Tahoe Science Advisory Council (TSAC)

Summary Science Report on Lake Tahoe Clarity and Associated Conditions, 2022

June 2022

TSAC Data Synthesis and Analysis (DSA) Project Subcommittee

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Executive Briefing on Lake Tahoe Clarity and Associated Conditions

May 2022

Lake Tahoe's clarity remains a key indicator of overall ecosystem status, and scientific understanding about factors affecting lake clarity continues to evolve. The purpose of this briefing memorandum is to summarize the status of clarity metrics and drivers of change discussed in the 2022 TSAC Data Synthesis and Analysis report.

Consistent with the Lake Tahoe Total Maximum Daily Load analyses, the concentrations of fine particles remain important to lake clarity. These include fine sediment particles from the watershed as well as small phytoplankton cells produced within the lake. This year, in addition to the analysis of Secchi depth clarity response to fine particle and small phytoplankton concentrations, we reviewed available data on fine sediment particles from streams and urban runoff.

Information summarized here is discussed further in the Tahoe Science Advisory Council (TSAC) Data Synthesis and Analysis reports (2022, 2021), the TSAC Lake Tahoe Seasonal and Long-Term Clarity Trend Analysis report (2020), and in annual State of the Lake reports produced by UC Davis Tahoe Environmental Research Center.

Main Highlights

- No major change in lake clarity for the water year from October 2020 through September 2021.
- Longer-term change in clarity is a more meaningful metric of the lake's health than year-to-year variations.
- The decline in annual average Secchi depth ended around twenty years ago, and has not changed significantly since that time.
- Lack of clarity improvement over the last 10–20 years is a matter of concern.
- 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 show a persistent pattern of improving clarity.
- Primary causes of Lake Tahoe's clarity remain unchanged. Fine particle concentrations and small *Cyclotella* diatoms plus other algae are the main factors that account for 68% of Secchi depth variation from 2008 through 2021.
- Of particular importance to lake clarity is the concentration of very fine particles (1–4 µm). Since 2017 the total water column concentrations of these particles increased and remained elevated, despite two successive dry years (2020–2021).
- These findings support continuing efforts to control fine sediment and nutrient inputs to the lake. They highlight the importance of research on in-lake particle characteristics and dynamics, the evaluation of biological relationships relevant to clarity, and continued refinement of fine particle loading estimates.
- Clarity measurements for water year 2021 included the period from late July through September, when wildfire effects and smoke-borne particles were prevalent in the Tahoe Basin.
- Runoff from the Caldor Fire area commenced with seasonal precipitation in October 2021.
- Research on impacts from wildfires is ongoing and will be summarized in science reports later this year.

1) Introduction

Lake Tahoe's clarity remains a key indicator of overall ecosystem status. Conditions in the lake vary in response to factors such as watershed disturbance and management, deluge, drought, wildfire, invasive species, and climate change. Our scientific understanding of these factors and their effects on lake clarity continues to evolve. The purpose of this project is to communicate how we currently perceive the status of lake clarity conditions over recent periods and in the context of longer-term patterns.

The Data Synthesis and Analysis (DSA) 2021 report showed that concentrations of fine sediment particles and small phytoplankton (*Cyclotella* spp.) accounted for about 60% of the variability observed in lake clarity since 2011, as measured by Secchi depth. This important finding supports a continuation of efforts to restore clarity by reducing inputs of fine particles and the nutrients that support algal growth. Other factors contribute both directly and indirectly to changes in lake clarity, but the majority of clarity variation is explained by the concentrations and size ranges of these two constituents suspended in the water column.

This DSA report focuses on further examination of particle concentrations in the lake and fine sediment particle (FSP) delivery to the lake from streams and urban runoff. First, we discuss longer-term trajectories observed from annual average and seasonal average Secchi depth measurements. This is followed by an updated assessment of the concentrations of both fine sediment particles and small phytoplankton cells suspended in the water column. Then we review the available loading data on FSP from streams and urban runoff, discuss the implications for management from recent work, and conclude with a short set of recommendations that should enhance the quality of data and our understanding of important processes that cause changes in lake clarity.

2) Lake Tahoe Secchi Depth Clarity

Secchi depths have been consistently measured 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) has been visited at roughly ten-day intervals since 1968, while the mid-lake site (MLTP) has been monitored on a monthly basis since 1980. Water samples and vertical profiles of temperature and several other variables also are collected during some of these visits. Annual averages are reported on a water year (WY) basis, which corresponds with the USGS hydrological year (from October 1st through September 30th) and is designated by the calendar year in which the WY ends.

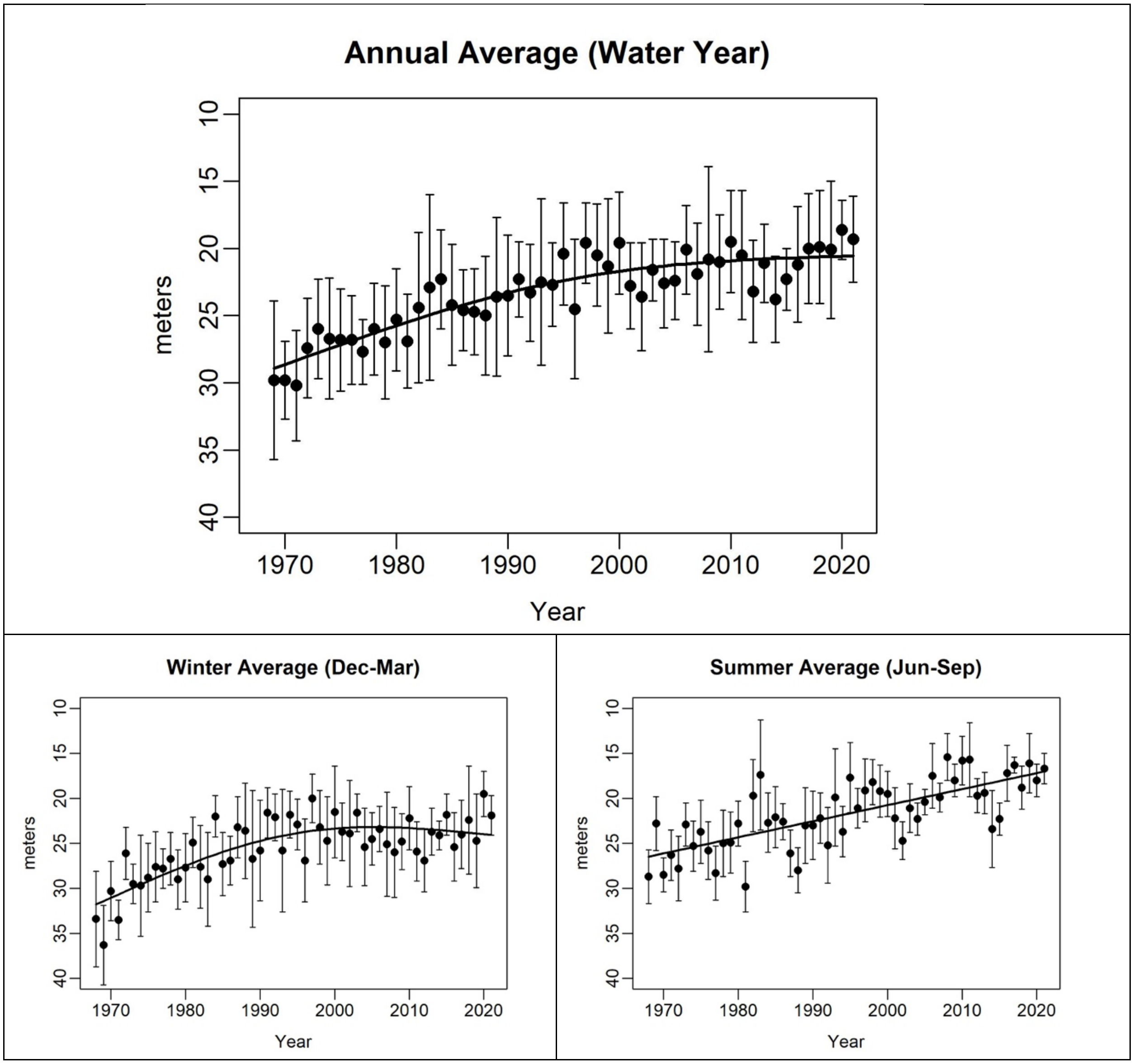

Figure 1. *Annual average and seasonal average Secchi depth measurements from water years 1968–2021. Vertical lines indicate the standard deviation of measurements taken during that respective year or season. Solid lines in each panel were fit with a generalized additive model to represent the longer-term patterns in Secchi depth clarity.*

The long-term pattern of declining annual average Secchi depth changed around twenty years ago, when it started to level off or plateau (Figure 1). Annual average clarity conditions have not statistically improved since then. Seasonal summer average clarity (June–September) continues to decline at a long-term linear rate of 0.62 feet per year (0.19 m/y) from 1968 through 2021, while winter average clarity (December–March) appears to have leveled off or is showing some signs of improvement, though not in 2020 or 2021. A closer look at the last twenty years shows that annual average and seasonal average clarity patterns have not established consistent clarity improvements since 2002 (Figure 2). The reasons behind this are unclear but likely associated with an apparent step change in lake particle concentrations observed since 2017 (discussed in Section 4).

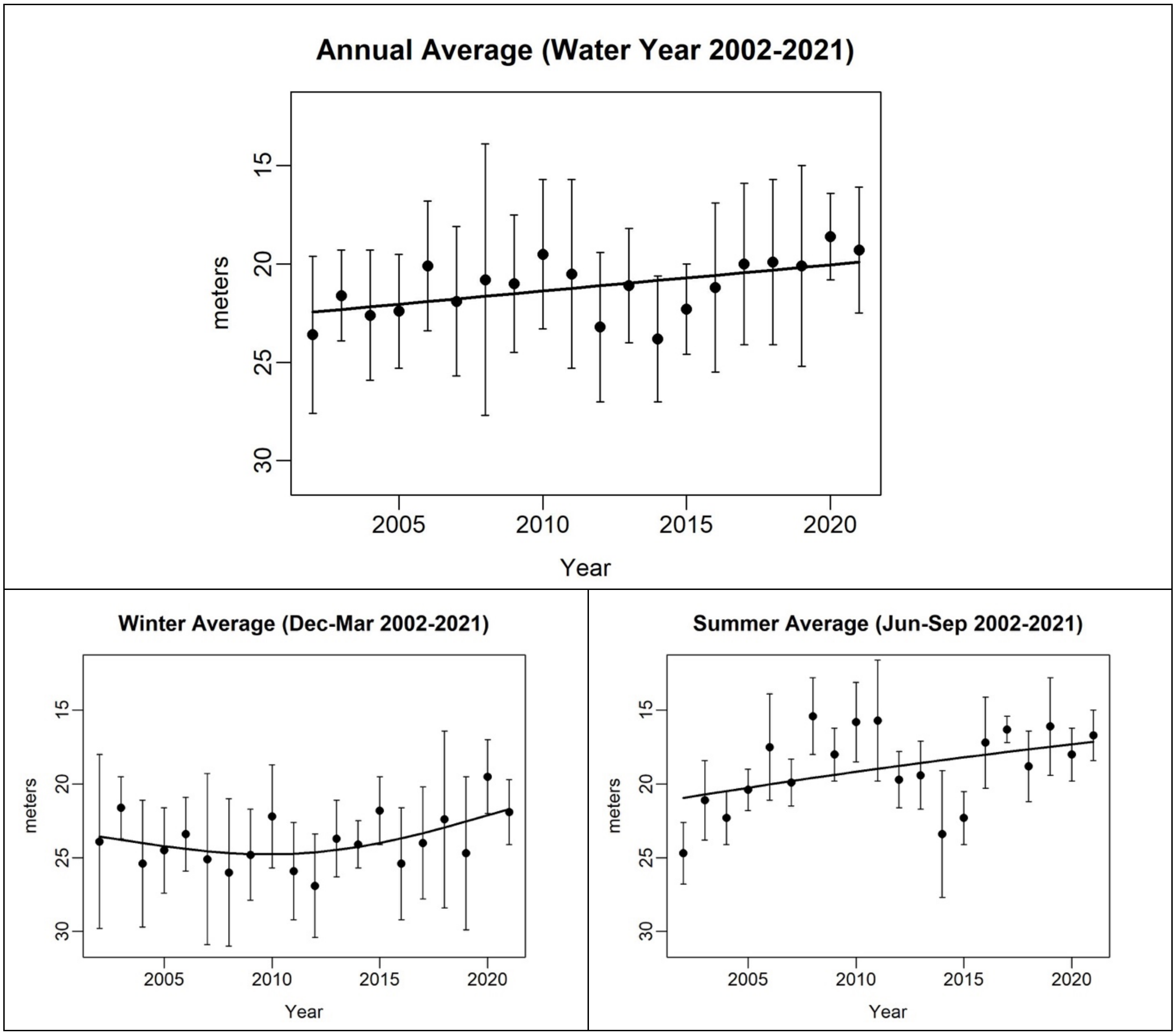

Figure 2. *Twenty-year annual average and seasonal average Secchi depth measurements from water years 2002–2021. Vertical lines indicate the standard deviation of measurements taken during each year or season. Solid lines in each panel were fit with a generalized additive model to illustrate the prevailing pattern in Secchi depth clarity over the full period.*

The pattern of individual Secchi depth measurements throughout WY 2021 is consistent with the range of values obtained during equivalent periods from the previous ten years, although values after winter tended toward a shallower range than average (Figure 3). Deepening of the lake's surface layer occurs during winter. This is often when lake clarity achieves its maximum depth, as clear, deep water becomes entrained with upper water and dilutes concentrations of suspended sediment particles and phytoplankton in the Secchi depth range. Influence of mixing depth on lake clarity has been variable, however, as summarized in the Supplemental Materials (S-1). The observed maximum depth of mixing in WY 2021 was 150 meters (on 2021-03-17), which is relatively shallow and not expected to provide much improvement to the annual average Secchi depth.

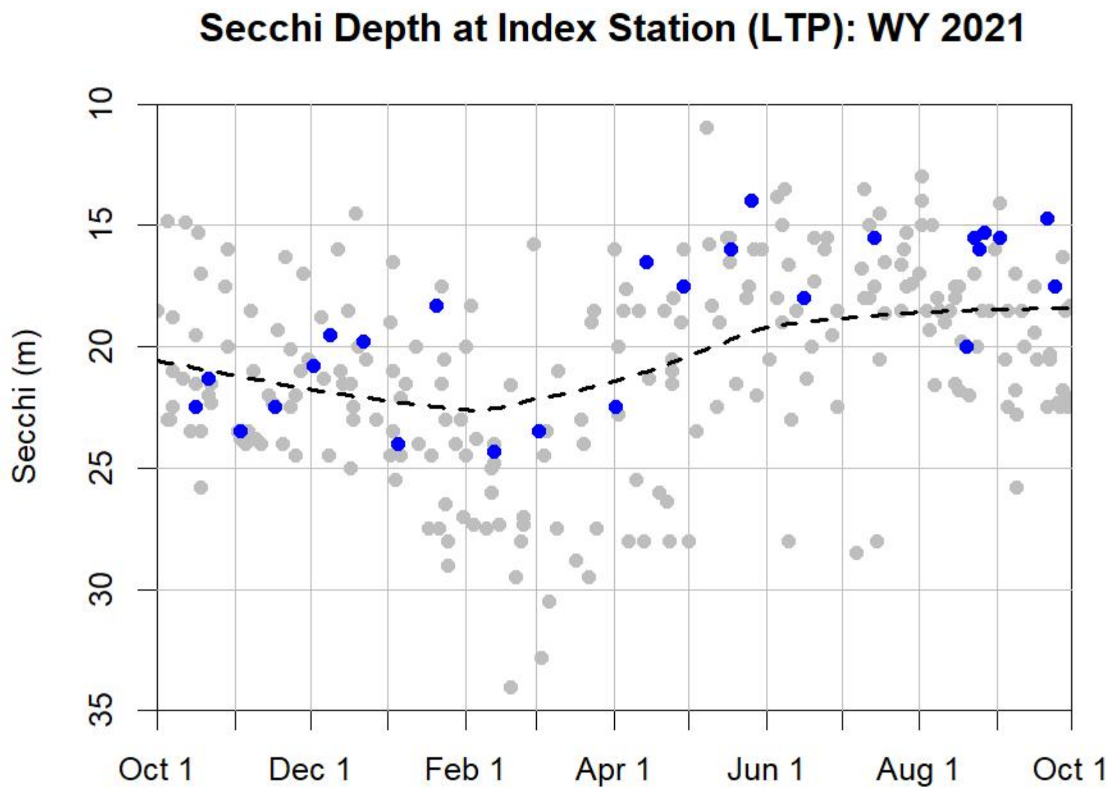

Figure 3. *Last ten years of individual LTP Secchi depth measurements. Blue points are the individual measurement taken during WY 2021. The grey dots are individual measurements taken since WY 2011 (not including WY 2021). Dotted line is a locally weighted scatterplot smoothing (LOWESS) curve over the span of y-axis values. Unlike calendar year, each water year (WY) begins Oct 1st and ends Sep 30th.*

3) Factors Directly Effecting Lake Clarity

The DSA-2021 statistical analysis of lake clarity and contributing factors showed that suspended sediment particles and small phytoplankton (*Cyclotella* spp.) cells were the two variables responsible for a majority of variation (61%) in Secchi depth measurements from 2011 through 2020. This year, the DSA-2022 analysis has extended that data record to 2008, the first year of reliable fine particle measurements in the lake, and found an equivalent percentage of Secchi depth variability was explained for WYs 2008 through 2021 using the same two variable model.

The relative effect of these two variables changed over time (Figure 4). From 2008 through 2016, the concentrations of *Cyclotella* spp. explained a greater percentage of variability (54%) in standard least squares linear regression against Secchi depth compared to the concentrations of fine sediments (47%), whereas the fine sediment concentrations exerted greater influence (57%) after 2016.

A third variable was added to the multiple regression analysis this year. Taken together, the concentrations of these three factors (fine particles, *Cyclotella,* and chlorophyll-*a*) account for 68% of total variability in Secchi depth measurements from WY 2008 through 2021 (see Supplemental Materials, S-2).

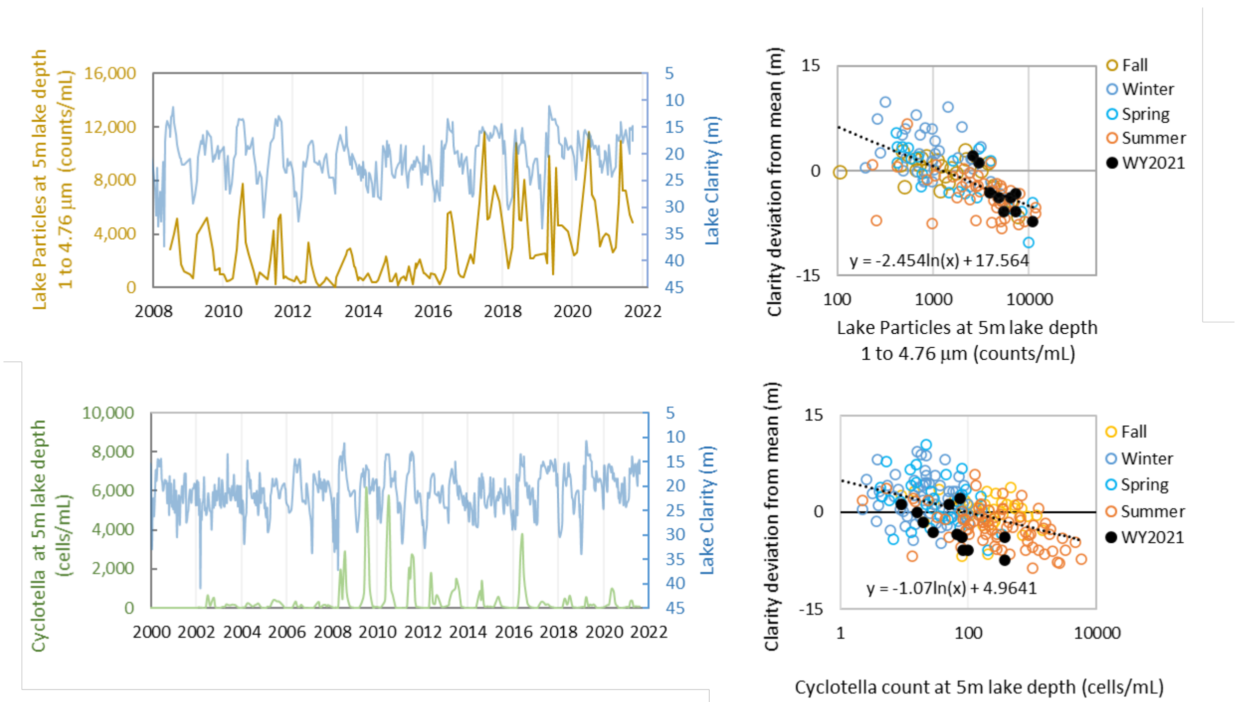

Figure 4. *Secchi depth clarity, Cyclotella and fine particle concentrations at 5 m in Lake Tahoe, WYs 2000 or 2008 through 2021. Lake particles and Cyclotella are present year-round but their influence on lake clarity is based on abundance. The right-hand panels show* that *the influence of fine particles (1–4.76 µm) on lake clarity is more pronounced at concentrations greater than 1000 particles/mL, while the influence of Cyclotella spp. on lake clarity is more pronounced at concentrations greater than 1000 particles/mL. The light-influencing properties of phytoplankton and inorganic particles are known to be different.*

Particles with greatest influence on lake clarity are those in the size range from 1–4 µm. This is a function of the number of particles in this size range and the effective scattering by these particles. Some of the examples and analyses in this report show a particle size range from 1–4.76 µm, but this is functionally equivalent to the 1–4 µm range for purposes here.

4) Changes in Fine Particle Concentrations in the Lake

Given the direct influence of fine particle concentrations on lake clarity, we examined particle accumulation and clearing in the lake by calculating the total number of fine particles in the full water column (per square meter), derived from particle measurements on discrete water samples from the mid-lake (MLTP) site including samples from within Secchi depths as well as samples from each 50-meter depth interval to 450 meters (Figure 5). Unlike particle concentrations within the Secchi depth range, total water column concentrations are not influenced by annual differences in the depth of maximum lake mixing and thus represent changes in total number of particles in the lake.

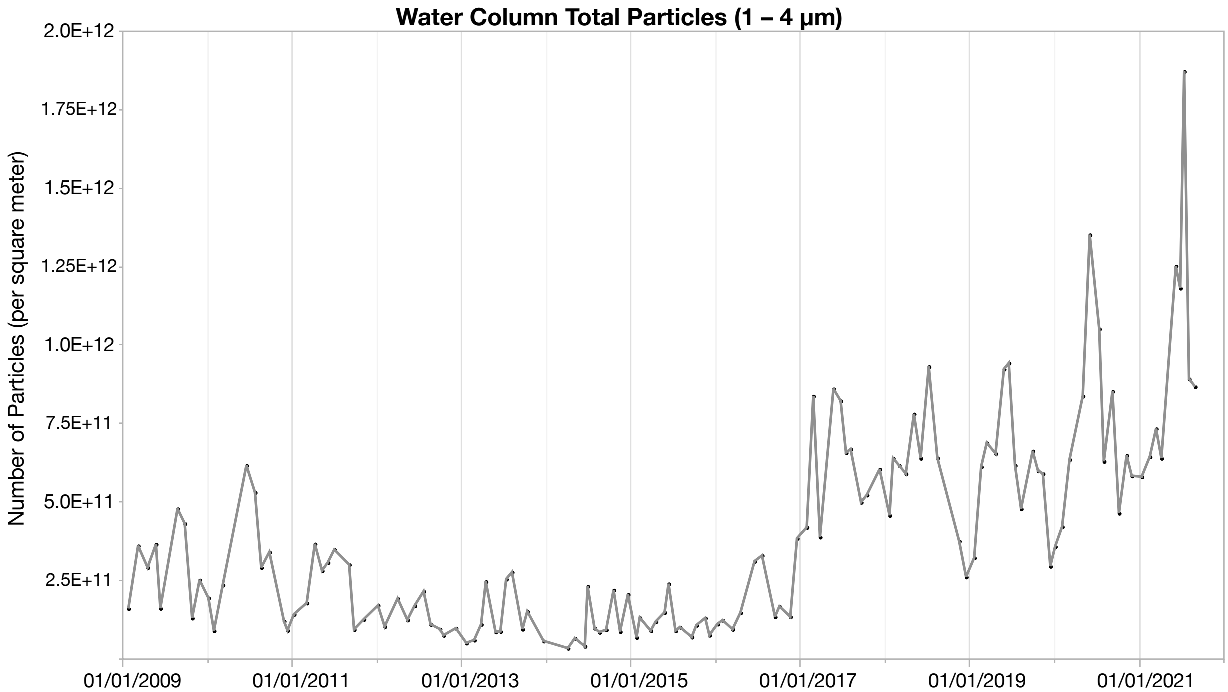

Figure 5. *Changes in total water column fine particle concentrations through water year (WY) 2021. After a slow decline in particle concentrations in the lake through WY 2016 the total water column particle concentrations began increasing beyond levels previously observed.*

This analysis shows that concentrations of particles most strongly affecting Secchi depth clarity (1–4 µm) were slowly decreasing from 2009 through 2015. That period coincided with a succession of years with precipitation well below average, except 2011 (see Supplemental Materials, S-3). After 2016, however, the water column concentrations began to increase year by year. Precipitation and runoff during WY 2017 were particularly high, leading to increased particle numbers delivered from streams and urban areas, as discussed below. Fine particles have continued to accumulate in the lake through WYs 2020 and 2021, years with less runoff than average. The processes behind this increase are not well understood, but it is likely that either more very fine particles are entering the lake during low runoff years than previously estimated, or something has changed so that more of these particles remain suspended in the lake for longer.

5) Fine Sediment Particles from LTIMP Streams

This year we initiated assessment of linkages from stream and urban runoff to fine particle concentrations in the lake. Rating curves have been established for the Upper Truckee River to accurately estimate FSP loading from continuous turbidity measurements, while discharge data and FSP rating curves for other LTIMP sites are in development as recommended in the DSA-2021 report. These turbidity-based estimates show that FSP (0.5–16 μm) loading has decreased since the large influx of WY2017 (Figure 6). Recent drought associated with WYs 2020–2021 have further reduced streamflow and FSP loading to the lake.

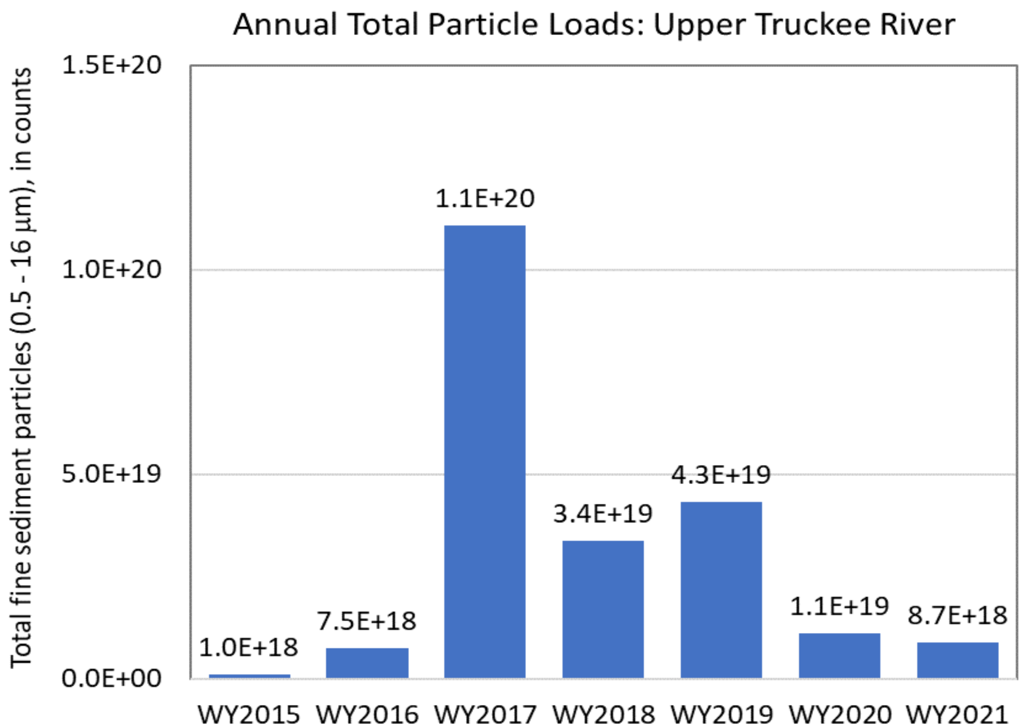

Figure 6. *Water year (WY) total fine sediment particle (FSP) loads from the Upper Truckee River (USGS 10336610), estimated from continuous turbidity monitoring with a site-specific rating curve for FSP concentration (0.5–16 μm).*

Annual loading of FSP from the Upper Truckee River has dropped since WY 2017, in contrast to water column fine particle concentrations that have increased since 2017. On average the Upper Truckee River contributes about 23% of hydrologic input to the lake. These FSP loads represent total particles from 0.5–16 μm, however, and should be divided into different size-fraction ranges to improve understanding of their impact on clarity. The concentrations of clarity-relevant fine particles (1–4.76 μm) entering the lake from the Upper Truckee River have increased and remain elevated since WY2017 (see Supplemental Materials, S-4).

6) Fine Sediment Particles from Urban Runoff

The Tahoe Regional Stormwater Monitoring Program (RSWMP) collects runoff from urban monitoring sites around the Tahoe basin. Six of these sites have been in operation since the beginning of WY 2015 (Table 1). Similar to how FSP loads are estimated from turbidity monitoring in the Upper Truckee River, these urban sites also monitor turbidity for estimating FSP loads. Rather than applying site-specific rating curves, however, the turbidity relationships were developed to cover spatial quadrants within the Tahoe basin. Standard practice by the Tahoe TMDL is to report both concentrations and loads of FSP at urban sites in units of mass for assessing load reductions associated with best management practices (BMPs) and for permit reporting purposes. Particle numbers and mass (in pounds) are both reported for total annual estimated FSP loads at each site by the Tahoe Resource Conservation District (Tahoe RCD).

Table 1. Locations and characteristics of Tahoe urban stormwater monitoring sites in continuous operation since water year 2015.

Station Name	Site ID	Latitude	Longitude	Drainage (acres)	Impervious Area	Single Family Residential	Multi-Family Residential	CICU* Landuse	Primary Roads	Secondary Roads	Vegetated Area
CJ Outflow	CJO	39.274	-119.947	1.4	89%	0%	0%	0%	89%	0%	11%
Pasadena Out	PO	38.945	-119.981	78.8	39%	52%	13%	5%	0%	16%	14%
Speedboat	SB	39.225	-120.010	28.9	30%	49%	3%	9%	4%	10%	25%
Tahoe Valley	TV	38.921	-119.998	338.4	39%	19%	12%	20%	2%	13%	34%
Tahoma	TA	39.067	-120.126	49.5	30%	41%	4%	12%	3%	15%	25%
Upper Truckee	UT	38.922	-119.990	10.5	72%	14%	7%	39%	14%	18%	8%

*CICU represents the aggregated of commercial, industrial, communications, and utility land use areas.

The six RSWMP monitoring sites in continuous operation since WY 2015 comprise 508 acres (205 ha) of drainage area, which are assumed to represent a reasonable distribution of urban land use types in the Tahoe basin. Aggregate annual FSP loading from these six sites has a pattern of increasing fine particle loads through WY 2017 followed by reduced loading in subsequent years (Figure 7). Water year 2021 had lowest FSP loadings since monitoring began at these sites. Annual aggregate mass of FSP loads (0.5–16 µm) from these sites are strongly correlated (R=0.96) with the corresponding annual average precipitation (Figure 8).

The site-specific response of FSP loading to precipitation amount is variable over time. Tahoe Valley (TV) is the largest drainage and had an increase with precipitation through WY 2017, and then dropped in subsequent years. In contrast, the Speedboat site (SB) also increased through WY 2017, but remained elevated into WYs 2018 and 2019.

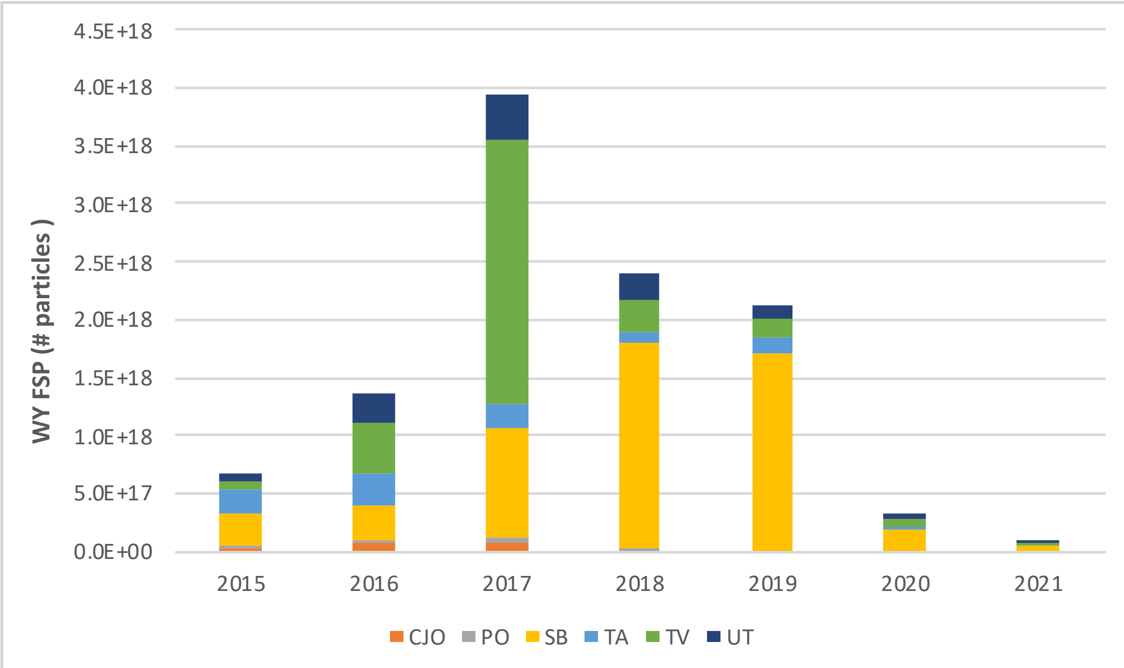

Figure 7. *Annual fine sediment particle (FSP) loads from long-term urban runoff sites monitored by the Tahoe Regional Stormwater Monitoring Program (RSWMP). Annual FSP loads for each drainage are estimated from continuous turbidity monitoring using established relationships to FSP concentration (0.5–16 µm). Total drainage area represented by these six urban sites is 508 acres (205 ha).*

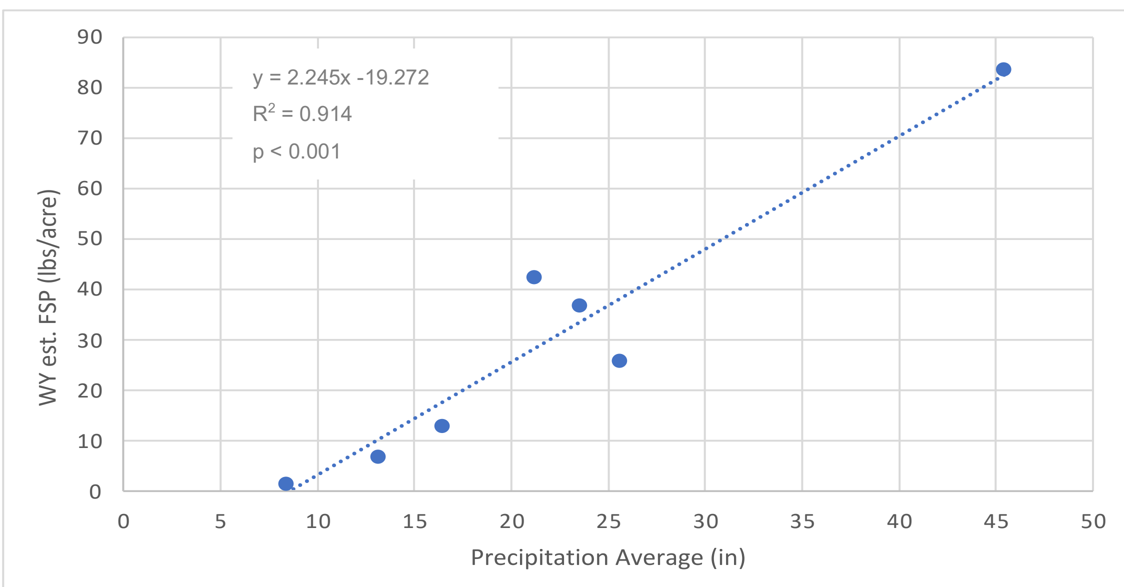

Figure 8. *Annual fine sediment particle (FSP) loading per acre from six Tahoe basin urban sites each water year (WY) 2015–2021 in relation to the average of precipitation across those sites each year. Cumulative mass of FSP (0.5–16 µm) was estimated from continuous turbidity monitoring at each site.*

7) Comparative Assessment of Fine Particle Loading from Streams and Urban Runoff

Based on particle numbers, both the Upper Truckee River (UTR) and the urban sites have dropped below or near to background FSP loading rates, referenced to WY 2016 (see Figures 6 and 7). This provides evidence that loading of FSP to the lake was lower in these last two years (WYs 2020 and 2021) compared to WYs 2017 through 2019. We would expect fine particle concentrations in the lake to have declined in response, but that has not been the case. Instead, particle concentrations in Lake Tahoe have been increasing through WY 2021 (see Figures 5 and S-4).

To make a comparative assessment of FSP loading from both upland and urban sources it is necessary to normalize annual loads. This has been done for the one LTIMP site where these data are currently available, at the Upper Truckee River, as well as for the six RSWMP urban sites. Annual loads from both sources were divided by their respective total drainage area to yield normalized loadings for WYs 2015–2021 (Figure 9). On a normalized basis the urban sites contribute greater amounts of FSP per unit area than the UTR, although total extent of urban area within the Tahoe Basin is much less than total upland watershed area. The total contribution from each source can be estimated by extrapolating from the UTR data to represent upland area and from RSWMP data to represent the urban area. This approach indicates that urban loading has been decreasing as a percentage of the total FSP loads (see Supplemental Materials, S-5).

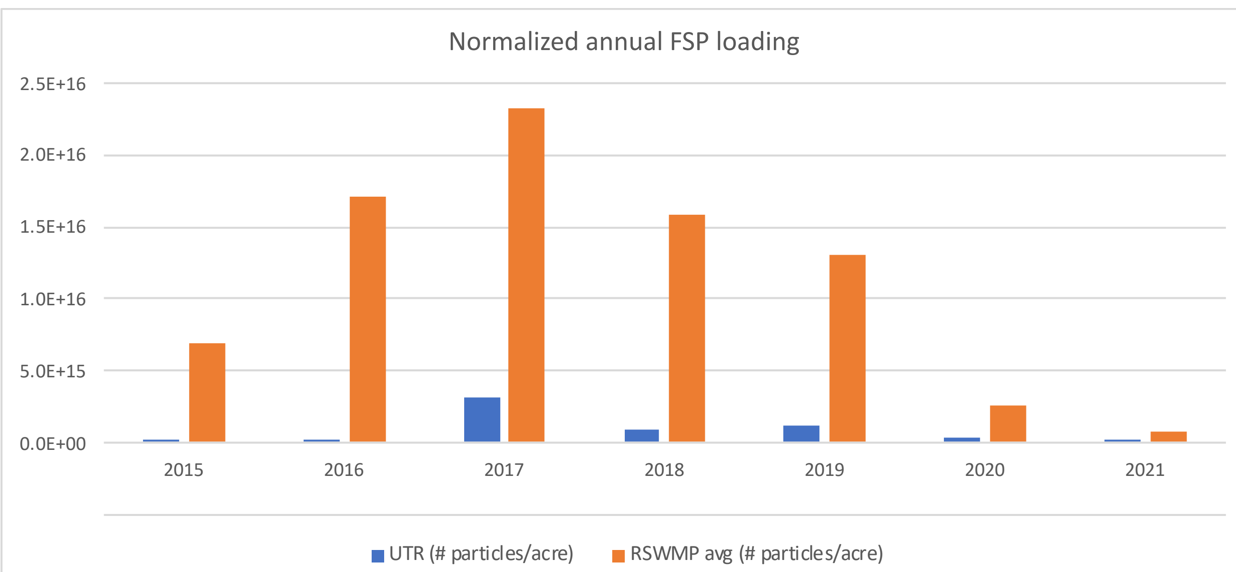

Figure 9. *Annual fine sediment particle loading from the Upper Truckee River (UTR) and from six Tahoe Basin urban sites (RSWMP) normalized to area across those sites for each water year from 2015–2021. Fine sediment particle (FSP) loading represents the number of particles (0.5–16 µm) estimated from continuous monitoring at each site.*

Although the concentration of fine particles in Lake Tahoe increased during WY 2017, and has been rising since that time (Figure 5), the evidence to date from available FSP (0.5–16 µm) monitoring data would suggest that overall loading from watershed sources, both upland and urban, have not been contributing to this increase since WY 2020 when the normalized loadings of FSP dropped to levels observed in 2015. Further evaluation is warranted, however, especially considering that very fine particle (1–4.76 µm) concentrations in the UTR remain elevated since WY 2017 (Figure S-4).

8) Key Questions and Relevant Scientific Results

Q1) What were the primary drivers of recent clarity conditions?

- DSA-2022 analysis accounted for 68% of Secchi depth variation from WYs 2008–2021 as a function of three factors: fine particle concentrations, *Cyclotella* spp. concentrations, and chlorophyll-*a* concentrations.
- Lake concentrations of fine particles (1-4 µm) had a step increase in WY 2017 and have been increasing since, despite decreasing stream and urban loads of FSP (0.5–16 µm) since that year.
- The clarity has not been improving recently because there are more fine particles in the lake.
- Whether processes within the lake that remove fine particles have changed is not known.

Q2) How much of the recent years' clarity conditions are within management control?

- Primary drivers of clarity remain the lake concentrations of fine particles and phytoplankton.
- Watershed loading of both fine particles and nutrients are subject to management control and should continue.
- Potential changes in processes within the lake that remove fine particles are topics for further investigation.
- Factors that control *Cyclotella* spp. growth in Lake Tahoe need further study.

Q3) Why did annual average Secchi depth clarity not improve during the drought period from WYs 2007–2015?

- Although clarity did not improve during the time of this drought, the drought probably did contribute to less clarity decline.
- Total lake water column fine particle concentrations were slowly decreasing during this period, although clarity remained variable.
- Summer clarity continues to decline, which contributes to lower annual average Secchi depths.
- Winter clarity is relatively stable (within annual variability).
- Internal processing of fine sediment particles leading to removal may slow as concentrations decrease.
- Whether natural lake processes are changing in response to climate or altered biological conditions requires study.

Q4) Why have lake fine particle concentrations remained elevated since the step-change increase of WY 2017?

- Lake accumulation of fine particles increased through WYs 2020 and 2021, although both were years with low runoff.
- Either more fine particles are entering the lake during low runoff years than previously, or more fine particles remain suspended in the lake for longer.

9) Recommendations

R1) We advise developing specifications for consistency when reporting data on particle size ranges from the Lake Tahoe Basin Interagency Monitoring Program (LTIMP).

- Currently, loads from LTIMP watersheds are not reported in the particle-size range of primary importance to clarity, so it remains difficult to compare load reductions and lake response.
- The appropriate size ranges for reporting will need to be identified (e.g. 1–4, 1–4.76, 1–8 µm) and adopted for consistency between programs (LTIMP and RSWMP).
- The USGS has begun developing turbidity rating curves for the 0.5–16 µm particle size range at LTIMP streams.
- Sediment loading of very fine particles in the clarity-relevant size range (e.g. 1–4.76 µm) should be estimated for all LTIMP streams. If alternative or additional ranges are needed they must be developed also.

R2) Tahoe RSWMP for urban monitoring should develop and adopt appropriate methods for assessing and reporting fine particle size ranges.

- Current RSWMP procedure is to report FSP over the full 0.5–16 µm size range, which conforms with existing TMDL requirements. However, the Tahoe RCD collects data on smaller particle size ranges and could report on the concentrations.
- Turbidity rating curves for estimating fine particle concentrations over additional size ranges will need to be developed for consistency with stream and lake data (e.g. 1–4.76 µm).
- Site-specific rating curves for turbidity-based load estimates should be evaluated on a water-year basis, as done by the USGS for LTIMP streams, using a weighted regression on time, discharge, and season (WRTDS) approach.
- The RSWMP data management system (DMS) should be retooled to automate calculations and produce the appropriate output, including for existing WY data.
- Pollutant data collected from urban sites prior to TMDL implementation could be reexamined, particularly in terms of FSP for the clarity-relevant size fraction. This may provide clues about whether BMP implementations prior to WY 2015 had already reduced loads to the lake that are not represented in existing RSWMP data.

R3) Evaluate the role of FSP mass for estimating reductions in fine sediment loading to the lake.

- Estimated mass of FSP reductions achieved by BMP projects is converted to number of particles, where 1 pound of FSP (0.5–16 µm) = 5 x 10^{13} particles].

- FSP mass over the full 0.5–16 µm size range reported from urban monitoring is based on the fraction of particle volume within that size range from samples measured for particle size distribution (PSD) and total suspended solids (TSS).
- Methods for estimating particle numbers in the very fine particle size range (1-4.76 µm) should be evaluated relative to results obtained from mass conversion.

R4) Examine questions about internal processes that may contribute to changing abundance of fine particles and *Cyclotella* spp. in Lake Tahoe.

- Why are lake fine particle concentrations increasing since 2017 if the loads from streams and urban runoff are stable or decreasing?
- Are dominant processes changing in terms of their relative contribution to rates of particle clearing in the lake?
- What contributes to increased growth and proliferation of *Cyclotella* spp. in some years?
- Would enumeration of *Cyclotella* spp. at additional depths than 5, 20 and 40 meters improve understanding of effects on clarity?
- Are picoplankton species contributing to clarity reductions?

9) Citations

Tahoe Resource Conservation District (Tahoe RCD). 2022. Annual Stormwater Monitoring Report, Water Year 2021. Submitted to the Lahontan Regional Water Quality Control Board and the Nevada Division of Environmental Protection, March 30, 2022.

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

Supplemental Materials

S-1) Depth of maximum lake mixing

Precipitation and depth of mixing are two factors that indirectly affect lake clarity. Figure S-1 shows the relative impact on clarity of annual maximum lake mixing depth, where clarity response is represented as the difference between maximum winter clarity and the clarity of preceding fall months. Normalized mixing depth ranges from 0 (minimum on record) to 1 (compete mixing to 450 meters). As can be seen, complete mixing sometimes, but not always, engenders a clarity improvement of 8 meters or more. This response appears to have been more robust over the last twenty years than previously.

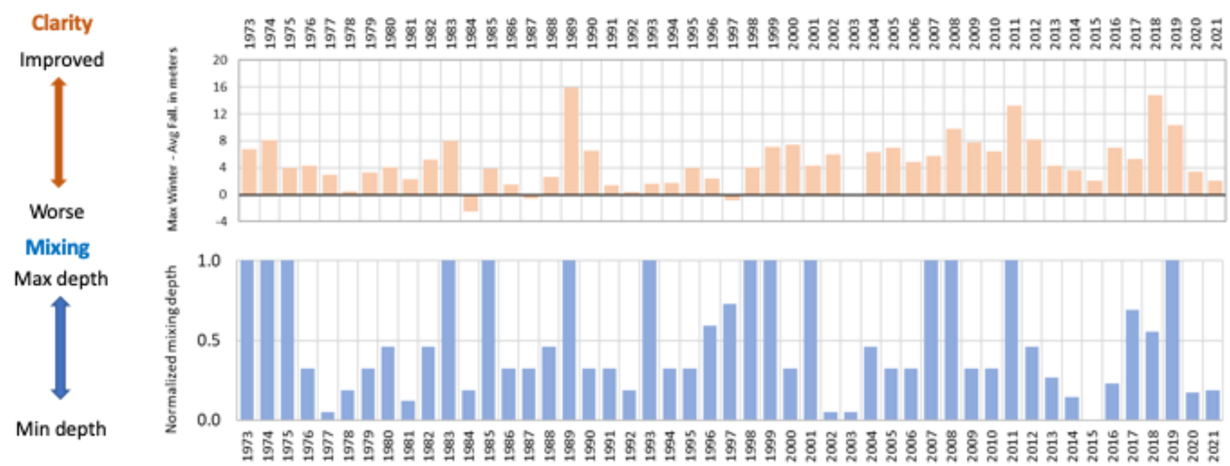

Figure S-1. *Maximum change in clarity during fall and winter months and normalized mixing depth. Upper panel corresponds the difference in clarity before and after the deepest mixing depth. Zero values correspond to no change in clarity, positive values are net improvement cause by deep mixing, negative values correspond to clarity values that are worse after mixing. The mixing depths were normalized by the maximum and minimum where 0 values correspond to the minimum and values of 1 are maximum mixing depth.*

S-2) Analysis of factors contributing to Secchi depth variability, WYs 2008–2021

Last year's statistical analysis showed that concentrations of fine particles and *Cyclotella* cells accounted for about 61% of variation in Secchi depth from WYs 2011–2020, estimated from multiple linear regression using the restricted maximum likelihood (REML) approach. The adjusted coefficient of determination (r^2) was 0.61 and all parameter estimates were significant at $p<0.0001$.

This year the data record was extended to WYs 2008–2021 and the chlorophyll-*a* concentration was added as a third contributing factor. The resulting multivariate model accounted for 68% of total variation in Secchi depth over that time using the REML approach, yielding an adjusted $r^2 = 0.68$ and parameter estimates all significant at $p<0.0001$. A partial least squares regression check against the same data accounted for 69% of the Secchi variability. The advantage of partial least squares regression is that it can produce reliable predictive relationships for a response variable even when there are redundant or collinear relationships between input factors (as between chlorophyll-a and *Cyclotella* spp. concentrations, for example), which would normally invalidate assumptions implicit to multiple linear regression.

The estimated (predicted) values for Secchi depth versus measured Secchi depths are shown in Figure S-2. Main points of departure between these two lines occurred during periods of maximum lake mixing depth.

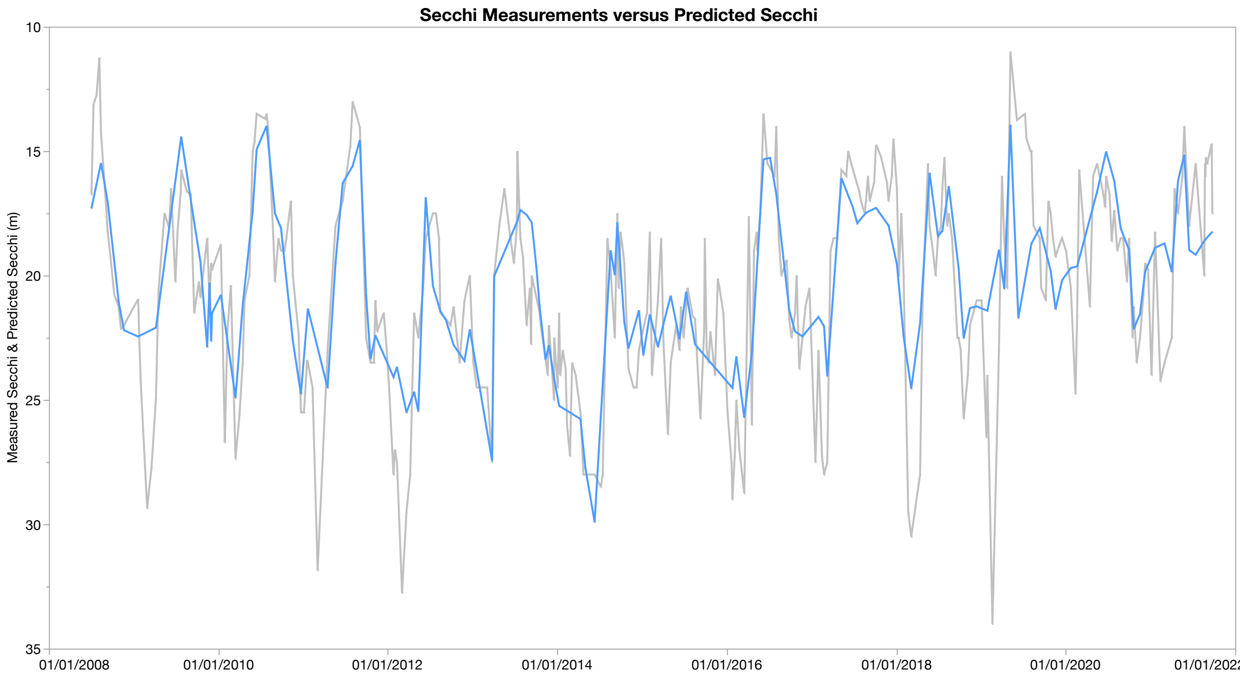

Figure S-2. *Estimates of Secchi depth clarity predicted by partial least squares regression with three input factors: log-transformed fine particle concentrations, log-transformed Cyclotella spp. concentrations, and log-transformed chlorophyll-a concentrations. The blue line shows model predicted values while the grey line shows measured Secchi depths.*

S-3) Precipitation

Water year 2021 was well below the 30-year Normal (median) precipitation for Lake Tahoe Basin SNOTEL stations. Accumulated precipitation through most of WY 2021 was at less than the 30th percentile of normal, and by May it had dropped within the 10th percentile range (Figure S-3a).

The previous year was also low precipitation (WY 2020), which followed four years of above-average precipitation, preceded by a nine-year drought (broken by one wet year in 2011). Overall, ten of the last 15 years have been below the long-term median of annual precipitation at Lake Tahoe (Figure S-3b).

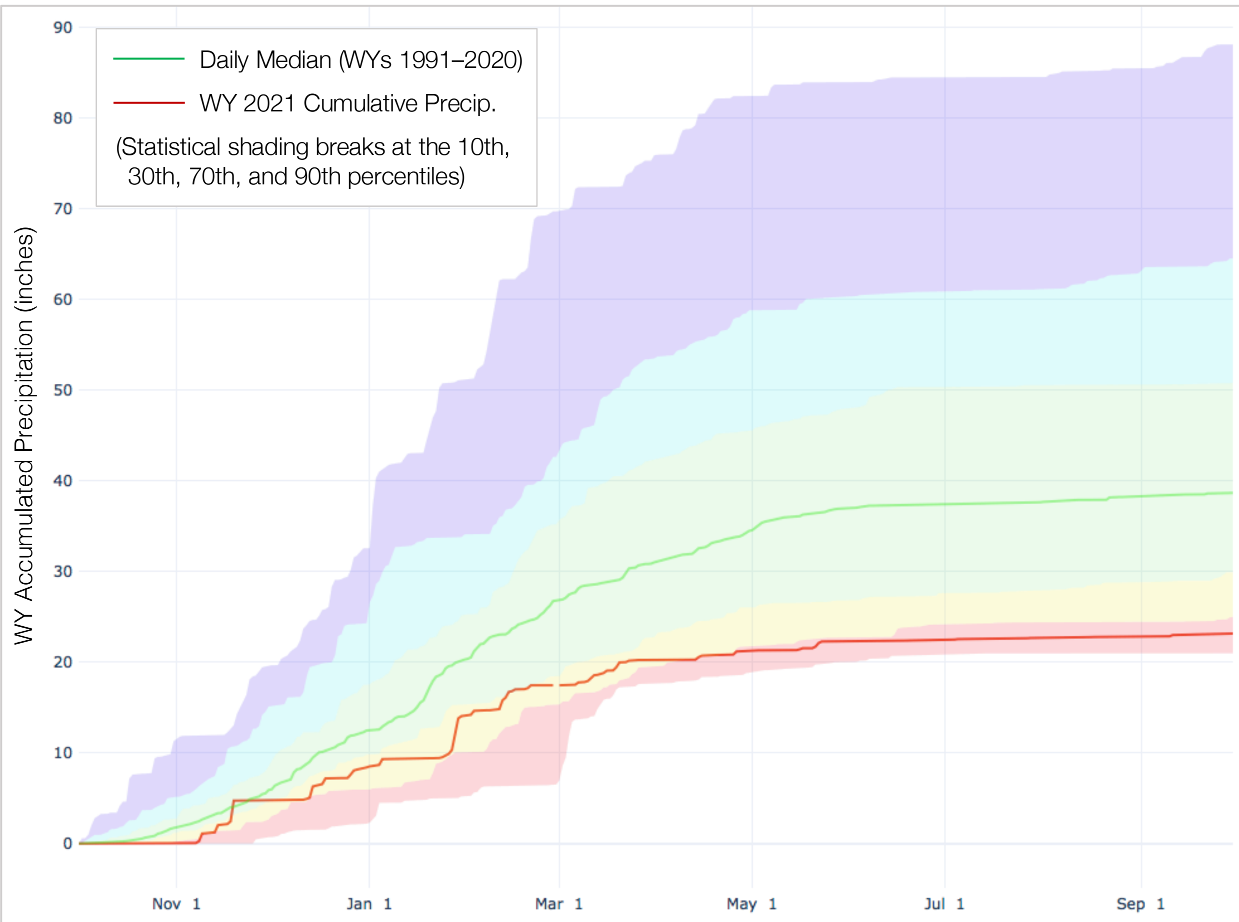

Figure S-3a. *Annual pattern of cumulative water year (WY) precipitation represented by the range of daily value medians from eight continuously operated SNOTEL stations in the Tahoe Basin (WYs 1981–2021). Percentiles of WY medians are shown as shaded areas (from minimum to 10%, 30%, 70%, and 90% to maximum). The 30-year Normal (WYs 1991-2020) is represented by a green line in the chart. Cumulative precipitation during WY 2021 is shown as a red line (from NRCS National Water and Climate Center).*

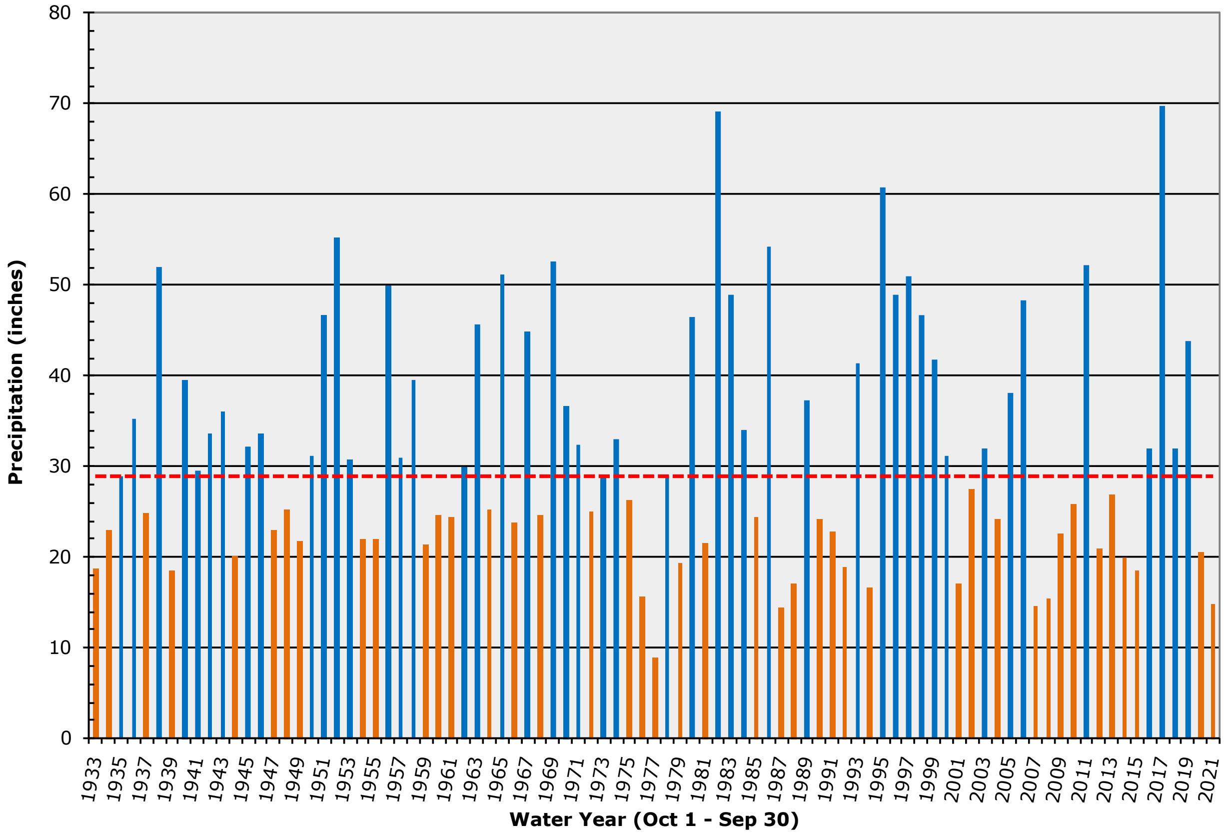

Figure S-3b. *Long-term precipitation record from Tahoe City meteorological station at Lake Tahoe, water years 1933–2021. Horizontal dashed red line represents the median amount of annual precipitation (29.0 inches) over the period of record. (NWS data, U.S. Water Master for Truckee River Operating Agreement).*

S-4) Upper Truckee River and lake particle concentrations, WYs 2009-2021.

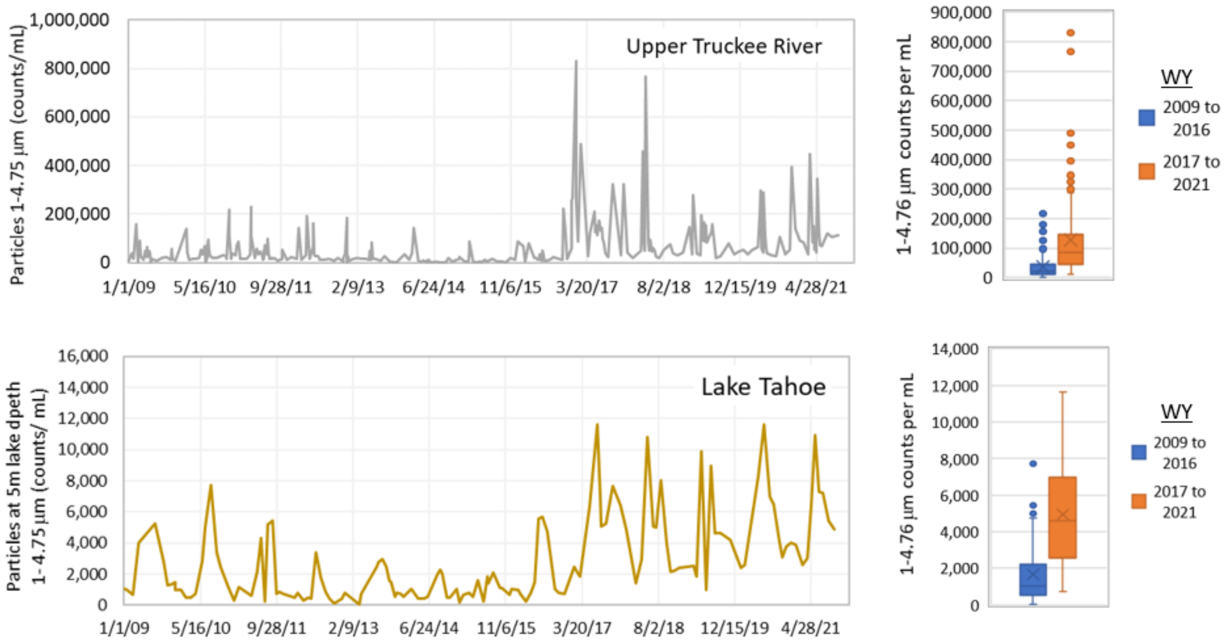

Figure S-4. Particle concentrations (1-4.76 µm) measured at the LTIMP gage at the Upper Truckee River and at the LTP site in Lake Tahoe. Since WY2017, particle concentrations have remained high in both the Upper Truckee River and Lake Tahoe. The net change in average concentration for the two periods shown on the right panel is 91,313 count/mL for Upper Truckee River and 3,277 counts/mL for Lake Tahoe. This would represent a net increase of particles in the Upper Truckee River and Lake Tahoe of 260% and 200%, respectively.

S-5) Extrapolated basin-wide FSP loading estimates

Basin-wide FSP loading estimates were extrapolated from LTIMP and RSWMP data reported for the period from WY 2015 through WY 2021. At present, only the Upper Truckee River (UTR) provides FSP loading data calculated from LTIMP continuous turbidity monitoring is available. The UTR watershed is 36,077 acres (146 km^2) and is used to represent upland areas. The six urban sites summarized in Table 1 (Section 6) are similarly used to represent the total 40,000 acres (162 km^2) of urban area under local jurisdictional management in the Tahoe basin. Results of this extrapolation are summarized in Table S-1 and shown in Figure S-5.

The percentage of FSP delivered from urban areas compared to upland areas has been dropping since WY 2015, which are the earliest records available for FSP loading at RSWMP urban sites. On average from WYs 2015–2021 the FSP contribution from urban areas has represented 73% of the total combined loading from urban and upland areas. Although these are considered rough preliminary estimations, extrapolated from limited spatial areas, they provide a perspective on FSP source contributions over the last seven years.

Table S-1. *Estimated total number of fine sediment particles (FSP, 0.5–16 µm) contributed each water year from 2015–2021 by area under local jurisdictional management relative to remaining upland area in the Tahoe basin not under county or city jurisdictional management.*

FSP, 0.5–16 µm (# particles)	Acres	2015	2016	2017	2018	2019	2020	2021	Average
Urban area	40,000	2.6E+20	6.6E+20	8.7E+20	5.3E+20	4.2E+20	9.2E+19	2.6E+19	4.1E+20
Upland area	160,500	4.6E+18	3.3E+19	4.9E+20	1.5E+20	1.9E+20	4.9E+19	3.9E+19	1.4E+20
Tahoe Basin	200,500	2.7E+20	7.0E+20	1.4E+21	6.8E+20	6.1E+20	1.4E+20	6.5E+19	5.5E+20
Urban portion	20.0%	98.3%	95.2%	63.9%	77.9%	68.7%	65.0%	40.5%	72.8%

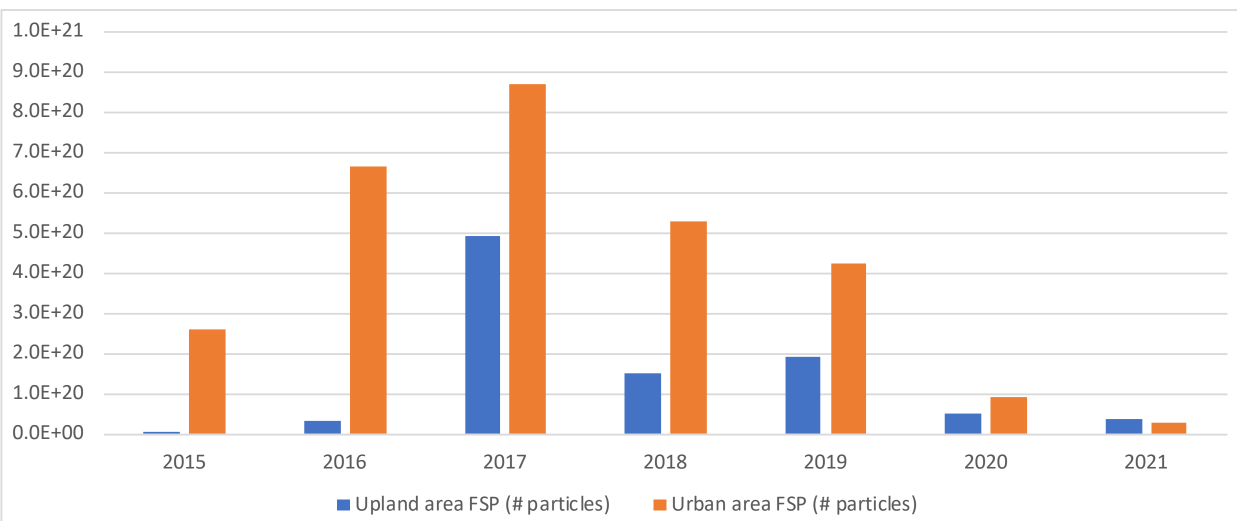

Figure S-5. *Estimated total annual FSP loading from Tahoe basin upland areas (not under local jurisdictional management) compared to estimated FSP loading jurisdictional urban areas for each water year from 2015–2021. Fine sediment particle (FSP) loading represents the number of particles from 0.5–16 µm.*