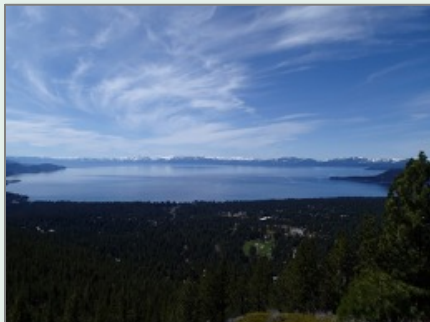
Tahoe Science Advisory Council (TSAC)

Summary Science Report on Lake Tahoe Clarity and Associated Conditions, 2021



August 2021

TSAC Data Synthesis and Analysis (DSA) Project Subcommittee

Alan Heyvaert, Ph.D.
Ramon Naranjo, Ph.D.
Shohei Watanabe, Ph.D.
John Melack, Ph.D.
Geoffrey Schladow, Ph.D.
Sudeep Chandra, Ph.D.

TSAC
TAHOE SCIENCE ADVISORY COUNCIL

Acknowledgements:

This summary analysis and assessment is the result of a collaborative effort on the part of many individuals who have contributed information, useful comments and thoughtful reviews.

Particular thanks are extended to Dan Segan and Julie Regan at the Tahoe Regional Planning Agency, Jason Kuchnicki and Paul Comba at the Nevada Division of Environmental Protection, Mary Wagner-Fiore, Ben Letton and Laura Korman at the California Lahontan Regional Water Quality Control Board, and Jacques Landy from the U.S. Environmental Protection Agency, as well as many others who participated in the spring DSA workshop.

The authors are also grateful for project assistance and coordination provided by Robert Larsen, out TSAC program officer. Funding was provided to the Tahoe Science Advisory Council by the California Natural Resources Agency, the Nevada Department of Conservation and Natural Resources, and the Tahoe Regional Planning Agency. We appreciate the continuing interest and participation of leaders from each of these agencies during the executive briefing this summer.

Any errors, omissions or misinterpretations are the responsibility of the TSAC authors.

Author Affiliations:

Sudeep Chandra – *University of Nevada, Reno*
Alan Heyvaert – *Desert Research Institute*
John Melack – *University of California, Santa Barbara*
Ramon Naranjo – *U.S. Geological Survey*
Shohei Watanabe – *University of California, Davis*
Geoffrey Schladow – *University of California, Davis*

This report is available at the Tahoe Science Advisory Council website:
https://www.tahoesciencecouncil.org/.

Preferred Citation:
Tahoe Science Advisory Council (TSAC). 2021. Summary Science Report on Lake Tahoe Clarity and Associated Conditions, August 2021. Incline Village, NV.

For more information contact:
Alison Toy
Tahoe Science Advisory Council
291 Country Club Dr., Suite 320
Incline Village, NV 89451
775-881-7566
natoy@ucdavis.edu

Executive Briefing on Lake Tahoe Clarity and Associated Conditions, 2021
June 2021

Lake Tahoe's clarity remains a key indicator of ecosystem health, and our scientific understanding about factors affecting lake clarity continues to evolve. This one-page briefing memorandum highlights findings from the 2021 TSAC Data Synthesis and Analysis report, which follows this executive summary and was the basis for discussion at the executive briefing on June 29th about the status of clarity metrics and drivers of change in Lake Tahoe presented during that meeting.

Notably, the concentration of fine particles in the upper 30–40 meters remain particularly important to lake clarity. These particles are clays and fine silts from the watershed as well as small phytoplankton produced within the lake, all of which are influenced by activities within the watershed.

Additionally, climate change is affecting other factors relevant to clarity and lake ecology, which include annual deep mixing, precipitation, and stratification in the upper water column.

Main Highlights

- The long-term rate of change in clarity is a more meaningful metric of the lake's health than year-to-year variations.
- Both management and data analysis efforts should remain focused on dominant drivers of trends rather than on individual data points.
- The decline in annual average Secchi depth ended around twenty years ago, and has not changed significantly since that time.
- Summer average clarity (Jun-Sep) continues to decline at a rate of 0.62 feet per year (0.19 m/y).
- Winter average clarity (Dec-Mar) does not currently show a trend of increasing or decreasing clarity.
- Fine sediment particles and small *Cyclotella* diatom species have accounted for 61% of Secchi depth variation from 2011 through 2020. This supports continuing efforts to control fine sediment and nutrient inputs to the lake.
- The relative impact of factors influencing lake clarity is variable over time. Lake and stream fine particle concentrations have been elevated since 2017, whereas *Cyclotella* concentrations exerted more influence on clarity from 2011 through 2016.
- Monitoring programs are the foundation of successful resource management. The data generated are necessary to quantify trends, assess relative influence of important drivers, inform the development of predictive models, discover changes in system function, and to inform discussions that identify opportunities for management actions.
- This project has demonstrated the value of agency-science collaboration for lake clarity assessment and management. The Science Council anticipates advancing its analysis and reporting schedule to provide a release of clarity results in the spring of each calendar year going forward.

1) Introduction

Lake Tahoe's clarity is a key indicator of system health, and the scientific understanding about factors affecting lake clarity continues to evolve. The purpose of this project is to communicate how clarity metrics changed over the previous calendar year and in the context of longer-term patterns.

In terms of direct effects on lake clarity, it is the amount of suspended particulate materials and dissolved organic matter that attenuate light transmission through the water column. In Lake Tahoe the concentration of fine particles in the upper 30–40 meters are particularly important to clarity, as estimated by Secchi depth visibility. These particles may be clays and fine silts from the watershed or small phytoplankton produced within the lake. Thus, scientists monitor the concentrations of both algae and fine particulates in the lake in addition to measuring the lake's clarity.

Other factors contribute indirectly to changes in lake clarity. These factors include seasonal mixing that redistributes materials through the water column. For example, dissolved nutrients that accumulate in the deep waters from decomposition of organic material can be mixed to the surface to enhance phytoplankton growth. Mixing can also affect clarity as water below the thermocline dilutes particulate concentrations near the surface. Lake surface stratification also plays a role, by potentially trapping inflowing waters to discrete, shallow layers where they can exert a disproportionate effect on clarity. Lake mixing is dependent on meteorological conditions; the windier and colder the weather for sustained periods, the greater the mixing depth, whereas calmer and warmer winters often result in shallower lake mixing depths. Inputs of nutrients and particulates from the watershed also depend on local and regional weather patterns, including winter snowfall, melting rates and rainfall. Land uses within the watershed and fires both near and far further modify inputs. As the climate changes temperature and precipitation, shifts in these factors are expected to influence lake clarity.

Resource management agencies in the Tahoe Basin depend upon analysis and reporting of the science and information behind hydrologic, climate, watershed and lake changes as these data are collected and become available to support ongoing collaborative development of adaptive management strategies. This report is the first iteration of a Tahoe Science Advisory Council (TSAC) project that will continue to compile, review and analyze relevant data on lake clarity and associated conditions to enhance collaboration, coordination and planning among agency partners and the Science Council. It will discuss dominant factors that seem particularly relevant for management and scientific inspection.

Additional information is discussed in the TSAC Lake Tahoe Seasonal and Long-Term Clarity Trend Analysis report (2020), and in the annual State of the Lake report produced by the UC Davis Tahoe Environmental Research Center (2021). Further materials are available from the Lake Tahoe Interagency Monitoring Program (LTIMP) conducted by the USGS and UC Davis, and from the Tahoe Regional Stormwater Monitoring Program (RSWMP) administered by the Tahoe Resource Conservation District and DRI.

2) Annual Average Lake Tahoe Secchi Depth Clarity

Secchi depths have been consistently estimated since 1968 using a 25 cm diameter white disk, with routine measurements made over the long-term at two locations in Lake Tahoe. The western site (LTP) is visited at roughly ten-day intervals, while the mid-lake site (MLTP) is monitored on a monthly basis. Water samples and vertical profiles of temperature and several other variables also are collected during these visits.

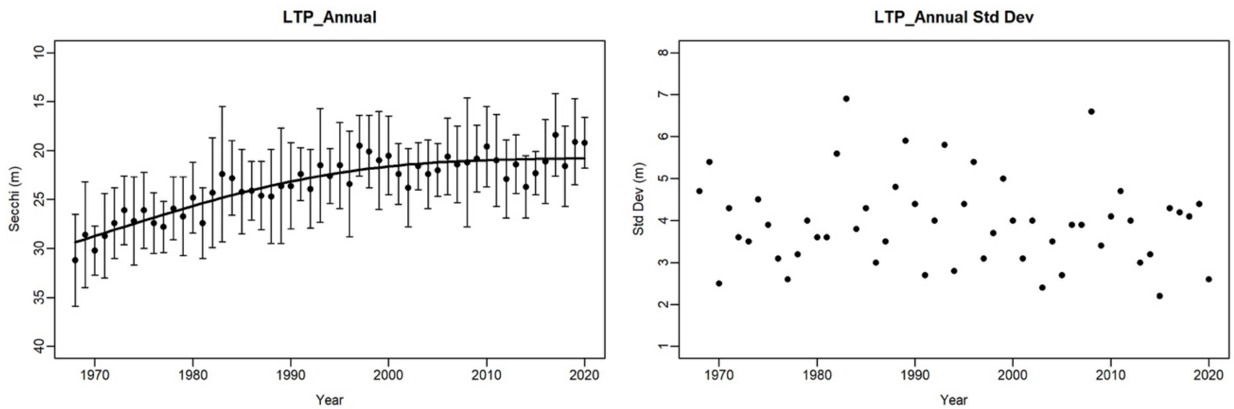


Figure 1. *Annual average Secchi depth measurements from 1968–2020. Vertical lines indicate the standard deviation of measurements taken during each calendar year (CY), plotted over time in the righthand panel.*

The Lake Tahoe TMDL tracks a five-year running average of Secchi depth to evaluate lake clarity response to evolving conditions. In CY 2019 the running average Secchi depth was 67.3 feet (20.5 m), while for 2020 the average was 65.2 feet (19.9 m). Figure 1 shows the best-fit line for Secchi depths over the years of record using a generalized additive model (GAM) to generate estimated values. This is a robust approach that is an extension of generalized linear models, but with a smoothing function to reduce the variability. As an example, values calculated by GAM produce a difference of 0.039 feet (0.012 m) between 2019 and 2020 estimated annual Secchi depths, which is less than the difference of 2.03 feet (0.62 meters) seen with a five-year running average.

The change in annual average Secchi depth has plateaued over the last 20 years, as noted in the analysis conducted as part of the Lake Tahoe Seasonal and Long-Term Clarity Trend Analysis project (TSAC 2020), and a new statistically significant trend of increasing or decreasing clarity has not been established as yet.

3) Lake Tahoe Seasonal Clarity Averages

Analyses of seasonal patterns in clarity indicated that winter clarity declined until about CY 2000, when it changed to having no statistically significant trend (TSAC 2020). In contrast, the trend for summer clarity has been one long-term steady rate of decline of 0.62 feet per year (0.19 m/y) from 1968 through 2019. The 2020 winter and summer clarity averages do not change these results.

The 2020 winter clarity value (Figure 2) is notable for its distance from the GAM-estimated line. LTP Secchi depth measurements are usually collected every ten days on average, but from the end of February to mid-April of 2020 no measurements were made at the LTP site because COVID-19 restrictions prevented work on the lake. This gap is evident in Figure 3, where blue symbols show CY 2020 Secchi depth measurements and grey symbols show data points from the previous nine years. The period in 2020 with the gap is typically the time of year when the deepest Secchi depths are recorded (with maximum lake mixing depth).

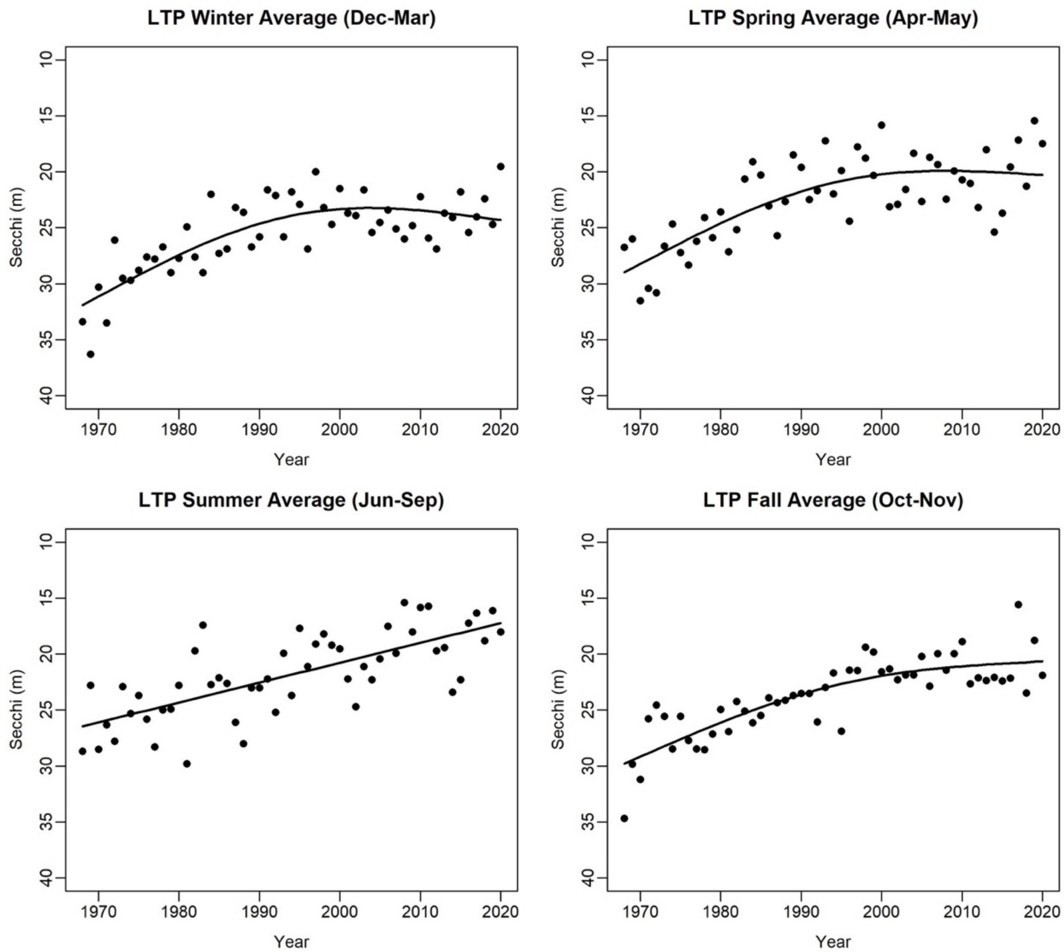


Figure 2. *Seasonal average Secchi depth clarity. Note that winter clarity averages include December from end of the preceding calendar year. Best fit lines are estimated from generalized additive models (GAM).*

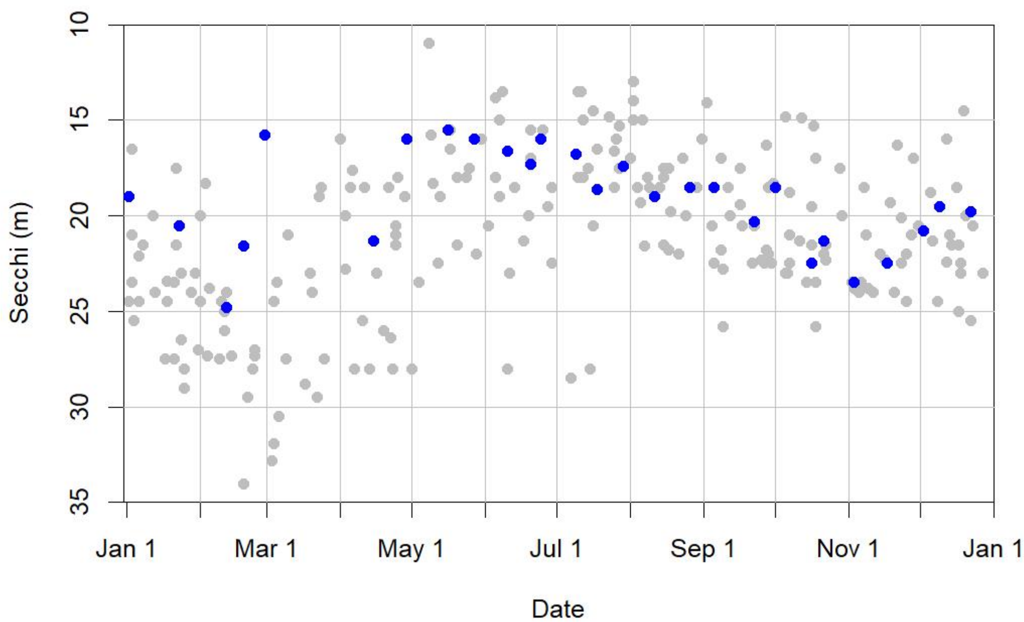


Figure 3. *Last ten years of individual LTP Secchi depth measurements (blue points are from CY 2020).*

4) Lake Mixing (1973-2020)

Lake surface waters mix with the colder deep (hypolimnetic) water as ambient air temperatures cool and increased winds are sustained across the lake surface. This happens on an annual basis in Lake Tahoe and the maximum mixing depth usually occurs from mid- to late winter (February through March). Vertical mixing generally improves the winter clarity average when it mixes to the bottom. Furthermore, as well-oxygenated surface water is transported downward it restores oxygen depleted in deep water zones. Annual deep lake mixing is an important process that redistributes nutrients and particles in the water column. The timing of maximum mixing depth is often linked to that year's greatest lake clarity, especially when the lake mixes all the way to the bottom, which has happened 14 times over the last 48 years (Fig. 4). The depth of maximum mixing depends upon winter conditions and the amount of heat that has accumulated in the lake during summer.

The timing of maximum mixing depth has advanced over the decades and it now occurs about one month earlier than it did in the 1970s (Supplemental material, Figure S1). Annual average volume-weighted water temperature has a long-term trend, increasing by about 1°F since 1970 (Supplemental material, Figure S2). This represents a considerable amount of heat storage in the lake and will contribute to less frequent full mixing over time if climate continues to warm.

The maximum mixing depth for 2020 was estimated at 145 meters from measurements on February 6, 2020. It could have been somewhat deeper but no measurements were conducted on the lake between March 9 and April 10, during the typical period of maximum mixing (Figure S1).

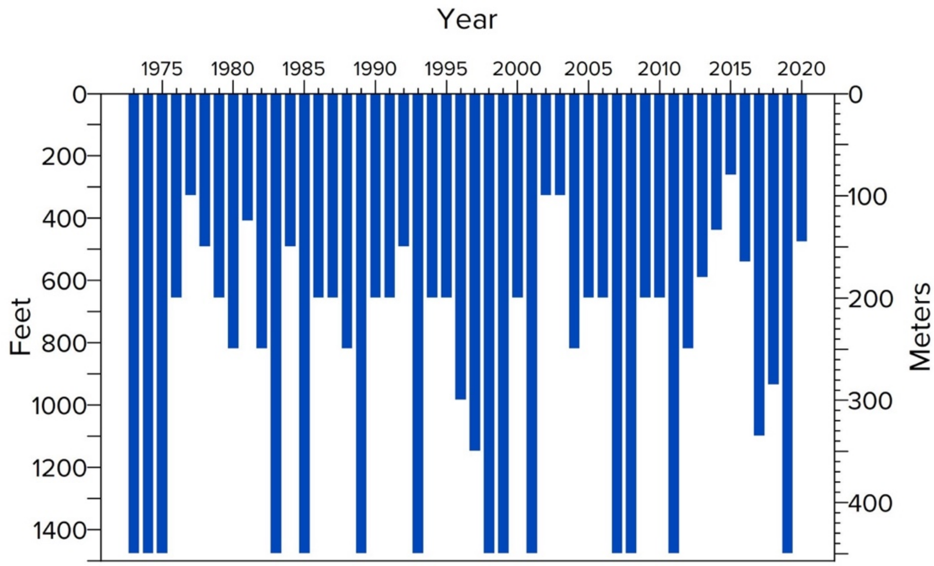


Figure 4. *History of maximum lake mixing depths (from measurements conducted during Secchi clarity excursions at MLTP site).*

5) 2020 Secchi Clarity Response to Fine Particle and Chlorophyll Concentrations

Secchi depths during 2020 had a typical pattern of shallower readings during spring and summer and deeper readings during the fall and winter (Fig. 5). The light attenuation from 0–20 meters was measured directly with a beam transmissometer lowered through the water column. This produces a beam attenuation coefficient that is considered an inherent optical property, compared to the apparent optical property represented by Secchi depth clarity. Secchi depth measurements and beam attenuation readings are taken to provide two independent lines of evidence of changes in Lake Tahoe's clarity, one of the most important metrics of lake condition. The beam attenuation was highly correlated with Secchi depth measurements ($R=|0.92|$, $p<0.0001$).

During calendar year 2020 the correlation of fine particle concentration (1–4 µm) and beam attenuation (Spearman's $\rho=|0.81|$, $p<0.001$) was marginally higher than with Secchi depth (Spearman's $\rho=|0.76|$, $p<0.0001$). As a predictor variable, fine particle concentration (both organic and inorganic particles) in the upper 20 meters accounted for about 60% of variability in beam attenuation ($r^2=0.61$, $p<0.001$) and for 50% of Secchi depth variation over the year ($r^2=0.50$, $p<0.0001$).

In contrast, chlorophyll concentration was not significantly correlated ($p<0.1$) with beam attenuation or with Secchi depth. It is believed that most of the chlorophyll is associated with large phytoplankton that do not impact clarity.

The strong relationship between fine particle concentration and clarity supports continued efforts to reduce fine sediment loads to Lake Tahoe. However, not all particles are considered equal. The focus on load reduction of fine sediment particles (FSP) currently uses a mass measurement of particles in the 0.5–16 µm range. In terms of effect on clarity, particle sizes in the range from 1 to 4 µm exert a dominant influence.

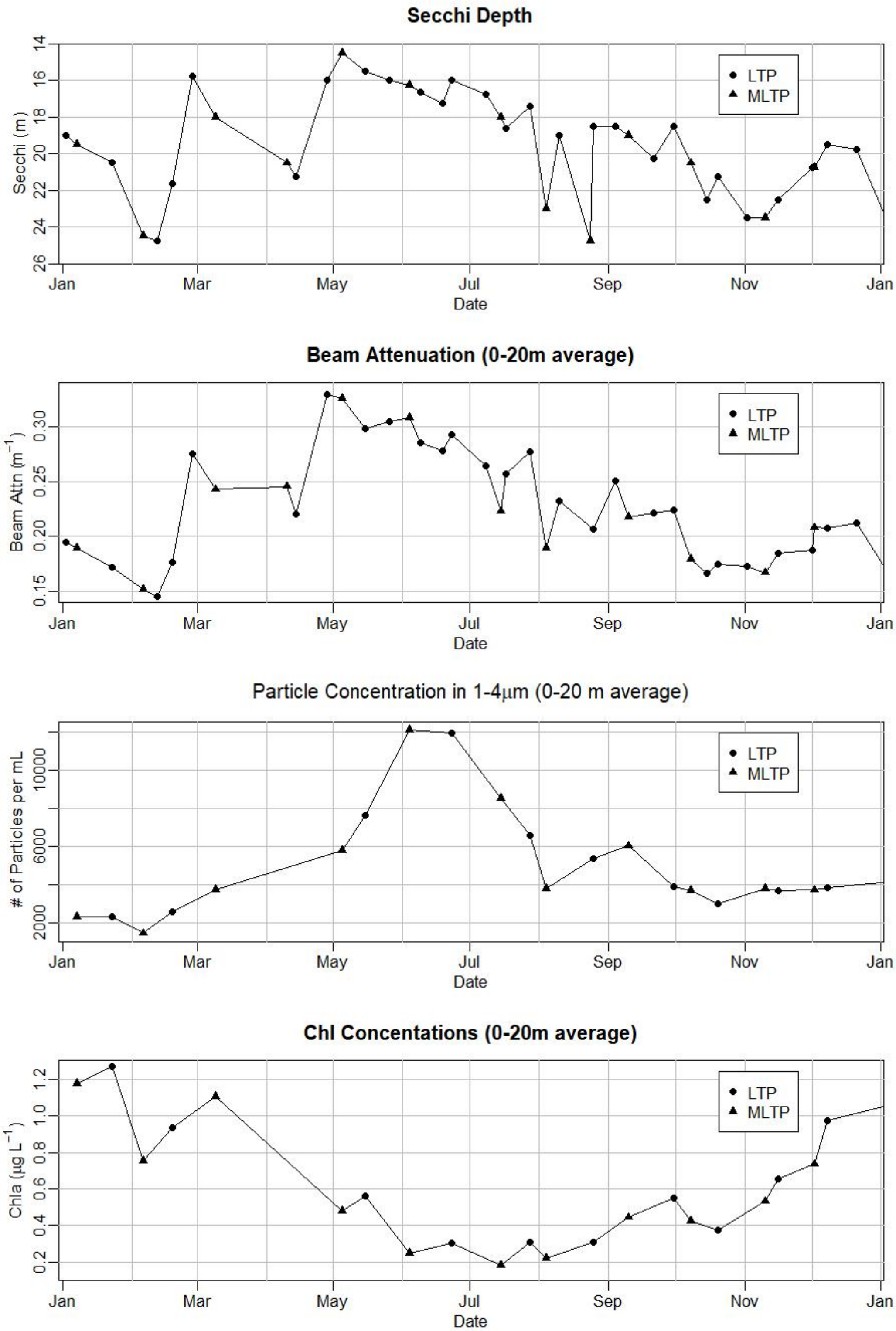


Figure 5. *Secchi depth clarity and transmissivity readings (beam attenuation), along with fine particle (1–4 μm) and chlorophyll-a concentrations measured during 2020. Samples analyzed for fine particle and chlorophyll concentrations were collected at 0, 2, 5, 10, 15, and 20 meters. These results were linearly interpolated at one-meter intervals and then averaged.*

6) 2020 Precipitation in the Longer-Term Context

Hydrologic data are examined by water year (WY), the period from October 1 through September 30, with WY designated by the calendar year in which it ends. The long-term pattern of annual WY precipitation at Lake Tahoe averages about 30 inches (76 cm) per year, from both rain and snow (Figure 6).

Watershed loading of FSP and nutrients to the lake is a primary target for management actions, for restoration projects, and for best management practices (BMPs) designed to reduce these loads. Interannual changes in precipitation and runoff influence these loads. Thus, we would expect lake clarity to respond to interannual variation in timing and volume of discharge from upland streams and urban areas, modulated by vertical mixing of the lake volume (156 km^3). Total annual precipitation accounts for about 30% of relative percent difference in annual Secchi depths from year to year since 1981, with the largest runoff years corresponding to larger decreases in Secchi depths.

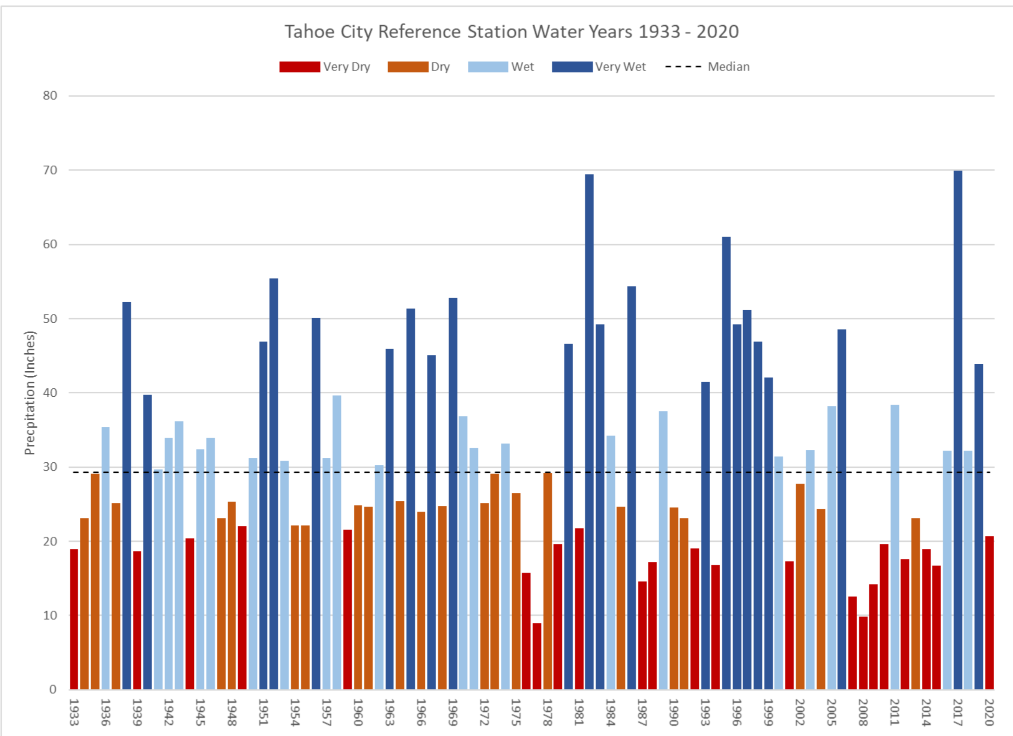


Figure 6. *Long-term precipitation records from the Tahoe City meteorological station, water years 1933–2020 (Tahoe RCD 2020).*

The 2020 water year was about 30% below the long-term average for precipitation in the Tahoe Basin. This followed four years of above average precipitation, preceded by a nine-year drought (broken by one wet year in 2011). Figure 7 illustrates variations as standard deviations of precipitation from year to year. Extreme water years include 1982 and 1997, which produced large runoff volumes and reduced clarity. Furthermore, there is some evidence of carry over effect (Fig. 8).

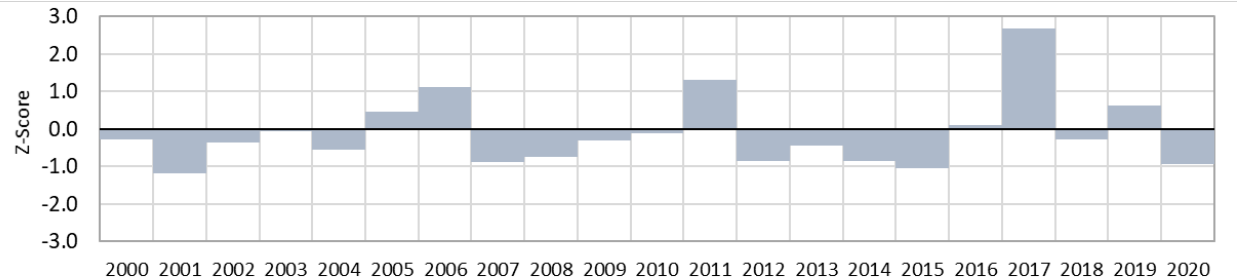


Figure 7. *Variations in water year precipitation compiled from NRCS gages in the Tahoe Basin. The Z-score at zero represents mean annual precipitation, and variations in the Z-score reflect relative above-average or below-average precipitation (see Figure 8). Z-score units are in standard deviations.*

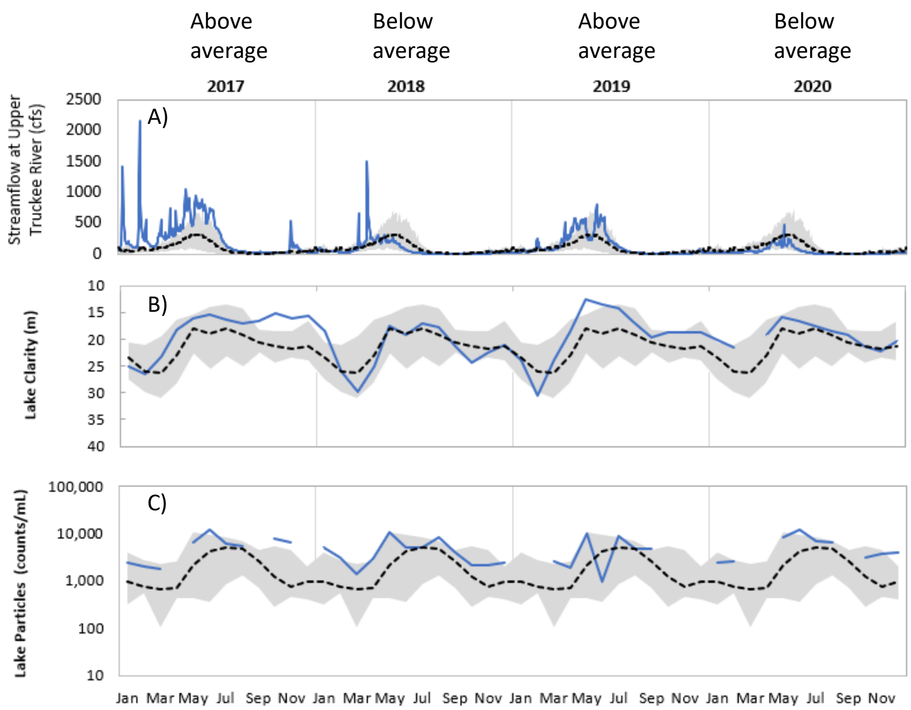


Figure 8. *Time-series of A) daily stream discharge measured at the USGS Upper Truckee River at South Lake gage (USGS 10336610), B) lake clarity measured at the LTP long-term monitoring site and C) lake particles (1-4 µm) measured at 5 m at the LTP site. Shaded area are the 90% confidence bounds, black dashes are from median monthly values, and the observed values are the blue line. Medians and confidence bounds computed for stream discharge, lake clarity and lake particles from 1980-2019, 2000-2019, and 2008-2019, respectively.*

Lake clarity can be influenced by periods with exceptional precipitation extending into the subsequent years. This carry-over affect is indicated by time required for clarity to return to monthly median values. Exceptional stream discharge was observed during 2017 and 2019 in comparison to median monthly values (Figure 8A). The large accumulation of snow in the Sierra Nevada during 2017 resulted in stream discharge exceeding the 90% confidence interval. As a result of increased stream discharge and sediment loads, lake clarity was impacted for 11 months extending into early 2018 when vertical lake mixing occurred to 285 meters and improved clarity in March 2018 (Figure 8B). During the remainder of 2018, stream discharge and lake clarity were at or below median monthly values. The high stream discharge in 2019 produced increased sediment inputs to the lake, contributing to a 17-month period of impaired clarity until returning to median monthly values in September 2020. In 2020, lake mixing depth was only partial (145 m) and did not improve clarity as was observed during maximum deep mixing that occurred in 2019 (450 m). Given that annual average clarity in 2017 and 2019 was the lowest (18.4 m) and second lowest (19.1 m) on record, it is not surprising that prolonged impacts on lake clarity would extend into subsequent years.

7) Clarity Response to Fine Particle and *Cyclotella* Concentrations, 2011–2020

Interannual changes in lake clarity are driven by fluctuations in the concentration of optically active materials in the water column. This includes light absorption and scattering by phytoplankton, by inorganic particles, and by dissolved organic material. From year to year (and within each year) the significance of these factors can shift in terms of both absolute and relative influence, depending on patterns of algae production, changes in lake loading rates, the timing and depth of lake mixing, and settling rates through the water column. Patterns in Secchi clarity over the last ten years show correlated shifts in response to interannual changes of fine particle concentrations and small algae (Figure 9).

There is a slight trend of decreasing clarity from 2011–2020, although it appears to be primarily due to a step change in fine particle concentration (Figure 9). The fine particle concentration (1–4 µm) in near-surface waters of Lake Tahoe increased substantially during 2017, a year with exceptionally large precipitation, and has remained elevated compared to the preceding 2011–2016 period. Reason(s) for continuing elevated concentrations are not known, although carry-over effects would contribute.

From 2011–2016 the concentrations of *Cyclotella* species were higher than after 2017. *Cyclotella* are diatoms common in oligotrophic environments, and since 2000 they have become the numerically dominant species within the clarity-impacting size range of algae for Lake Tahoe (Winder et al. 2008). They are small, centric diatoms better adapted than other diatoms in the lake to increasing stratification and shifting nutrient supplies. The smallest of the *Cyclotella* species in Lake Tahoe are numerically dominant, with maximum sizes ranging from about 4–7 µm. Their effect on clarity becomes pronounced when concentrations exceed about 100 cells per mL (Supplemental material, Figure S4).

Reducing the concentration of fine particles and nutrients that support algae in the lake has been the focus of management efforts at Lake Tahoe. The utility of these efforts is supported by data indicating both *Cyclotella* and fine particles are contributing to the variability observed in Secchi clarity over the last decade (Supplemental material, Figure S5). From 2011–2020 the correlation of fine particle concentration and Secchi clarity was significant (Spearman's rho = $|0.72|$, $p<0.0001$). During this same period the concentration of *Cyclotella* spp. was also correlated with clarity, but less so (Spearman's rho = $|0.59|$, $p<0.0001$). The fine particle and *Cyclotella* concentrations had a low but significant correlation (Spearman's rho = $|0.38|$, $p=0.0001$), likely because analysis of lake samples for fine particles does not distinguish between biogenic and mineral particles.

Taken together the concentrations of fine particles and *Cyclotella* cells account for about 61% of the variation in Secchi clarity from 2011–2020, estimated from multiple linear regression using the restricted maximum likelihood (REML) approach (Supplemental material, Figure S6). The adjusted coefficient of determination was 0.61 and all parameter estimates were significant at $p<0.0001$. Predicted values for Secchi depth from this model based on fine particle and diatom concentrations tracked measured Secchi depth patterns but did not fully capture all extremes, particularly for the larger (deeper) Secchi depth values. This suggests that fine particles and *Cyclotella* account for most of the variation observed during conditions of reduced clarity, as expected, but other factors must contribute additional variation when lake clarity is deeper.

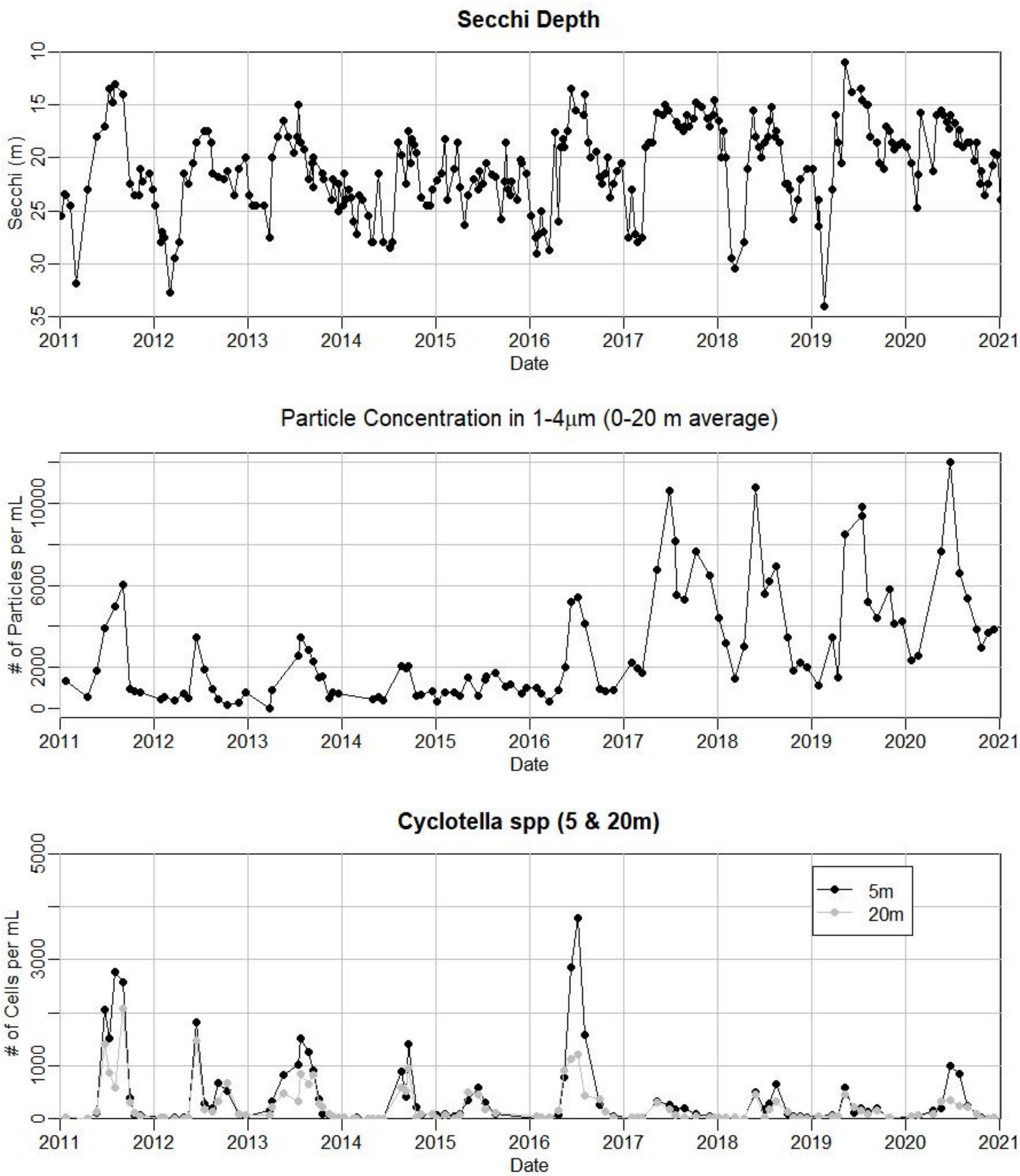


Figure 9. *Secchi depths, fine particle (1–4 μm) and Cyclotella concentrations at LTP site (CY 2011–2020). Samples analyzed for fine particle concentrations were collected at 0, 2, 5, 10, 15 and 20 meters. These results were linearly interpolated at one-meter intervals and then averaged.*

8) Management Questions and DSA Responses

1. What were the primary drivers of recent clarity conditions?

    - Fine particles in the size range from 1–4 μm were a significant factor influencing lake clarity along with *Cyclotella* concentrations, which taken together account for about 61% of the variability in Secchi depth clarity since 2011.

- Another factor that would influence clarity over recent years includes dilution from vertical lake mixing. This was minimal in 2020 (~145 meters), but the lake fully mixed in 2019 (to 450 meters).
- Carry-over effects from WY 2019 runoff contributed to lower than average clarity in CY 2020.

2. How much of the recent year's clarity condition is due to factors beyond local resource management control?
    - Low precipitation in WY 2020 (and likely 2021) should reduce loadings to the lake (see Supplemental material, Figure S7).
    - Climate change effects on the lake will continue to increase with higher temperatures, prolonged stratification, less snowpack accumulation, and more extreme variability in runoff.
3. Was the lake's response to monitored variables consistent with our current understanding of how clarity works?
    - Fine particles (both organic and inorganic) continue to exert a dominant influence on lake clarity.
    - Algae (esp. *Cyclotella spp.*) concentrations contribute to clarity changes as well. However, *Cyclotella* microscope counts are only taken at two depths, so there is ambiguity when comparing to fine particles counts (which includes *Cyclotella*) measured at 6 depths.
    - WY 2019 was an above average runoff year and there were carry-over effects on CY 2020 Secchi clarity.
    - Winter clarity is calculated as the average of Secchi depth measurements from December through March, which includes the period when mixing occurs. Because Secchi depths were not measured from mid-February to mid-April of 2020 due to COVID-19, the average winter clarity value does not include this period.
4. What monitoring program adjustments could support better understanding of future clarity conditions?
    - The urban stormwater monitoring program should be reviewed for efficacy in quantifying fine sediment and nutrient loads and load reduction on a basin-wide basis.
    - Although changes to reporting frequency will not improve our understanding of future conditions, the opportunity to communicate with agency partners would benefit from Secchi depth clarity reported on a quarterly basis (at the end of each subsequent quarter).
    - Protocols should be implemented to estimate and report nutrient and FSP loads from LTIMP streams on a regular basis (quarterly or at least within a few months after each water year).
    - The RSWMP (urban) and LTIMP (stream) monitoring programs assess dominant sources of pollutant loading to Lake Tahoe. These programs should be aligned to produce equivalently reliable estimates of loads and yields and to report results on similar schedules for the DSA.

8) **Science Questions for Subsequent DSA Cycle**

- What is the rate of change needed from present conditions to attain TMDL clarity targets at designated dates, and at that rate how many years of data are needed to detect a change in trend given historical annual variability?

- What caused the step-change in fine particle concentrations in Lake Tahoe in 2017 that has remained elevated, along with the LTIMP stream concentrations of FSP (Supplementary material, Figure S8)?
- *Cyclotella* concentrations are currently enumerated at only two depths. Should that be increased to improve estimates of their concentrations over the range of Secchi depth?
- Should beam attenuation be averaged over the full range of corresponding Secchi depths each sampling event, rather than over a consistent 0–20 m average?
- To what extent would nutrient and organic matter load reductions from restoration projects in the Tahoe Basin improve deep-lake lake oxygen concentrations over the long-term? (Lower production of algae and organic matter decomposition in the lake would reduce demand for oxygen in the deep waters and may ameliorate effects from less frequent deep mixing anticipated from climate change.)

9) Recommendations

- Communicate the importance of watershed management activities that reduce particle loads in the 1–4 µm size fraction as part of overall efforts to control fine sediment particle (FSP) loading over the full 0.5–16 µm range.
- Consider new approaches to statistical data analysis. For example, empirical dynamic modeling (nonlinear state space analysis) represents an emerging data-driven approach for modeling and elucidating the behavior and interactions of nonlinear dynamic systems like Lake Tahoe.
- Support continued and coordinated development of both process-based and statistical models for evaluating changes in lake condition and ecological processes over time. These are mutually supportive efforts.
- Continue analyses that attempt to distinguish mineral particles from biogenic particles (esp. diatoms and diatom frustule fragments).
- Focus on the longer-term data trends (rather than singular data points or short excursions from trend lines) to develop appropriate adaptive management strategies.
- Develop confidence bands for the GAM best-fit lines of Secchi depth clarity. Points outside these confidence intervals would receive increased attention during data synthesis and analysis.
- Evaluate factors affecting lake conditions on a water year basis or by corresponding hydrologic seasons to align with reporting and analysis of hydrologic data.
- Develop projections of potential impacts on ecological conditions in the lake and its watershed resulting from continued climate change.

10) DSA Timeline and Next Steps

This data synthesis and analysis project resulted from recommendations in the Lake Tahoe Science-to-Action Plan (TSAC 2019), which included developing a process for periodic data review, analysis and consultations with resource management agency representatives to examine progress on lake clarity restoration and to collaboratively discuss the scientific and management understanding of factors driving changes over time. This project is being implemented in a phased approach, as summarized below.

- Phase 1 of this project began in November 2020 to evaluate project objectives and to design a process that would achieve these objectives. This included meetings with agency partners to review the objectives, discuss management questions and the DSA process.

- Phase 2 initiated analysis and reporting activities in March 2021. This included assembling available data, conducting analyses, and selecting relevant findings to communicate in a summary science report that informed agency/science discussions during the spring DSA workshop in May 2021. The product of that workshop was a concise executive briefing memorandum, followed by a DSA meeting with affiliated Basin executives to discuss priority results and implications for management.
- Phase 3 is scheduled to commence in October 2021 to continue this process of annual reporting on conditions associated with Lake Tahoe clarity. As proposed, it will begin with a workshop that collaboratively discusses perspectives and priorities on management and science questions, leading into data synthesis and analysis for 2022. Data management remains an important objective, along with periodic updates for analysis and reporting. Over the longer-term, new and updated statistical models and projections of status and trends in key water quality parameters will be incorporated to augment this ongoing DSA process.
- Given the compressed timeframe for this initial implementation of the DSA process, our agency/science team workshop and executive briefing occurred later in the year than we anticipate for subsequent annual iterations. We recommend the following (subject to further discussions with agency partners):
    - Monthly science team meetings.
    - Annual science/agency team coordination meeting and updates in Nov/Dec.
    - DSA summary science report by March
    - Annual agency/science team workshop in April.
    - Executive memo and briefing provided in Apr/May.

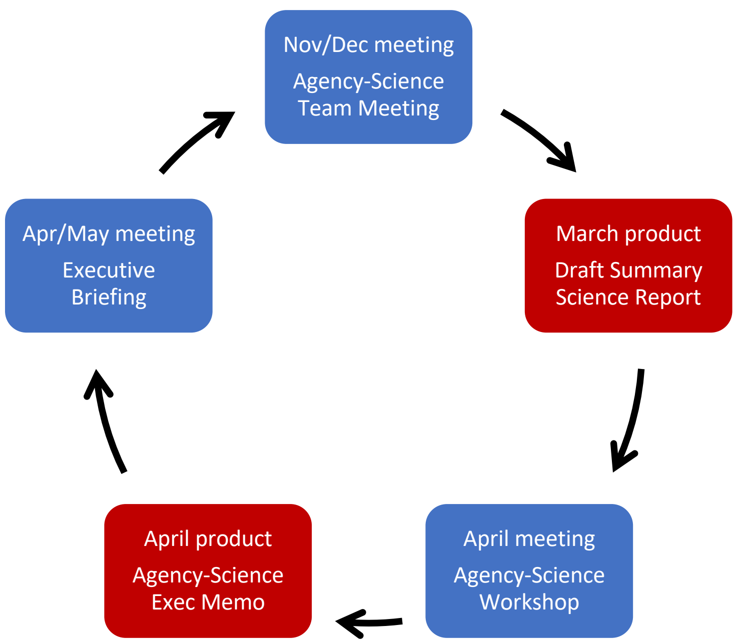


Figure 10. *Annual scheduling of major DSA events and products for Phase 3 implementation.*

11) Citations

Tahoe Resource Conservation District (Tahoe RCD). 2020. Annual Stormwater Monitoring Report, Water Year 2020. Submitted to the Lahontan Regional Water Quality Control Board and the Nevada Division of Environmental Protection, March 30, 2021.

Tahoe Science Advisory Council (TSAC). 2019. Science to Action Planning, Project Briefing and Science Vision for Lake Tahoe, 2019. TSAC Technical Report, August 2019. Incline Village, NV.

Tahoe Science Advisory Council (TSAC). 2020, Lake Tahoe Seasonal and Long-Term Clarity Trend Analysis. TSAC Technical Report, October 2020. Incline Village, NV.

Winder M., J.E. Reuter, and S.G. Schladow. 2009. Lake warming favours small-sized planktonic diatom species. Proc. R. Soc. B; 276: 427-435.

University of California, Davis, Tahoe Environmental Research Center. 2021. Tahoe: State of the Lake Report, 2021. Incline Village, NV.

Supplemental Materials

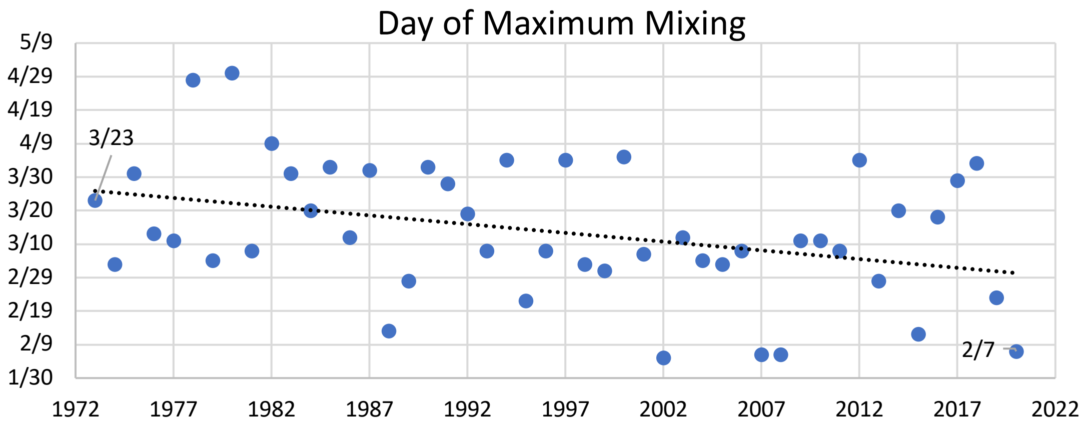


Figure S1. *Dates of maximum Lake Tahoe mixing depth each year. Overall, the date of maximum mixing has advanced by about one month (from March to February).*

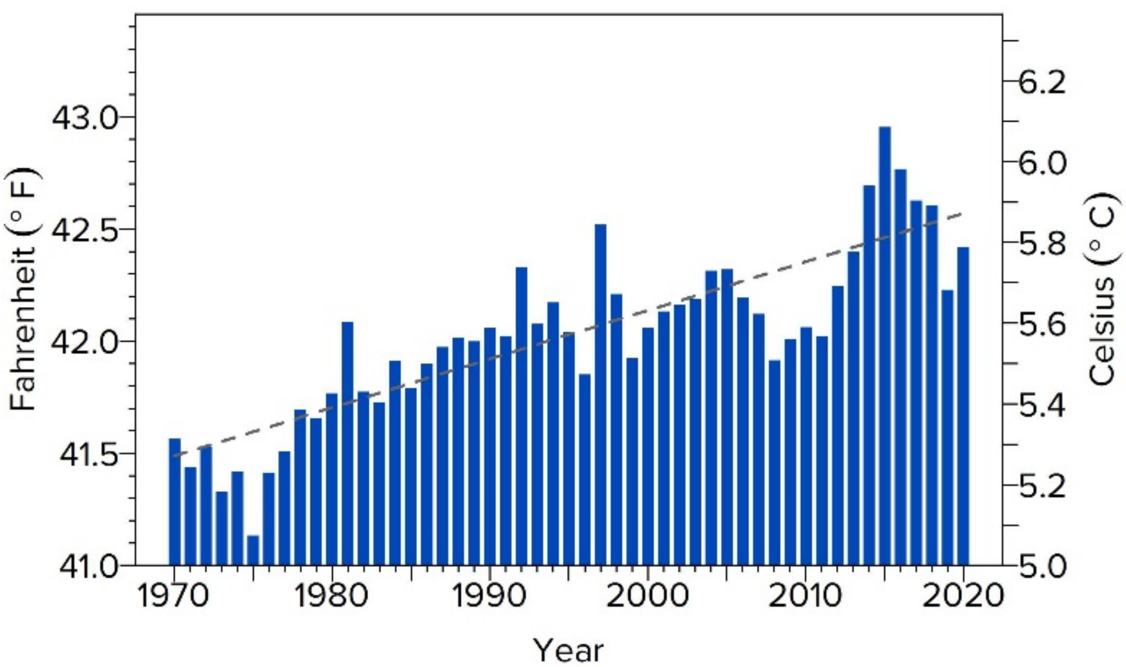


Figure S2. *Calculated annual volume-weighted average water temperatures 1970–-2020 (CY).*

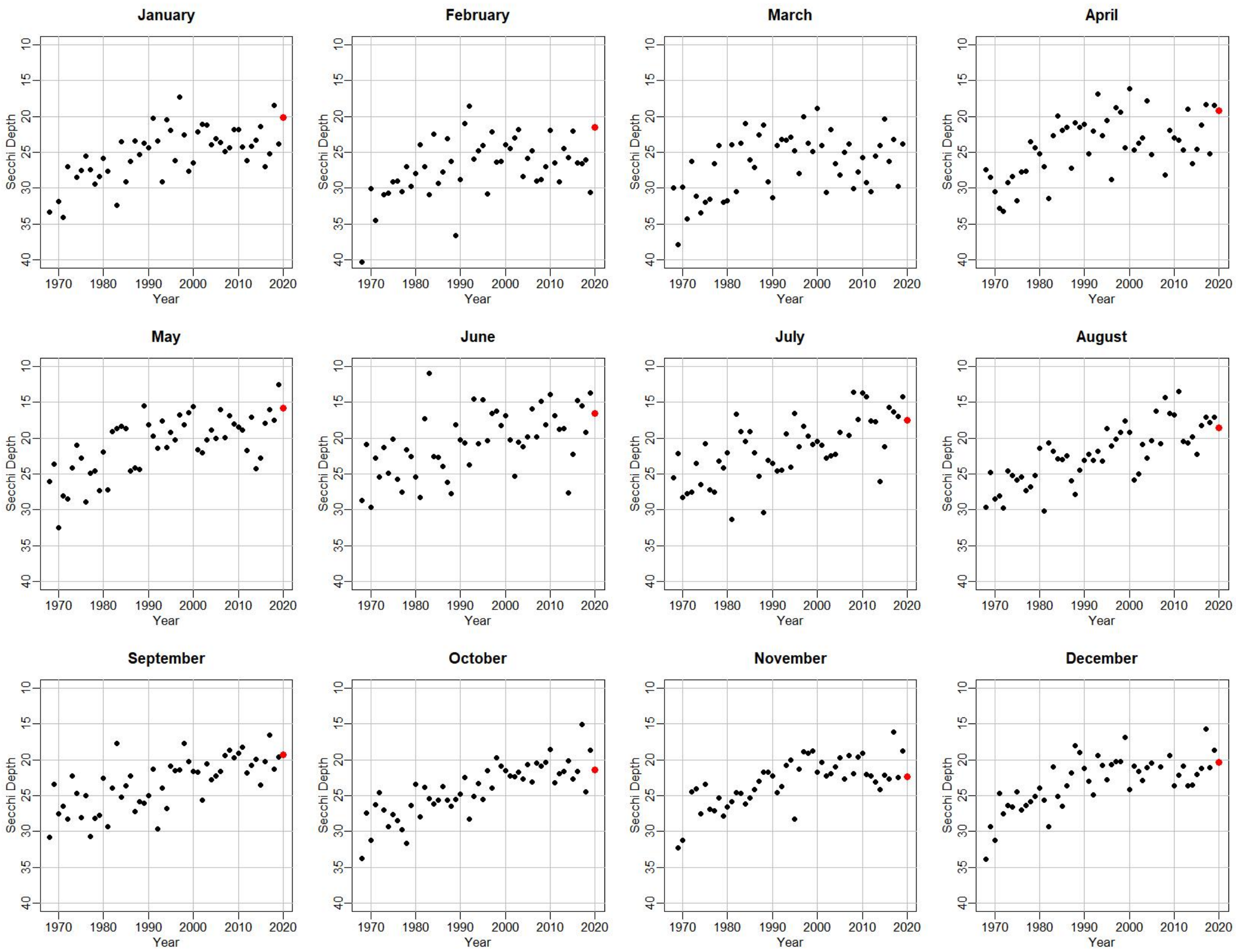
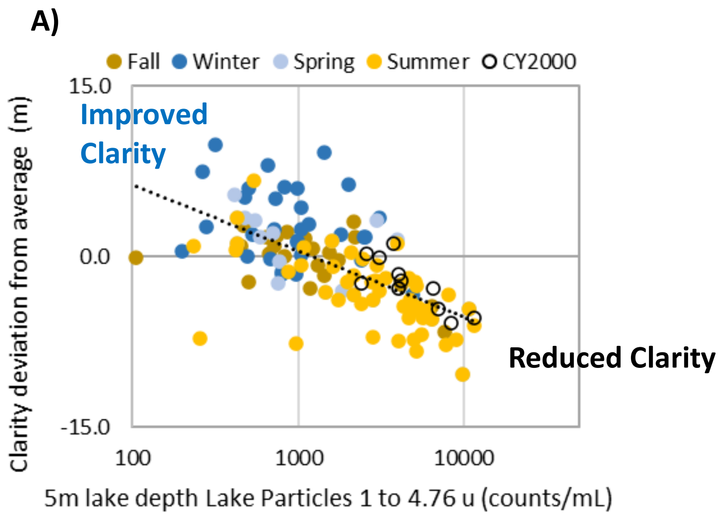


Figure S3. *Monthly Secchi clarity averages CY 1968–2020. Red symbol data points indicate CY 2020 monthly averages. Note the absence of Secchi depth measurements in March 2020, due to COVID-19 restrictions on fieldwork.*



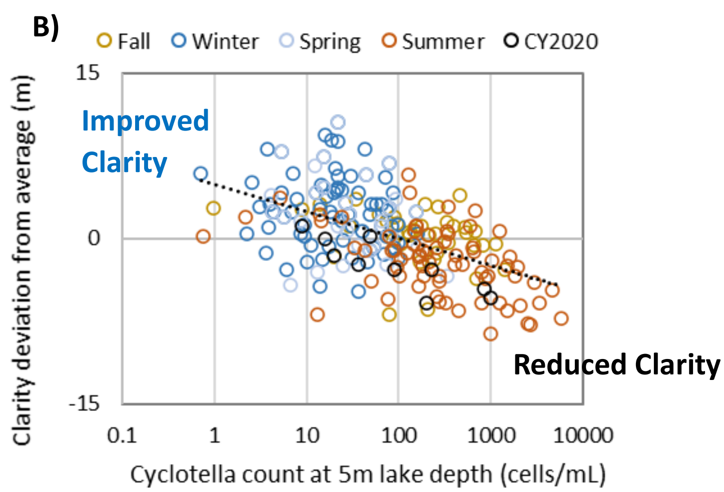


Figure S4. *Relationship between clarity deviation from the 20-year average (CY 2000–2020) for A) measured values of lake particles (1.0–4.76 µm) during CY 2020, and for B) Cyclotella measured at 5 m during CY 2020. Positive values of clarity deviation reflect improved clarity (values greater than average) whereas negative values reflect reduced clarity (values less than the average). For lake particles and Cyclotella measured at 5 m, values having the greatest impact on clarity exceed 100 counts/mL and 1000 cells/mL, respectively. Clarity deviation was computed by taking the difference in monthly average values from the 20-year average.*

The seasonal clarity trend analysis (TSAC, 2020) evaluated particles and *Cyclotella* by examining the values that caused the greatest impacts on lake clarity (Figure S4). Particles and *Cyclotella* measured at 5 m were compared to clarity deviations from the 20-year average (2000–2020). Clarity deviation was computed by taking the difference in monthly average values from the 20-year average. Particles exceeding 1000 counts/mL negatively impact clarity, and *Cyclotella* counts greater than 100 cells/mL negatively impact clarity. In calendar year 2020 (CY2020), in most month particle counts were greater than 1000 counts/mL; *Cyclotella* exceeded 100 cell/mL for three months.

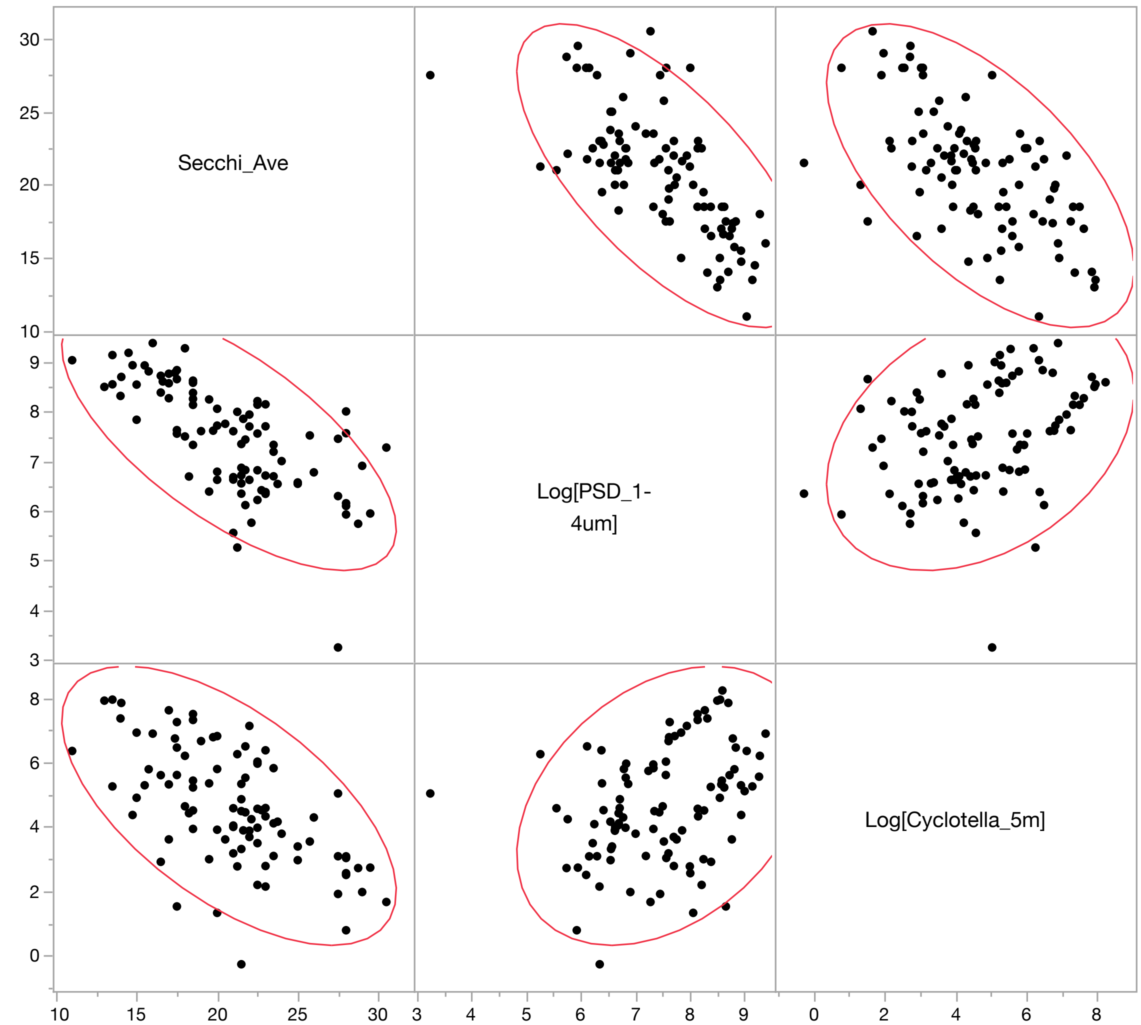


Figure S5. *Scatterplot matrix of nonparametric correlations for Secchi depth clarity, log-transformed fine particle concentrations and log-transformed Cyclotella concentrations (for data shown in Figure 9). Spearman's rho correlation coefficients and p-values are listed in the table below.*

Variable	by Variable	Spearman ρ	Prob>|ρ|	-.8 -.6 -.4 -.2 0 .2 .4 .6 .8
Log[PSD_1-4um]	Secchi_Ave	-0.7174	<.0001*	
Log[Cyclotella_5m]	Secchi_Ave	-0.5934	<.0001*	
Log[Cyclotella_5m]	Log[PSD_1-4um]	0.3772	0.0001*	

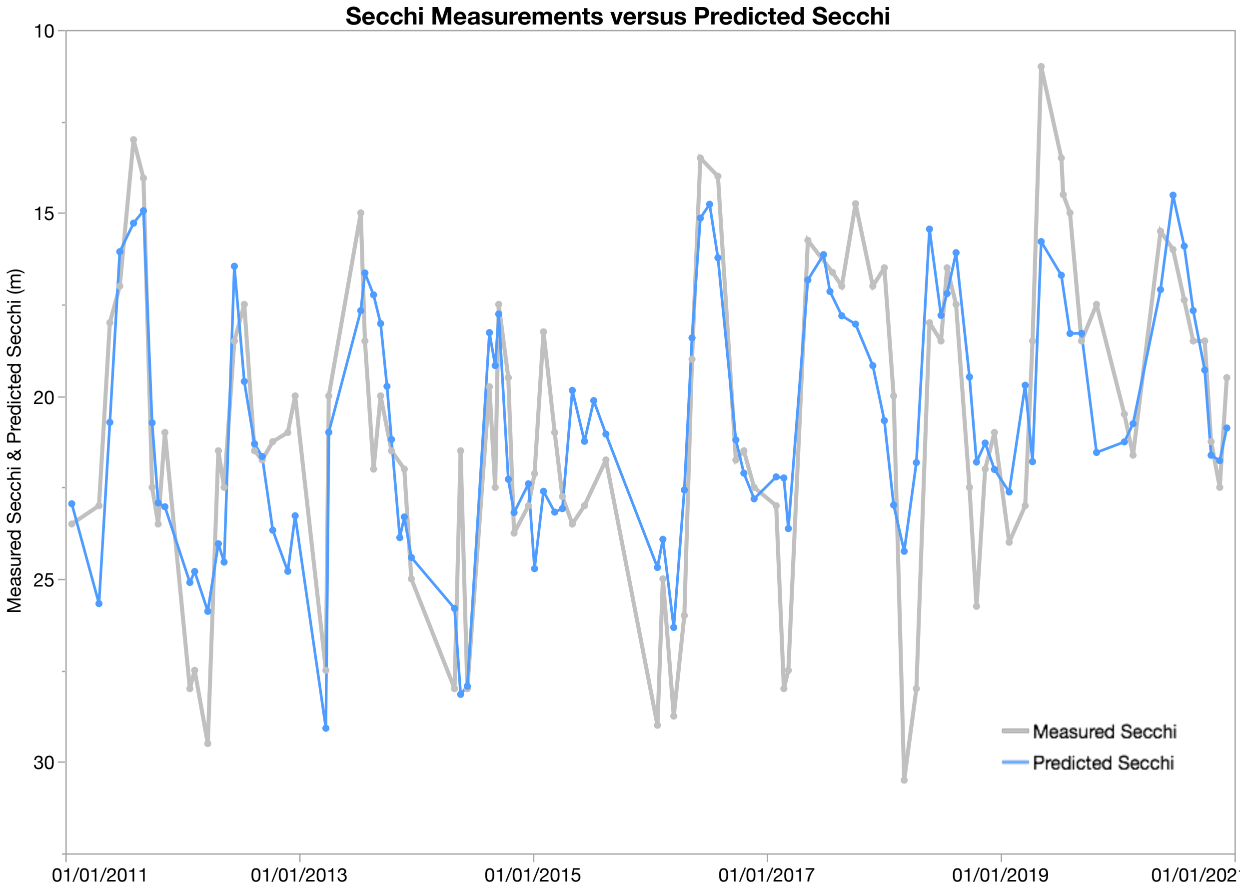
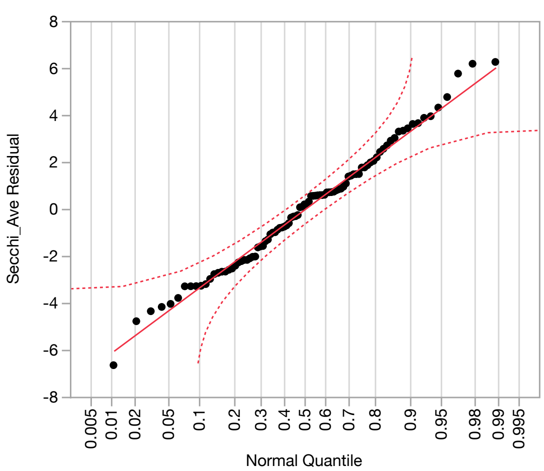
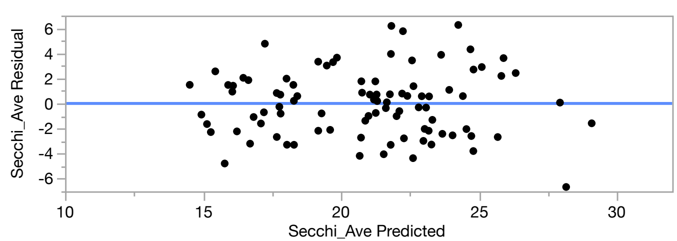


Figure S6. *Multiple regression estimation of Secchi depth clarity from log-transformed fine particle concentrations and log-transformed Cyclotella concentrations, using a restricted maximum likelihood (REML) approach. Model was run without interaction effects between the two variables (insignificant when tested). Residuals were well behaved in the Q-Q plot. The adjusted coefficient of determination was 0.61 and all parameter estimates were significant at p<0.0001. Both the residual normal quantile plot and the plot of residuals against predicted values are shown below.*





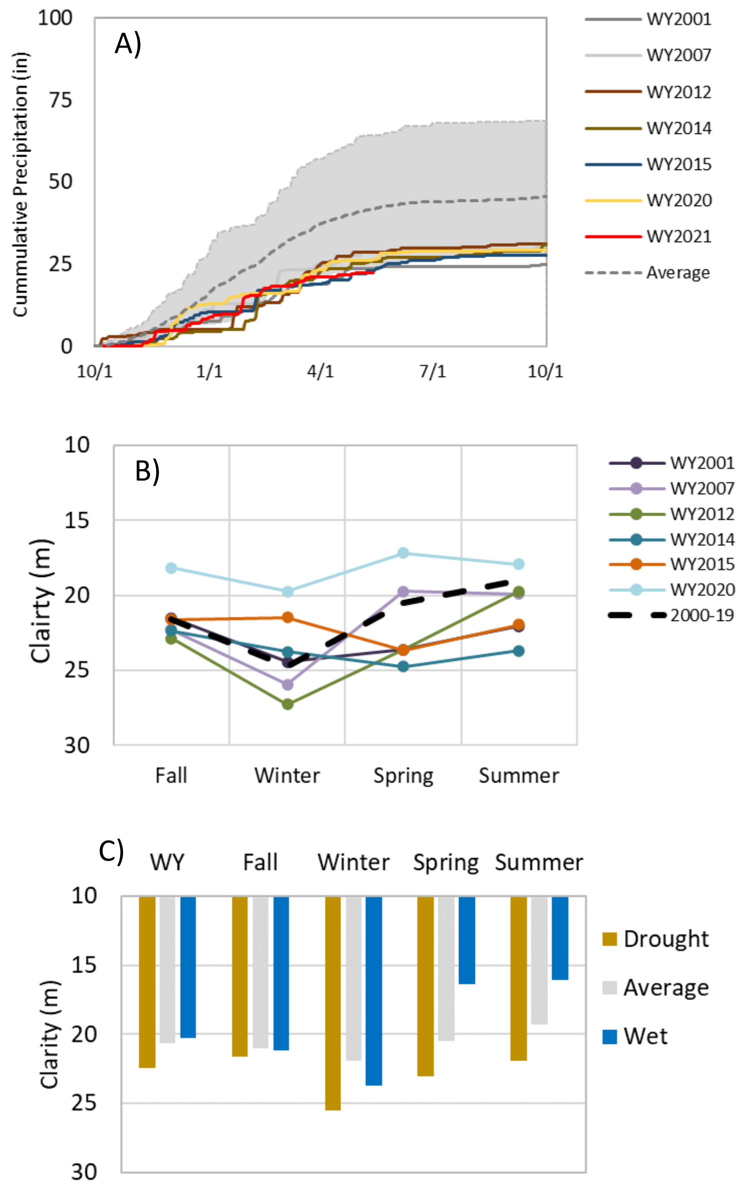


Figure S7. *A) Water year (WY) 2021 cumulative precipitation compared to 7 years with droughts within the last 20 years (WY 2001, 2007, 2012, 2014, 2015 and 2020); and B) associated seasonally averaged clarity; and C) averaged clarity during drought, average and above average conditions as reported in the seasonal clarity analysis (TSAC, 2019). Precipitation data measured by the NRCS averaged for the Tahoe Basin (from 1981-2020, with 90% confidence bounds as shaded area and the average as dashed line).*

Given the current clarity and precipitation conditions we can infer what to expect for the remainder of 2021. Periods of drought consistently have improved seasonal clarity compared to above-average and average precipitation years (TSAC 2020). As of May 2021, accumulated precipitation within the Tahoe Basin is below average and at the 10% level for the period of record (1981–2020). Evaluating years of clarity within the 20-year period during drought conditions, seasonal clarity is markedly improved from the average (Figure 3.1B). Despite WY2020 being a period of below average precipitation, the carry over affect from WY2019 resulted in lower than average seasonally averaged clarity. If precipitation patterns remain consistent for the rest of 2021, it is expected that seasonal clarity will be improved over the 20-year averaged period (2000–2020).

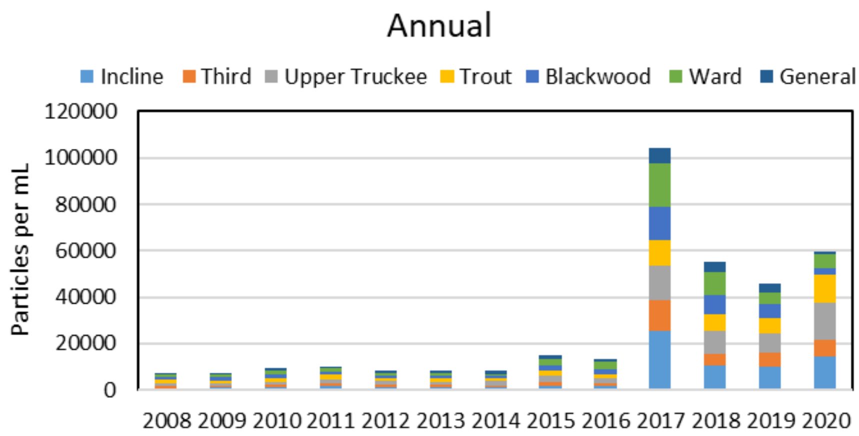


Figure S8. *Fine particle counts at monitored tributaries to Lake Tahoe, and at the two in-lake monitoring stations (LTP and MLTP). Particle counts are per milliliter and include all particles in the 1.0–4.76 µm size range. In-lake values are vertically averaged over the top 50 m of the lake.*

Appendix A. Data sets used during the Data Synthesis and Analysis project, 2021.

Variable	Location	Units	Available Frequency	Series start	Data Access	Note #
Secchi (lake clarity depth)	LTP	meters	Approx. every 14 days	1967	UCD-TERC	
Secchi (lake clarity depth)	MLTP	meters	Monthly	1980	UCD-TERC	
Beam attenuation	LTP	1/m	Approx. every 14 days	2005	UCD-TERC	1
Beam attenuation	MLTP	1/m	Monthly	2005	UCD-TERC	1
Particle concentration	LTP	particles/mL	Monthly	2008	UCD-TERC	2
Particle concentration	MLTP	particles/mL	Monthly	2008	UCD-TERC	2
Chlorophyll-a concentration	LTP	µg/L	Monthly	1984	UCD-TERC	3
Chlorophyll-a concentration	MLTP	µg/L	Monthly	1984	UCD-TERC	3
Lake water temperature	LTP	degree C	Approx. every 14 days	1967	UCD-TERC	4
Lake water temperature	MLTP	degree C	Monthly	1980	UCD-TERC	5
Tahoe City precipitation	Tahoe City gage	inches	Daily	1931	NWS	6
Tahoe Basin precipitation	Basin gages (11)	inches	Daily	1981	NRCS	
Lake mixing depth (maximum)	MLTP	meters	Annual estimation	1973	UCD-TERC	7
Cyclotella concentration	LTP	cells/mL	Monthly	2008	UCD-TERC	8
Stream discharge	LTIMP streams (7)	cfs	Daily	1972-1988	USGS *	9
Particle concentration	LTIMP Streams (7)	particles/mL	20-25 times each year	2008	USGS/UCD	10

1) 0-30m continuous.

2) Sampled at 0, 2, 5, 10, 20, 30, 40, 50m (only 0-20m data used in DSA report). Size bin breaks: 0.5, 0.63, 0.79, 1.0, 1.41, 2, 2.83, 4, 4.76, 5.66, 6.73, 8, 11.31, 16µm.

3) Measured at 0, 2, 5, 10, 20, 30, 40, 50m (only 0-20m data used in DSA report).

4) From 0-100m. 1967-1996: approx. every 3m; 1996-2005: every 1m; after 2005: continuous, binned averages for 1m intervals.

5) From 0-450m. 1967-1996: approx. every 50m; 1996-2005: every 1m (0-200m only); after 2005: continuous, binned averages for 1m intervals.

6) NWS Cooperative Observer Program.

7) Includes estimated date of maximum lake mixing depth each year.

8) Enumerated at 5m and 20m.

9) Upper Truckee River, and Incline, Third, Trout, Blackwood, Ward, General Creeks (start years vary).

10) Upper Truckee River, General Creek, Blackwood Creek, Ward Creek, Trout Creek, Third Creek, Incline Creek.

* USGS Site Numbers: 10336610, 10336645, 103360, 10336676, 10336780, 10336698, 10336700 (data at https://nwis.waterdata.usgs.gov/nv/nwis/inventory/).