sixty year mean from 1938-1998; each year considered the same (see text for further discussion).

[c] Assumed that fine particles affecting clarity (≥ 0.5 µm) did not have significant transport via groundwater.

[d] Measurements in Adams and Minor (2001) as total-P and total Kjeldahl-N only.

[e] Particles < 16 µm in diameter.

Figure 2. TMDL loading estimates and confidence levels associated with pollutant sources affecting Lake Tahoe clarity. This table is reproduced directly from the LRWQCB and NDEP Final TMDL Report, 2010.

**Appendix A.** Summary of current monitoring programs relevant to clarity and lake condition.

Several lake and water quality monitoring programs have been established at Tahoe over the years, beginning with lake and tributary monitoring, then adding stormwater monitoring, AIS and nearshore monitoring as these issues took on more importance. Implementation of these various monitoring efforts has occurred only when awareness of associated environmental impacts required informed management response.

The objective of this document is to begin to look at the scope of our current monitoring efforts and to identify opportunities for improving the acquisition of crucial information that will be needed to inform scientific and management planning for climate change. Much of the monitoring described below intersects with the existing TMDL and with the TMDL Management System. We do not make these recommendations because the TMDL is not working. Rather, it's because we believe climate change is going to have massive effects on how the system functions. Most of these recommendations, therefore, address issues and data gaps that will become apparent with climate change. We are trying to get ahead of that crisis by developing the data and scientific information that will be needed to inform policy and management decisions.

Current annual funding expenditures on monitoring programs associated with lake condition are summarized in Table A-1. This shows that more than one and a half million dollars are spent annually for this monitoring. Over 35% of this, however, comes in the form of matching contributions from UC Davis and the USGS in support of their scientific efforts with these programs. In aggregate, we must recognize that maintaining the long-term health of Lake Tahoe and its significant economic value in the face of challenging transformations beginning to manifest will require a much larger investment over the long-term.

TSAC recommendations listed below represent a framework for developing the knowledge base that will be needed to develop robust management strategies in anticipation of the changes that are coming, and to account for benefits expected from project implementation along with performance measures that will document progress toward achieving resource management goals. We expect this framework to be built out over some period of time, but that process must begin now and this document lays out a roadmap for beginning to move collaboratively in that direction with stakeholders and agency partners in the Tahoe basin.

**Table A-1.** Summary of annual funding currently spent on lake clarity and associated conditions.

| | Annual Funding Provided | | | | | | |
|---|---|---|---|---|---|---|---|
| **Monitoring Program** | **TRPA** | **LRWQCB** | **CTC** | **Local Gov** | **UC Davis** | **USGS** | **Total** |
| Tributaries (LTIMP) | $184,094 | $55,063 | $15,051 | -- | $69,135 | $152,200 | $475,543 |
| Mid-Lake (pelagic) | $173,329 | -- | -- | -- | $205,463 | -- | $377,000 |
| Near Shore (littoral) | -- | $197,217 | -- | -- | $139,180 | -- | $338,000 |
| Stormwater (RSWMP) | -- | -- | -- | $276,000 | -- | -- | $276,000 |
| Stormwater (RAM) | -- | -- | -- | $150,000 | -- | -- | $150,000 |
| Aquatic Invasives (AIS) | | | | | | | |
| **Total** | $357,423 | $252,280 | $15,051 | $426,000 | $413,778 | $152,200 | **$1,616,543** |

**1) Lake Tahoe Interagency Monitoring Program (LTIMP)**

Early LTIMP tributary monitoring began in 1979 to address the decline in lake clarity for Lake Tahoe. The monitoring program, in its current form, began in 1988 as a cooperative program between the U.S. Geological Survey (USGS), the Tahoe Regional Planning Agency (TRPA), and the University of California, Davis (UCD). It was designed specifically to assess and document the loading contributions of sediment and nutrients (nitrogen and phosphorus) to the lake from its tributaries.

Since its inception the LTIMP tributary data has been an essential part of integrated science in the Lake Tahoe Basin, having informed many scientific, management and regulatory activities. The most comprehensive use of LTIMP data was in development of the Total Maximum Daily Load (TMDL) for lake clarity. Local, state, and federal agencies, and academic institutions continue to use LTIMP data in a variety of applications, including assessments of compliance with water-quality standards, documentation of the effectiveness of stream-restoration projects, computation of streamflow statistics for the design of transportation infrastructure and channel restoration, estimation of erosional potential at current and previously restored reaches, and assessments on effects of wildfires, fuels reduction and forest management practices on watershed health.

Current research and management concerns are beginning to focus more on the effects of climate change, which will impact snowmelt timing and duration, magnitude and frequency of runoff, fine sediment and nutrient loadings to the lake, and success of Best Management Practices (BMPs) and the Environmental Improvement Program (EIP). Data from LTIMP will allow regulatory and scientific agencies to monitor evolving hydrological processes associated with climate change, the changing extent to which streams are controlling loading to the lake, and the changing ability of streams to serve as critical spawning areas for native fish. However, not all drainages entering Lake Tahoe are actively being monitored and over the last decade, many monitoring sites have been removed due to lack of funding. Further, declines in snow pack and persistent droughts caused by climate change may impart changes to runoff and associated nutrient and sediment loads in ungaged basins and upper tributaries in ways that remain uncertain.

LTIMP was originally designed to monitor water quality entering Lake Tahoe at 7 primary sites and water quality at locations upstream of urban development at 10 secondary sites. Data from the 7 primary sites provide estimates of sediment and nutrient loadings to the lake. These data represent an integration of the geology, soils, land-use, and the resultant effect on stream water quality from restoration and water quality improvement projects within the basin. The 10 secondary sites were located upstream of primary sites in either upland or urbanized reaches. Taken together, these data from the primary and secondary sites provided information on changing conditions in streamflow and water quality from both upstream and downstream land uses. Funding was discontinued for all secondary sites between 2010 and 2015. In 2018, the monitoring program includes 7 primary sites in California and Nevada (see LTIMP website).

Current monitoring at LTIMP sites include:

- **Streamflow Monitoring** – 9 surface water gages are in the LTIMP network to measure stream discharge. Seven gages are co-located at water-quality sampling sites, the Glenbrook site is used for NWS River Forecasting on the east shore of Lake Tahoe, and the Upper Truckee at Highway 50 gage is in the middle reach of the Upper Truckee for stream restoration projects. Continuous discharge is used to calculate loadings of nutrients and sediment and flood frequency calculations for stream restoration.
- **Water-Quality–** Seven primary water-quality sites are located in 7 watersheds near mouth of Lake Tahoe. Nutrients and sediment are sampled over the range of hydrologic conditions at these sites, totaling 21-25 samples per site annually. Water-quality analytes include total nitrogen, TKN, nitrate and nitrite, orthophosphate, total phosphorus, fine (<20 µm) sediment, and suspended sediment concentration.
- **Continuous Turbidity–** Turbidity and temperature are measured continuously at 5 sites, which will be used to more accurately calculate annual sediment load for TMDL regulations.

These data are used by the TRPA, LRWQCB and NDEP to assess water-quality standards and to estimate pollutant loadings as part of the TMDL Management System. Specifically, the resource management agencies use this information for the following purposes:

- Estimate stream flows
- Estimate pollutant loads reaching the lake
- Assess trends in flow-weighted pollutant loads
- Calibrate LSPC model for estimating basin-wide watershed loadings
- Assessment of whether tributary standards and thresholds being achieved

The data are also critical input drivers for the Lake Tahoe Clarity Model, and for assessing impacts on the nearshore lake water quality environment.

**Indicators and performance measures for monitoring**

Threshold indicators used for tributary monitoring are listed on the LT Info Threshold Indicators website for water quality as follows:

- Nitrogen concentration
- Phosphorus concentration
- Iron concentrations
- Suspended sediment concentration
- Nitrogen load
- Phosphorus load
- Suspended sediment load
- Fine sediment load

Performance measures listed in the 2017 TMDL Performance Report as relevant to stream channels and forested uplands are shown in Table A-2. These are considered output performance measures.

**Table A-2.** Performance measures relevant to LTIMP tributaries (from TMDL Report, 2017).

| PERFORMANCE MEASURE | SOURCE CATEGORY | DESCRIPTION |
|---|---|---|
| Miles of Roads Treated | Forest Uplands | Tracks the miles of permanent forest roads, paved or unpaved, that are decommissioned or on which stormwater best management practice (BMP) retrofits are implemented |
| Miles of Roads Inspected and Maintained | Forest Uplands | Tracks the miles of permanent forest roads, paved or unpaved, that are inspected and/or maintained to reduce stormwater pollution |
| Miles of Roads Created | Forest Uplands | Tracks the miles of permanent forest roads, paved or unpaved, that are created or added to a road owner's permanent road network |
| Acres of Disturbed Area Restored or Enhanced | Forest Uplands | Tracks the total acres of disturbed area, not including roads or Stream Environment Zones (SEZ), in the Forested Uplands that is restored, enhanced or created |
| Facilities with Stormwater Retrofits | Forest Uplands | Tracks the number of public facilities (as parcels) in the Forested Uplands that are retrofitted with BMPs to reduce runoff volumes of and remove fine sediment particles and nutrients therein |
| Linear Feet of Stream Channel Restored or Enhanced | Stream Channel | Tracks linear feet of stream channel restoration and enhancement |

Groundwater monitoring was conducted as part of the LTIMP until 2011. Threshold indicators used for groundwater monitoring are listed on the LT Info Threshold Indicators website for water quality as follows:

- Nitrogen discharge to groundwater
- Phosphorus discharge to groundwater
- Iron discharge to groundwater
- Turbidity discharge to groundwater
- Oil and grease discharge to groundwater
- Nitrogen discharge to the lake
- Phosphorus discharge to the lake
- Iron discharge to the lake
- Turbidity discharge to the lake
- Oil and grease discharge to the lake

**Recommendations**

Current annual funding for LTIMP monitoring and reporting is $475,543, of which $221,678 (47%) is provided as matching funds by UCD ($69,135) and USGS ($152,543). Additional funding should be allocated to support the following.

1) *Lake Tahoe tributary site installations.*
Over the years, budget constraints have eliminated several upstream LTIMP monitoring stations, which limits the ability to quantify pollutant loadings from undeveloped upland non-urban areas versus urban areas, especially as we begin to see more extreme climatic and hydrologic conditions. We do not know if climate change effects on the form of precipitation (rain vs. snow), peak streamflow timing and duration, along with stream flows in excess of those used for the TMDL modeling will change the absolute loadings of nutrients and FSP or their origin (urban or upland). This is critical information for determining the types of projects to which restoration funding should be allocated. Therefore, we recommend re-establishing three to four selected upland LTIMP monitoring stations to specifically address this issue (e.g. UTR, Blackwood, Trout, Ward, Incline or Third). Also, many agencies recognize estimates of sediment loads entering the lake are improved when calculated using continuous observations of stream turbidity; however, there are LTIMP sites where turbidity is not actively being measured (i.e. Incline and Third Creek) along with streamflow. It is important to use consistent methods at all gages to recognize deviations in loads caused by intense runoff events or extreme climate conditions. Thus, when measuring contributions of

from upland areas, proposed upland gauges should include real-time temperature and turbidity in addition to flow. Consideration should also be given to installing meteorological stations at these locations. Costs include streamflow, nutrient sampling and analysis, turbidity, temperature, and specific conductance. Data will be uploaded real-time and archived on NWIS.

2) *Landscape water budget for the Tahoe Basin.*
The water budget of the basin influences the health of the forests, and the ecology of streams and meadows, which in turn impacts the basin's water budget. This hydrologic budget will change with new climate trajectories given the predictions for longer droughts, less snow/more rain and warmer temperatures. Also influencing water budget components are forest management actions (e.g. Lake Tahoe West and similar landscape-scale projects) and wildfires. As recommended above, upland stream gauges in key catchments will help to quantify water and nutrient budgets. This will also help document climate change impacts at higher elevations, where some of the initial and most subtle changes are likely to occur. Additionally, soil moisture and nutrient monitoring is needed to provide key information for quantifying subsurface components of the budgets and their changes. Therefore, we recommend establishing transects of sites located in four drainages located in the north, south and east and west basin quadrants to evaluate changes in recharge associated with shifts in snow precipitation toward higher elevations. Where possible, these locations will be collocated with streamflow gages, so that the linkages between streamflow and groundwater could be better understood and evaluated with process-based models. Data will be uploaded and archived on NWIS.

3) *Groundwater hydrology and loading update.*
Groundwater monitoring used to be part of the LTIMP program, but funding was completely terminated in 2011. Groundwater hydrology and nutrient loadings were evaluated as part of the TMDL development, but important questions persist on the fate of nutrients in urban areas over lacustrine deposits and alluvial soils close to the lakeshore and streams. TMDL estimates show that 36% of the orthophosphate (as SRP) and 17% of the dissolved inorganic nitrogen (DIN) loading into Lake Tahoe is derived from groundwater. Both of these nutrient species are bioavailable forms quickly taken up by algae, compared to broader categories of total phosphorus and total nitrogen, which is both a nearshore and mid-lake problem. The TMDL groundwater loading estimates were based on surveys of available data from various studies throughout the basin at that time, and most of the data derived from 32 groundwater sites sampled between 1990 to 1992 (Thodal 1997). The U.S. Army Corps of Engineers (2003) issued an assessment of these data along with their modeling results that estimated groundwater flows across five broad regions in the Tahoe Basin. Confidence assessment for these data, based on supporting lines of evidence and best professional judgment, ranged from 5 to 7 (on a scale of 1 to 10, with ten indicating high confidence). This was a moderate level of confidence at that time, but conditions have changed since the 1990s in terms of climate, hydrology and urbanization. Specifically, on-site infiltration and stormwater infiltration basins have become common best management practices (BMPs) for nutrient, pollutant and sediment load reductions to Lake Tahoe. These early studies were not designed to represent the effects from stormwater infiltration and mitigation in close proximity to receiving waters, and very limited fieldwork has been done since that time. A few studies

have reported lower concentrations of nutrients in groundwater under stormwater treatment systems than in the upgradient stormwater and groundwater samples (Green et al., 2008; 2NDNature, 2006), but these data typically represent detention basins or wet basins rather than BMPs designed specifically to function as infiltration systems. Thus, we do not yet know the extent to which stormwater pollutants are transported to the lake via groundwater from infiltration sites, nor whether improved maintenance requirements would ensure continued effectiveness. A recent study demonstrated increased concentrations of dissolved phosphorus and nitrate in the lake attributable to groundwater discharge and correlated to increases in algal biomass in the nearshore area (Naranjo et al. 2019). Therefore, we recommend synoptic sampling of the 32 previously monitored LTIMP wells to examine changes since the last period of sampling, and a subset of be selected for annual monitoring. Costs include water level, field parameter monitoring (temperature, specific conductance, pH, dissolved oxygen) and nutrient sampling. Data will be uploaded and archived on NWIS.

4) *Response to regional climate changes.*
Landscape hydrology and lake models will be reapplied for new scenario assessments as downscaled global and regional climate models are periodically updated (every 3–5 years). This will provide managers with technical updates on predicted conditions scaled to regional climate change projections for the Tahoe basin.

**2) Mid-Lake (Pelagic) Monitoring**

Mid-lake monitoring was initiated by UC Davis in 1959. At that time, the goal was simply to document changing conditions in the lake that were attributed to unregulated development in the Tahoe basin. Funding precluded regular sampling, so the data from 1959 to 1968 is rarely reported (with the exception of primary productivity). In 1968 regular sampling was initiated and has largely continued to this day. The funding was a combination of TRPA and UC Davis funding. This 50-year data set represents the longest, most complete long-term data set for a lake in the western US, and as well as having fundamental importance for Tahoe, it is a resource for water resource management in the Sierra and the west.

Modifications were made along the way. For example, following rigorous statistical analysis it was concluded that some variables (e.g. primary productivity) were being monitored more frequently than was required to identify the important trends and that cost savings could be achieved by decreasing the frequency. There have been several cycles of review over the 50 years of monitoring, and it is considered unlikely that any substantial savings exist (without compromising the integrity of the data set). By contrast, over time it was found that new variables emerged as being important to monitor. An example of this is fine particle concentrations, which were only identified in 2000 as being the controlling variable for lake clarity at that time. It is possible that changing conditions may call for new variables to be added in the future.

The mid-lake monitoring occurs at two locations – the mid-lake (MLTP) station and the Index (LTP) station. The MLTP is near the deepest part of the lake (500 m) and is on the California-Nevada border. Sampling at this station allows for the entire water column to be sampled. The LTP is 1 km off the shoreline near Homewood, CA. Despite its proximity to shore, it is still in

125 m of water. Sampling at this station allows for greater spatial resolution to be achieved in the upper part of the water column. Its location was selected as it represented the station that was closest to the spatial mean, when a synoptic survey was conducted in the 1960s. In general, the two stations give similar results, although the index station displays greater temporal variability due to internal wave impacts. This variability is important to be aware of, and to track into the future as it responds to changes in climate conditions.

In one of the more recent reviews and reductions of monitoring frequency, it was agreed with TRPA that each site be monitored monthly in a staggered fashion, so that effectively water samples are taken every 2 weeks. Previously water sampling had taken place every 10 days at the LTP station. Subsequently, LTP was still monitored using instruments every 10 days, but actual water sampling (and the subsequent laboratory chemistry) was only done monthly.

**Table A-3.** Annual sampling at Lake Tahoe Index (LTP) Station.

| **Index Monitoring Station** | | |
|---|---|---|
| **Parameter** | **Sampling Location in Water Column** | **Sampling frequency** |
| Secchi Depth | -- | Bi-weekly (at least 24 readings/year) |
| Light Transmission (Vertical Extinction Coefficient) | Continuous profile, measurements starting > 1m depth | Once monthly (at least 24 profiles/year) |
| Specific Electrical Conductance (µmhos per cm at 20$^o$ c, sec) | At 15 meters | Once every other month (6 samples/year) |
| Dissolved Oxygen | Profile (to calculate profile average) | Once monthly (12 profiles/year) |
| Nitrate | 6 depths | Once monthly (12 samples at each depth/year) for a total of 72 samples/year |
| Total Hydrolyzable (soluble) Phosphorus | 6 depths | Once monthly (12 samples at each depth /year) for a total of 72 samples/year |
| Fluorescence – relative abundance of phytoplankton algae | Profile | Once monthly (12 profiles/year) |
| Phytoplankton Chlorophyll *a* | 6 depths | Once monthly (12 samples at each depth/year). 72 samples/year |
| Primary Productivity | 13 depths | Once monthly (12 samples at each depth/year) for a total of 156 samples/year. |
| Temperature | Profile | Once monthly (12 profiles/year) |

**Table A-4.** Annual sampling at Lake Tahoe MLTP Station.

| **Midlake Monitoring Station** | | |
|---|---|---|
| **Parameter** | **Sampling location in water column** | **Sampling frequency** |
| Total Nitrogen | At 15 meters | Once every other month (6 samples/year) |
| Nitrate (used to also calculate Dissolved Inorganic Nitrogen) | 11 depths | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Ammonium (used to also calculate Dissolved Inorganic Nitrogen) | 11 depths | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Hydrolyzable (soluble) Phosphorus | 11 depths | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Total Phosphorus | 11 depths | Once monthly (12 samples at each depth/year) for a total of 132 samples per year. |
| Fluorescence | Profile | Once monthly (12 profiles/year) |
| Secchi Depth | Profile | Once monthly (12 profiles/year) |
| Light Transmission (Vertical Extinction Coefficient) | Profile | Once monthly (12 profiles/year) |
| Temperature | Profile | Once monthly (12 profiles/year) |
| Dissolved Oxygen | Profile | Once monthly (12 profiles/year) |

In addition, limited atmospheric sampling takes place at the MLTP station.

**Table A-5. Atmospheric Pollutant Deposition Monitoring Data**

| **Parameter** | **Sampling Location** | **Sampling frequency** |
|---|---|---|
| Dissolved Inorganic Nitrogen | Midlake | Bi-weekly (at least 24 readings/year) |
| Total nitrogen | Midlake | Bi-weekly (at least 24 readings/year) |
| Soluble reactive phosphorus | Midlake | Bi-weekly (at least 24 readings/year) |
| Total phosphorus | Midlake | Bi-weekly (at least 24 readings/year) |

**Indicators and performance measures for monitoring**

The most important performance measure emanating from the lake monitoring is the Secchi depth. It was the reduction in Secchi depth from 1959 to 1997 that spurred the EIP and the TMDL, and the Secchi depth is the primary TMDL indicator. Though often maligned as just a single variable, it integrates the impact of many complex variables and has long been recognized by limnologists globally as being a very effective indicator of lake health and status.

However, while Secchi depth helps explain how the lake is changing over time, it cannot alone say why the lake is changing or give managers or decision makers the necessary information needed to differentiate between a range of actions.

The mid-lake monitoring program as currently designed tracks all the important variables that could affect lake clarity as well as a range of other conditions that threaten the lake. Two factors are important to realize:

1. Many of these other variables do not change monotonically each year, but can change in response to a number of factors. The low clarity of 2017 is a prime example, where the available data record could explain much of what was observed with clarity.
2. Because of Lake Tahoe's size, some changes play out over many years and decades. A short-term monitoring effort could well miss the underlying trend.

Physical parameters such as lake temperature are critical, since it controls water density and is the key variable for lake mixing. It also impacts metabolic rates, and ecological niches. Water temperature distribution is used to quantify the annual depth of mixing. Deep mixing is important for transferring oxygen to the bottom of the lake. A lack of bottom oxygen in the future could produce a tipping point or environmental threshold, where lake conditions suddenly shift and the lake is dramatically different from its previous state. As dissolved oxygen approaches zero, the lake becomes hypoxic and nutrients are released from the lake sediments at a rate that dwarfs current watershed inputs.

This lack of mixing also allows watershed-derived nutrients to build up in the lake. The lack of deep mixing in the last 7 years (the longest period on record) may be responsible for the evident increase in both nitrate and phosphorus in Lake Tahoe over the same period.

**Recommendations**

Current annual funding for pelagic monitoring and reporting is $384,546, of which $213,643 (56%) is provided as matching funds by UCD.

Additional funding should be allocated to support the following.

1) *Update the Lake Clarity Model.*
   The existing clarity model, developed as part of the TMDL studies, should be updated and re-applied to evaluate the benefits of past load reduction efforts in the context of the meteorological and hydrological conditions experienced since TMDL adoption in 2011. If the model output agrees with measurements to date, it would be a powerful validation of the model under some very extreme events (i.e., recent droughts and floods). If, on the other hand, the model fails it could indicate where the model assumptions require refinement, or what new processes may be more important now than when the science phase of the TMDL was undertaken. This is an important first step in preparation for reporting on the Clarity Challenge, as it would help to (1) confirm our general understanding of and ability to predict

clarity; and (2) justify the recommendations for further data collection, model refinements, and/or management changes.

2) *Continuous lake profiling.*
Temperature and dissolved oxygen are the critical factors affecting long-term lake health and clarity. Both of these factors and lake hydrodynamics are strongly affected by climate. It is essential to acquire the data and to analyze emerging patterns of changes in lake stratification, oxygen levels and hydrodynamics to inform the predictive models of lake function and response. With modern measurement methods these data will provide the information needed to develop management actions that will prevent dramatic changes from lake hypoxia, fish kills, internal loading, and species shifts.

3) *Meteorological network for lake and watershed modeling.*
Build out the existing set of meteorological stations to provide accurate lake level wind-field measurements, landscape precipitation and other metrics needed to inform finer scale model predictions of climate change impacts.

4) *Statistical lake response assessments.*
Data analyses and findings from annual briefing workshops will be incorporated into a statistical model that projects lake response in near-term conditions to dominant factors influencing lake clarity. This will yield advance notice of conditions to be expected during each water year, based on provisional data patterns developing through the year. This product will ultimately support the annual mid-year briefings and will provide quantitative evaluation of system functions and assessment of uncertainties.

**3) Nearshore (Littoral) Monitoring**

The nearshore environment is integral to lake function and health. It is the interface between the landscape and mid-lake environments, modulating and responding to changing conditions in the watersheds and in the lake. Growth of attached algae (periphyton) was one of the first indicators of cultural eutrophication in Lake Tahoe in the 1960s (Goldman 1967). The subsequent appearance of aquatic invasive species (AIS) in the nearshore, along with growth of suspended algae (phytoplankton), changes in nearshore clarity and in the biological community are manifestations of impacts due to anthropogenic factors and climate.

The nearshore is where visitors and residents most often interact with the lake. Thus, conditions here draw public attention when they appear to deteriorate. Since the nearshore of Lake Tahoe is expected to be particularly sensitive to climate change, a coordinated program of assessment and attribution is needed to determine when, where and why nearshore (littoral) conditions change.

In October 2013, the Desert Research Institute, University of California at Davis, and the University of Nevada at Reno issued the Lake Tahoe Nearshore Evaluation and Monitoring Framework Report (Heyvaert et al., 2013), representing the first comprehensive assessment of available information on the nearshore and an integrated strategy for continued monitoring evaluation. Building upon this report and recent monitoring, management partners in the Tahoe basin have been developing resources to support this effort, to enhance scientific understanding of nearshore processes, and to more effectively target management actions that will preserve nearshore conditions.

The nearshore report identified ten key metrics in four indictor categories as crucial for tracking nearshore conditions and for understanding changes over time:

- Light transmission and turbidity (nearshore clarity)
- Chlorophyll, phytoplankton and periphyton (trophic status)
- Macrophytes, macro-invertebrates and fish (community structure)
- Harmful microorganisms and toxins (conditions for human health)

To date, some components of the nearshore monitoring and assessment program have been implemented as pilot, demonstration or experimental projects, but full integrated implementation remains incomplete.

**Indicators and performance measures for monitoring**

Threshold indicators for the nearshore (littoral) zone of Lake Tahoe include:

- Nearshore attached algae
- Littoral nitrogen loading (from surface runoff, groundwater and atmospheric sources)
- Nearshore turbidity (with and without stream influence)
- Littoral phosphorus loading (effects on phytoplankton and periphyton)
- Littoral nitrogen loading (effects on phytoplankton and periphyton)
- Littoral iron loading (effects on phytoplankton and periphyton)

**Recommendations**

Current annual funding for pelagic monitoring and reporting is $338,000, of which $139,180 (41%) is provided as matching funds by UCD.

Additional funding should be allocated to support the following.

*Integrated nearshore assessment.*
Conditions in the nearshore are particularly sensitive to climate change, so impacts here will be greater, occur rapidly and be more evident to the public than changes in the mid-lake. Establishment of regular sampling along the littoral zone is needed to improve the understanding of ecological and hydrological connections throughout the lake. This is particularly important as changing patterns in basin hydrology and temperatures are likely to manifest more quickly and evidently in the nearshore. Specifically, we recommend integrated implementation of the Nearshore Monitoring and Evaluation Framework (Heyvaert et al. 2013) combined with development of appropriate data analysis, modeling tools and linkage to mid-lake clarity.

**4) Regional Stormwater Monitoring Program (RSWMP)**

The Lake Tahoe Clarity TMDL demonstrated from pilot monitoring that most of the lake clarity loss was due to fine sediment particle loading from urbanized areas (LRWQCB and NDEP, 2008), as well as a large proportion of the total phosphorus loading from urban runoff. Therefore, the Tahoe Regional Stormwater Monitoring Program was developed to support a range of purposes, including the Lake Tahoe Total Daily Maximum Load (TMDL) management system and the jurisdictional National Pollutant Discharge Elimination System (NPDES) for permit and Inter-local Agreement requirements. RSWMP was also introduced to support capital improvement effectiveness evaluations, Pollutant Load Reduction Model (PLRM) improvements, and continued scientific research on Tahoe basin urban stormwater issues.

The Tahoe RSWMP was developed over time, beginning with Phase I (2007–2011) that focused on producing the conceptual framework and the documentation needed for initiating a comprehensive stormwater monitoring program in the Lake Tahoe Basin. Led by Dr. Alan Heyvaert at the Desert Research Institute (DRI) and the Tahoe Science Consortium (TSC), a Core Working Group was assembled to develop the motivation and products needed to support a phased implementation. The Core Working Group consisted of eighteen individuals representing various interests, including regulatory agencies, funding groups, science community, and local and state implementing agencies at Lake Tahoe. Phase 2 (2013–2016) was orchestrated by the CA Tahoe Resource Conservation District (Tahoe RCD) and focused on design specifications for the RSWMP framework, including specific guidance on stormwater monitoring, analysis, data reporting and program organization, along with development of a comprehensive Tahoe RSWMP Data Management System (DMS). Phase III (2017–present), represents coordinated implementation of the program by the CA TRCD, working with agency and jurisdictional stakeholders, to establish appropriate monitoring sites along with continued support and development of improved methods for monitoring, data management, analysis and reporting.

The Tahoe RSWMP is now collecting information on urban stormwater runoff through a coordinated network of monitoring sites using consistent data collection, management, analysis and reporting formats. It reports out results for implementers to collectively fulfill California National Pollutant Discharge Elimination System (NPDES) permit requirements and Nevada Interlocal Agreement commitments, as well as the data needed by jurisdictions for the Lake Tahoe TMDL Crediting Program (Crediting Program), which was developed to track progress made toward achieving the TMDL clarity standard. The Crediting Program (LRWQCB and NDEP 2011) recommends using the urban hydrology and water quality Pollutant Load Reduction Model (PLRM) to estimate average annual pollutant loads from urban drainage catchments in the Tahoe Basin (NHC et al. 2009). Pollutant loading estimates derived from the PLRM are used by the Crediting Program to identify progress that local jurisdictions are making towards Lake Tahoe TMDL load reduction milestones. Longer term RSWMP data is used to refine PLRM predictions and for identifying status and trends in the watershed. Shorter term RSWMP studies identify performance characteristics of best management practices (BMPs) and support applied research on urban stormwater management.

Current RSWMP monitoring includes (Tahoe RCD, 2018):

- **Urban catchment sites** – Seven catchments are monitored for runoff and water quality characteristics. These catchments were chosen because of their direct hydrologic connectivity to Lake Tahoe, diversity of urban land uses, range of sizes, and a reasonably equitable distribution among the participating jurisdictions. Continuous monitoring sensors for bptj flow and turbidity have been installed at each site along with autosamplers. Data are collected and reported on discharge, turbidity, total nitrogen, TKN, nitrate and nitrite, total phosphorus, fine sediment particles (FSP), and total suspended solids.

- **BMP effectiveness sites –** Three different BMPs are monitored for performance evaluation of treatment effectiveness. These BMPs were selected for their potential efficacy in treating storm water runoff at Tahoe, the broad interest in their application and lack of conclusive data regarding efficiency, and the importance of determining maintenance intervals required to retain effectiveness). Continuous monitoring sensors for both flow and turbidity have been installed at each site along with autosamplers. Two monitoring stations are located at each site for assessing the difference between inflow and outflow characteristics. Data are collected and reported on discharge, turbidity, total nitrogen, TKN, nitrate and nitrite, total phosphorus, fine sediment particles (FSP), and total suspended solids.
- **Meteorological sites** – Six meteorological stations are located within or near each of the seven monitored urban catchments. Each station collects continuous data on a five or ten minute interval for precipitation and air temperature.

**Indicators and performance measures for monitoring**

Threshold indicators used for surface runoff monitoring are listed on the LT Info Threshold Indicators website for water quality as follows:

- Nitrogen concentration
- Phosphorus concentration
- Iron concentrations
- Suspended sediment concentration
- Total Nitrogen load
- Phosphorus load
- Suspended sediment load
- Fine sediment load

**Recommendations**

Current annual funding for RSWMP monitoring and reporting is $276,000, most of which is provided by jurisdictional implementers participating in the program for their permit compliance. An additional $150,000 is used for conducting Road Rapid Assessment Monitoring (RAM). Additional funding should be allocated to support the following.

*Regional Stormwater Monitoring Program enhancements.*
New methods and technology are available to improve the quality and utility of data produced for stormwater loading assessments, BMP performance accounting, and management practices. We recommend a TSAC project working with RSWMP managers to review the goals of this monitoring program, and to ensure the current sampling and evaluation methods meet those goals. There are new opportunities to implement lower cost solutions for data acquisition and analysis. This would allow the program to expand beyond its seven catchment sites currently monitored (eleven instrumented locations) and to increase statistical representation and reduce uncertainty. We also recommend developing and evaluating a statistical sampling approach for

monitoring culvert outfalls, since there are over 150 of these that discharge directly into the lake and the nearshore environment. This would be included as part of the existing RSWMP program, with an emphasis on flow and turbidity monitoring to assess FSP loading in particular. The TSAC Peer Review Committee would then submit the resulting recommendation for independent external review prior to implementation.

**5) The Tahoe Basin Invasive Species Program**

Monitoring and management of invasive species falls under the Environmental Improvement Program (EIP) focus area of Watersheds, Habitats, and Water Quality (see https://eip.laketahoeinfo.org/EIPProgram/Detail/4). The program addresses both terrestrial and aquatic invasive species. Invasive species pose a major threat to ecosystem health in the Tahoe Basin. Past resource management practices, including fire suppression, grazing, development, logging, and nearshore development have significantly altered native habitats. In their altered state, ecosystems are less able to support wildlife and are unable to adequately respond to natural or imposed disturbances.

These degraded ecosystems face a growing threat from invasive species, which can replace native species, alter natural balances and significantly reduce habitat for other plant and animal species. The environmental and economic impacts of these invasions could be substantial as they crowd out native populations, impair habitats and water quality, and reduce recreational opportunities.

The primary focus of this program is to improve the biological integrity of ecosystems in the Basin, and in doing so ensure the existence of a full range of native species, seral stages, habitats, and ecological processes. Aquatic invasive species (AIS) pose one of the most serious threats to Lake Tahoe's ecosystem and also to adjacent lakes Fallen Leaf, Echo, Marlette, and Cascade. Such species can be extremely detrimental to native species in addition to threatening water quality and other beneficial uses. There are currently large infestations of noxious weeds in the Lake including Eurasian water milfoil and curlyleaf pondweed. Additionally, researchers have documented large concentrations of the Asian clam in multiple locations in Lake Tahoe.

A number of agencies and NGOs participate in the AIS program, which is overseen by the AIS Coordinating Committee. The AIS program has three main program elements:

Prevention of new introductions: Recent detections of quagga and zebra mussels in the Western United States pose a significant threat to Lake Tahoe. These introductions could have enormous environmental and economic impacts in the Basin. In response, agencies implemented a mandatory watercraft inspection program in 2008 (see https://tahoercd.org/tahoe-aquatic-invasive-species-programs/), which is the primary focus of the prevention program element.

Control and eradication of existing infestations: Efforts under this program element has focused on control and local eradication of aquatic invasive plants (see https://tahoercd.org/tahoe-aquatic-invasive-species-resources/), and to a lesser extent invasive fishes. Some efforts have been made to control the invasive clam, *Corbicula amurensis*, but these efforts have not continued. More recent control efforts have focused on the removal of aquatic plant infestations in marinas and surrounding areas. Control of the substantial aquatic plant infestation in the Tahoe Keys also is a major focus area that is currently in the planning/environmental review stage (see https://www.keysweedsmanagement.org/)

Education and Outreach: Education is key to any effective prevention program and is an important part of a successful control/eradication program as well. Programs to educate the public about the impacts of AIS, the methods to prevent introduction and further spread in the Region.

**Performance measures and monitoring:**

Progress under the AIS program is evaluated based on six EIP performance measures:

- Acres Treated for Invasive Species
- Watercraft Inspections for Invasive Species
- New Invasive Species Locations Detected
- Acres of Invasive Species Inventoried
- Funds Expended
- Number of Projects Completed

All of these performance measures inform program outputs. Project level monitoring has also occurred to document the near-term results of completed projects. In contrast, the regional outcomes, system-wide conditions (e.g., population status and trends) and ecological change are not regularly evaluated. Nor are there regular systematic surveys to determine if new introductions have occurred.

**Recommendations**

*Aquatic species audits for Lake Tahoe.*
Sensitive aquatic species will be placed at increasing risk with climate change, while some invasive species will acquire competitive advantages. The Lahontan cutthroat trout is one example of a native species at risk from climate change on which considerable resources are being invested for restoration. Formalized early detection monitoring is necessary for AIS, and a regular, systematic lake-wide monitoring program is needed to document changes in the size and distribution of existing populations of sensitive aquatic species.

**Attachment 1 (following).** Draft responses to ten questions memo about 2017 Lake Tahoe clarity, and the original white paper discussion of 2017 clarity results (Schladow and Watanabe, 2018).

**July 29, 2018**

**To:** Secretary J. Laird (CA Natural Resources Agency), and
Director B. Crowell (NV Department of Conservation and Natural Resources)

**From:** Tahoe Science Advisory Council (TSAC)

**RE:** Draft responses to ten questions memo on 2017 Lake Tahoe clarity

This draft set of responses is provided as a starting point for a broader discussion on the factors that contribute to changes in Lake Tahoe clarity, particularly as it pertains to the clarity measured in 2017. These responses are a work in progress, as the Tahoe Science Advisory Council (TSAC), working with agency partners and associates, will continue to assemble scientific perspectives on these and related questions over the next few months. what

Our responses are based on available information and best professional judgment. In the absence of some critical data, some of these questions are difficult to answer definitely. Furthermore, relevant data are still incoming or being revised. We present these assessments with the understanding that time, along with informed data collection and additional analysis, may lead to revised conclusions and improved understanding of important mechanistic drivers.

A range of factors (e.g., wildfire; continued land-use, invasive species, climate change) are expected to exert growing influence on the system. To better understand how the system will respond, we must emphasize the importance of a broad-based and integrated approach to management and stewardship of the Tahoe Basin. To be successful this will required a new paradigm of data collection, analysis, and prediction to provide decision-makers with the information they will need. The TSAC is prepared to provide expertise in the relevant disciplines and to work with Basin stakeholders and agency partners to assemble a long-term strategic plan that delivers an integrated ecosystem-based approach. This document is a first step toward that.

A separate White Paper summarizing the clarity changes observed in 2017 and presenting the current scientific consensus on the causes of that change is intended to be a supplement to this document. Where necessary, reference is made to specific figures in that document.



## DRAFT RESPONSES – 10 QUESTIONS

### 1. What does the 2017 clarity result tell us about the overall health of the Lake and its watershed? What additional information would enable us to better understand the change in 2017 and the relative impact on the Lake and/or the connection to the Basin's broader ecosystem health?

While lake clarity is very important, and is a good index for several processes, it is not an all-inclusive metric for what is happening in the Tahoe Basin. There are many impacted ecosystem processes and "services" that do not translate directly to lake clarity or to the scale of a specific year, like 2017. Taken by itself, therefore, the 2017 clarity result (Fig. 2, White Paper) tells us little about the overall health of the lake and its watershed

There has always been natural variability in the year-to-year annual average lake clarity, reflecting in part the fluctuations of climate and precipitation, and in part changes internal to Lake Tahoe itself. It is important to note that within this inherent variability a statistical trend of stabilizing annual average clarity continues, which suggests that some aspects of lake and watershed health are not deteriorating as previously, at least to the extent that lake clarity integrates and represents myriad conditions and processes occurring within the ecosystem.

Annual average 2017 lake clarity is thought to be an outlier over the longer-term. It arose from the combined effects of a severe multi-year drought, an extremely wet year during which the snowmelt onset occurred very late, a record early onset of thermal stratification and record warm lake surface temperatures. Unseasonable precipitation falling as rain in late autumn/early winter of 2017 was also considered to be a factor.

**2. Why was the negative impact on lake clarity in 2017 different from other years with extreme wet weather conditions?**

While 2017 was not the snowiest year on record, total precipitation was high. Late-season snow accumulation also caused spring runoff to start later and extend further into summer (Fig. 7 and Fig. 9, White Paper). Clarity was influenced by the volume of sediment-laden inflow, and the timing of the hydrograph.

There have been other large precipitation years at Lake Tahoe with reduced summer clarity. Annual precipitation accounted for about 30% of the variability observed in percentage change of annual average clarity relative to the previous year, for 1981 through 2017 (Tahoe City SNOTEL data).

A low clarity response to an extreme snow and rain series of storms has been observed before. Following the New Year's flood of 1997, for example, the average annual clarity experienced a greater percentage decline (17%) than was observed in 2017 (14%), although that previous "worst" year for clarity had a similar sediment load. 1982 was another year with extreme precipitation that produced an 11% clarity decline from the previous year. Each of the four years with largest percentage decrease in clarity (>10%) were higher than average precipitation years, while the four years with the largest percentage increase in clarity (>9%) were lower than average precipitation years (see Figure 1 below).

The multi-year drought from 2012–2016 is also considered to have contributed to a decrease in Secchi clarity. The purported mechanism is that extreme precipitation and snowmelt events in 2017 mobilized sediments that accumulated in channels and across the landscape during the drought years. Unfortunately no data exist to confirm this, nor do data exist to reveal if the sediment size distribution was finer in 2017.

Even with these meteorological and hydrologic factors, it is unlikely that they alone would have produced the observed clarity decline without some exceptional occurrences within the lake. Specifically, the early onset of thermal stratification and the exceptionally high surface water temperatures served to trap enough of the fine particle load at the lake surface to negatively impact clarity from May to December (Fig. 13, White Paper).

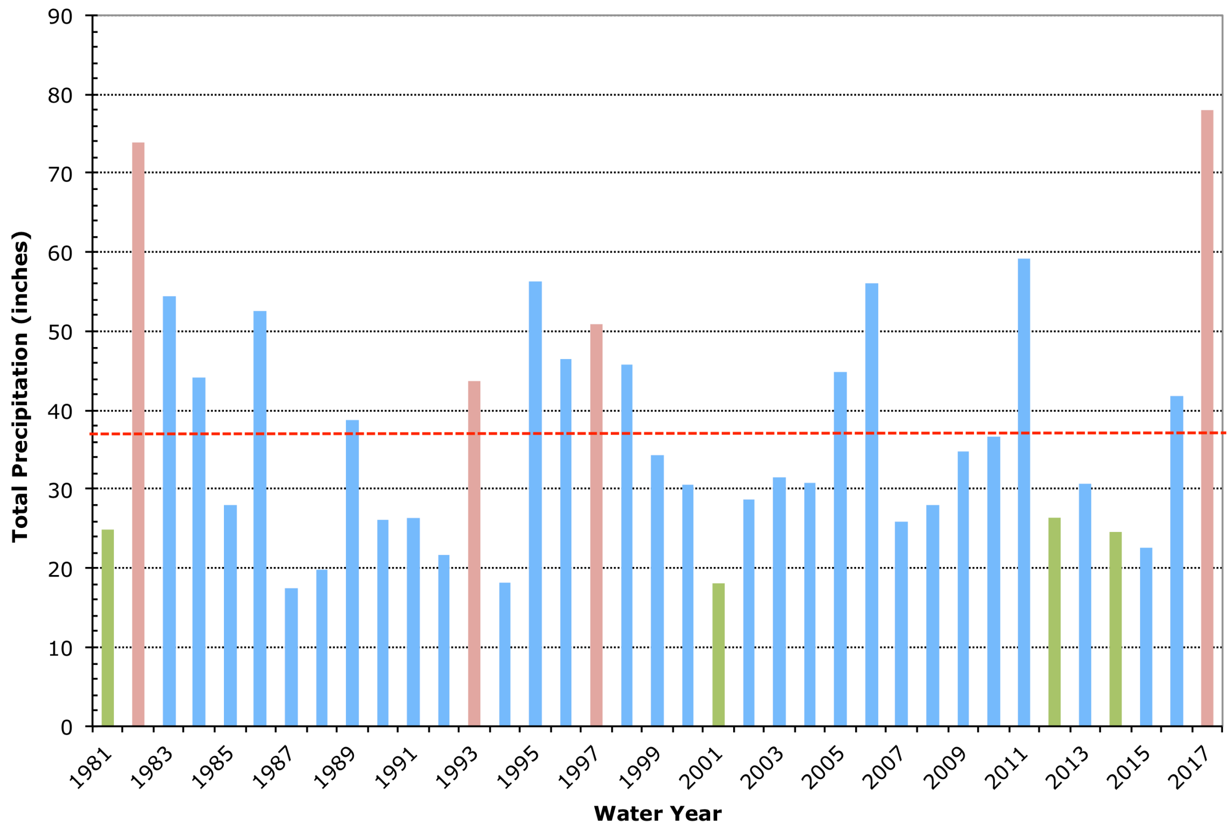



Figure 1. Tahoe City SNOTEL precipitation data from 1981 through 2017, compared to the average annual precipitation over this period (37.1 inches). The four years with largest percentage decreases in clarity from previous year (>10%) are shown as red bars, while the four years with largest percentage increases in clarity from previous year (>9%) are shown as green bars.

**3. How much, if any, did warming of the Lake's surface waters or other impacts from effects of a changing climate influence 2017 clarity?**

Lake Tahoe recorded its warmest surface temperatures ever in summer 2017. We believe that this had an impact on clarity. More important was the temperature stratification (or gradient) that was established early in the year. The stratification enabled sediment to be trapped in the surface layer of the lake. However, without the large volume of runoff entering the lake during an extended snowmelt season, it is unlikely that the clarity would have changed to the degree observed.

The increased turbidity in the surface layer may also have contributed to the warmer water temperatures, due to increased absorbance of solar radiation. This positive feedback would have enhanced the thermal stratification.

This stronger and more persistent stratification could also have diminished the usual lake mixing that begins to occur seasonally as the lake cools. The result would have been reduced dilution of surface water with deeper (and clearer) lake water.

**4. The 2017 annual clarity result was heavily influenced by seasonal data during the Fall of 2017. Are Lake Tahoe's seasonal dynamics changing? If so, why, and what impact may that have on the Lake's long-term ecosystem health?**

Existing data show that some of Lake Tahoe's seasonal dynamics have changed in response to climate change, consistent with changes in lakes around the world. It has also been hypothesized on the basis of modeling that continued climate change will affect the future dynamics of lake internal processes, resulting in less deep mixing and delayed onset of the annual mixing process. Typically, spring warming and snowmelt are starting earlier (although snowmelt actually had a delayed start in 2017) and the Fall-like conditions are extending later into the year. Impacts on the lake include a declining frequency of deep mixing (and the potential for hypolimnetic anoxia; i.e., deep-lake oxygen deficit). It is also likely that the nearshore dynamics will change as a combination result of declining snowpack and earlier spring snowmelt, which will change groundwater dynamics and lake pollutant inputs.

The results of recent climatic modeling (work in progress) indicates that the predicted rate of air temperature increase will be different for each season, with summers having a much higher rate of increase than winters. This trend, if borne out, would further exacerbate changes in seasonal dynamics.

**5. How much worse might clarity be today had investments in the EIP and the TMDL not been made?**

Data that shows the pollutant load reduction either do not exist or have not been analyzed to our knowledge. The TMDL planning process attempted to address this question, as described below, but those predictions have large uncertainty and do not reflect the impacts of climate change. Later research, funded through the SNPLMA program, did attempt to examine the impact of climate change on the lake and the delivered loads, but a reassessment of the "do nothing" scenario was not made. Climate prediction science is rapidly advancing, as is our knowledge of the impacts of climate on the Lake Tahoe and its watershed, so a quantitative reassessment of this question may be in order.

The TMDL Technical Report showed in 2010 that if nothing was done to reduce the input of pollutants, and assuming that future climate remained stable (statistically stationary), then by 2017 the long-term clarity trendline would continue to decrease and have a value around 17 m (see Figure 2 below). Currently the annual average trendline for Lake Tahoe is either flat or slightly improving, with 21.3 m the current value for the trendline value. As stated previously, the value of 18.2 m for 2017 should be considered an outlier at this time, but still representative of the range of variability we may expect to see. Of note, the TMDL predictive modeling in the Technical Report also indicated the possibility of years with clarity worse than 2017, even with more aggressive load reduction actions than those currently in place. In this context, the events of 2017 may be viewed as within the expected range. The positive impacts of management actions included as part of the TMDL are expected to take many years to materialize. Thus, it is likely that the full positive impacts of actions over the last 10 years are still accruing.

Of importance, however, is consideration that climate change impacts are expected to give rise to greater variability in lake and watershed conditions. Climate change science has rapidly evolved in recent years, with an increasing focus on the occurrence of extreme events. Present indications are that climate change will have an impact on a range of projects, and future EIP programs should be re-evaluated both in respect to their performance and their resilience in the face of a changing climate.

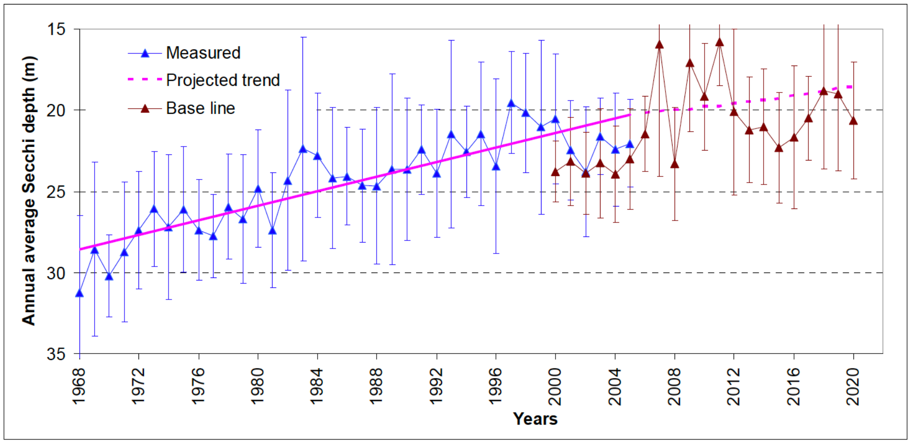



Figure 2. Historical trend of annual average clarity from 1968–2005, followed by the projected change in trend expected without implementation of the TMDL and EIP (Figure 6.18 from TMDL Technical Report, 2010).

**6. Do 2017 sources of pollutant load differ from those identified in the TMDL?**

It is not likely that the source categories of pollutants identified in the TMDL are different from the dominant sources in 2017. However, the fraction of loads assumed for different source categories may change under changing climate regimes. While data are not available to confirm this, it stands to reason that higher streamflows due to more rain and less snow, may result in larger contributions from non-urban parts of the watershed. Whether this did indeed occur in 2017 cannot be answered due to an absence of data. A monitoring strategy that permits basin-wide *a posteriori* analysis of annual events (particularly extreme events) is needed to provide definitive information on the causes of year-to-year changes in lake clarity. Extreme, or at least different, years will continue to occur and the Basin should be equipped to fully understand them and make adaptations as necessary.

**7. Once the likely cause(s) of the 2017 clarity decline are identified, how likely are these factors to repeat, persist, or cause a change in trend?**

Although a repeat of the 2017 chain of events in the near future is considered unlikely, climate change is expected to increase the frequency and amplitude of extreme events, and to increase warming and stratification of the lake.

We can expect droughts that last longer and occur more often, interspersed by high intensity precipitation events that can cause flooding. It is likely that we will see a greater variability in lake clarity associated with these changes. Loading rates may not change on average, if watershed management programs continue. However, other factors, such as lake surface warming and stronger stratification, will affect the trends in lake clarity. Conditions in the Tahoe basin will continue to change, and the practices that served the basin well in the past may no longer be appropriate.

**8. Should the annual clarity average report be adjusted to analyze a different time scale to better determine various causes and impacts related to changes in Lake clarity?**

The annual clarity value is the metric upon which the TMDL is predicated and it remains the TRPA, Nevada and California standard, so for legal/administrative reasons it needs to be continued.

From a scientific perspective it is useful to look at clarity across multiple time scales. There is a seasonal dynamic to lake clarity, for example, and reporting to agencies on a seasonal basis could be useful for identifying variability ranges and for early detection of periods that begin to fall outside the range of previous values. Consideration should be given to how agencies intend to respond to questions on clarity changes over shorter time intervals. Data needed to account for short-term clarity changes (e.g. nutrient analysis plus QA/QC; suspended sediment analyses; phytoplankton ID and enumeration) may not be available at the same time as Secchi depth readings.

For the specific case of 2017, for the first 9 months of the year, the clarity values were on track to be similar to the previous year's data. It was only in the last 3 months that clarity measurements transitioned from a "normal year" to the "worst" year. It is unclear how a changed reporting timeframe would have played out any differently with regard to agency or public response.

**9. When assessing the health of the Lake ecosystem and watershed, what other metrics for determining ecosystem health are most important for analyzing in conjunction with Lake clarity?**

Lake clarity responds to impacts from the watershed, the airshed and from within the lake itself. As such, it is a useful integrating metric. It is also the metric with the longest record, including both the "pre-disturbance condition" of the lake, and the history of altered lake ecosystem health. However, it is not intended to be a singular indicator of the Basin's ecosystem health and is not all-inclusive. Given the depth and volume of the lake, it tends to be a lagging indicator.

The TRPA is currently in the process of working with the TSAC to revise its existing Thresholds, with the aim of having fewer, more meaningful metrics. The goal is to develop a comprehensive, integrated suite of indicators that represent sensitive factors important to lake and watershed functions, and then to support the monitoring programs that tracks those specific indicators.

For example, indicators that describe watershed resource conditions such as forest structure and composition, road and trail conditions, terrestrial and aquatic species and communities, fire dynamics, forest management activities, and urban development activities would provide valuable information on risks, benefits, and potential causal factors affecting lake conditions. Both the Lake Tahoe West and the Upper Truckee River decision support framework projects are also investigating ecosystem metrics.

Equally important to consideration of other metrics for representing ecosystem health, are the renewed consideration of variables needed to explain the outcomes. As this present exercise perfectly demonstrates, the need to account for an unexpected change in the lake clarity metric requires a great deal of data, some of which we have but much of which is absent.

**10. Given the questions above, what local or regional impacts are causing the greatest impact and/or pose the largest threat to protecting the Lake and surrounding Tahoe Basin ecosystem?**

The lake and its watershed are constantly responding to an evolving set of inter-related drivers, and identifying the greatest threat is simply not possible. Climate, development, invasive species, wildfire and extreme events to name a few, are all important and are all likely to evolve in ways we have not as yet experienced. Their relative impact year-to-year is likely to be different.

**We ask TSAC to recommend future research needs and to identify actions to help us better understand the underlying impacts to the ecological health of Lake Tahoe.**

TSAC members have discussed a range of needs and actions that we believe would help understand the current and future ecological health of Lake Tahoe and its watershed. It is critical that we be proactive in efforts to not only monitor indicators of change, but also to monitor those variables that are driving that change. It is the latter that will build the necessary understanding of why the system is changing, and thereby enable agencies to develop or adapt the necessary projects and programs.

While the limited monitoring data we have suggest the EIP and TMDL have helped break the linear decline in average annual clarity, more substantive incorporation of climate change evaluations into EIP planning and project selection is absolutely necessary to maintain the benefits achieved and to sustain progress toward longer-term lake clarity goals.

The task of providing a comprehensive yet achievable applied research and monitoring framework is going to require more time and resources than were immediately available. The TSAC also wishes to solicit the input of Agency partners and other Stakeholders on our current assessment, before proceeding with specific recommendations.

At this, however, we do anticipate the framework will ultimately require committed long-term funding to support coordinated program-level monitoring (rather than project by project monitoring).

CALIFORNIA natural resources AGENCY

NEVADA DEPARTMENT OF CONSERVATION & NATURAL RESOURCES

June 12, 2018

Tahoe Science Advisory Council
291 Country Club Drive
Incline Village, NV 89451

Dear TSAC members,

As the co-chairs of the Tahoe Science Advisory Council (TSAC) Executive Committee we are requesting that the Tahoe Science Advisory Council undertake a special review of the 2017 Lake Tahoe annual clarity report data and the underlying cause for the unprecedented decline. This extraordinary review is intended to help inform the TSAC Executive Committee at its annual priority setting meeting in August. We seek to gain a deeper understanding of recent data showing significant seasonal declines in clarity and to leverage TSAC's scientific expertise to better understand the factors impacting lake clarity. The TSAC's findings will help policymakers best protect Lake Tahoe.

The TSAC was established as a bi-state partnership to link scientific research with smart, targeted planning and resource management. We have a shared obligation to ensure that sound science remains the foundation of our collective resource management and planning programs. Recent examples of effective science-based management partnerships include Lake Tahoe West's study of large-scale forest ecosystem restoration and TRPA's review to improve and update the environmental threshold standards embodied in the bi-state Compact to reflect the best contemporary science. These factors, among many others, are a reminder that protecting the unique and complex Lake Tahoe ecosystem requires comprehensive and coordinated science that is the foundation for natural resource protection and remediation efforts throughout the Lake Tahoe watershed. The TSAC is integral to these, and many other, efforts across the Basin.

Unfortunately, in 2017 one of the most iconic indicators of Lake Tahoe's health – lake clarity – registered its lowest recorded annual level. While annual clarity declines are not unusual, the record decline experienced in 2017 warrants additional investigation to help further understand ecosystem impacts, and to propose potential remedies. We understand that looking at clarity alone year-by-year does not necessarily reveal a trend. Nonetheless, considering the large reduction in clarity, the states need to have a better understanding of how the 2017 reported results relate to expected trends for the overall health of Lake Tahoe.

As the natural resources leads for our states, we want to engage the broader scientific community working within the Basin. We ask TSAC to recommend future research needs and to identify actions to help us better understand the underlying impacts to the ecological health of Lake Tahoe. In turn, this will help inform future conservation actions to help ensure the 2017 decrease in clarity is an anomaly, and not a trend. Specifically, we request TSAC to address the following questions and to offer other information that the Council feels may directly address this critical issue:

1. What does the 2017 clarity result tell us about the overall health of the Lake and its watershed? What additional information would enable us to better understand the change in 2017 and the relative impact on the Lake and/or the connection to the Basin's broader ecosystem health?
2. Why was the negative impact on lake clarity in 2017 different from other years with extreme wet weather conditions?
3. How much, if any, did warming of the Lake's surface waters or other impacts from effects of a changing climate influence 2017 clarity?
4. The 2017 annual clarity result was heavily influenced by seasonal data during the Fall of 2017. Are Lake Tahoe's seasonal dynamics changing? If so, why, and what impact may that have on the Lake's long-term ecosystem health?
5. How much worse might clarity be today had investments in the EIP and the TMDL not been made?
6. Do 2017 sources of pollutant load differ from those identified in the TMDL?
7. Once the likely cause(s) of the 2017 clarity decline are identified, how likely are these factors to repeat, persist, or cause a change in trend?
8. Should the annual clarity average report be adjusted to analyze a different time scale to better determine various causes and impacts related to changes in Lake clarity?
9. When assessing the health of the Lake ecosystem and watershed, what other metrics for determining ecosystem health are most important for analyzing in conjunction with Lake clarity?
10. Given the questions above, what local or regional impacts are causing the greatest impact and/or pose the largest threat to protecting the Lake and surrounding Tahoe Basin ecosystem?

The protection and restoration of Lake Tahoe remains a core priority for California and Nevada. On behalf of the TSAC Executive Committee, we look forward to receiving the Council's scientific expertise to help ensure that best available science is used to guide management policies and environmental improvement actions. We look forward to discussing preliminary results of this special review and initiating a cooperative effort to focus our joint conservation efforts at our upcoming annual priority setting meeting this August.

Sincerely,

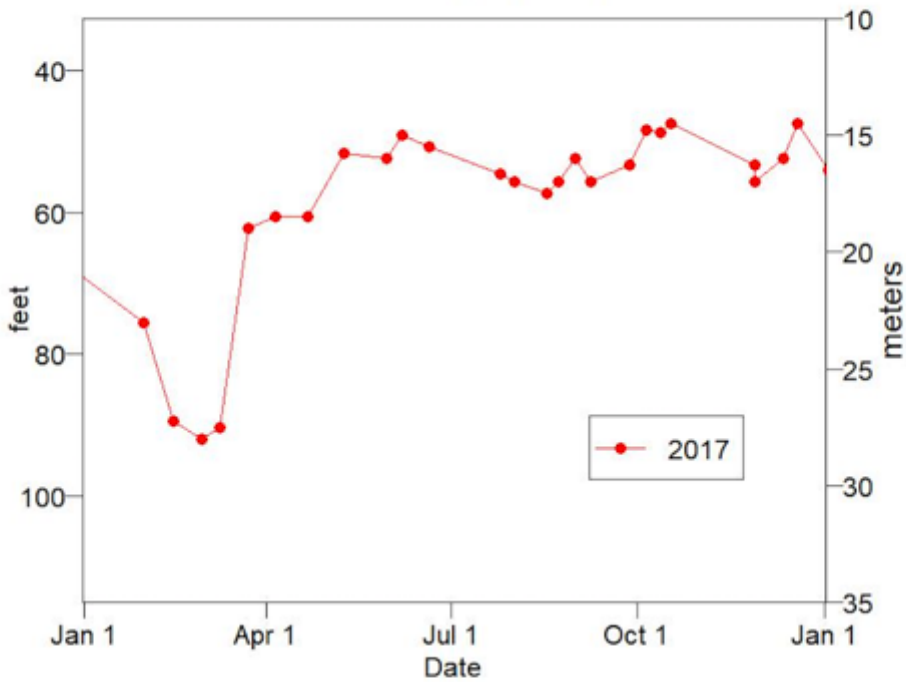
John Laird
Secretary for Natural Resources
State of California

Bradley Crowell
Director of Conservation and Natural Resources
State of Nevada

# Lake Tahoe Clarity in 2017 – White Paper

**S. Geoffrey Schladow and Shohei Watanabe**

UC Davis Tahoe Environmental Research Center




Lake Tahoe Secchi depth measurements for 2017

This report was prepared by S. Geoffrey Schladow and Shohei Watanabe of the UC Davis Tahoe Environmental Research Center. The report was reviewed by members of the Tahoe Science Advisory Council (Alan Heyvaert – DRI; John Melack – UCSB; Ramon Naranjo – USGS; Steven Sadro – UCD; Scott Tyler – UNR; Adam Watts - DRI) and Michael Dettinger of the US Geological Survey, and their comments and suggestions were incorporated into the final document.

## Introduction

In response to inquiries about the measured clarity of Lake Tahoe in 2017 and possible reasons for the unusual loss of clarity, this preliminary analysis was conducted. Time and resources limited the extent of the analysis, as did the preliminary nature of some of the data that were required. Nonetheless, the available data does permit a reasonably complete accounting for the factors that played a significant role in the 2017 clarity.

## Clarity Data

In 2017, 26 individual clarity readings (as estimated by Secchi depth) were taken at the long-term LTP station on the west side of Lake Tahoe (see Figure 1). Clarity decreased in 2017 to the lowest level on record. The time-weighted, average annual clarity level for 2017 was 59.7 feet, a 9.5 foot decrease from the previous year. Both the summer (June - September) and winter (December – March) average clarities decreased, although neither of these values were the lowest on record. The winter value for 2017 was 76.4 feet, 10.8 feet deeper than the lowest recorded level of 65.6 feet in 1997. The summer value of 53.5 feet was 3 feet deeper than the lowest recorded level of 50.5 feet in 2008. The highest value recorded in 2017 was 90.2 feet on March 9, and the lowest was 47.6 feet on October 17 and December 19. These latter dates are noteworthy in that Fall at Lake Tahoe has never previously been associated with low clarity values**.**


Fig. 1. Location of clarity measurement station

The long-term records of annual average, winter average and summer average clarity in Lake Tahoe are shown in Figure 2. The figure of annual average values (top) shows a dip in clarity in 2017, though winter and summer values are not the lowest on record. The actual data points are included as Appendix A.

Secchi depth measurements in Lake Tahoe "typically" follow a seasonal pattern. Note the emphasis on "typical", as year-to-year variability in factors such as ratio of rain to snow, runoff, groundwater intrusion, algal speciation and antecedent conditions such as lake stratification make the annual variation of clarity a multi-variable response, with information on most of the variables either limited in availability or simply not available. Some of these factors are discussed in Jassby et al. 1999. In summer clarity is usually at its lowest, with the impact of spring runoff delivering fine particles and nutrients at its peak, combined with warm temperatures and long hours of sunlight stimulating algal growth. As winter approaches the surface layer of the lake deepens due to convective cooling processes. This tends to dilute the deepening upper layers with clearer bottom (hypolimnetic) water. This clearing through the winter "typically" continues until the following spring when the pattern starts again. The pattern is complicated and also impacted by factors such as the depth of winter mixing, which brings up clear hypolimnetic water while at the same time introducing higher concentrations of nutrients; the seasonal cooling of the water; and a reducing amount of daily insolation.  While no two years are identical, this general pattern has long been established.

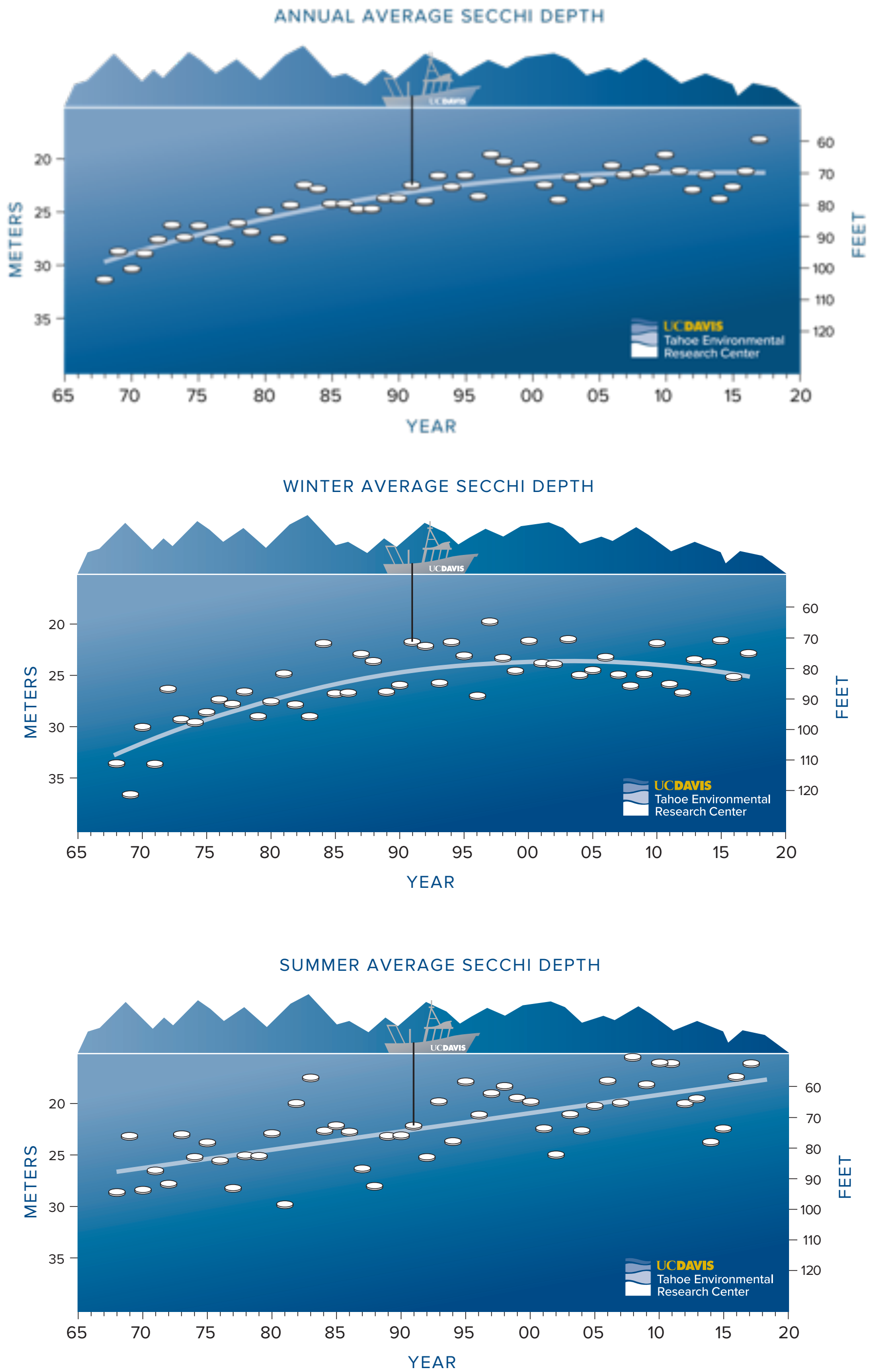



Fig. 2. Annual average, winter average and summer average clarity in Lake Tahoe

The year 2017 had a departure from this seasonal pattern. In Figure 3, the individual values of Secchi depth are shown for the years 2010 through 2017. The 2010 to 2016 values are shown as hollow circles, while the 2017 values are filled circles. Until September 2017, values generally fell within the range of the last 7 years, with values through mid-March actually better than many of the recent years. From September through the end of the year, the 2017 clarity values were 3-6 m less than the range of the last 7 years. It is the Secchi disk values in this 3-month period of time that are responsible for the record low clarity of 2017. The usual winter clearing of the winter column did not initiate before the end of December.

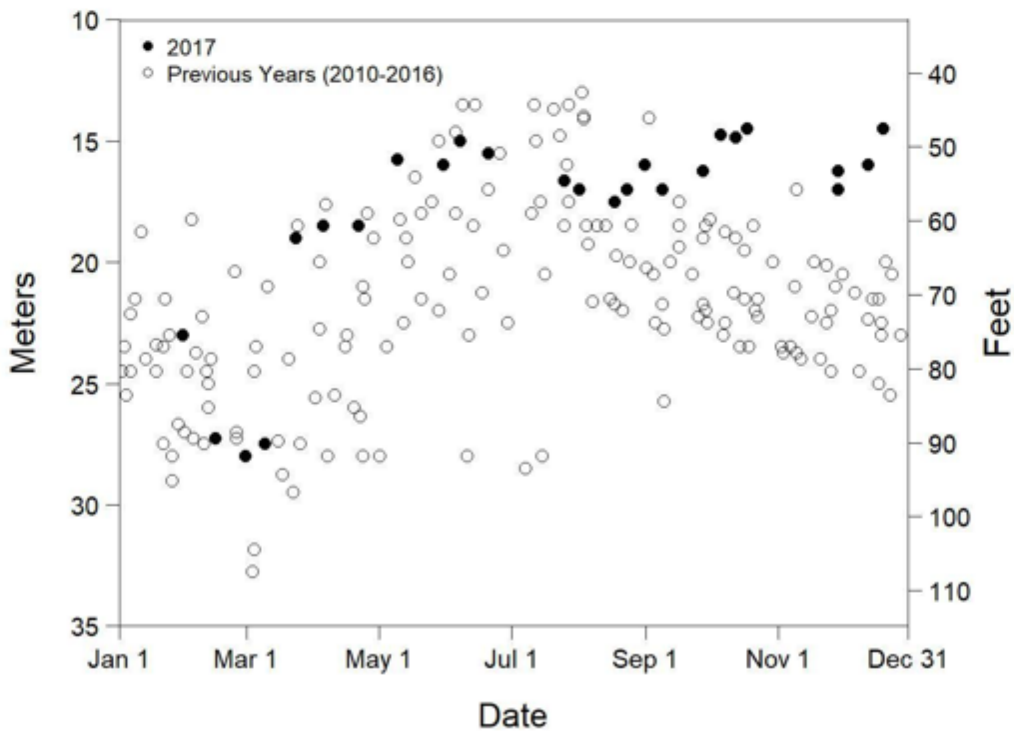



Fig. 3. Individual Secchi depth measurements for 2010-2016 (hollow circles) and 2017 (filled circles).

**The Climatic, Hydrologic and Limnological Drivers Behind the 2017 Clarity Values**

Based on the available data, a combination of two extreme climatic and hydrologic events and the timing of key events in the limnological cycle appear to be the primary drivers of the unprecedented clarity change in 2017. The first key event was the record drought that commenced in 2012. From 2012 to 2014, the drought was considered the most extreme in 1600 years (Griffin and Anchukaitas 2015). Total precipitation, as well as the fraction of precipitation as snow was particularly low in the northern Sierra Nevada (Hatchett and McEvoy 2018). It would stand to reason that the normal transport of erosional material from the watershed to the lake would be reduced during drought years.

Figure 4 shows lake levels during this period. The modest annual rise of lake level each spring between 2012 and 2016 is evident. A gauge height of 3 ft. represents the natural rim of the lake, so values below 3.0 indicate periods when water did not flow through the dam at Tahoe City.

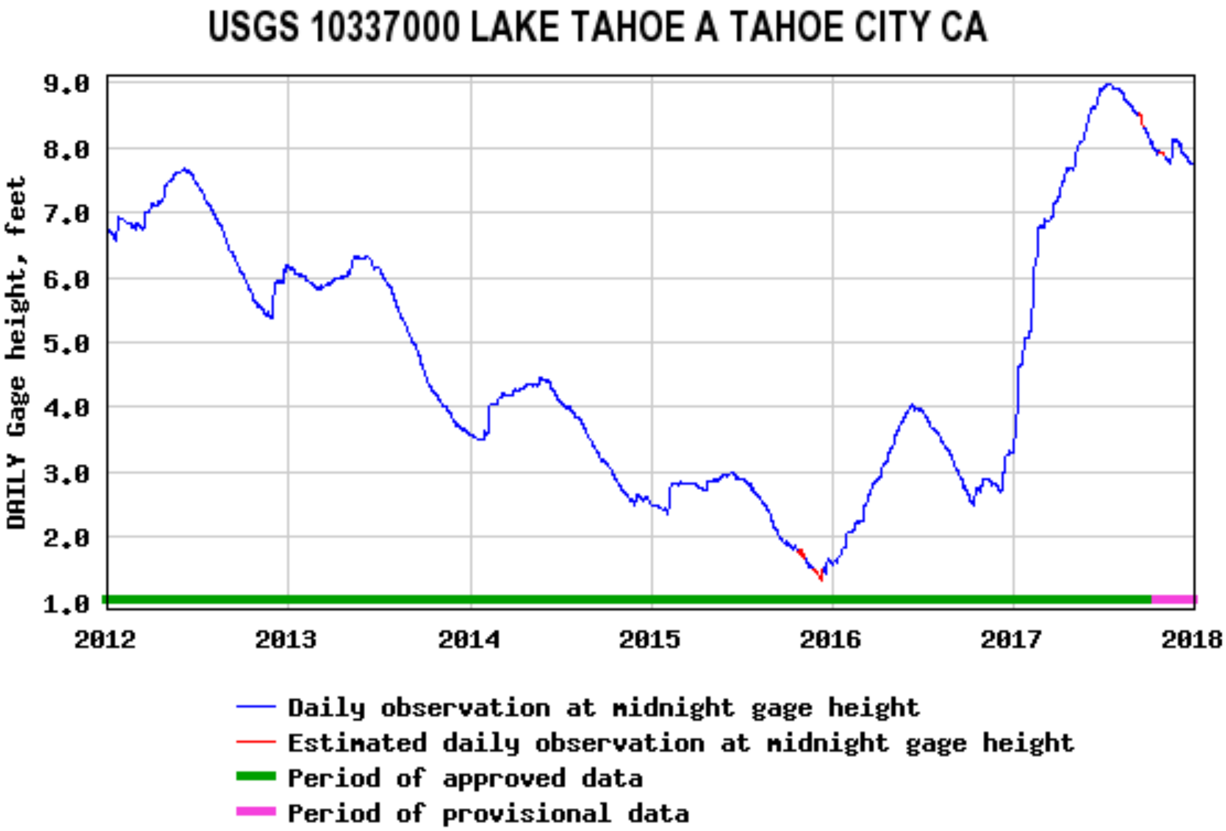



Fig. 4. Water level of Lake Tahoe measured at the USGS gaging station at Tahoe City, showing the annual drop in lake level and the rise during 2017. Natural rim of the lake is at 3 feet.

The second key event was the record high precipitation that occurred in 2017 to officially end that drought. Water Year 2017 (Oct. 2016 - Sept. 2017) was California's 2nd wettest and Nevada's 7th wettest in a 122-year record (CNAP 2017), due primarily to the unprecedented number of atmospheric rivers (ARs) that brought precipitation to California (see Fig. 5). In Water Year 2017 there were 68 landfalling ARs over the West Coast. In addition, an early winter storm in November 2017 added considerable sediment to the lake at a time that is typically quite dry (see Fig. 6). Figure 4 indicates a lake level rise of over 6 ft in a 6-month period in 2017 due to the very wet year. A gauge height of 9 ft. represents the maximum legal water level in the lake.

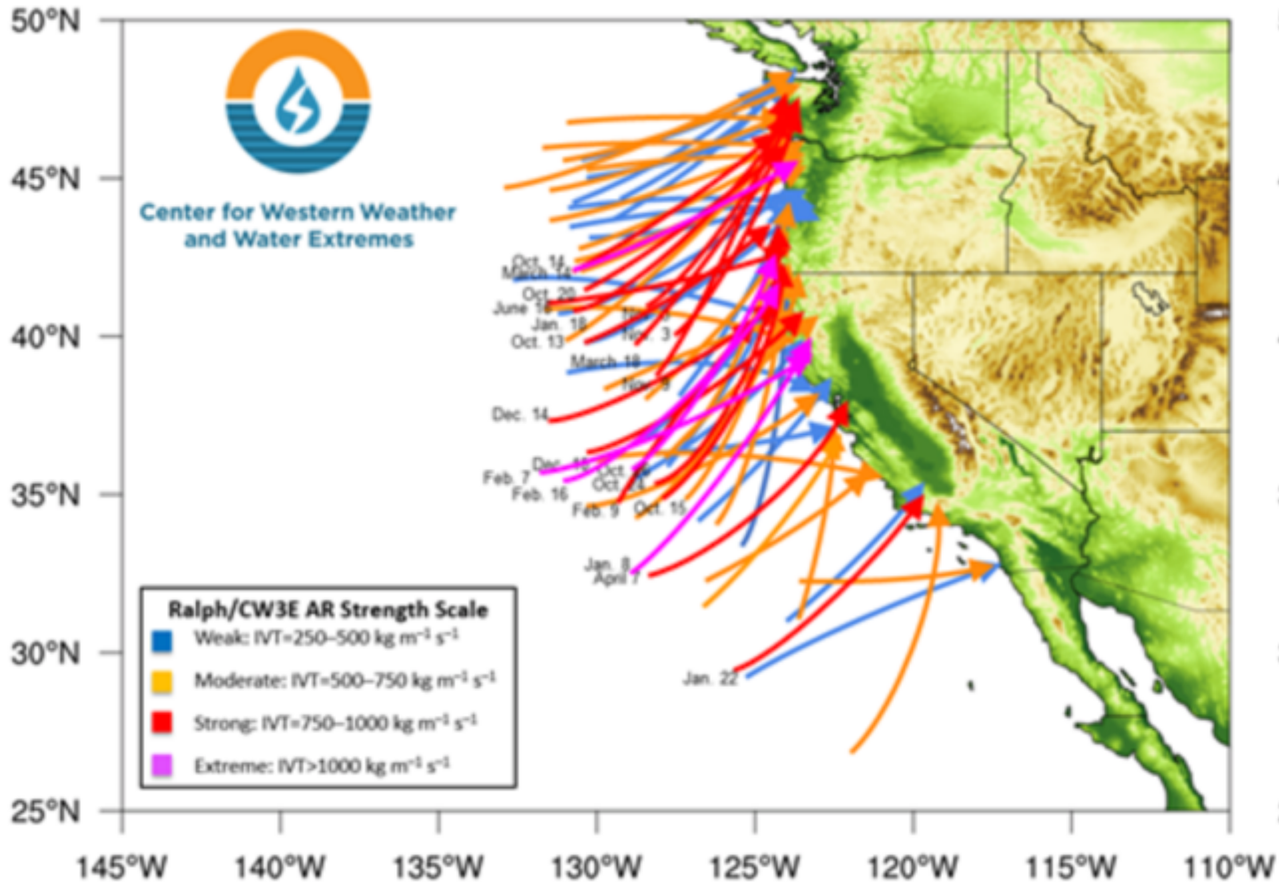



Fig. 5. Map with the 68 atmospheric rivers that cross the coast during Water Year 2017. (http://cw3e.ucsd.edu/wp-content/uploads/2018/05/WY2018_LandfallingARs/slide3.PNG)

Figure 6 provides a Tahoe-specific context to the relative impacts of these two extreme events. The figure shows data for the period 1980 through 2017 for Secchi depth, precipitation at Tahoe City, Upper Truckee River daily discharge, suspended sediment concentration (SSC) for the Upper Truckee River, fine particle concentration (only available since 2006) and chlorophyll-*a* (algal) concentration at a depth of 10 m in the lake.

The Secchi depth record clearly shows the singularity of 2017 compared to all the previous years. For nearly the entire year the Secchi depth values were lower than 20 m (66 feet), with no seasonal improvement toward the end of the year. The relatively low precipitation drought years as well as the wet year of 2017 are clearly evident in the precipitation record. Precipitation lasted into May, with a large event in November as well. The correspondingly broad impact of this precipitation on the Upper Truckee River streamflow is evident, together with the large SSC values; the late-2017 storm is striking. The large increase in fine particles (< 16 microns diameter) at a depth of 10 m depth in the lake is apparent. The concentrations are far higher than those of any previous years. It is these particles that directly impact the passage of light in water, and hence Secchi depths.

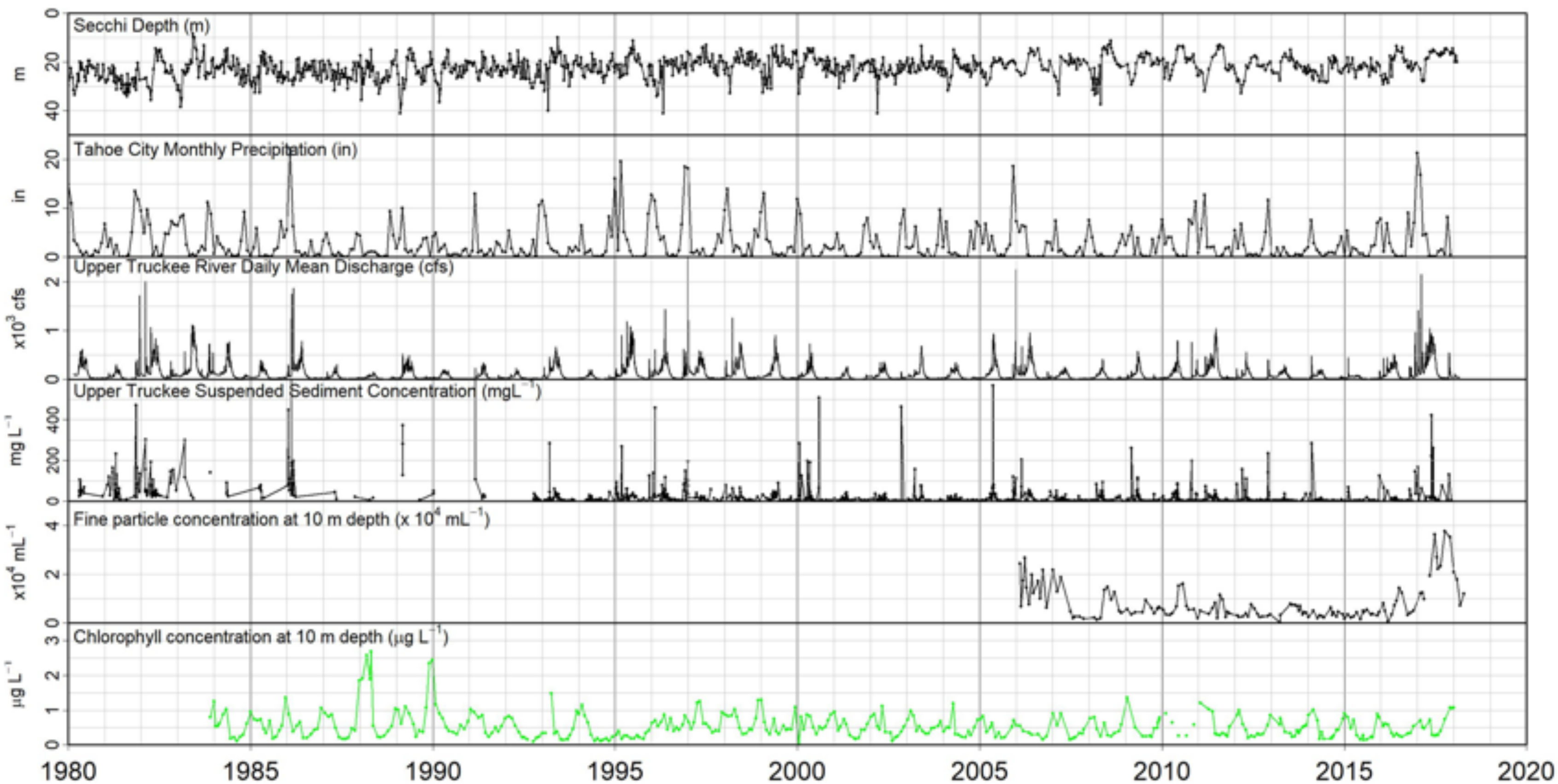



Fig. 6. The entire record for Secchi depth (meters), precipitation (inches), Upper Truckee River discharge (cubic feet per second), suspended sediment concentration (mg/l) in the Upper Truckee River, fine particle concentration at 10 m depth (#particles/ml), and Chlorophyll–*a* concentration at 10 m depth (micrograms/l) in the lake. Note that prior to 1993, SSC measurements were taken relatively infrequently, hence the "erratic" appearance of the graph in some years.

The Chlorophyll-*a* concentrations are not significantly higher than other years, at least not to levels that could account for the extremely low clarity in 2017. Years where algae did control clarity were when a particular diatom, *Cyclotella gordonensis*, was present in high concentrations. In 2017 *Cyclotella gordonensis* was largely absent (TERC 2018). This suggests that sediment, rather than algal concentrations was primarily responsible for the observed clarity decline in 2017. Coincidentally, *Cyclotella gordonensis* was present in high concentrations during several of the drought years, thus accounting for years of low clarity during low inflow years (TERC 2017).

A comparison of 1997, the previous lowest clarity year, with 2017 is illustrative. Upper panels of Figure 7 compare the flow of the Upper Truckee River (the largest inflow to the lake) for both these years. In 1997 major flooding downstream of Lake Tahoe occurred in early January, as well as low clarity conditions during the year. While 1997 had a larger peak flow, 2017 had more frequent peaks and a more sustained snowmelt flow well into August. The panels for suspended sediment concentration and load (the product of flow and concentration) indicate that both years had a similar cumulative suspended sediment load, but with significant timing differences. The red dashed line indicates a cumulative load of 2500 MT, approximately half the annual load for both years. In 1997, this load value was reached in early January, whereas in 2017 it was not reached until approximately April or May. This is an important timing difference, as it indicates that sediment was being introduced to the lake later and over a longer period in 2017. These plots are for the Water Year (October 1 – September 30), so 2017 does not include the sediment flux associated with the large rainfall and flow event in November 2017.

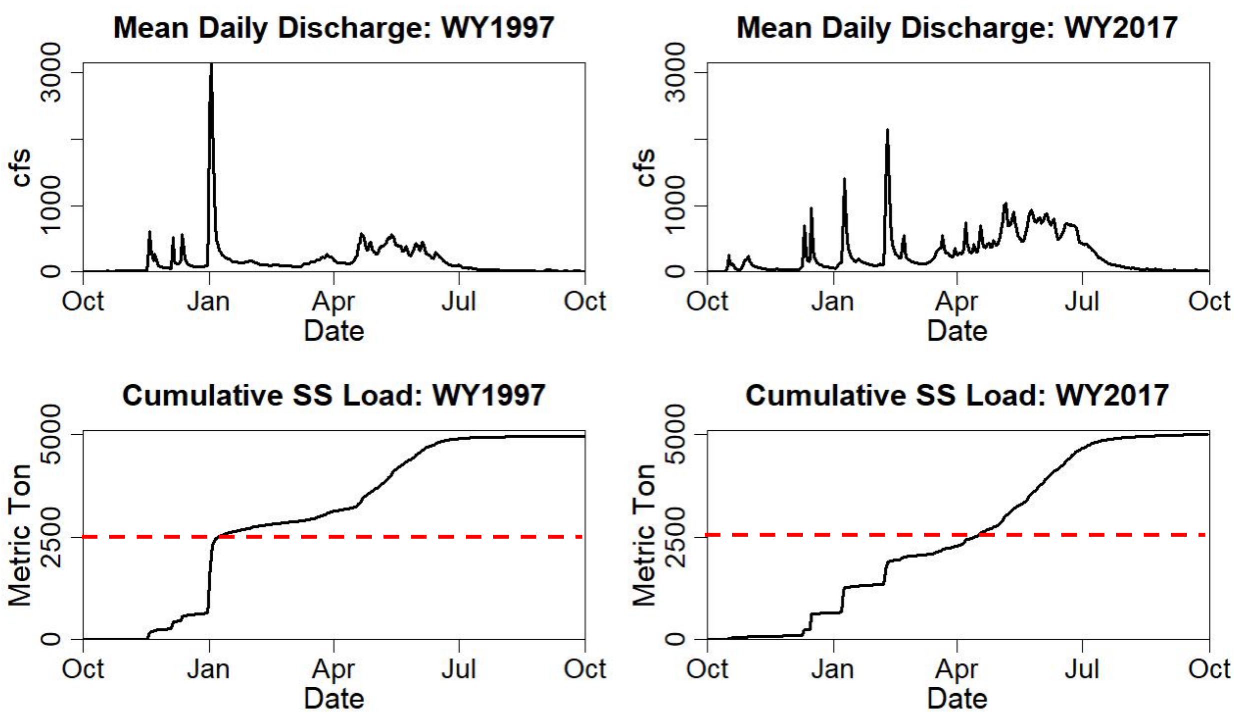



Fig. 7. The Upper Truckee River in Water Year 1997 and Water Year 2017. Upper panels are discharge (cubic feet per second) and lower panels are suspended sediment cumulative load from Oct 1st.

It is important to bear in mind that the fine sediments that are responsible for clarity reduction (<16 microns) are not well represented by the measured suspended sediment. The vast majority of suspended sediment by weight is in size classes that have no effect on clarity. Thus, it is not possible to say whether 1997 or 2017 yielded different amounts of fine sediment load to the lake. In the last few years, real time turbidity sensors have been added to several Tahoe streams. Turbidity is better correlated with fine particle concentration.

Figure 8 shows the Calendar Year Secchi depth data for 2017, together with the "turbidity load" (the product of stream discharge and turbidity) for the Upper Truckee River in 2017. Several features discussed above can be seen here. First, the improvement in turbidity during winter is very obvious, with Secchi depths approaching 90 ft. in February. Second, in mid-March there is a large reduction in Secchi depth soon after the observed abrupt increase in turbidity load. Third, as the turbidity load increases and then plateaus, clarity remains low. About Day 275 (end of September) clarity appears to start improving in the normal seasonal pattern. However, the early-November storm referred to earlier is seen to boost the turbidity load and the clarity remains poor through the end of the year.

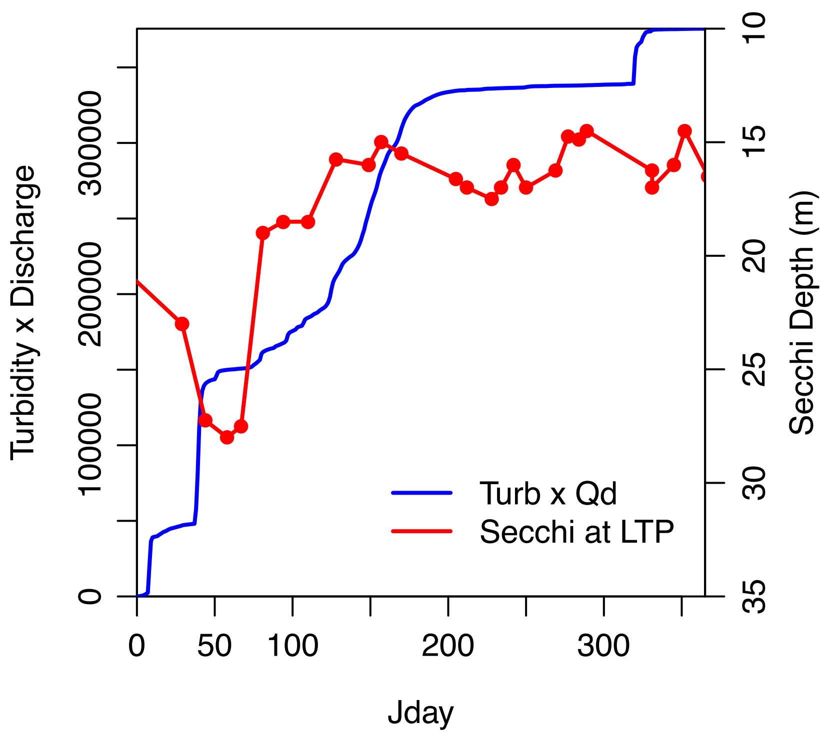



Fig. 8. Secchi depth and cumulative turbidity load for the Upper Truckee River for Calendar Year 2017. The time axis is in Julian Days, with Day 1 being January 1 and Day 365 being December 31.

Figure 9 indicates the annual suspended sediment load from the Upper Truckee River to the lake for each water year from 1989 through 2017 (TERC 2018). Here it can be seen that while 2017 was a high load year, it was not totally unique. The 2017 load is larger than the sum of all the loads for the previous five years combined, an indication of the low loads of the drought years.

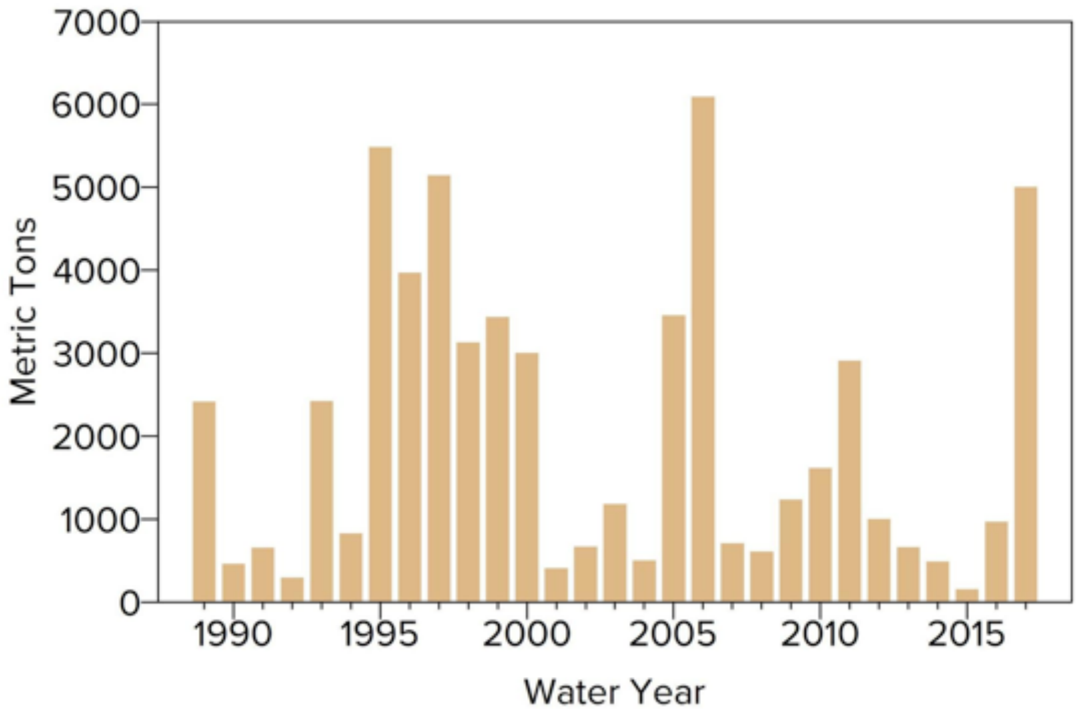



Fig. 8. Annual suspended sediment load of Upper the Truckee River to the lake (Metric Tons)

As alluded to in Figure 7, 2017 had a later date on stream inputs of sediment than 1997. How does the timing of the snowmelt compare with other years? Figure 9 shows the calculated date on which the onset of snowmelt occurs in every year since 1961. The onset of the pulse is calculated as the day when the flow in five gauged streams exceeds the mean flow for the period Jan. 1 to July 15. Although the date on which snowmelt commences varies from year to year, it has shifted earlier an average of 16 days since 1961. This shift is statistically significant and is one effect of climate change at Lake Tahoe. In 2017, the onset of snowmelt occurred on April 25, over 5 weeks later than 2016, and placed it well above the trend line associated with climate change.

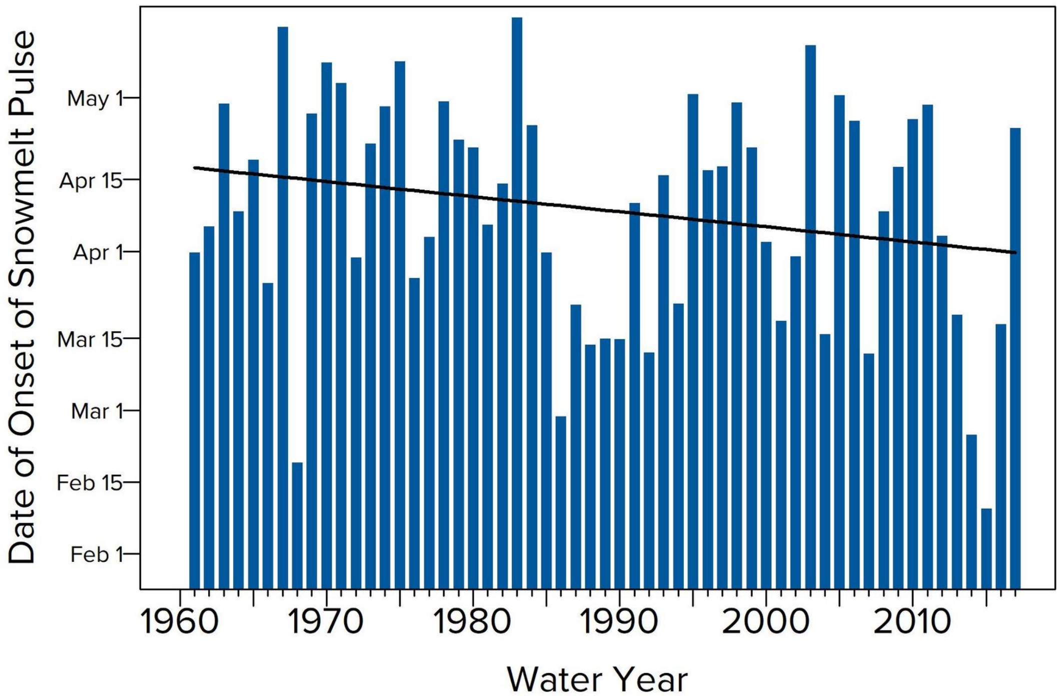



Fig. 9. The onset of the snowmelt pulse for streams in the Tahoe basin.

**Lake Conditions**

As stated previously, the timing of key events is believed to be one of the three factors that led to the low clarity conditions in 2017. The late onset of the snowmelt and the November storm are the two hydrologic timing factors. Conditions in the lake itself also introduced another important timing factor. In 2017, the onset of thermal stratification occurred earlier than at any time since 1968 (TERC 2018). The onset of stratification is defined as when the stratification index exceeds a specific threshold value (Sahoo et al. 2016). The amount of time that Lake Tahoe is stratified has been lengthening since 1968 (TERC 2018). One reason for this is the increasingly early arrival of spring as evidenced by the earlier commencement of thermal stratification. Stratification occurs approximately ten days earlier than it did in 1968. The commencement of the stratification season is typically in late May or early June. In 2017, stratification began on Day 126 (May 5), the earliest such date on record.

When the lake is thermally stratified, it exerts control over the depth at which stream and urban inflows are discharged into the lake. When a cold, turbid inflow enters a stratified lake, it will partially mix (i.e. exchange) with the ambient lake water. While most of the cold inflow will tend to plunge to deeper layers of the lake, a part of the turbid water gets trapped at the surface of the lake. With the late onset of snowmelt (April 25th), and the early onset of stratification (May 5th), it is evident that conditions for more turbid water being added at the lake surface were enhanced in 2017.

The extent of stream mixing and entrainment is also affected by the temperature difference between the inflowing stream water and the lake surface. In 2017, lake surface temperatures were unusually warm.

July lake surface water temperature (measured from 4 buoys in the deep part of the lake at 2-minute intervals for the entire month) was the highest value ever recorded, as seen in Figure 11.

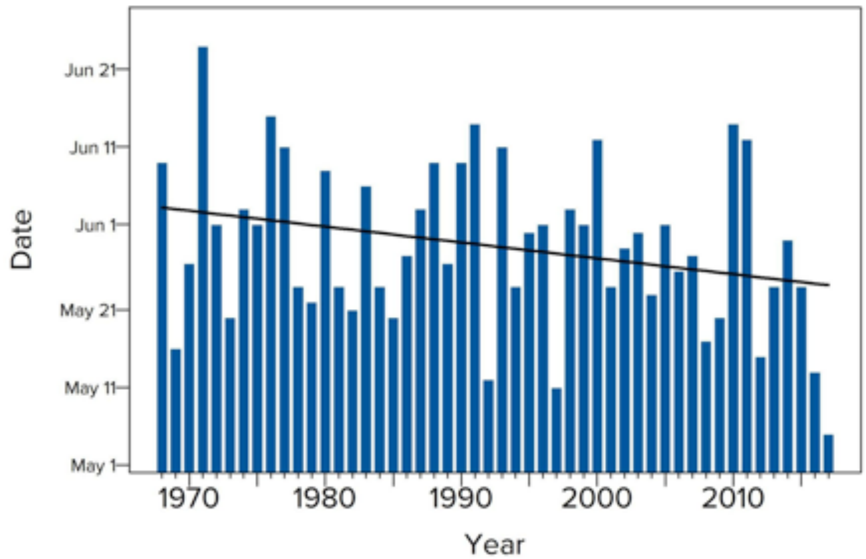



Fig. 10. The change in the onset of lake stratification since 1968. The trend line is considered to be reflective of climate change.

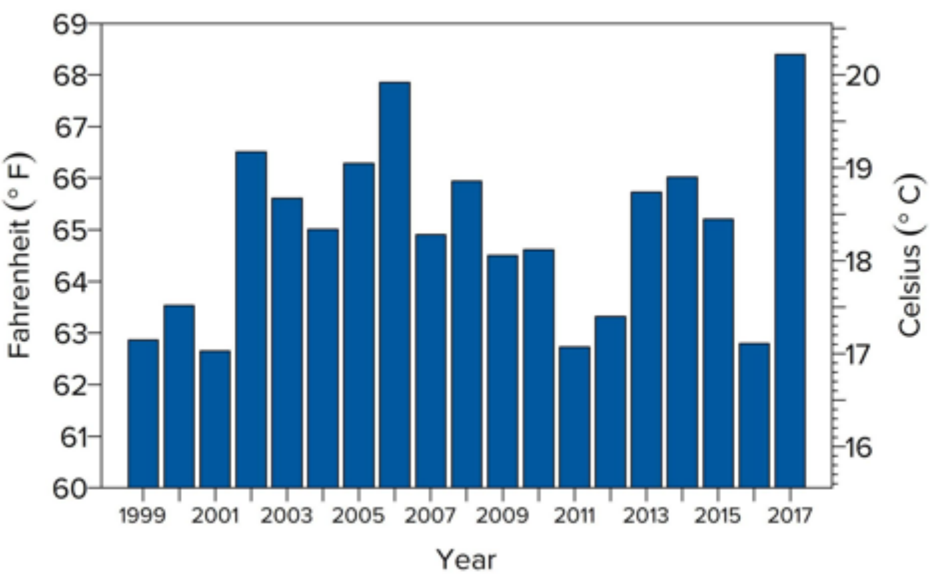



Fig. 11. The July average surface water temperature.

Throughout the summer of 2017 water temperatures were the warmest on record at Lake Tahoe. As evident in Figure 12, the elevated water temperatures extended into September, 2017, later than is the norm for the lake. Both the warmer surface temperatures and the early onset of the lake's thermal stratification would tend to trap part of the fine sediment load suspended in the upper part of the lake.

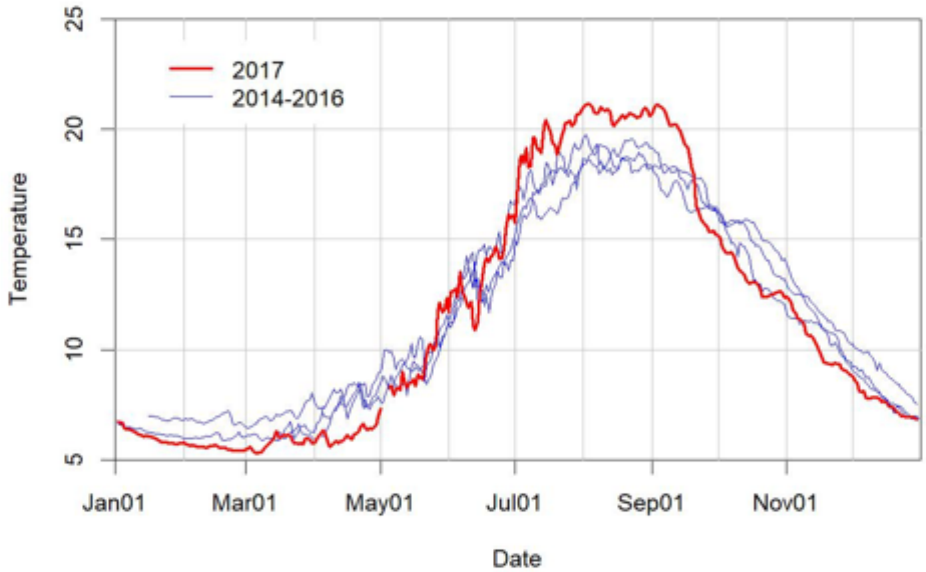



Fig. 12. Water temperature (measured at 2 min. intervals) at 5.5 m depth at NASA Buoy TB3 for four years. 2017 is indicated in red.

This is in fact precisely what occurred. Fine sediment was kept in suspension in the upper part of the lake in the latter part of 2017, as shown in Figure 13, where the concentration of fine particles (less than 16 microns diameter) are shown over the full lake depth. From early May, coincident with the onset of thermal stratification, until the end of the year a distinctly high concentration layer of fine particles (those causing the loss in clarity) is trapped in the upper 50 m (165 ft.) of the water column. Normally, seasonal convective cooling and lake mixing would begin to dilute this surface layer with deeper and clearer water.

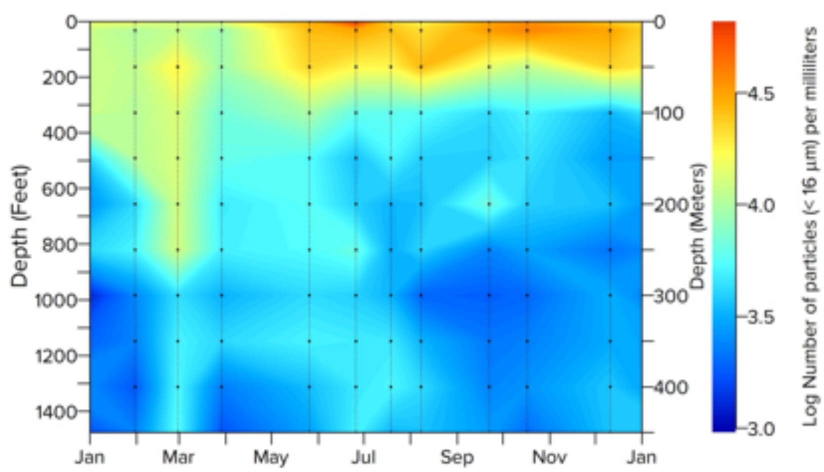



Fig. 13. Distribution of fine particles in Lake Tahoe in 2017. Vertical lines represent dates of sampling, and dots indicate the depths from which water samples were taken.

**Concluding Points**

After a review of the available data, our opinion is that in 2017 Lake Tahoe's change in clarity was likely the combined result of several unusual events. These were the ending of the multi-year drought by an extremely high precipitation year, the relatively delayed onset of the spring snowmelt pulse, the earliest onset of thermal stratification on record, and the warmest lake temperatures on record. It is not possible to fully break apart the impact that each of these had, as in many ways they were inter-related.

It is also not possible at this point in time to say to what role climate change played in this. Some of the observations, such as the late onset of spring snowmelt, were counter to the expected impact of climate change. Others, such as the lake warming and early onset of thermal stratification, are consistent with climate change expectations.

Regardless of the precise causes, we believe that the clarity value for 2017 should be viewed as being an outlier and should not be considered as representing the underlying long-term trend. Extreme high and low clarity years were in fact predicted in the Lake Tahoe TMDL Technical Report (2010) as part of specific load reduction scenarios. Clarity data for the first 6 months of 2018, as shown in Figure 14, appear to show a return to the "regular" Lake Tahoe range of clarity readings.

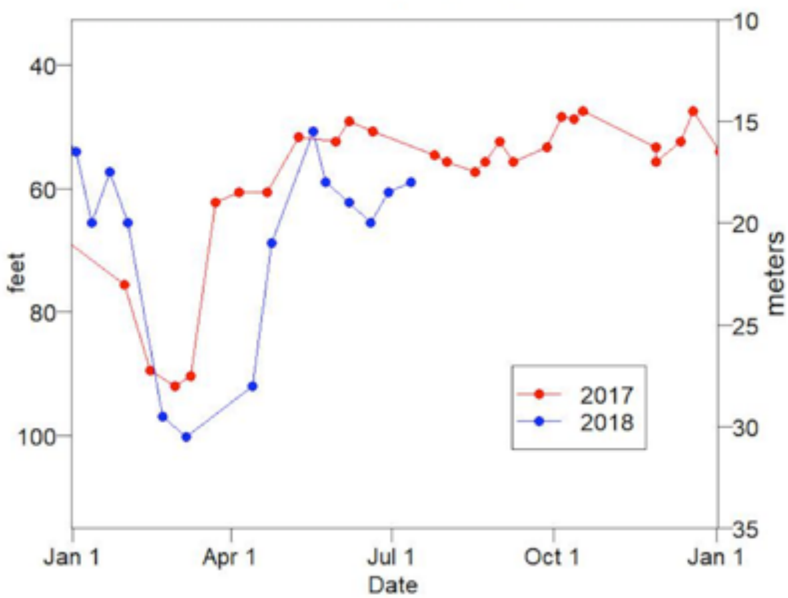



Fig. 14. Secchi depth measurements for 2017 (red) and 2018 (blue) showing the return to clarity values in the expected range.

While sufficient data did exist to reveal likely factors that contributed to the clarity decline of 2017, there are many important questions that could not be answered. Extreme years, such as 2017, offer important learning opportunities. It is critical that current data collection efforts are reviewed at this time to better position the science and management community for learning more from the next set of extreme events.

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TERC 2018. Tahoe: State of the Lake Report 2018. http://tahoe.ucdavis.edu/stateofthelake/

Appendix A

| Average Lake Tahoe Secchi Depth | | | | | | |
|---|---|---|---|---|---|---|
| Year | Annual (meters) | Winter (meters) | Summer (meters) | Annual (feet) | Winter (feet) | Summer (feet) |
| 1968 | 31.2 | 33.4 | 28.7 | 102.4 | 109.6 | 94.2 |
| 1969 | 28.6 | 36.3 | 22.8 | 93.8 | 119.1 | 74.8 |
| 1970 | 30.2 | 30.3 | 28.5 | 99.1 | 99.4 | 93.5 |
| 1971 | 28.7 | 33.5 | 26.3 | 94.2 | 109.9 | 86.3 |
| 1972 | 27.4 | 26.1 | 27.8 | 89.9 | 85.6 | 91.2 |
| 1973 | 26.1 | 29.5 | 22.9 | 85.6 | 96.8 | 75.1 |
| 1974 | 27.2 | 29.7 | 25.3 | 89.2 | 97.4 | 83.0 |
| 1975 | 26.1 | 28.8 | 23.7 | 85.6 | 94.5 | 77.8 |
| 1976 | 27.4 | 27.6 | 25.8 | 89.9 | 90.6 | 84.6 |
| 1977 | 27.8 | 27.8 | 28.3 | 91.2 | 91.2 | 92.8 |
| 1978 | 25.9 | 26.7 | 25.0 | 85.0 | 87.6 | 82.0 |
| 1979 | 26.7 | 29.0 | 24.9 | 87.6 | 95.1 | 81.7 |
| 1980 | 24.8 | 27.7 | 22.8 | 81.4 | 90.9 | 74.8 |
| 1981 | 27.4 | 24.9 | 29.8 | 89.9 | 81.7 | 97.8 |
| 1982 | 24.3 | 27.6 | 19.7 | 79.7 | 90.6 | 64.6 |
| 1983 | 22.4 | 29.0 | 17.4 | 73.5 | 95.1 | 57.1 |
| 1984 | 22.8 | 22.0 | 22.7 | 74.8 | 72.2 | 74.5 |
| 1985 | 24.2 | 27.3 | 22.1 | 79.4 | 89.6 | 72.5 |
| 1986 | 24.1 | 26.9 | 22.6 | 79.1 | 88.3 | 74.1 |
| 1987 | 24.6 | 23.2 | 26.1 | 80.7 | 76.1 | 85.6 |
| 1988 | 24.7 | 23.6 | 28.0 | 81.0 | 77.4 | 91.9 |
| 1989 | 23.6 | 26.7 | 23.0 | 77.4 | 87.6 | 75.5 |
| 1990 | 23.6 | 25.8 | 23.0 | 77.4 | 84.6 | 75.5 |
| 1991 | 22.4 | 21.6 | 22.2 | 73.5 | 70.9 | 72.8 |
| 1992 | 23.9 | 22.1 | 25.2 | 78.4 | 72.5 | 82.7 |
| 1993 | 21.5 | 25.8 | 19.9 | 70.5 | 84.6 | 65.3 |
| 1994 | 22.6 | 21.8 | 23.7 | 74.1 | 71.5 | 77.8 |
| 1995 | 21.5 | 22.9 | 17.7 | 70.5 | 75.1 | 58.1 |
| 1996 | 23.4 | 26.9 | 21.1 | 76.8 | 88.3 | 69.2 |
| 1997 | 19.5 | 20.0 | 19.1 | 64.0 | 65.6 | 62.7 |
| 1998 | 20.1 | 23.2 | 18.2 | 65.9 | 76.1 | 59.7 |
| 1999 | 21.0 | 24.7 | 19.2 | 68.9 | 81.0 | 63.0 |
| 2000 | 20.5 | 21.5 | 19.5 | 67.3 | 70.5 | 64.0 |
| 2001 | 22.4 | 23.7 | 22.2 | 73.5 | 77.8 | 72.8 |
| 2002 | 23.8 | 23.9 | 24.7 | 78.1 | 78.4 | 81.0 |
| 2003 | 21.6 | 21.6 | 21.1 | 70.9 | 70.9 | 69.2 |
| 2004 | 22.4 | 25.4 | 22.3 | 73.5 | 83.3 | 73.2 |
| 2005 | 22.0 | 24.5 | 20.4 | 72.2 | 80.4 | 66.9 |
| 2006 | 20.6 | 23.4 | 17.5 | 67.6 | 76.8 | 57.4 |
| 2007 | 21.4 | 25.1 | 19.9 | 70.2 | 82.3 | 65.3 |
| 2008 | 21.2 | 26.0 | 15.4 | 69.6 | 85.3 | 50.5 |
| 2009 | 20.8 | 24.8 | 18.0 | 68.2 | 81.4 | 59.1 |
| 2010 | 19.6 | 22.2 | 15.8 | 64.3 | 72.8 | 51.8 |
| 2011 | 21.0 | 25.9 | 15.7 | 68.9 | 85.0 | 51.5 |
| 2012 | 22.9 | 26.9 | 19.7 | 75.1 | 88.3 | 64.6 |
| 2013 | 21.4 | 23.7 | 19.4 | 70.2 | 77.8 | 63.6 |
| 2014 | 23.7 | 24.1 | 23.4 | 77.8 | 79.1 | 76.8 |
| 2015 | 22.3 | 21.8 | 22.3 | 73.2 | 71.5 | 73.2 |
| 2016 | 21.1 | 25.4 | 17.2 | 69.2 | 83.3 | 56.4 |
| 2017 | 18.2 | 23.3 | 16.3 | 59.7 | 76.4 | 53.5 |