
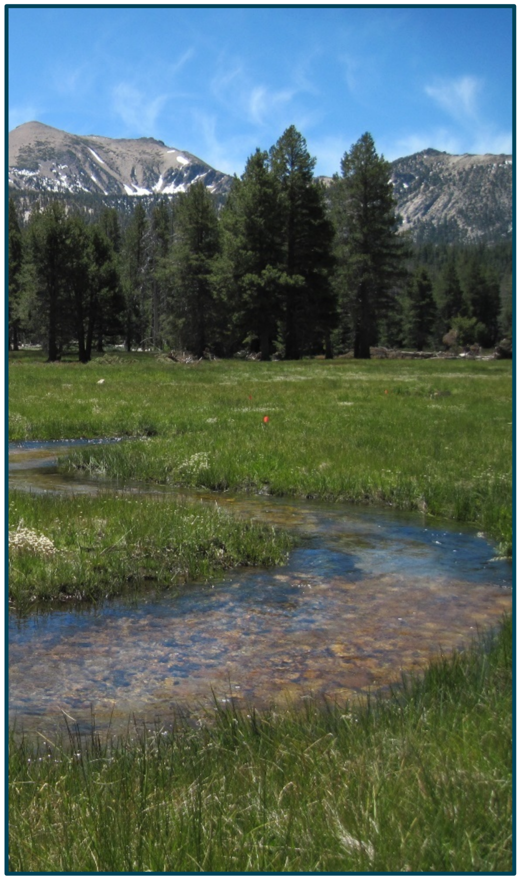
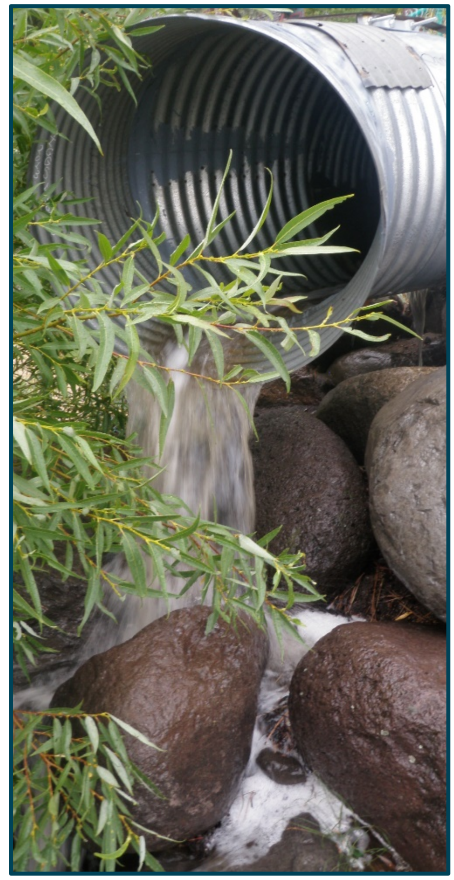

Characteristics, Composition, and Relative Sources of Very Fine Particles Affecting Water Clarity in Lake Tahoe

(*Aquatic Particles Project*)

December 2024

Desert Research Institute

TAHOE RESOURCE CONSERVATION DISTRICT

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Introduction

World renowned as one of the largest and clearest subalpine lakes in the world, Lake Tahoe encompasses about 500 km^2 of surface area surrounded by 800 km^2 of watershed. Most of the Tahoe basin is forested and remains largely undeveloped, with about 160 km^2 of urbanized area under local jurisdictional management dispersed around the lake perimeter and up the tributaries that drain from higher elevations.

Lake clarity, as measured by Secchi disk, has been decreasing since the early 1960s at about one third of a meter per year until around 2000 when the rate of loss in annual average Secchi depth clarity began to level off, although it has not improved on a statistical basis since that time (Heyvaert et al. 2021, Heyvaert et al. 2022, Naranjo et al 2022, Naranjo 2024). Long-term loss in lake clarity has been associated primarily with increased loading of nutrients and sediment particles from the landscape. Macro-nutrients, like phosphorus and nitrogen, have supported increased phytoplankton growth in the water column, while small sediment particles accumulate and settle slowly through the depths of this lake. These pollutants together serve as the focus of a total maximum daily load (TMDL) management plan.

Research to inform development of the Tahoe TMDL (LRWQCB and NDEP, 2012) indicated that fine sediment particles <16 micrometers (FSP) have a greater impact on lake clarity than nutrients, so FSP load reductions have been the primary target of best management practices (BMPs) for the TMDL. While results from ongoing lake monitoring show the annual average Secchi depth clarity appears to have stabilized, the winter clarity does not yet show a persistent pattern of improvement, and the summer clarity continues to deteriorate (Naranjo, 2024; Smits, 2024). Nonpoint source pollution from urbanized areas and the runoff from tributaries in 63 watersheds will likely contribute to further declines in summer clarity and to a continuing degradation in winter clarity, unless targeted management practices can be identified and implemented.

Winter clarity does not show consistent improvement, and summer clarity continues to decline, largely due to very fine sediment particles in the 1–5 micrometer size range. The characteristics of these particles are not well understood.

Current water quality monitoring in the Lake Tahoe basin comprises a Lake Tahoe Interagency Monitoring Program (LTIMP) that conducts stream monitoring of representative tributaries, a Regional Stormwater Monitoring Program (RSWMP) that implements monitoring of urban runoff, and a lake monitoring program that routinely collects discrete depth samples from the water column at a mid-Lake Tahoe profiling (MLTP) station.

However, these three monitoring programs measure particle concentrations and their size distributions using different instruments and methods, so the results are not directly comparable. The objective of this Aquatic Particles Project is to assess fine particle characteristics in runoff and in the lake in terms of composition, relative concentrations and contributing sources using computer-controlled scanning electron microscopy with energy dispersive spectroscopy (CCSEM-EDS) analysis. It is a proof-of-concept approach intended to refine scientific understanding of particulate composition and concentrations directly affecting the Lake Clarity threshold standard. It also represents the development of a unified approach for monitoring and assessing changes in clarity-reducing particle sources and processes that affect their abundances in the water column.

The goal of this project is to refine scientific understanding of the very fine particle concentrations and their characteristics in samples from lake, stream, and urban runoff sources. This will help inform management strategies to restore lake clarity.

Recent analysis of the Lake Tahoe data found that fine particle concentrations and small *Cyclotella* diatoms account for 68% of Secchi depth variation from 2008 through 2021 (Heyvaert et al. 2022). Of particular importance to lake clarity is the concentration of very fine particles in the 1–5 micrometer (µm) size range.

This project builds on the work described above to develop an approach that will enhance ecosystem model development and improve the understanding of linkages from natural and anthropogenic watershed inputs to lake response. Understanding the dominant particle types, their composition, and their potential sources will help to inform management strategies that advance TMDL progress in the restoration of lake clarity.

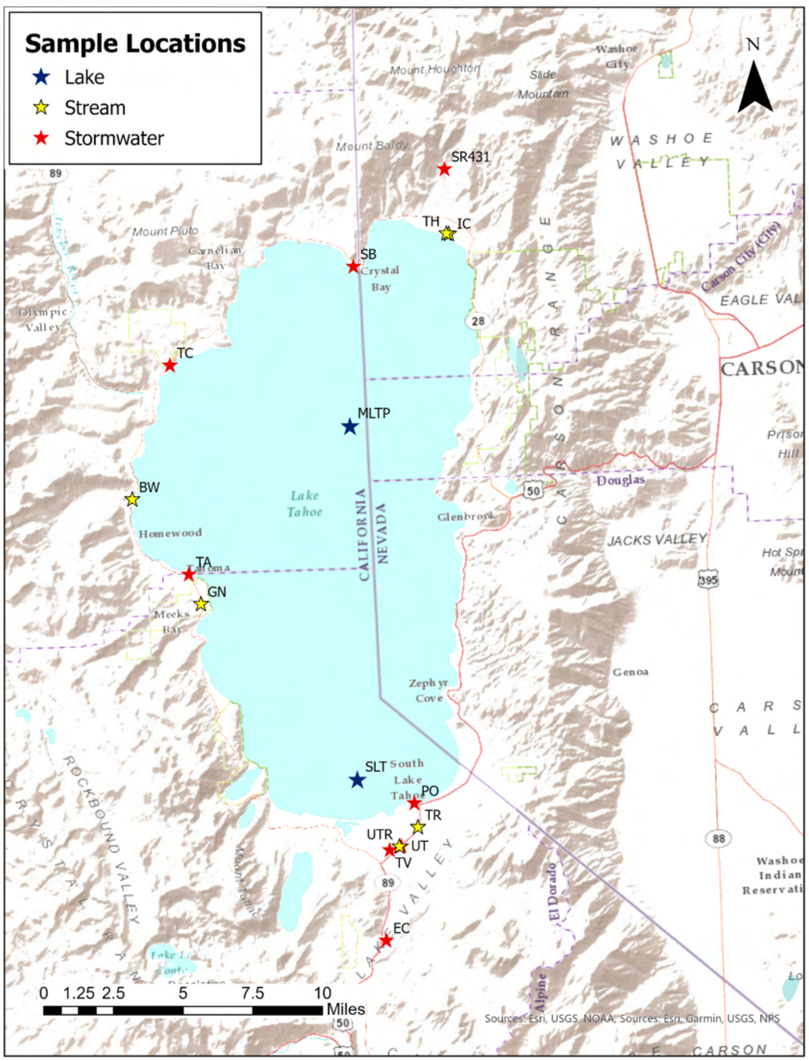
Methods

The Aquatic Particles Project commenced in late April of 2023 with preliminary samples taken from Lake Tahoe to evaluate the CCSEM-EDS options for setup and application. Subsequent samples were then collected periodically from lake, stream and urban stormwater runoff sites while the necessary logistical procedures, sample processing techniques, and analysis methods were developed and refined. The following section summarizes methods applied by this project, often drawing upon existing procedures from the Lake Tahoe Interagency Monitoring Program (LTIMP) and the Regional Stormwater Monitoring Program (RSWMP).

Lake Tahoe Sampling (UNR)

The University of Nevada, Reno, Global Water Center (GWC) collected samples from the lake as part of their investigation on the zooplankton ecology of Lake Tahoe. Two preliminary samples were collected from the south end of the lake at the start of this project. All other samples were collected from near the long-term UCD-TERC established mid-lake (MLTP) monitoring site (**Figure 1**).

Lake water column samples were collected by 4-gallon Van Dorn sampler deployed from the R/V Mount Rose to 300 meters maximum rope depth. Individual samples were collected sequentially at discrete depths from top to bottom of the accessible water column and transferred into 1-gallon pre-rinsed I-Chem LDPE cubitainers (Thermo-Scientific). These were kept on ice and in the dark for transfer to the Desert Research Institute (DRI) Water Analysis Laboratory for sample processing.



KEY	
MLTP	Mid-Lake Tahoe
SLT	South Lake Tahoe
BW	Blackwood Creek
GN	General Creek
IC	Incline Creek
TH	Third Creek
TR	Trout Creek
UTR	Upper Truckee
WR	Ward Creek
EC	Elks Club
PO	Pasadena
SB	Speedboat
SR431	SR431
TC	Tahoe City
TV	Tahoe Valley
TA	Tahoma
UT	Upper Truckee

Figure 1. Locations of Aquatic Particle Project sampling sites, with lake sites shown in blue, stream sites in yellow, and stormwater sites in red.

Lake samples were collected on six occasions beginning in April 2023 and ending in April 2024 (**Table 1**). Routine sampling down the water column at twelve consistent depths occurred in July, September, and November of 2023, followed by a final depth profile sampling in April 2024. Conditions were calm each time while the UNR crew were sampling. Secchi depths were measured after sample collection at around noon each time.

After samples arrived at the DRI laboratory they were passed through a 20-µm stainless steel sieve (Gilson Company) before splitting for subsequent analyses. The procedure for sample splitting was to lightly shake the sample post-sieving and pour subsamples for subsequent analyses into pre-cleaned and rinsed LDPE bottles. Samples and subsamples were kept in the dark at 4°C until analysis. Analyses included standard turbidity measurements (Hach 2100N), fine sediment particle counts (FSP) by LiQuilaz (Particle Measuring Systems), and then particle size and composition analysis by SEM-EDS (Tescan Mira3 SEM with Bruker Quantax 200 EDS).

Table 1. Lake Tahoe sampling sites, dates, water column sample depths, and site Secchi depths.

Location	Date	Site ID	NAD83 Lat.	NAD83 Long.	Sample depths (m)	Secchi depth (m)
South Lake Tahoe	4/22/23	na	38.9577	-120.0181	20, 30	na
Mid-Lake Tahoe	6/1/23	MLTP	39.1417	-120.0153	5, 15, 20	na
Mid-Lake Tahoe	7/26/23	MLTP	39.1413546	-120.0151161	2, 5, 10, 15, 20, 30, 40, 50, 100, 150, 250, 300	16.2
Mid-Lake Tahoe	9/15/23	MLTP	39.1427044	-120.0121731	2, 5, 10, 15, 20, 30, 40, 50, 100, 150, 200, 300	18.9
Mid-Lake Tahoe	11/22/24	MLTP	39.1443959	-120.0127649	2, 5, 10, 15, 20, 30, 40, 50, 100, 150, 200, 300	15.6
Mid-Lake Tahoe	4/23/24	MLTP	39.1366079	-120.0050817	2, 5, 10, 15, 20, 30, 40, 50, 100, 150, 200, 300	16.9

Lake Tahoe Interagency Monitoring Program (LTIMP)

The U.S. Geological Survey (USGS) has monitored discharge (Q) and collected discrete water-quality (QW) samples from seven tributaries (**Table 2**) in the Lake Tahoe Basin since the 1970’s under the Lake Tahoe Interagency Monitoring Program (LTIMP) to assess suspended-sediment concentration (SSC) and nutrient inputs from these watersheds. The USGS and the University of California-Davis (UCD) began analyzing these QW samples for fine-sediment particles (FSP) in 2002. Real-time turbidity (TURB) sensors were added to California LTIMP surface water gages in 2015 water year (WY, October through September), and Nevada LTIMP surface water gages in 2019 WY.

The LTIMP collects approximately 20 QW samples annually at each tributary. Samples are collected over a range of hydrologic conditions that typically include 3 storms, 7 baseflow (July to February), and 10 snowmelt runoff samples (March to June). Cross-section QW samples are collected downstream of the gage house using the equal-width-increment (EWI) method with 10 vertical sections composited for analysis. A DH-

81 sampler is used when conditions are wadable (up to 250 ft^3/s). In un-wadable conditions, a D-74 aluminum sampler is used to collect EWI samples with a bridge board mounted A-reel. Subsamples are split using an 8-liter cubit-style churn.

Table 2. LTIMP monitoring locations for discharge, sediment and nutrient collection.

		Begin Date Continuous Data		**Begin Date Water Quality Data**	
Site No.	**Site Name**	Discharge (Q)	Turbidity (TURB)	Suspended Sed. Conc. (SSC)	Fine-sediment particles (FSP)
10336610	UPPER TRUCKEE RV AT SOUTH LAKE TAHOE, CA	1971-10-01	2014-10-07	1971-11-11	2002-04-02
10336645	GENERAL C NR MEEKS BAY CA	1980-07-07	2015-01-15	1981-04-30	2002-04-02
10336660	BLACKWOOD C NR TAHOE CITY CA	1960-10-01	2015-01-20	1973-11-12	2002-04-02
10336676	WARD C AT HWY 89 NR TAHOE PINES CA	1972-10-01	2015-01-15	1972-12-20	2002-04-02
10336780 **10336790***	TROUT CK NR TAHOE VALLEY, CA	1960-10-01	2014-10-03	1972-03-04	2002-04-03
10336698	THIRD CK NR CRYSTAL BAY, NV	1969-10-01	2019-09-30	1969-10-15	2002-04-01
10336700	INCLINE CK NR CRYSTAL BAY, NV	1969-10-01	2019-09-30	1969-10-15	2002-04-01

Sample Collection and Analysis

Sample collection for the Aquatic Particles Project were strategically collected during routine LTIMP sampling at all seven tributaries, primarily during peak runoff in spring of 2023 and 2024. Three to four samples were collected at each tributary to provide sufficient volume for the 8-liter churn splitter.

Each sample was churn-split into two subsamples, one to DRI for processing and subsequent SEM-EDS analysis, and a second split submitted to LTIMP for processing and the following QW analyses. These QW samples were analyzed for SSC at the USGS Sediment Laboratories in Santa Cruz, California or the Cascade Volcano Observatory using the filtration method (USGS parameter code 80154, in units of milligrams per liter or mg/l) and turbidity using broad band light source (400-680 nm), multiple beam detectors at multiple angles (USGS parameter code 63675 in units of Nephelometric Turbidity unit, or NTU). Select SSC samples with noticeable sand content were passed through a 63 µm sieve to determine percent mass passing (USGS parameter code 70331, Sediment, finer than 63 micrometers in percentage). The total

SSC mass was multiplied by the percentage mass passing for all subsequent analyses (i.e., the sand mass was removed from SSC to develop all regressions).

Samples were analyzed for FSP by UCD at the Tahoe Environmental Research Center using a LiQuilaz-S liquid particle counter via laser diffraction (PMS 2009). The FSP counts are reported for each size bin (USGS parameter codes 70354 to 70366 in units of counts per liter, or c/l). **Table 3** presents particle diameter bin sizes and parameter codes.

Table 3. Water quality and surface water gage parameter codes and descriptions for analyses used in regression models at each LTIMP gage locations.

Surface water gage data		
Parameter	**Code**	**Description**
Q	0060	Discharge, cubic feet per second
TURB	63680	Turbidity, water, unfiltered, monochrome near infra-red LED light, 780-900 nm, detection angle 90 +-2.5 degrees, formazin nephelometric units (FNU)
Water quality samples		
Parameter	**Code**	**Description**
SSC	80154	Suspended sediment concentration, milligrams per liter
SED	70331	Sediment, suspended-sediment material finer than a sieve diameter of 0.062 mm, percentage
TURB	63675	Turbidity, water, unfiltered, broad band light source (400-680 nm), detection angle 90 +-30 degrees to incident light, nephelometric turbidity units (NTU)
FSP Bin 1	70354	Suspended sediment laser diffraction particle count 0.50 to 0.63 um, counts per liter
FSP Bin 2	70355	Suspended sediment laser diffraction particle count 0.63 to 0.79 um, counts per liter
FSP Bin 3	70356	Suspended sediment laser diffraction particle count 0.79 to 1.00 um, counts per liter
FSP Bin 4	70357	Suspended sediment laser diffraction particle count 1.00 to 1.41 um, counts per liter
FSP Bin 5	70358	Suspended sediment laser diffraction particle count 1.41 to 2.00 um, counts per liter
FSP Bin 6	70359	Suspended sediment laser diffraction particle count 2.00 to 2.83 um, counts per liter
FSP Bin 7	70360	Suspended sediment laser diffraction particle count 2.83 to 4.00 um, counts per liter
FSP Bin 8	70361	Suspended sediment laser diffraction particle count 4.00 to 4.76 um, counts per liter
FSP Bin 9	70362	Suspended sediment laser diffraction particle count 4.76 to 5.66 um, counts per liter
FSP Bin 10	70363	Suspended sediment laser diffraction particle count 5.66 to 6.73 um, counts per liter
FSP Bin 11	70364	Suspended sediment laser diffraction particle count 6.73 to 8.00 um, counts per liter
FSP Bin 12	70365	Suspended sediment laser diffraction particle count 8.00 to 11.31 um, counts per liter
FSP Bin 13	70366	Suspended sediment laser diffraction particle count 11.31 to 16.00 um, counts per liter

LTIMP Site Hydrographs and Sample Collection (Figures 2a – 2g)

Upper Truckee River at South Lake Tahoe, CA

Four samples were collected from the Upper Truckee River at South Lake Tahoe (Station 10336610) during peak flow (3 samples) and one during baseflow conditions.

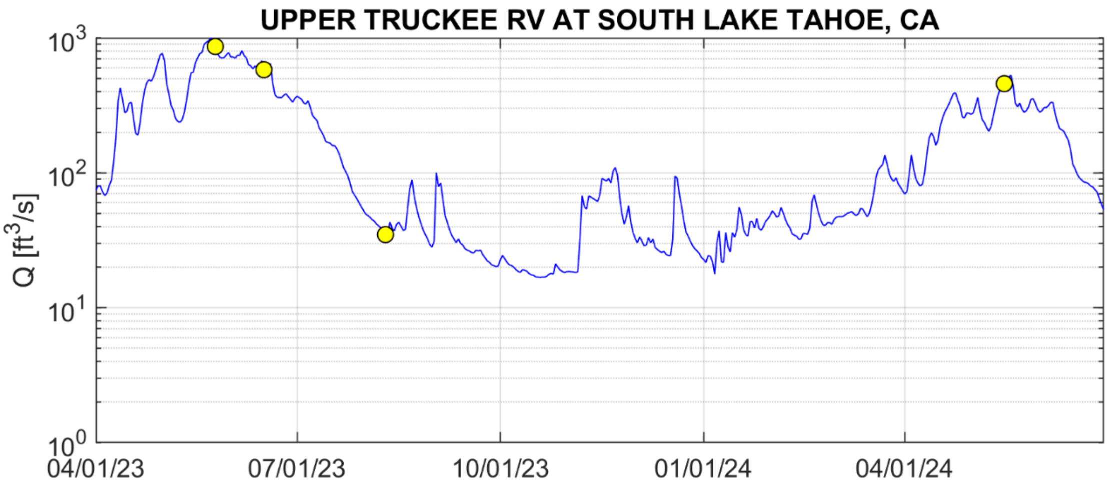


Figure 2a. Upper Truckee River at South Lake Tahoe hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

General Creek near Meeks Bay, CA

Three samples were collected from the General Creek near Meek Bay (Station 10336645) during peak flow.

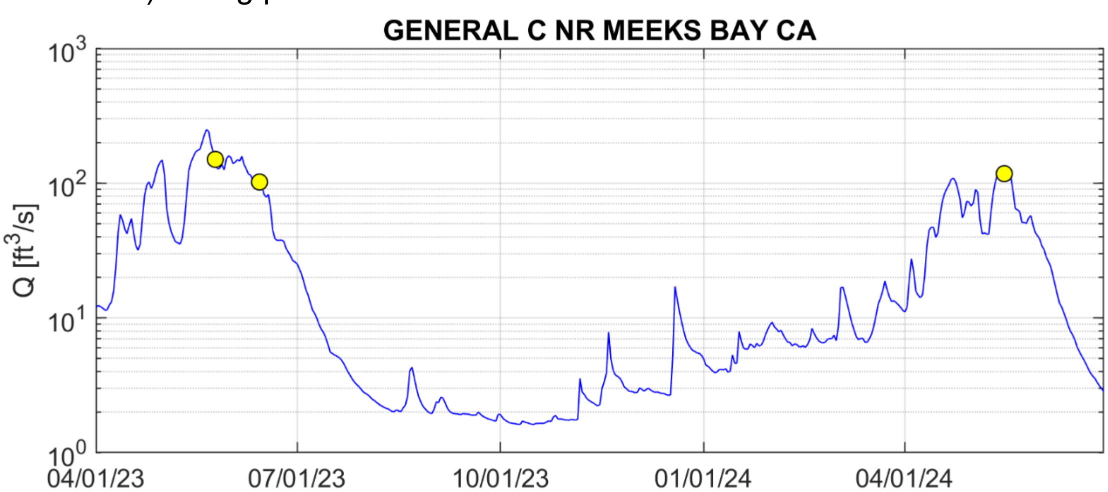


Figure 2b. General Creek near Meeks Bay hydrograph from April 1, 2023, through June 30, 2024showing events sampled for the Aquatic Particles Project in yellow.

Blackwood Creek near Tahoe City, CA

Three samples were collected from Blackwood Creek near Tahoe City (Station 10336660) during peak flow.

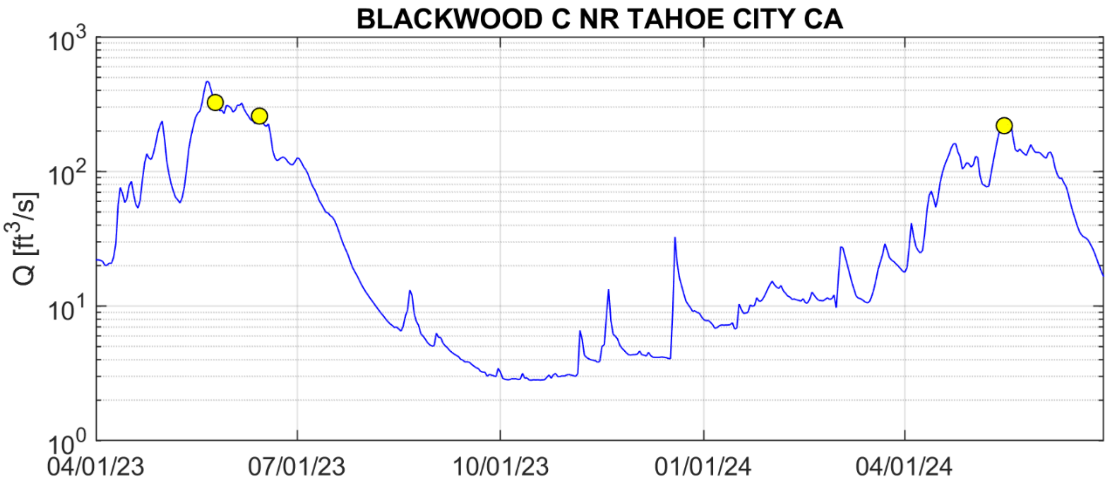


Figure 2c. Blackwood Creek near Tahoe City hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

Ward Creek at Hwy 89 near Tahoe Pines, CA

Three samples were collected from Ward Creek near Highway 89 near Tahoe Pines (Station 10336676) during peak flow.

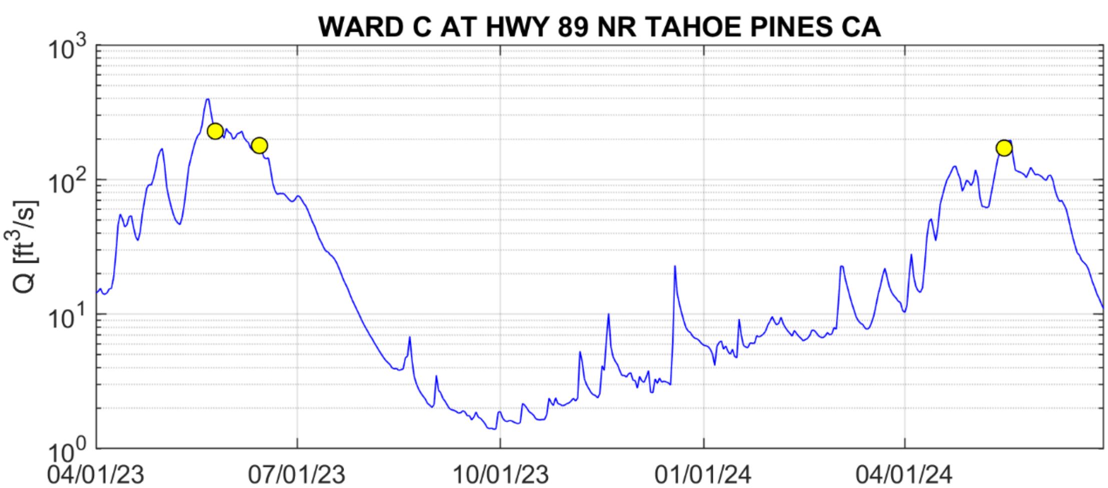


Figure 2d. Ward Creek near Tahoe Pines hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

Trout Creek near Tahoe Valley, CA

Four samples were collected from Trout Creek near Tahoe Valley (Station 10336780/10336790) during peak flow (3) and one during baseflow conditions.

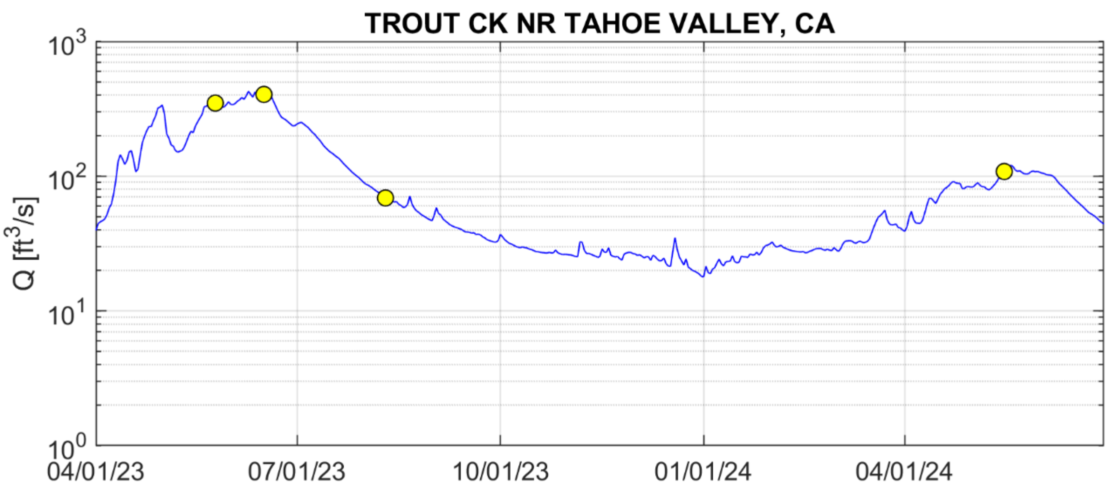


Figure 2e. Trout Creek near Tahoe Valley hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

Third Creek near Crystal Bay, NV

Four samples were collected from Third Creek near Crystal Bay (Station 10336698) during peak flow (3) and one during baseflow conditions.

Figure 2f. Third Creek near Crystal Bay hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

Incline Creek near Crystal Bay, NV

Four samples were collected from Incline Creek near Crystal Bay (Station 10336700) during peak flow (3) and one during baseflow conditions.

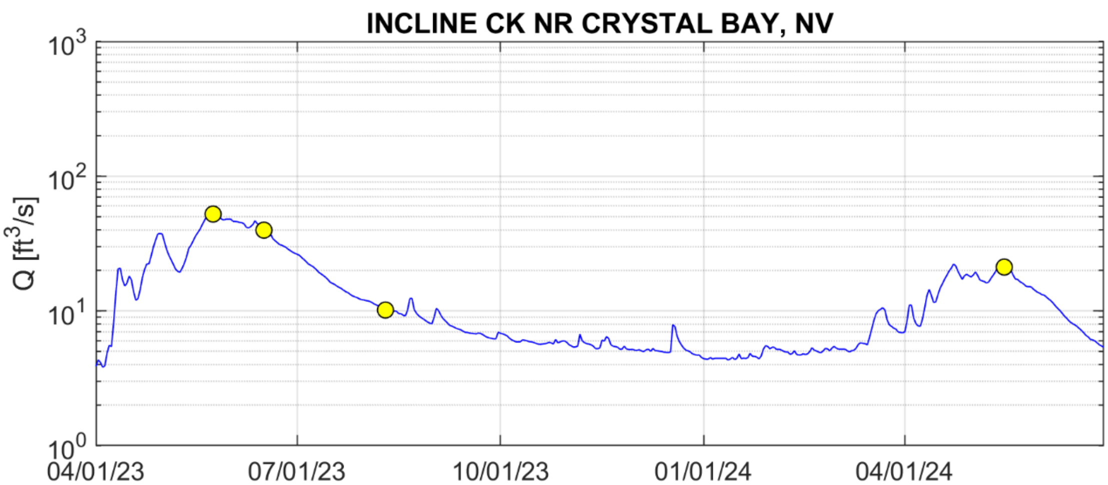


Figure 2g. Incline Creek near Crystal Bay hydrograph from April 1, 2023 through June 30, 2024 showing events sampled for the Aquatic Particles Project in yellow.

Regional Stormwater Monitoring Program (RSWMP)

To comply with the Tahoe TMDL permit requirements, local jurisdictions are expected to maintain their stormwater treatment infrastructure and to support water quality monitoring through the RSWMP to evaluate pollutant reductions from implemented BMP actions. RSWMP has been collecting samples and information on urban stormwater runoff from a coordinated network of monitoring sites since Water Year (WY) 2014. These sites routinely collect information to support the assessment of status and trends in response to management actions and water quality improvement projects in urban catchments.

Sample Collection and Analysis

Urban runoff samples were collected from established sites in the RSWMP monitoring network in conjunction with their usual sampling routine. Continuous hydrology and stormwater samples were collected using 24-bottle carousels in ISCO brand autosamplers and following standard RSWMP guidance (Tahoe RCD 2017). Flow was logged at constant time intervals, generally every 5 minutes.

Weather was routinely monitored and autosamplers were programmed to initiate sampling at the beginning of selected runoff events then to continue sampling at equal runoff volume intervals throughout the event hydrograph in accordance with RSWMP guidance (Tahoe RCD 2017, sections 10.2.1.4 and 10.2.1.5). After each event the data from a site's hydrograph was used to calculate aliquot volumes from individual bottles auto-collected during the event to create a flow-weighted, event-mean composite for that site (Tahoe RCD 2017, section 10.2.1.10). In this project, the only deviation from standard RSWMP processing procedures was that event composites were passed through a 20-µm sieve before sample splitting for analyses. Subsamples split from sieved composites were analyzed for: turbidity at Tahoe RCD labs (Hach 2100N); total suspended solids (TSS, by SM 2540 D) at the High Sierra Water Laboratory, Inc. in Oakland, OR; and particle size distribution (PSD, SM 2560 D) at the UC Davis Tahoe Environmental Research Center Laboratory in Incline Village, NV to determine fine sediment particle concentrations. A one-liter sieved subsample was also provided to DRI for compositional analysis of particles by scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS).

Site Selection and Characteristics

Eight urban catchments were selected from the RSWMP monitoring network for this project: Elks Club, Pasadena, Speedboat, SR431, Tahoe City, Tahoe Valley, Tahoma, and Upper Truckee. These catchments were chosen because of their direct hydrologic connectivity to Lake Tahoe, diversity of urban land uses, range of sizes, and distribution around the perimeter of Lake Tahoe. **Table 4** summarizes the characteristics of these selected catchments, including jurisdiction, total area, percent impervious area, and dominant land uses in each catchment. These characteristics likely affect the distribution of particles sizes, their composition and sources in water quality samples. **Figure 1** shows the locations of the stormwater sampling sites in red.

Table 4: Urban Sample Site Catchment Characteristics. Dominant urban land use is highlighted in dark pink, second most dominant in medium pink, and third most dominant in light pink. The vegetated class was not considered in this ranking.

Site Name	Site Acronym	Jurisdiction	Total Acres	Impervious Area	Landuse					
					Single Family Residential	Multi-Family Residential	CICU*	Primary Roads	Secondary Roads	Vegetated
SR431	CI/JI	NDOT	1.4	89%	0%	0%	0%	89%	0%	11%
Elks Club	EC	El Dorado	14.4	29%	50%	0%	0%	9%	19%	22%
Pasadena	PO	CSLT	78.8	39%	52%	13%	5%	0%	16%	14%
Speedboat	SB	Placer	29.0	30%	49%	3%	9%	4%	10%	25%
Tahoe City	TC	Placer, Caltrans	4.4	62%	12%	10%	23%	49%	0%	6%
Tahoe Valley	TV	CSLT, Caltrans	338.4	39%	19%	12%	20%	2%	13%	34%
Tahoma	TA	Placer, El Dorado, Caltrans	49.5	30%	41%	4%	12%	3%	15%	25%
Upper Truckee	UT	CSLT, Caltrans	10.5	72%	14%	7%	39%	14%	18%	8%

*Commercial, Industrial, Communications, Utilities

Event Types Sampled

Many factors can affect the concentrations and characteristics of particles in stormwater runoff, including the time of year, type of precipitation event, and the location. During this project, samples were collected from several types of runoff events. Rain events (frontal storms), whether on bare ground or on existing snow cover, are generally one to several days in duration and typically result in large volumes of runoff with higher concentrations of sediment at the beginning and lower concentrations toward the end. Thunderstorms tend to be much shorter in duration (several minutes to several hours) but with higher rainfall intensity than frontal storms, often producing greater erosion and more sediment transport. Event snowmelt occurs when the precipitation falls as snow but melts on the ground during the event and runs off. These tend to produce smaller runoff volumes but may carry higher concentrations of minerogenic particles from vehicular grinding of traction abrasives applied to the roadways for public safety.

Twenty-seven samples of urban runoff were collected during this project: two at the SR431 highway site (CI/JI) near Country Club Drive in Incline Village, four at Elks Club (EC) a predominately residential area near Meyers in South Lake Tahoe, one at Pasadena outflow (PO) into the lake at South Lake Tahoe, four at Speedboat (SB) a residential area with some highway runoff, five from Tahoe City (TC) with mostly commercial and highway runoff, four at Tahoe Valley (TV) a mixed use and vegetated site, two at Tahoma (TA) another mainly residential site on the west shore, and five at the Upper Truckee (UT) a mainly commercial site with runoff discharged into the Upper Truckee River. See **Table 5** for sample dates and event types for each catchment. The site characteristics and sampling events are described below.

Elks Club (EC)

The Elks Club monitoring site (EC) was established WY18 and is located on the northwest corner of Elks Club Drive and Bel Aire Circle in El Dorado County. At 14.4 acres, it is a relatively small catchment comprised primarily of single family residential and secondary road land uses.

Source apportionment analyses of particles from this catchment showed that the dominant particle sources include asphalt aggregate, asphalt binder, traction abrasives, vegetation debris, roadside soil, and tire and brake pad wear. It is likely that particles in similar catchments have a similar composition.

This site was sampled four times (**Figure 3**), once during a rain event on 11/6/23 that resulted in 3,201 cubic feet (cf) of runoff with a peak flow of 0.18 cubic feet per second (cfs), once during a rain event on 12/18/23 that resulted in 2,565 cf of runoff with a peak flow of 0.09 cfs, once during a rain on snow event on 3/22/2024 that resulted in 1,764 cf of runoff with a peak flow of 0.14 cfs, and once during a thunderstorm on 8/3/24 that resulted in 1,946 cf of runoff with a peak flow of 1.25 cfs. These event types, their volumes, and peak flows are typical of this site.

Table 5: Sampling events and runoff types at each monitored site.

Location	Site-ID	Date	Runoff Type	Runoff Volume (cf)	Peak Flow (cfs)
Elks Club	EC	11/6/2023	Rain	3,201	0.18
Elks Club	EC	12/18/2023	Rain	2,565	0.09
Elks Club	EC	3/22/2024	Rain on Snow, Event Snowmelt	1,764	0.14
Elks Club	EC	8/3/2024	Thunderstorm	1,946	1.25
Pasadena	PO	8/20/2023	Rain	1,144	0.57
Speedboat	SB	6/11/2023	Thunderstorm	27,252	9.53
Speedboat	SB	12/18/2023	Rain	13,922	1.06
Speedboat	SB	3/22/2024	Rain on Snow, Event Snowmelt	2,525	0.44
Speedboat	SB	5/4/2024	Event Snowmelt	1,440	0.07
SR431	CI/JI	6/10/2023	Thunderstorm	829	0.55
SR431	CI/JI	12/18/2023	Rain	2,242	0.18
Tahoe City	TC	8/20/2023	Rain	1,997	0.27
Tahoe City	TC	11/6/2023	Rain	5,038	0.64
Tahoe City	TC	12/18/2023	Rain	8,754	0.45
Tahoe City	TC	3/22/2024	Rain on Snow, Event Snowmelt	3,025	0.23
Tahoe City	TC	5/4/2024	Event Snowmelt	6,519	0.17
Tahoe Valley	TV	8/20/2023	Rain	24,054	1.25
Tahoe Valley	TV	11/6/2023	Rain	23,020	0.79
Tahoe Valley	TV	5/4/2024	Event Snowmelt	14,910	3.16
Tahoe Valley	TV	8/3/2024	Thunderstorm	1,824	0.67
Tahoma	TA	6/10/2023	Thunderstorm	716	0.08
Tahoma	TA	11/6/2023	Rain	7,010	0.75
Upper Truckee	UT	8/20/2023	Rain	5,801	0.45
Upper Truckee	UT	12/18/2023	Rain	14,698	0.68
Upper Truckee	UT	3/22/2024	Rain on Snow, Event Snowmelt	9,034	0.65
Upper Truckee	UT	5/4/2024	Event Snowmelt	5,944	0.33
Upper Truckee	UT	8/3/2024	Thunderstorm	6,346	5.24

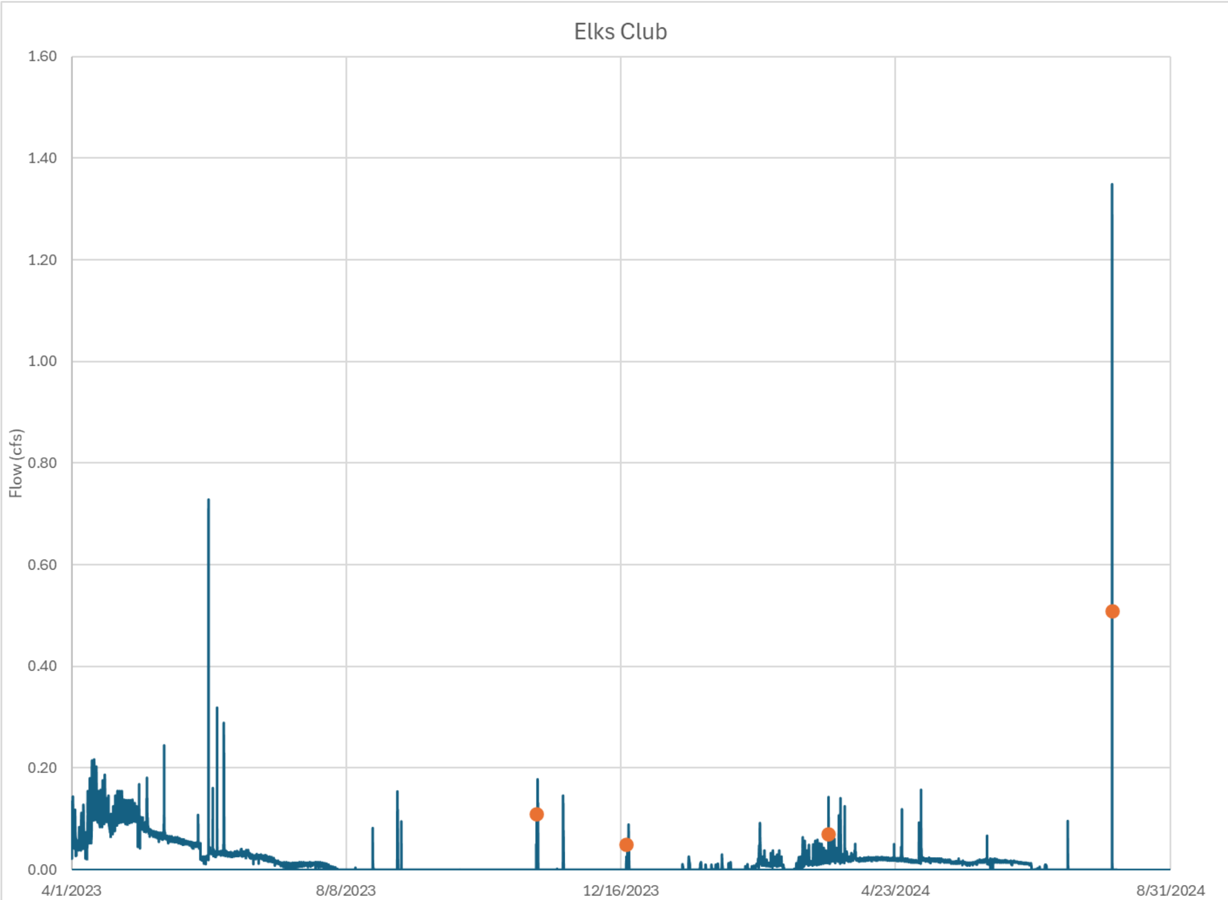


Figure 3. Elks Club runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Pasadena (PO)

The Pasadena monitoring site was established WY14 and is located at the northernmost end of Pasadena Avenue in the City of South Lake Tahoe (City). The dominant land uses are moderate density single-family residential, multi-family residential and secondary roads. Thirty-nine percent of the catchment is impervious. Several in-situ infiltration BMPs, including upstream permeable and porous road shoulders and perforated storm drainpipes, a pre-treatment Vortechnics storm vault and two Contech Stormfilter cartridge filter vaults were installed in parallel in 2010 at the end of the catchment before discharge to the lake through a 36-inch CMP.

This site was sampled once during a rain event on 8/20/2023 that resulted in 1,144 cf of runoff with a peak flow of 0.57 cfs. This event type, volume, and peak flow is typical of the site. See **Figure 4** for the site hydrograph from April 1, 2023 through August 31, 2024 showing sampled event. This event type, volume, and peak flow is typical of this site.

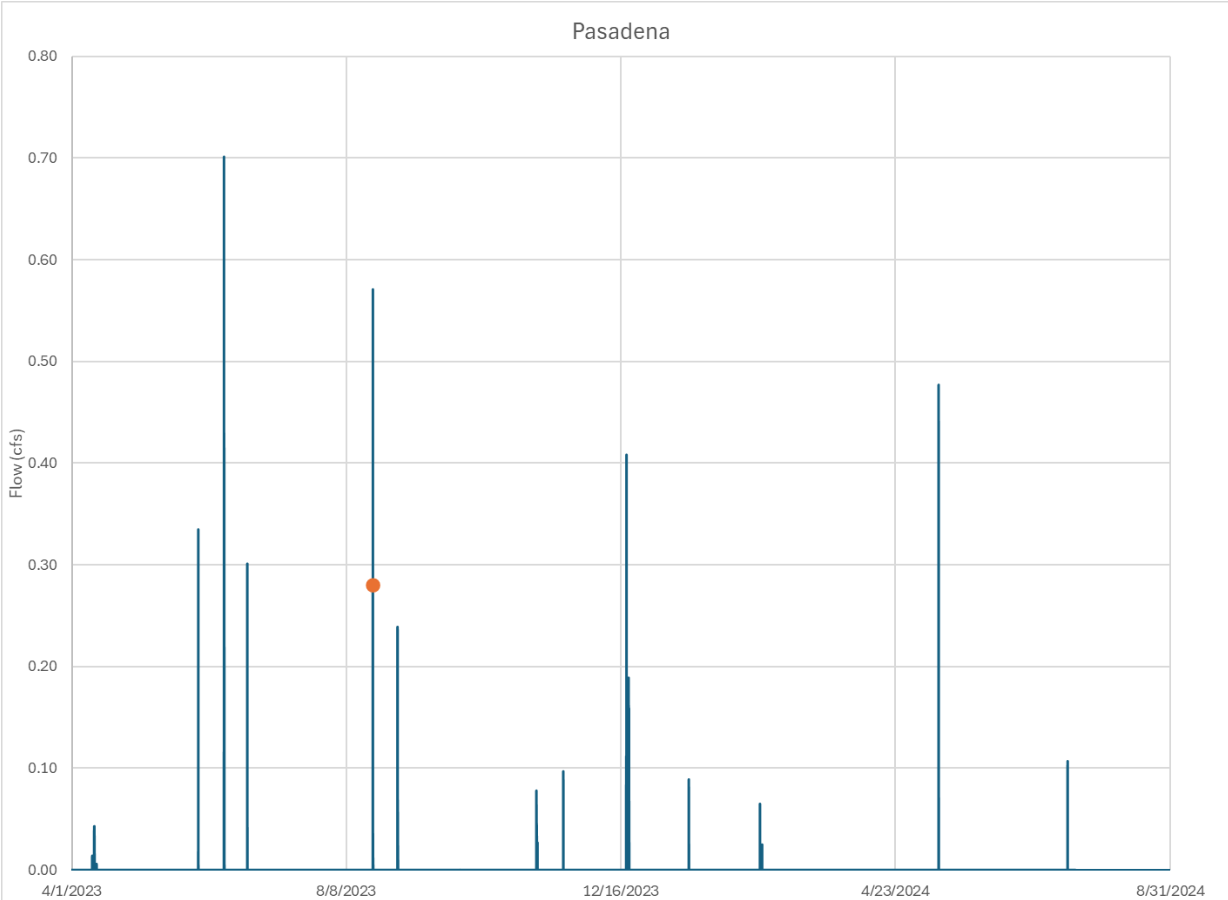


Figure 4. Pasadena runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Speedboat (SB)

The Speedboat monitoring site was established WY15 and is located midway along the western side of Speedboat Avenue just south of Dip Street in Kings Beach, California. The 29.0-acre catchment receives co-mingled runoff from Placer County and Caltrans jurisdictions. The catchment is comprised of thirty percent impervious surfaces and drains a steep area that is characterized predominately by single family residences, vegetation, and secondary road land uses.

This site was sampled four times (**Figure 5**), once during a thunderstorm on 6/11/23 that resulted in 27,252 cf of runoff with a peak flow of 9.53 cfs, once during rain event on 12/18/23 that resulted in 13,922 cf of runoff with a peak flow of 1.06 cfs, once during a rain on snow event on 3/22/2024 that resulted in 2,525 cf of runoff with a peak flow of 0.44 cfs, and once during an event snowmelt on 5/4/2024 that resulted in 1,440 cf of runoff with a peak flow of 0.07 cfs. These events types, their volumes, and peak flows are typical of this site.

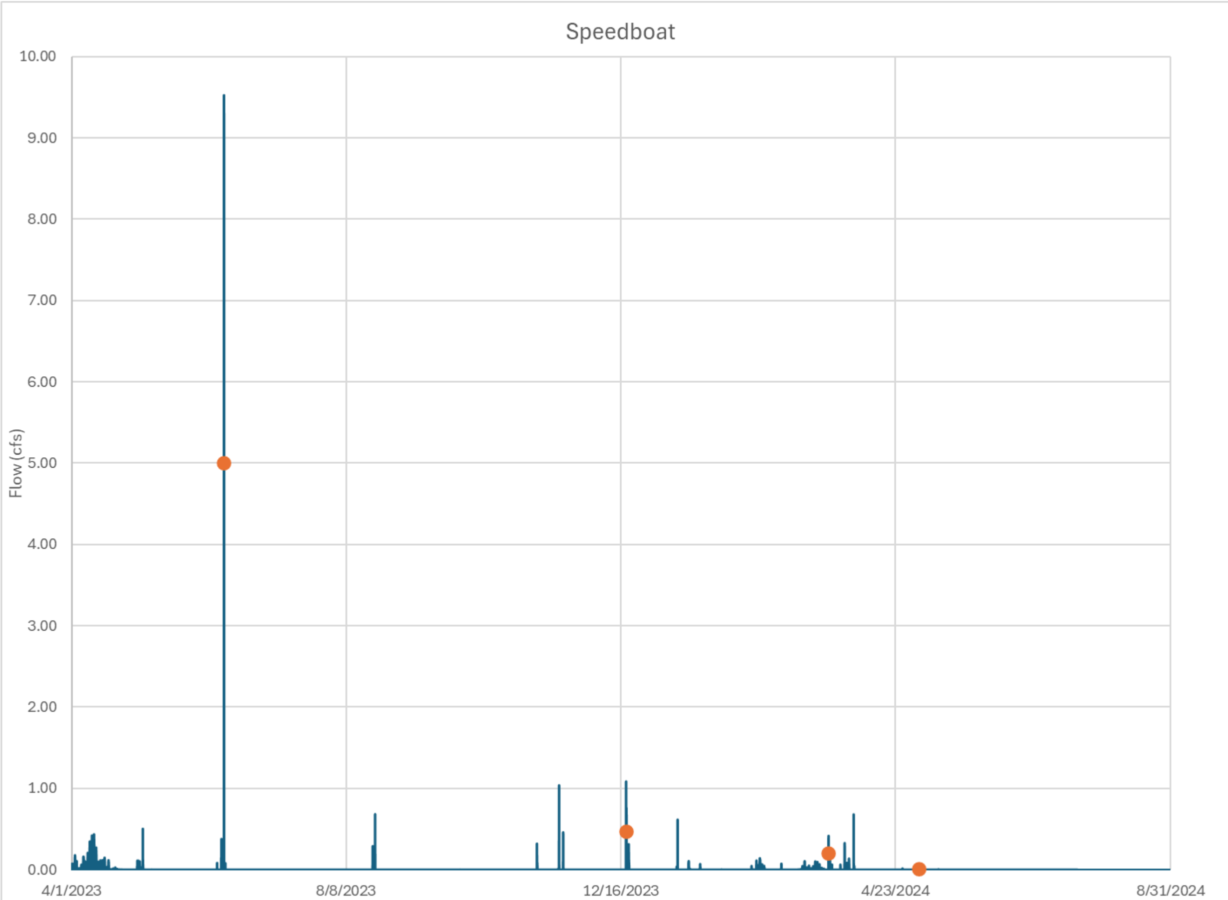


Figure 5. Speedboat runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

SR431 (CI/JI)

The SR431 monitoring site was established in WY14 and is located on State Route 431 in Washoe County above Incline Village, Nevada. The 1.4-acre catchment encompasses the NDOT right-of-way, of which approximately 89% is impervious surface and located in a rural area with moderate highway traffic density. The SR431 location is the only site that isolates runoff from primary roads and can therefore be used to characterize particles from one land use type. There are two monitoring stations in this catchment that theoretically receive the same runoff. Runoff enters a splitter chamber and is equally divided between the two monitoring sites, CI and JI. These two monitoring sites can be considered equivalent for the purposes of this study.

This site was sampled twice (**Figure 6**), once during a thunderstorm on 6/10/23 that resulted in 829 cf of runoff with a peak flow of 0.55 cfs, and once during rain event on 12/18/23 that resulted in 2,242 cf of runoff with a peak flow of 0.18 cfs. These event types, their volumes, and peak flows are typical of this site.

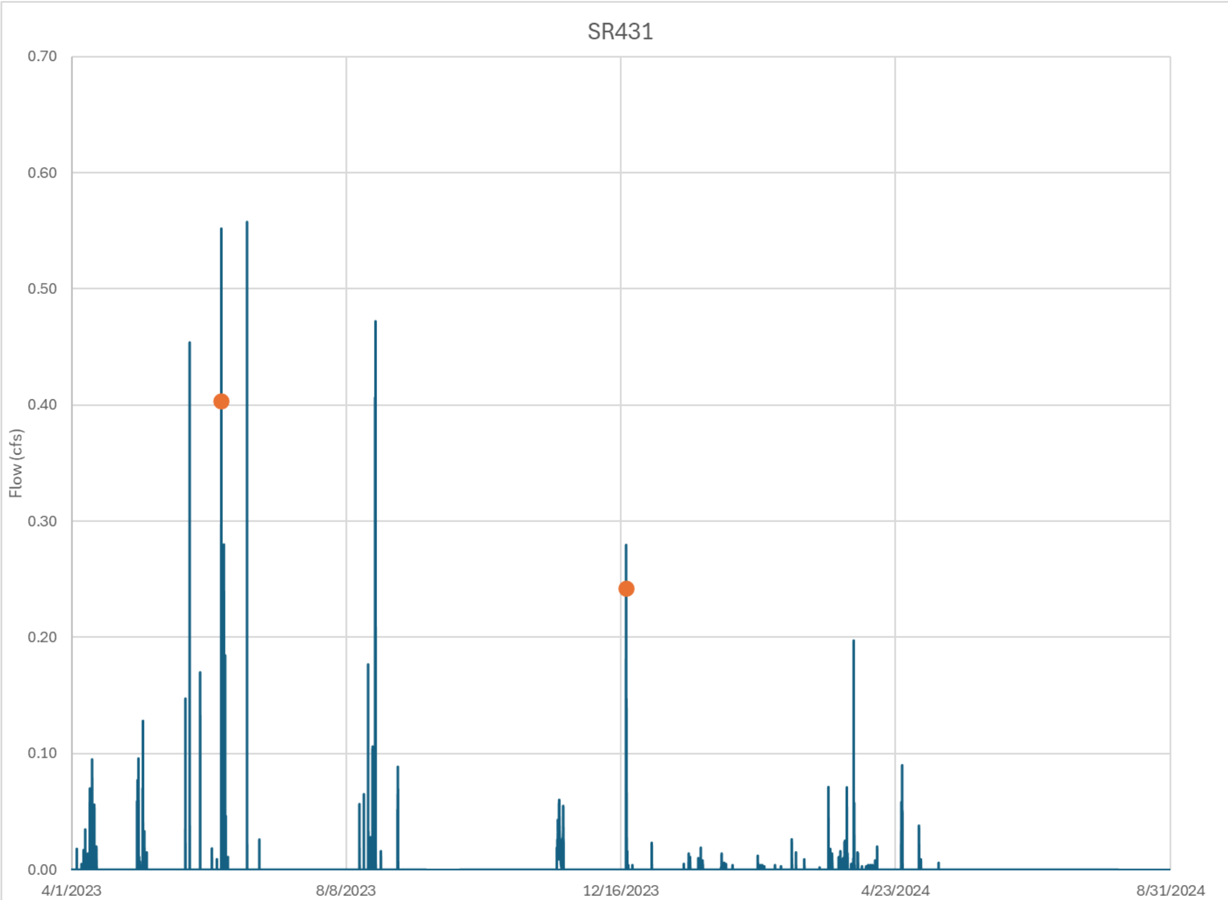


Figure 6. SR431 runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Tahoe City (TC)

The Tahoe City monitoring site was established WY20 and is located at the outflow from a Delaware Sandfilter installed by Caltrans along Highway 28, half a mile to the east of the Tahoe City commercial corridor. The 4.4-acre catchment is 62% impervious surface, and dominant land uses include primary roads, commercial/ industrial/ communications/ utilities (CICU), and single-family residential. Curb and gutter along highway 28 direct flow to a Sandfilter.

This site was sampled five times (**Figure 7**), once during a rain event on 8/20/23 that resulted in 1,997 cf of runoff with a peak flow of 0.27 cfs, once during rain event on 11/6/23 that resulted in 5,038 cf of runoff with a peak flow of 0.64 cfs, once during a rain event on 12/18/2023 that resulted in 8,754 cf of runoff with a peak flow of 0.45 cfs, once during rain on snow event on 3/22/2024 that resulted in 3,025 cf of runoff with a peak flow of 0.23 cfs, and once during an event snowmelt that resulted in 6,519 cf with a peak flow of 0.17 cfs. These event types, their volumes, and peak flows are typical of this site.

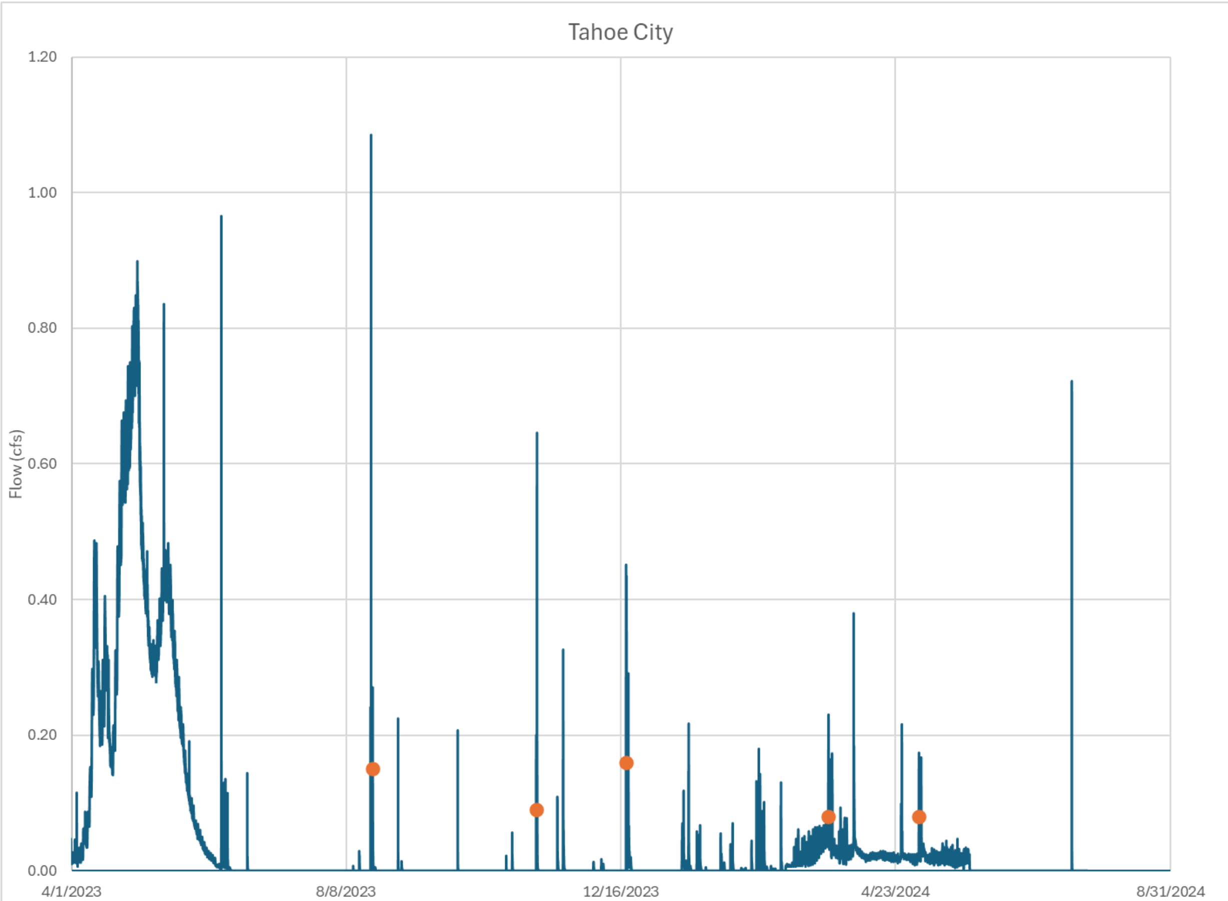


Figure 7. Tahoe City runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Tahoe Valley (TV)

The Tahoe Valley monitoring site was established WY15 and is located on the eastern side of Tahoe Keys Boulevard just north of the intersection with Sky Meadows Court in South Lake Tahoe. With an area of 338.4 acres, it is the largest catchment monitored. It is a relatively flat, highly urbanized catchment consisting primarily of CICU, single family residences, secondary roads, and vegetation land uses. Thirty-nine percent of the catchment is impervious surface.

This site was sampled four times (**Figure 8**), once during a rain event on 8/20/23 that resulted in 24,054 cf of runoff with a peak flow of 1.25 cfs, once during rain event on 11/6/23 that resulted in 23,020 cf of runoff with a peak flow of 0.79 cfs, once during an event snowmelt on 5/4/2024 that resulted in 14,910 cf of runoff with a peak flow of 3.16

cfs, and once during a thunderstorm on 8/3/2024 that resulted in 1,824 cf of runoff with a peak flow of 0.67 cfs. These event types, their volumes, and peak flows are typical of this site.

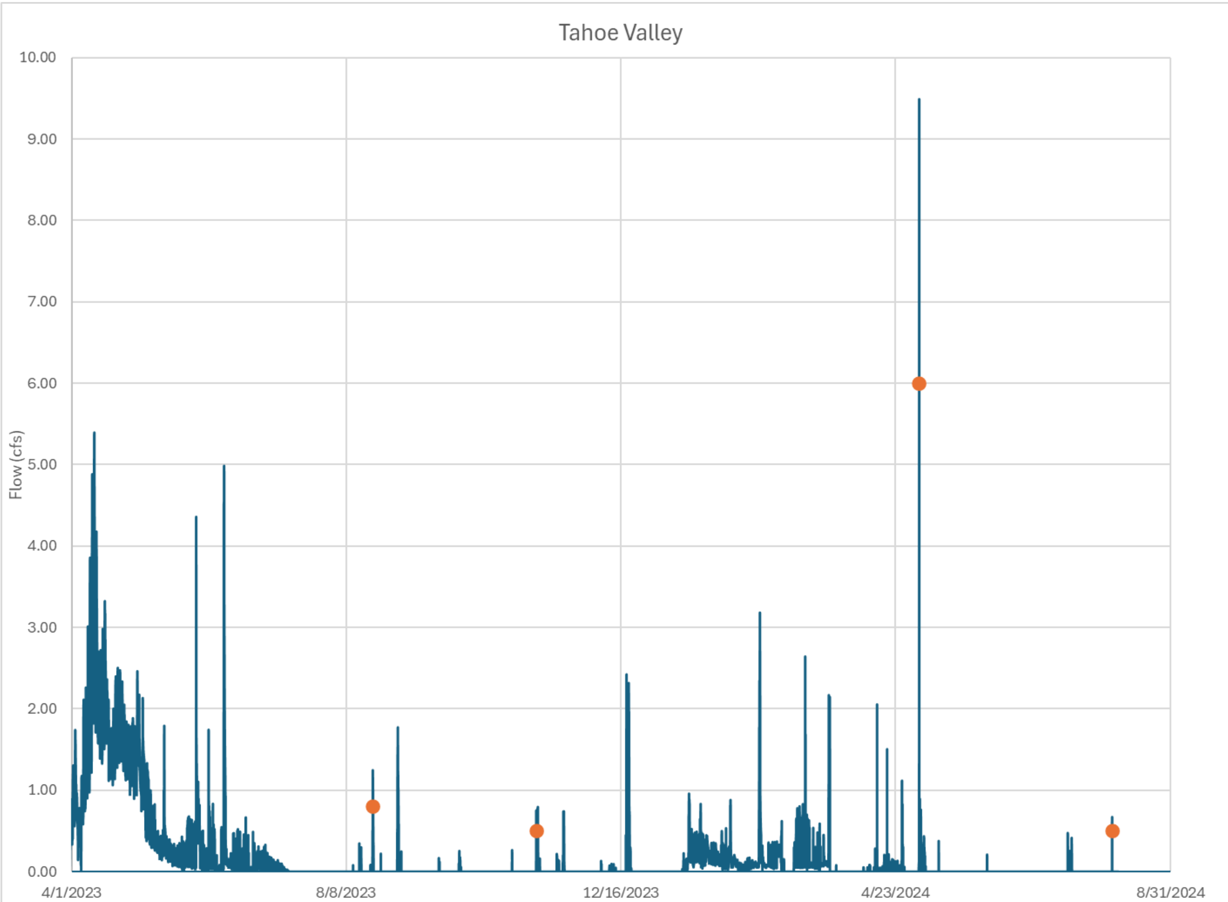


Figure 8. Tahoe Valley runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Tahoma (TA)

The Tahoma monitoring site was established WY14 and is located at the bottom of Pine Street right at the lake's edge in Tahoma. The 49.5-acre catchment straddles the Placer County/El Dorado County border and comingles runoff from both jurisdictions, plus waters from the Caltrans maintained Highway 89. The land uses in this catchment are primarily moderate density residential and secondary roads in the Tahoe Cedars subdivision, but also include some CICU and primary roads. Thirty percent of the catchment area is impervious surface.

This site was sampled twice (**Figure 9**), once during a thunderstorm on 6/10/23 that resulted in 716 cf of runoff with a peak flow of 0.08 cfs, and once during rain event on

11/6/23 that resulted in 7,010 cf of runoff with a peak flow of 0.75 cfs. These event types, their volumes, and peak flows are typical of this site.

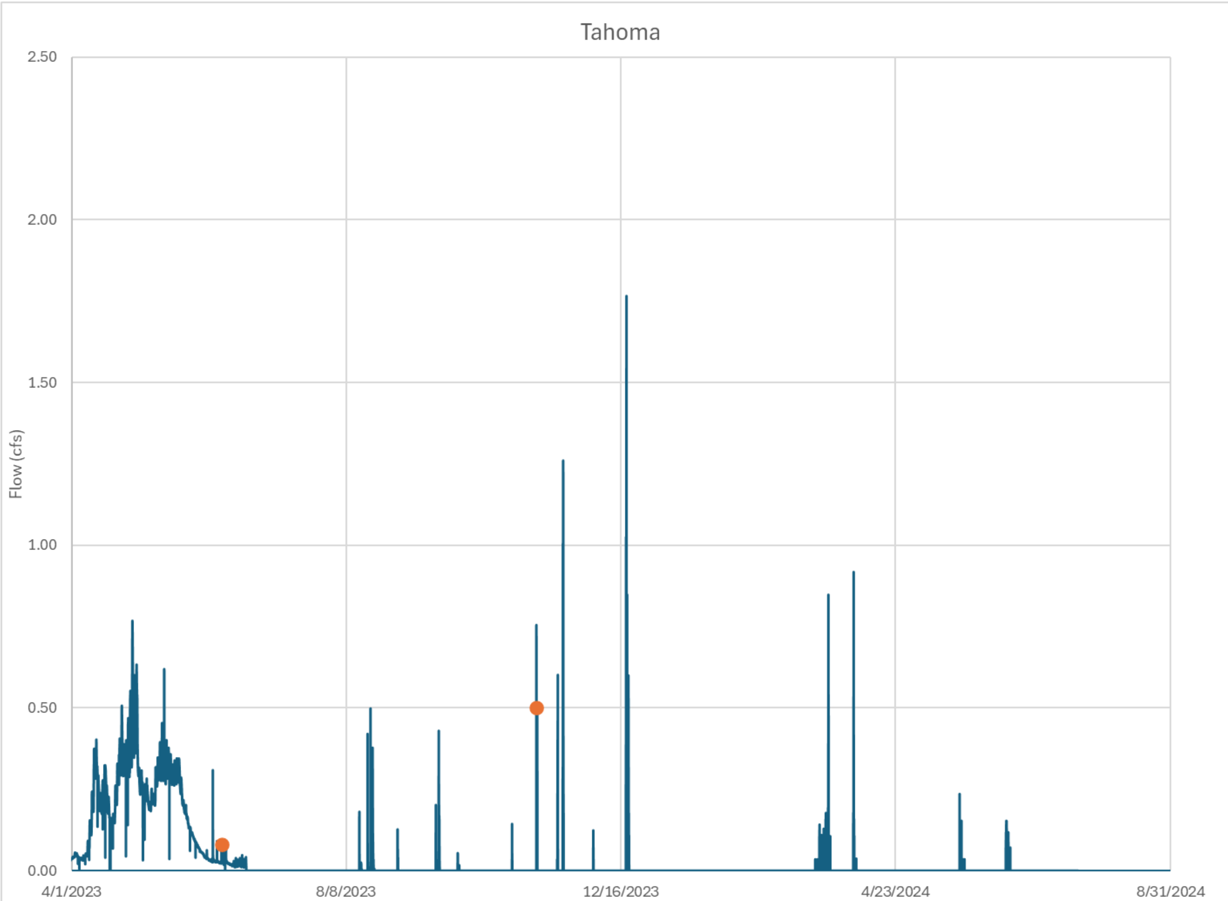


Figure 9. Tahoma runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Upper Truckee (UT)

The Upper Truckee monitoring site was established WY15 and is located east of the Upper Truckee River at the intersection of Highway 50 and River Drive upstream of the bridge on Highway 50 that crosses the Upper Truckee River in the City of South Lake Tahoe. The 10.5-acre catchment drains a highly urbanized area primarily composed of CICU, primary and secondary roads, and single-family residences. This is the third smallest catchment monitored, but with a high percentage of impervious surface (72%). It receives relatively high volumes of co-mingled runoff from the City and Caltrans jurisdictions.

In the summer of 2019 Caltrans completed installation of a large underground concrete vault that captures and treats Caltrans Highway 50 runoff only. A 6-foot wall separates it into 2 chambers; the first for settling out larger particles and once water reaches a depth of 6 feet it spills over into the second chamber with sand to filter FSP. Particles discharged from this catchment should only be the very smallest particles that are nearly impossible to filter out.

This site was sampled five times (**Figure 10**), once during a rain event on 8/20/23 that resulted in 5,801 cf of runoff with a peak flow of 0.45 cfs, once during rain event on 12/18/23 that resulted in 14,698 cf of runoff with a peak flow of 0.68 cfs, once during a rain on snow event on 3/22/2024 that resulted in 9,034 cf of runoff with a peak flow of 0.65 cfs, once during an event snowmelt on 5/4/2024 that resulted in 5,944 cf of runoff with a peak flow of 0.33 cfs, and once during thunderstorm that resulted in 6,346 cf with a peak flow of 5.24 cfs. These event types, their volumes, and peak flows are typical of this site.

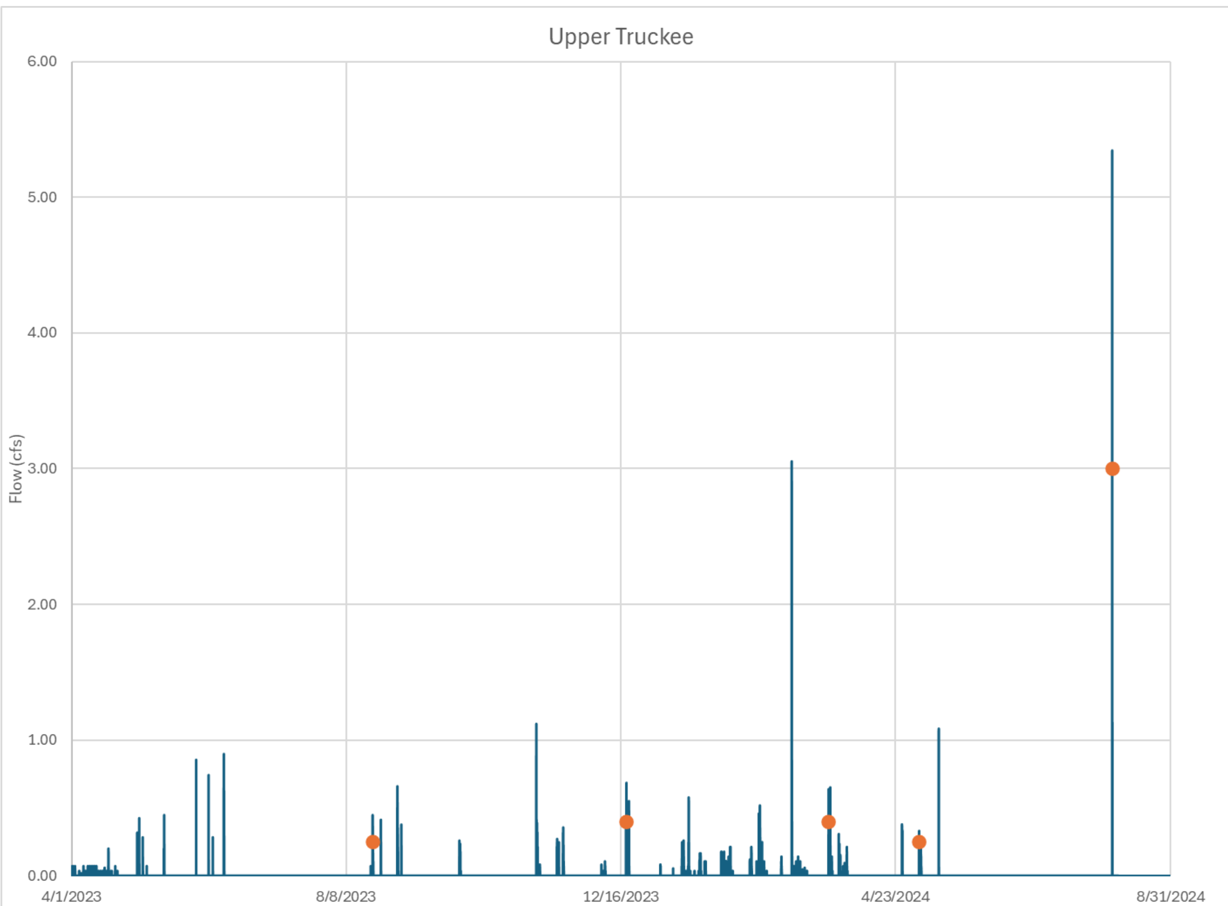


Figure 10. Upper Truckee runoff hydrograph from April 1, 2023 through August 31, 2024 showing events sampled for the Aquatic Particles Project in orange.

Sample Processing for Analysis

All samples collected from April 2023 through August 2024 are shown in **Table 6**. Lake and LTIMP stream samples were delivered in coolers to DRI as raw, unprocessed samples, which were then screened at <20 µm through a stainless steel sieve before sample splitting for subsequent analyses. Turbidity was measured with a Hach 2100N lab instrument immediately after sieving each sample. Particle size distributions were determined on the sieved samples with a LiQuilaz S Series laser particle counter for lake and stream samples, and with a Beckman Coulter LS laser diffraction particle size analyzer for urban runoff samples. The runoff event samples from urban sites were processed as event mean composites (EMCs). Prior to September 2023 these were provided without sieving but were screened through a 20 µm stainless steel sieve at DRI during sample processing. After that date, urban EMC samples were provided pre-screened at <20 µm.

All samples were stored in the dark at 4°C prior to and after the sample screening and subsampling. In the case of urban runoff samples, however, problems with refrigerated storage resulted in some samples not maintaining these conditions. Urban samples from August 2023 and from March 2024 were frozen during storage, which may have an effect on subsequent particle analysis. Urban samples from December 2023 were found to have reached undesirably high temperatures due to refrigeration equipment malfunction. Additional samples from subsequent events were collected to substitute for the frozen or overheated samples. Not all samples collected were submitted for SEM-EDS particle analysis, as indicated with an asterisk in **Table 6**.

SEM-EDS Sample Preparation

The particulate matter in samples processed (<20 µm) for CCSEM-EDS analysis was dispersed in water using ultrasonic agitation while still in their LDPE subsample bottles. Two drops of Aerosol OT surfactant (approximately 0.1 mL) were added to each suspension before filtration to help disperse the particulate matter evenly and minimize particle agglomeration. Particles were deposited onto a 0.2 µm nominal pore size polycarbonate (PC) 47 mm diameter filter using vacuum filtration techniques. Turbidity measurements and a visual inspection of the suspension were used to estimate the appropriate volume of water needed to achieve a suitable particle loading for automated particle analysis.

For lake samples, approximately 200 mL of the original suspension were used for deposition onto the PC filter, while 50 mL were used for stream samples. For samples with high turbidity, primarily from urban areas, a 5 mL aliquot was pipetted from the original suspension, after sonication and Aerosol OT addition, which was then diluted to an appropriate filtration volume with 0.2 µm filtered water. The PC filters were examined under a light microscope to ensure a uniform, monolayered distribution of particulate matter. If the initial sample amount resulted in an excessively loaded filter, a section of the filter was removed, resuspended in filtered water using ultrasonic agitation, and re-deposited onto a new PC filter. The aliquot volume of each sample was recorded, along with information on any redeposition fraction to calculate the sample filtration volumes. Finally, a section of each PC filter was mounted onto an SEM stub and coated with a thin layer of carbon by evaporative deposition to create a conductive surface for the SEM-EDS analysis.

SEM-EDS Sample Analysis

Stub-mounted filter sections was analyzed by computer-controlled SEM-EDS, which automates the process of finding, measuring, and characterizing microscopic features in the SEM. This CCSEM-EDS analysis provided: (1) detection of ~600 particles within the size range from 0.5–20 µm, (2) measurement of size and shape for each of these particles, and (3) determination of elemental constituents for identified particles.

The SEM-EDS analysis integrates a Mira3 SEM (field emission source) and a Bruker Quantax 200 energy dispersive spectroscopy (EDS) system incorporating a silicon drift detector. Magnified SEM images were produced with a high-energy electron beam of 20 keV. The resulting emissions include secondary electrons (SE) used to form topographical images, backscattered electrons (BSE) indicative of the average atomic number of the area of the specimen, and characteristic x-rays used to determine the elemental constituents. Particle measurement was accomplished using a rotated Feret box technique. Following detection and measurement, the characteristic X-rays were collected from each particle using EDS to identify the presence and relative amounts of each element detected in the particle. Elements commonly detected in these particles included carbon, sodium, magnesium, aluminum, silicon, potassium, calcium, titanium and iron, as well as less frequently phosphorus, chromium, copper, nickel and zinc. The resulting data were then sorted according to user-defined criteria to categorize particles into distinct types, based on classification schemes established by analyzing the EDS results obtained from lake, stream and urban runoff water samples. Particle concentrations were estimated from the volume of sample filtered and the number of particles counted per unit area identified in the SEM.

Table 6. Samples collected during the project period from lake, stream, and urban runoff sites. All samples were prescreened through a 20 µm sieve prior to sample splitting and analysis. The results of turbidity analysis are shown in nephelometric turbidity units (NTU). Sample IDs with asterisks were not submitted for SEM-EDS analysis.

Sample ID	Location	Site-ID	Depth (m)	Date	Time	Type	Received	NTU (<20 µm)
L-01	Lake Tahoe south mid-lake	SMLT	20	4/22/23	na	Van Dorn, raw	Cooler, 4°C	0.116
L-02	Lake Tahoe south mid-lake	SMLT	30	4/22/23	na	Van Dorn, raw	Cooler, 4°C	0.116
S-01	Incline Creek near Crystal Bay, NV	10336700	na	5/24/23	16:10	Churn split, raw	Cooler, 4°C	2.38
S-02	Upper Truckee River at South Lake Tahoe, CA	10336610	na	5/25/23	6:25	Churn split, raw	Cooler, 4°C	3.08
S-03	Trout Creek at South Lake Tahoe, CA	10336790	na	5/25/23	7:30	Churn split, raw	Cooler, 4°C	2.04
S-04	Ward Creek at HWY 89 near Tahoe Pines, CA	10336676	na	5/25/23	13:20	Churn split, raw	Cooler, 4°C	1.80
S-05	Blackwood Creek near Tahoe City, CA	10336660	na	5/25/23	14:25	Churn split, raw	Cooler, 4°C	2.71
S-06	General Creek near Meeks Bay, CA	10336645	na	5/25/23	15:20	Churn split, raw	Cooler, 4°C	0.533
S-07	Third Creek near Crystal Bay, NV	10336698	na	5/25/23	16:15	Churn split, raw	Cooler, 4°C	1.85
L-03	Lake Tahoe near MLTP	MTLP	5	6/1/23	na	Van Dorn, raw	Cooler, 4°C	0.074
L-04	Lake Tahoe near MLTP	MTLP	15	6/1/23	na	Van Dorn, raw	Cooler, 4°C	0.093
L-05	Lake Tahoe near MLTP	MTLP	20	6/1/23	na	Van Dorn, raw	Cooler, 4°C	0.089
U-01	Tahoma	TA-AC	na	6/10/23	15:31	EMC, raw	Cooler, 4°C	22.2
U-02	SR431	CI-AC	na	6/10/23	14:03	EMC, raw	Cooler, 4°C	74.8
U-03	Speedboat	SB-AC	na	6/11/23	20:18	EMC, raw	Cooler, 4°C	80.4
S-08	Ward Creek at HWY 89 near Tahoe Pines, CA	10336676	na	6/14/23	8:15	Churn split, raw	Cooler, 4°C	0.532
S-09	Blackwood Creek near Tahoe City, CA	10336660	na	6/14/23	9:10	Churn split, raw	Cooler, 4°C	0.489
S-10	General Creek near Meeks Bay, CA	10336645	na	6/14/23	10:05	Churn split, raw	Cooler, 4°C	0.217
S-11	Upper Truckee River at South Lake Tahoe, CA	10336610	na	6/16/23	9:45	Churn split, raw	Cooler, 4°C	1.14
S-12	Trout Creek at South Lake Tahoe, CA	10336790	na	6/16/23	10:50	Churn split, raw	Cooler, 4°C	1.02
S-13	Third Creek near Crystal Bay, NV	10336698	na	6/16/23	13:45	Churn split, raw	Cooler, 4°C	1.37
S-14	Incline Creek near Crystal Bay, NV	10336700	na	6/16/23	13:50	Churn split, raw	Cooler, 4°C	0.822
L-06	Lake Tahoe near MLTP	MTLP	2	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.169
L-07	Lake Tahoe near MLTP	MTLP	5	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.165
L-08	Lake Tahoe near MLTP	MTLP	10	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.160

Sample ID	Location	Site-ID	Depth (m)	Date	Time	Type	Received	NTU (<20 µm)
L-09	Lake Tahoe near MLTP	MTLP	15	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.155
L-10	Lake Tahoe near MLTP	MTLP	20	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.188
L-11	Lake Tahoe near MLTP	MTLP	30	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.180
L-12	Lake Tahoe near MLTP	MTLP	40	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.222
L-13	Lake Tahoe near MLTP	MTLP	50	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.225
L-14	Lake Tahoe near MLTP	MTLP	100	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.103
L-15	Lake Tahoe near MLTP	MTLP	150	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.093
L-16	Lake Tahoe near MLTP	MTLP	250	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.110
L-17	Lake Tahoe near MLTP	MTLP	300	7/25/23	na	Van Dorn, raw	Cooler, 4°C	0.113
S-15	Trout Creek at South Lake Tahoe, CA	10336790	na	8/10/23	11:30	Churn split, raw	Cooler, 4°C	2.10
S-16	Upper Truckee River at South Lake Tahoe, CA	10336610	na	8/10/23	12:40	Churn split, raw	Cooler, 4°C	0.770
S-17	Third Creek near Crystal Bay, NV	10336698	na	8/10/23	15:45	Churn split, raw	Cooler, 4°C	0.745
S-18	Incline Creek near Crystal Bay, NV	10336700	na	8/10/23	15:50	Churn split, raw	Cooler, 4°C	1.28
U-04*	Tahoe City	TC-AC	na	8/20/23	22:10	EMC, raw	Frozen	12.5
U-05*	Pasadena	PO-AC	na	8/20/23	23:16	EMC, raw	Frozen	24.5
U-06*	Upper Truckee	UT-AC	na	8/20/23	21:33	EMC, raw	Frozen	23.2
U-07*	Tahoe Valley	TV-AC	na	8/20/23	20:45	EMC, raw	Frozen	7.44
L-18*	Lake Tahoe near MLTP	MTLP	2	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.129
L-19	Lake Tahoe near MLTP	MTLP	5	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.124
L-20*	Lake Tahoe near MLTP	MTLP	10	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.132
L-21	Lake Tahoe near MLTP	MTLP	15	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.153
L-22*	Lake Tahoe near MLTP	MTLP	20	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.160
L-23	Lake Tahoe near MLTP	MTLP	30	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.172
L-24*	Lake Tahoe near MLTP	MTLP	40	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.165
L-25	Lake Tahoe near MLTP	MTLP	50	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.132
L-26*	Lake Tahoe near MLTP	MTLP	100	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.080
L-27	Lake Tahoe near MLTP	MTLP	150	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.068

Sample ID	Location	Site-ID	Depth (m)	Date	Time	Type	Received	NTU (<20 µm)
L-28*	Lake Tahoe near MLTP	MTLP	250	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.070
L-29	Lake Tahoe near MLTP	MTLP	300	9/15/23	na	Van Dorn, raw	Cooler, 4°C	0.073
U-08	Tahoe Valley	TV-PCL	na	11/6/23	0:46	EMC, <20 µm	Cooler, 4°C	53.3
U-09	Tahoe City	TC-PCL	na	11/6/23	0:51	EMC, <20 µm	Cooler, 4°C	40.9
U-10	Elks Club	EC-PCL	na	11/6/23	2:00	EMC, <20 µm	Cooler, 4°C	15.9
U-11	Tahoma	TA-PCL	na	11/6/23	3:35	EMC, <20 µm	Cooler, 4°C	16.4
L-30*	Lake Tahoe near MLTP	MTLP	2	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.157
L-31	Lake Tahoe near MLTP	MTLP	5	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.171
L-32*	Lake Tahoe near MLTP	MTLP	10	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.045
L-33	Lake Tahoe near MLTP	MTLP	15	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.039
L-34*	Lake Tahoe near MLTP	MTLP	20	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.142
L-35	Lake Tahoe near MLTP	MTLP	30	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.149
L-36*	Lake Tahoe near MLTP	MTLP	40	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.043
L-37	Lake Tahoe near MLTP	MTLP	50	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.126
L-38*	Lake Tahoe near MLTP	MTLP	100	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.068
L-39	Lake Tahoe near MLTP	MTLP	150	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.043
L-40*	Lake Tahoe near MLTP	MTLP	250	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.057
L-41	Lake Tahoe near MLTP	MTLP	300	11/22/23	na	Van Dorn, raw	Cooler, 4°C	0.068
U-12*	SR431	JI-PCL	na	12/18/23	8:25	EMC, <20 µm	Overheated	83.4
U-13*	Speedboat	SB-PCL	na	12/18/23	9:16	EMC, <20 µm	Overheated	76.0
U-14*	Tahoe City	TC-PCL	na	12/18/23	8:38	EMC, <20 µm	Overheated	183
U-15*	Elks Club	EC-PCL	na	12/18/23	11:55	EMC, <20 µm	Overheated	38.2
U-16	Upper Truckee	UT-PCL	na	12/18/23	9:21	EMC, <20 µm	Overheated	205
U-17	Tahoe City	TC-PCL	na	3/22/24	18:06	EMC, <20 µm	Frozen	26.8
U-18	Elks Club	EC-PCL	na	3/22/24	20:23	EMC, <20 µm	Frozen	10.7
U-19	Speedboat	SB-PCL	na	3/22/24	20:30	EMC, <20 µm	Frozen	157
U-20	Upper Truckee	UT-PCL	na	3/22/24	21:06	EMC, <20 µm	Frozen	147

Sample ID	Location	Site-ID	Depth (m)	Date	Time	Type	Received	NTU (<20 µm)
L-42	Lake Tahoe near MLTP	MTLP	2	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.123
L-43	Lake Tahoe near MLTP	MTLP	5	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.120
L-44	Lake Tahoe near MLTP	MTLP	10	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.118
L-45	Lake Tahoe near MLTP	MTLP	15	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.132
L-46	Lake Tahoe near MLTP	MTLP	20	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.160
L-47	Lake Tahoe near MLTP	MTLP	30	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.155
L-48	Lake Tahoe near MLTP	MTLP	40	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.142
L-49	Lake Tahoe near MLTP	MTLP	50	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.133
L-50	Lake Tahoe near MLTP	MTLP	100	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.093
L-51	Lake Tahoe near MLTP	MTLP	150	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.082
L-52	Lake Tahoe near MLTP	MTLP	250	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.090
L-53	Lake Tahoe near MLTP	MTLP	300	4/23/24	na	Van Dorn, raw	Cooler, 4°C	0.072
U-21	Tahoe City	TC-PCL	na	5/4/24	11:01	EMC, <20 µm	Cooler, 4°C	51.5
U-22	Tahoe Valley	TV-PCL	na	5/4/24	11:50	EMC, <20 µm	Cooler, 4°C	36.6
U-23	Upper Truckee	UT-PCL	na	5/4/24	12:25	EMC, <20 µm	Cooler, 4°C	92.5
U-24	Speedboat	SB-PCL	na	5/4/24	13:30	EMC, <20 µm	Cooler, 4°C	92.8
S-19	Ward Creek at HWY 89 near Tahoe Pines, CA	10336676	na	5/16/24	12:00	Churn split, raw	Cooler, 4°C	1.09
S-20	Blackwood Creek near Tahoe City, CA	10336660	na	5/16/24	9:29	Churn split, raw	Cooler, 4°C	1.53
S-21	General Creek near Meeks Bay, CA	10336645	na	5/16/24	10:55	Churn split, raw	Cooler, 4°C	0.520
S-22	Upper Truckee River at South Lake Tahoe, CA	10336610	na	5/16/24	11:05	Churn split, raw	Cooler, 4°C	3.07
S-23	Third Creek near Crystal Bay, NV	10336698	na	5/16/24	15:45	Churn split, raw	Cooler, 4°C	2.63
S-24	Incline Creek near Crystal Bay, NV	10336700	na	5/16/24	15:15	Churn split, raw	Cooler, 4°C	4.02
S-25	Trout Creek at South Lake Tahoe, CA	10336790	na	5/16/24	12:30	Churn split, raw	Cooler, 4°C	3.18
U-25	Elks Club	EC-PCL	na	8/3/24	13:18	EMC, <20 µm	Cooler, 4°C	66.6
U-26	Tahoe Valley	TV-PCL	na	8/3/24	13:11	EMC, <20 µm	Cooler, 4°C	199
U-27	Upper Truckee	UT-PCL	na	8/3/24	14:13	EMC, <20 µm	Cooler, 4°C	23.8

Results

The target for CCSEM-EDS analysis was to acquire data on ~600 particles from each sample to represent the distribution of characteristics for particles from 0.5–20 µm. While this is fewer than the total number of particles commonly detected by other methods, such as LiQuilaz particle size analysis, it is a computationally efficient number used in SEM-EDS. Not all particles were accepted for sample compilations. Thus, particle numeration gaps exist in the data series when a particle is rejected from compilation for being too small (<0.5 µm) or too large (>20 µm), because the EDS counts are too low, or there is edge-touching overlap with other particle(s). In almost every case, however, near to 600 particles were analyzed by EDS and reported for each sample. The average dimension of each particle is given in microns and the roundness was estimated as a measure of how closely the particle image resembles a circle, with a perfect circle having a value of one. Two magnification levels were used for particle characterization: one for particles in the 2–20 µm size range (Mag 0) and another for particles in the 0.5–2 µm size range (Mag 1).

Particle Concentrations

Particle counts per milliliter (#/mL) were calculated as the product of the number of particles per square centimeter on the SEM PC filter and the corresponding volume filtered for that sample (**Appendix A).** These results are shown on a comparative basis in **Figure 11** for the FSP counts (0.5–15 µm) by SEM and for FSP counts (0.5–16 µm) by standard analyses used in water quality monitoring programs for the Tahoe TMDL, which consist of a Particle Measuring Systems LiQuilaz S Series volumetric optical laser particle counter for lake and stream samples, and a Beckman Coulter LS 13 320 laser diffraction particle size analyzer for urban runoff samples.

- The median FSP concentration from lake samples was 5,331 particles/mL by SEM and 7,171 particles/mL by LiQuilaz (at DRI, n=41).
- For stream samples the median FSP concentration was 319,472 particles/mL by SEM and 196,217 particles/mL by LiQuilaz (available data reported by USGS for samples collected in 2023, n=18).
- Urban samples had a median FSP concentration of 4,138,748 particles/mL by SEM and 9,456,900 particles/mL by Beckman Coulter (calculated from Tahoe RCD data, n=19).

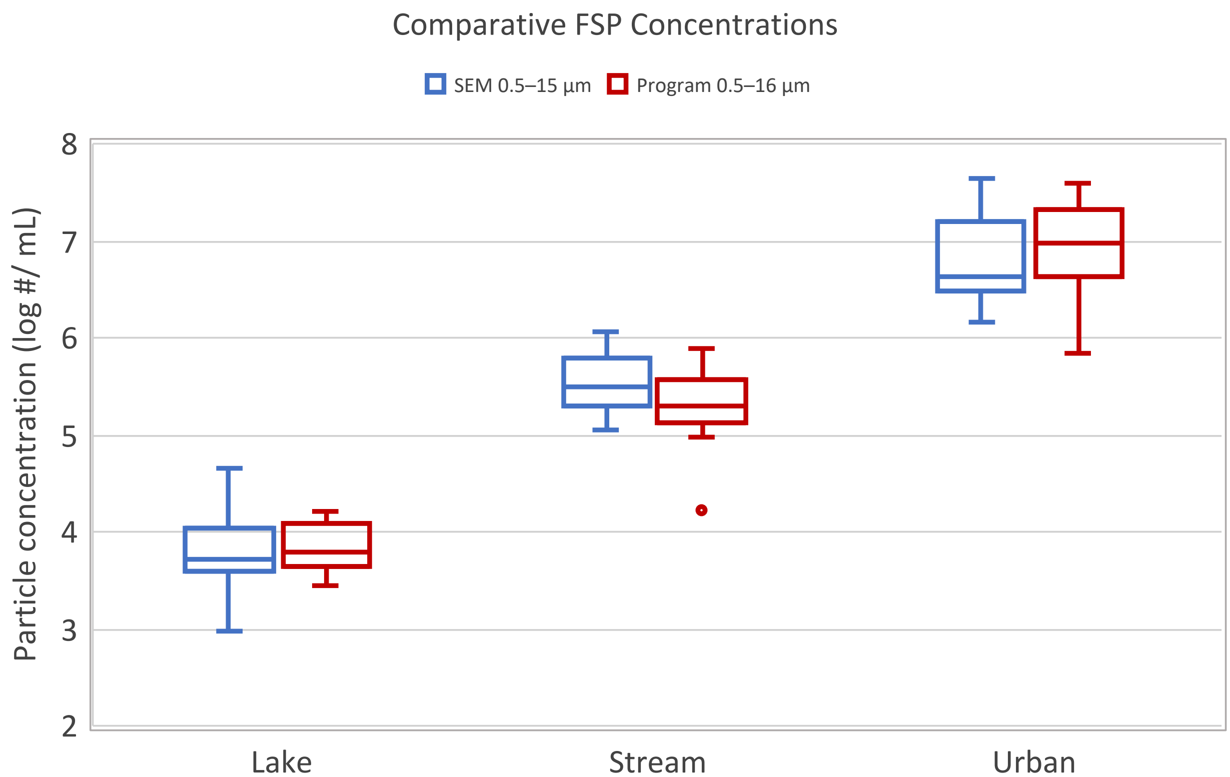


Figure 11. Fine sediment particle (FSP) concentrations for lake, stream, and urban runoff samples. Blue box plots show the results from SEM analysis while the red box plots show concentrations measured by established TMDL methods. The box format shows the first quartile, the median, and the third quartile. Whiskers extend beyond the quartile box by 1.5 times the interquartile range (IQR) with extreme values shown as individual points.

Turbidity has been used for continuous on-site monitoring as a surrogate for estimating FSP concentrations and loads in stream and urban runoff monitoring for the Lake Tahoe TMDL (**Appendix B**). Therefore, the results from turbidity on sieved samples (<20 µm) measured at DRI were compared to the SEM-estimated particle concentrations for FSP (0.5–15 µm) and to the FSP measurement methods used by or available from established TMDL monitoring programs. These comparative results are shown in **Figure 12** for the lake, stream and urban samples collected for this project.

- A regression of laboratory-measured turbidity on lake samples against the FSP particle concentrations from SEM (0.5–15 µm) yields an R^2 of 0.21 (with a two-tailed p-value <0.01). There is considerable spread in the data, however, which is not surprising given characteristic limitations when measuring turbidity at extremely low values. These results are somewhat better when the turbidity is compared to FSP measured by LiQuilaz analysis at DRI (R^2 = 0.37). Note that sample L-04 was withheld from this analysis as an outlier, likely associated with unusually high concentrations of FSP estimated by the SEM analysis.

- For stream samples the regression coefficient of turbidity against FSP by SEM is better, yielding an R^2 of 0.67 (p-value <0.001). However, results obtained from the USGS on these same stream samples analyzed by LiQuilaz at the UCD Tahoe Environmental Research Center yield a much higher $R^2 = 0.88$ ($p<0.001$), which suggests a superior application of their analytic method refined over many years.
- For urban samples the regression of turbidity against SEM-estimated FPS yields an R^2 of 0.42 ($p<0.001$). Notably, the regression of sample turbidity against particle concentrations measured by the Beckman Coulter laser diffraction instrument yields an R^2 of 0.88 ($p<0.001$), suggesting that this particle analysis method is well suited for calculating urban FSP concentrations.

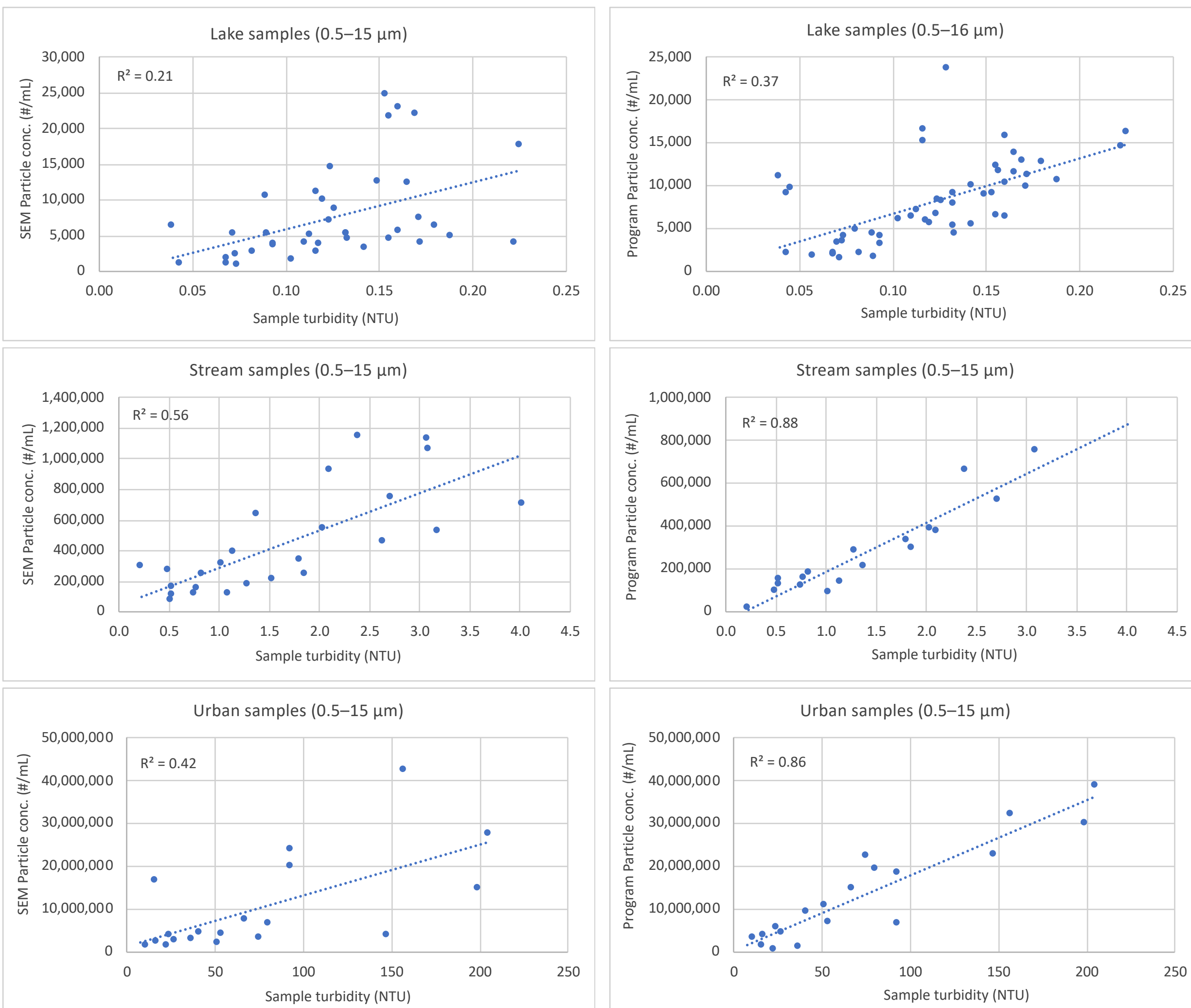


Figure 12. Sample turbidity (<20 µm) versus FSP results estimated by SEM (in the left-hand panels) compared to FSP results (right-hand panels) obtained from established TMDL methods (lake samples measured at DRI by LiQuilaz, stream sample data provided by USGS, urban sample data calculated from Tahoe RCD results). Sample L-04 SEM particle concentration withheld as an extreme value outlier.

Particle Size Distribution by Source

Particle size distribution is an important factor for TMDL management strategies to restore lake clarity. A long-term monitoring focus on the fine sediment particle concentrations derives from work of Jassby et al. (1999), which was further developed by Swift et al. (2006) who showed that light scattering by fine suspended particulates contributed 70–80% of the total lake clarity attenuation, with approximately 58% of attenuation due to inorganic particles and 25% due to organic particles. For the inorganic particles they estimated that 75% of the light scattering was due to particles from 0.5–5 µm. This was consistent with the findings from Heyvaert et al. (2021, 2022) which showed that concentrations of very fine sediment particles (1–4 µm) and the small *Cyclotella* diatom species in Lake Tahoe could explain over 60% of the variance in Secchi depth clarity (2008–2021). Therefore, this study included a focus on particle concentrations and characteristics within the 1–5 µm fraction of the FSP size range.

Particle masses were calculated from SEM-derived estimates of particle size, assuming a prolate spheroid shape and oxide densities associated with their element composition (**Appendix C**). Overall, the relative percentage of particle numbers and mass in the size classes shown for samples from the lake (**Figure 13**), stream (**Figure 14**) and urban sources (**Figure 15**) show that as size class increases the particle numbers decrease and the average particle mass increases.

The stream and urban samples are quite similar in their range of relative distributions among the size classes. The urban samples show a slightly larger range for percentage number distribution at the smaller size classes. The stream samples show a larger range for the percentage mass distribution at the largest size class. Lake samples differ from both the stream and urban samples with a wider range of percentage particle concentrations in most size classes (0.5–1, 1–2, 2–3, 3–4, 4–5, and 5–10 µm).

The size class percentage medians for particle numbers and mass were grouped into discrete sets to represent three specific size ranges of interest (**Table 7**). Most of the particle mass over the 0.5–20 µm range is associated with the larger particle classes from 5–20 µm, while most of the concentration for number of particles is associated with the smaller particle classes 1–5 µm (with similar percentages in the 0.5–1 µm fraction).

Table 7. Average of group medians from each size class shown in Figures 12–13.

	Particle Number (percent of total)			Particle Mass (percent of total)		
	0.5–1 µm	1–5 µm	5–20 µm	0.5–1 µm	1–5 µm	5–20 µm
Lake (n=41)	36.8%	52.4%	10.7%	0.4%	17.3%	81.9%
Stream (n=25)	48.6%	48.4%	3.1%	1.1%	23.7%	75.3%
Urban (n=19)	43.5%	52.4%	4.1%	0.9%	25.1%	74.2%

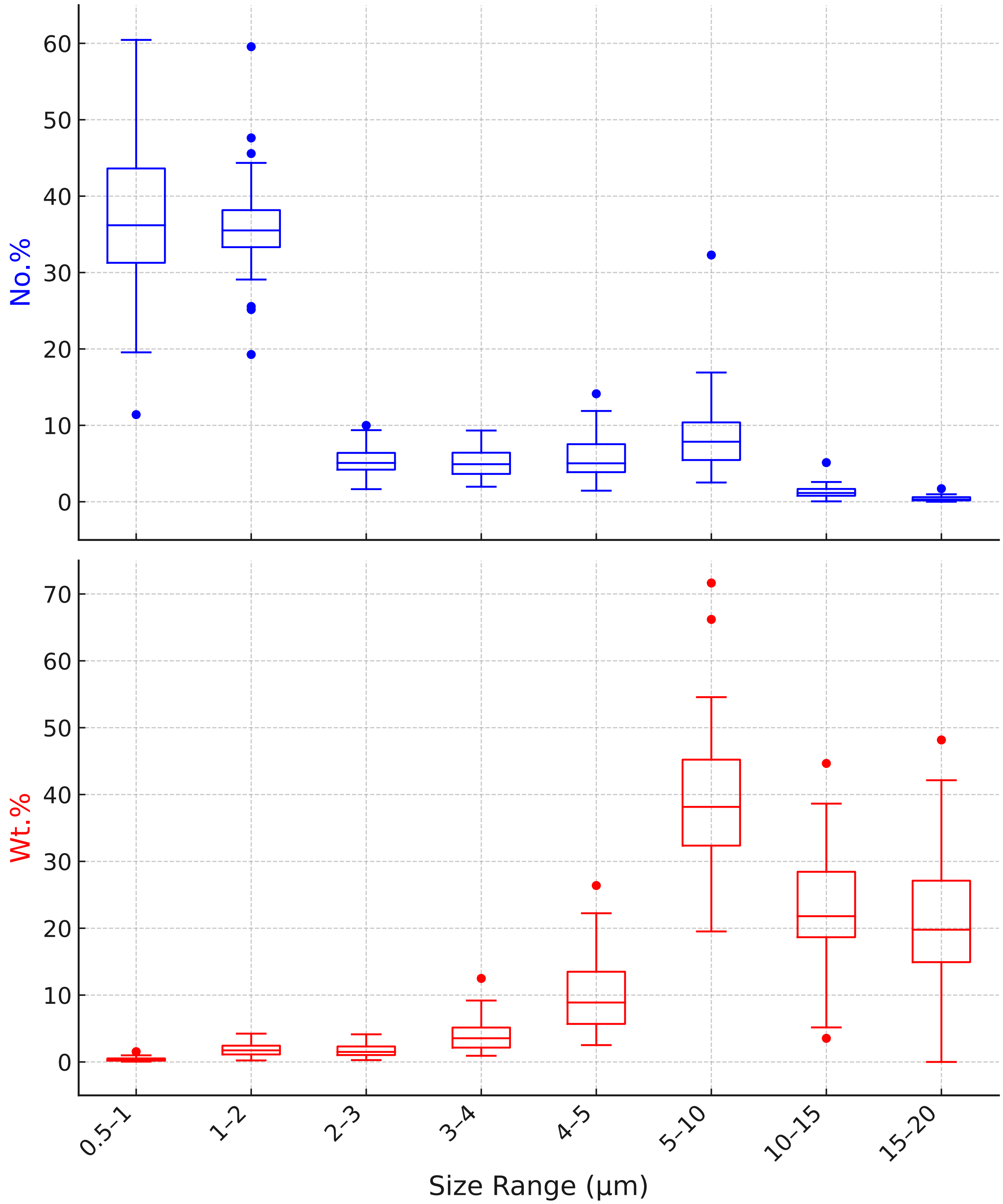


Figure 13. Boxplots of Lake samples analyzed by SEM for particle size distributions. The top panel shows the range of relative distribution for particle numbers (No.%) in eight size classes from 0.5–20 µm from all lake samples shown in Appendix A. The bottom panel gives equivalent information in Wt.%. Boxplot features are as described in Figure 11.

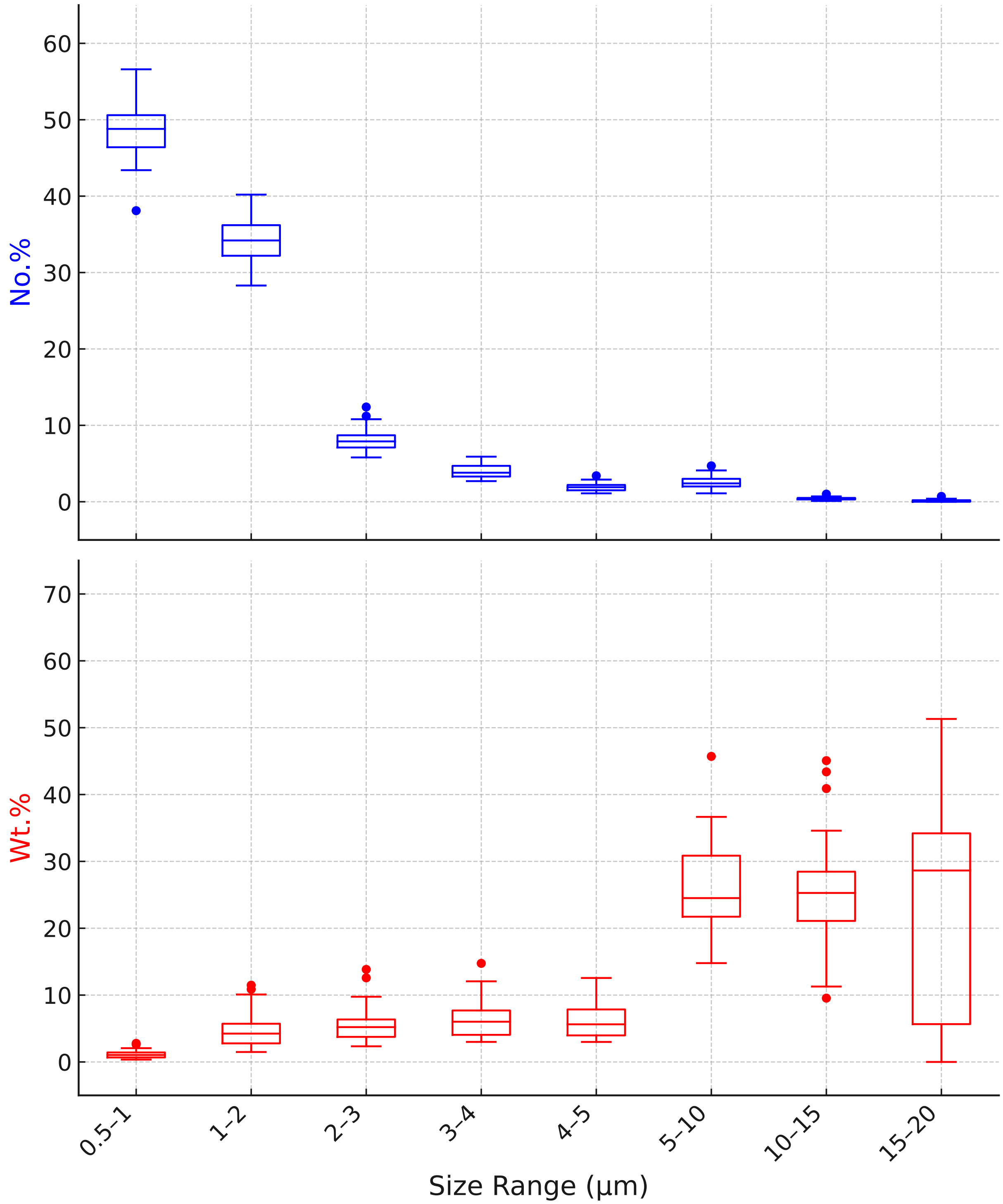


Figure 14. Boxplots of Stream samples analyzed by SEM for particle size distributions. The top panel shows the range of relative distribution for particle numbers (No.%) in eight size classes from 0.5–20 µm from all lake samples shown in Appendix A. The bottom panel gives equivalent information in Wt.%. Boxplot features are as described in Figure 11.

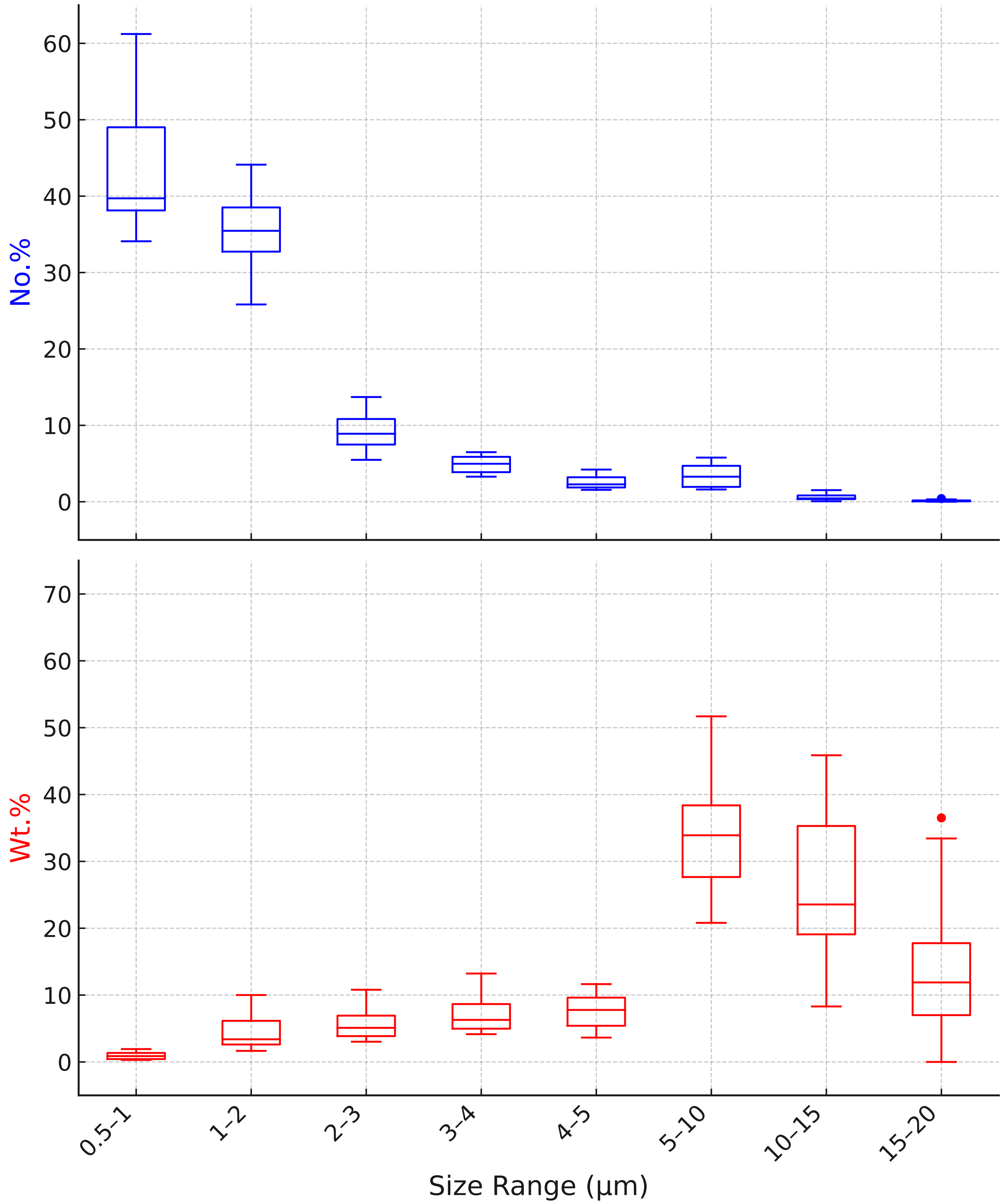


Figure 15. Boxplots of Urban samples analyzed by SEM for particle size distributions. The top panel shows the range of relative distribution for particle numbers (No.%) in eight size classes from 0.5–20 µm from all lake samples shown in Appendix A. The bottom panel gives equivalent information in Wt.%. Boxplot features are as described in Figure 11.

The measurement of total suspended sediment mass cannot serve as a direct surrogate for estimating particle numbers in the 1–5 µm size range, unless it is accompanied by a corresponding estimate of volumetric particle distributions for that fraction or reasonable estimates of the average particle densities within that size fraction. Ultimately, CCSEM-EDS data could provide average particle densities within discrete groups as a function of their individual size, shape, and element compositions.

Particle Element Percentages by Source

Relative concentration of elements detected in each particle are given terms of their percentage composition for Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn and C. These results are summarized from sample averages for all particles from 1–5 µm in each of the three sample sources (**Figure 16**).

Carbon is the dominant element (48%) in lake samples for this size range, whereas silicon dominates in the stream (41%) and urban (46%) samples. Carbon remains a major contributor to percentage composition in the stream and urban samples, however, comprising 29% and 25% on average in samples from each of these sources, respectively. Notably, estimates of carbon concentrations may vary somewhat based on particle topography, size and thickness, since the electron beam can penetrate extremely small, thin particles and detect some carbon in the underlying polycarbonate filter. This may occur, for example, with the smallest of diatoms in lake samples, given the somewhat porous nature of their frustules.

Carbon is the dominant element in very fine lake particles, while silicon is the dominant element in very fine particles from stream and urban sources.

Aluminum is a major component of element composition for particles from both stream and urban samples (17% each) but does not contribute as much to the lake particles (4%). This is likely because the diatoms that dominate in the silica-rich fraction do not contain aluminum, unlike the silica-rich feldspar particles common to stream and urban samples, as discussed in the next section.

Iron, calcium, and magnesium are relatively common in particles from all sources but occur at lesser concentrations, representing their contribution from common rock-forming minerals in the Tahoe basin. Percentage compositions for sodium, potassium and sulfur were elevated above 1% average for samples from urban sources, which was not the case for lake and stream samples. Phosphorus was present at about 2% average for particles from lake samples in the 1–5 µm size range, but not above 1% in the stream and urban samples.

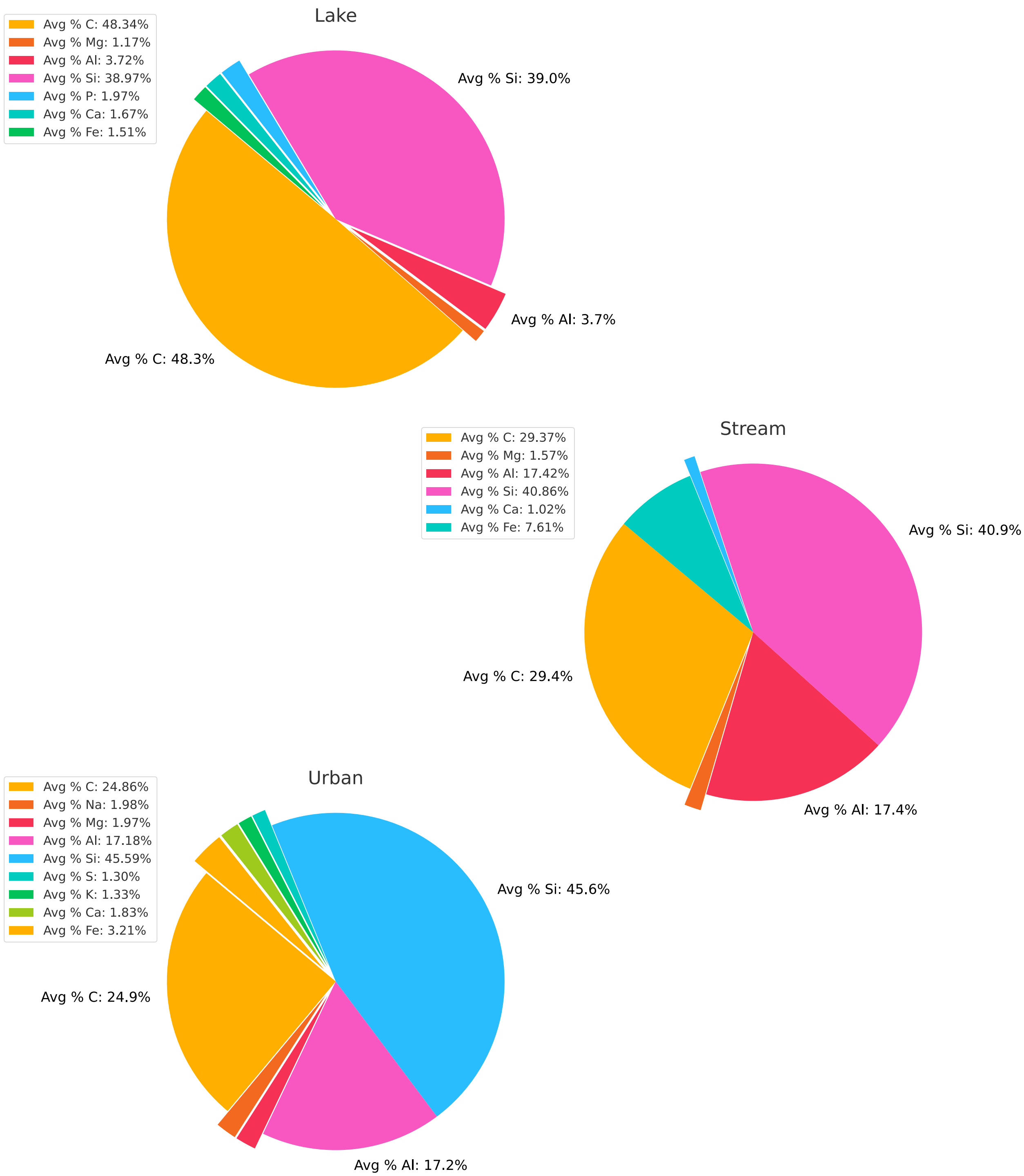


Figure 16. Pie chart distributions of average percent element composition for particles from 1–5 µm in samples from lake, stream and urban runoff sources analyzed by SEM-EDS. Silicon, carbon and aluminum are the dominant elements for particles from each source. Lake samples include phosphorus, calcium, iron and magnesium. Stream samples include iron, magnesium and calcium. Urban samples contain iron, sodium, magnesium, calcium, potassium and sulfur. Elements present at <1% average composition in this size range are not shown (e.g. Ti, Cr, Cu, Zn, etc.)

Although titanium was often detected in particles from all three sample sources, it remained at relatively low concentrations, with an average in the lake, stream and urban source particles of 0.24%, 0.15% and 0.44%, respectively. Other elements commonly associated with anthropogenic activities like copper, zinc and nickel were occasionally present in sample particles but represented less than 0.01% of the average composition across all sources.

Characterization of Particle Types

Particles detected in this study comprise a range of element compositions that reflect characteristics derived from geological, biological, and anthropogenic processes. The abundance of silicon and aluminum concentrations indicate the prevalence of natural materials, while the presence of carbon reflects contributions from biological and perhaps anthropogenic sources. Certain classes of element associations would be expected from natural weathering and erosion of soils as well as from autochthonous production of diatoms and other organisms in the lake and streams, and from contributions of terrestrial vegetation fragments and anthropogenic materials.

The 400-mile long Sierra Nevada Batholith, within which Lake Tahoe is located, consists primarily of Jurassic–Cretaceous era granitic intrusive rocks, with granodiorite being the most abundant (Burkins et al. 1999). Bedrock in the Tahoe Basin is mainly granodiorite, along with some quartz diorite, diorite and gabbro are also present in smaller quantities (Burnett 1971, Saucedo 2005). Mineral composition of granodiorite samples from the Fallen Leaf quadrangle were described by Burnett (1971) as consisting of plagioclase feldspar (43–55%), quartz (15–32%), potassium feldspar (10–20%), biotite (6–15%), hornblende (1–8%), and augite (0–0.35%). Diorite and gabbro had similar mineral distributions but with less quartz and more hornblende but no K-feldspar or augite.

Tertiary volcanism in the north and northwestern areas of the Tahoe basin produced some rhyolite ashflow tuffs, extensive mudflow breccias, and lava flows of andesite, basalt and latite (Kortemeir et al. 2018, Burnett, 1971). The typical minerals include the alkali feldspars (Na-K), calcic plagioclase (anorthite), olivine, augite, and hornblende Saucedo 2005). Interestingly, geologic-scale lake-level changes produced sedimentary rocks from lacustrine sediments in some of the paleo-shoreline areas that now contain Late Pliocene to Early Pleistocene diatomaceous strata (Kortemeir et al. 2018).

The composition of particles from sample sources in this SEM-EDS study are expected to exist as common oxides. Given the geology of parent and soil materials in the Lake Tahoe basin, as described above, one would expect the following minerals to be prevalent:

- Quartz (SiO_2)
- Feldspars (and their intermediate compositions, Na–Ca, Na–K):
    - Na-rich plagioclase ($NaAlSi_3O_8$, albite endmember)
    - Ca-rich plagioclase ($CaAl_2Si2O_8$, anorthite endmember)
    - Potassium feldspar (KAl_2Si2O_8, orthoclase endmember)
- Olivine (magnesium iron silicate, $(Mg,Fe)_2SiO_4$)
- Biotite (phyllosilicate, $K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$)
- Hornblende (Ca-amphibole group, $Ca_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$)
- Augite (a pyroxene, $(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$)
- Diatoms (amorphous SiO_2, contemporary production and Pleistocene deposits).

The various classes shown in **Figure 17** for data from the 1–5 μm particles generally correspond with these expectations.

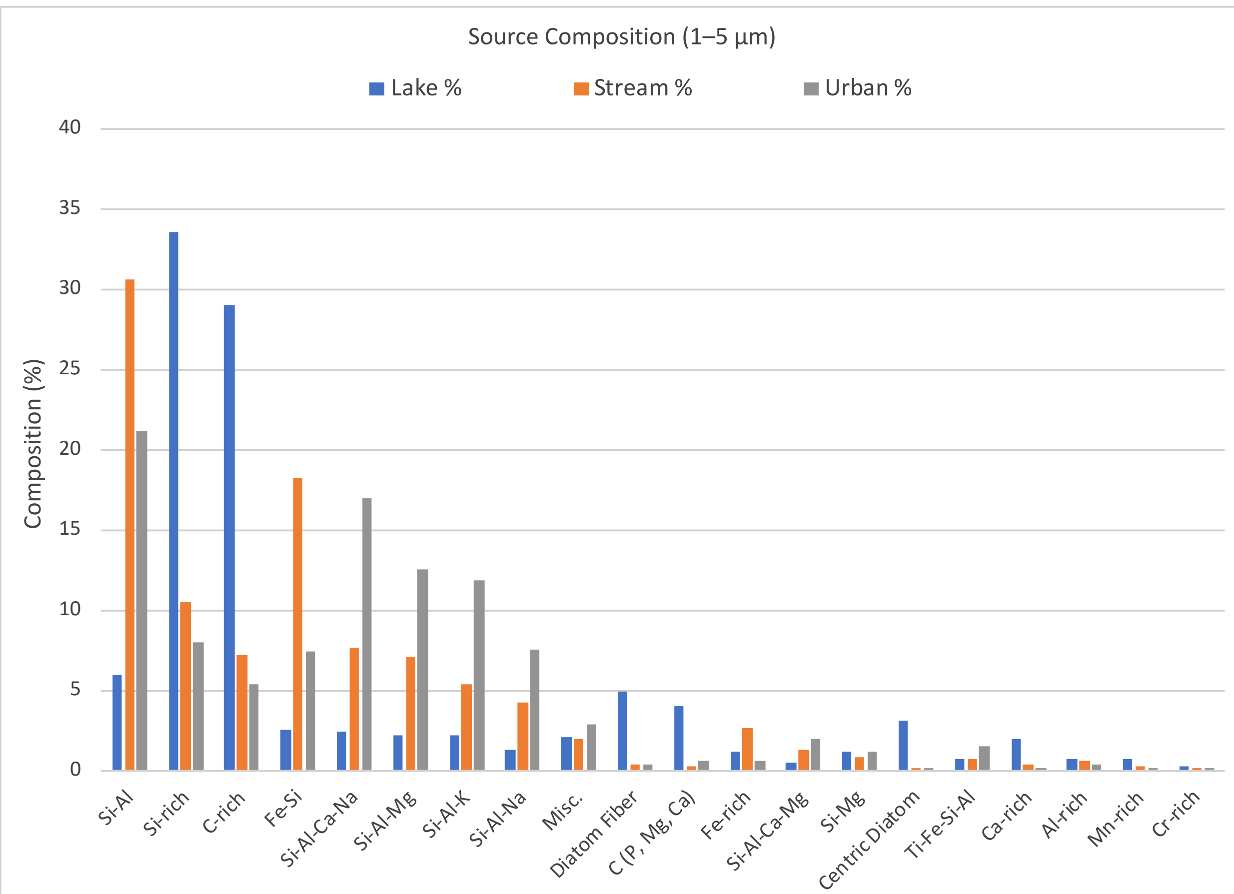


Figure 17. Relative presence of different compositional particle types from lake, stream and urban runoff sources. Some fraction of silicon-rich particles in the lake samples shown here probably include diatoms, which were not adequately distinguished by computer-controlled SEM-EDS image analysis of particle shape and subsequent category assignment.

The aluminosilicate class (Si-Al) dominates overall, likely representing products of silicate mineral weathering (e.g. kaolinite). This is the dominate class in stream source samples.

The silica-rich particles are usually quartz grains (SiO_2), although silica-rich particles in the lake samples also include significant numbers of diatoms that were not appropriately distinguished by the computer-controlled SEM-EDS image analysis of particle shape (roundness) and the subsequent automated category assignment.

Carbon-rich particles were most common in the lake, as expected given autochthonous production of organisms here. However, C-rich particles were also present at significant quantities in the stream and urban runoff samples. This was previously observed in Tahoe basin roadside dust samples where on average the organic carbon was 34%, elemental carbon was 8%, aluminum was 3%, and silicon was 12% of the mass on the PM10 and PM2.5 filters (Dolislager et al. 2012).

The iron-silica class of particles may represent an iron-rich endmember of the olivine group, as commonly found in ultramafic volcanic deposits and rhyolites. Whereas the silica-magnesium class may represent magnesium-rich endmember of the olivine group.

The Si-Al-Ca-Na class best represents element composition ranges within the plagioclase feldspar mineral series, as does the Si-Al-Na class. The Si-Al-K class of particles is more closely related to orthoclase feldspars. Taken together these presumptive feldspar classes dominate the particle types found in urban source samples.

Diatoms are represented by both a fiber-shaped class (e.g. fragments from *Asterionella* spp.) that includes some diatom fragments, as well as by the centric-shaped class (e.g. *Cyclotella* spp.) Diatoms are most common in lake samples, although the numbers would be much higher with appropriate classification by the automated CCSEM-EDS program. A post-analysis manual screening of images with samples L-19 and L-21, for example, increased total diatom counts by 7-fold (689%) and decreased the number of particles in the Si-rich class by about 75%. Additional fine-tuning of the automated classification would improve performance but post-process manual screening is an option that can be made relatively efficient as well.

Particle Image Examples

The following set of high-quality field emission SEM (FESEM) images shown in **Figure 18** represent several of the characteristic types of particles identified in source samples used to develop **Figure 17**.

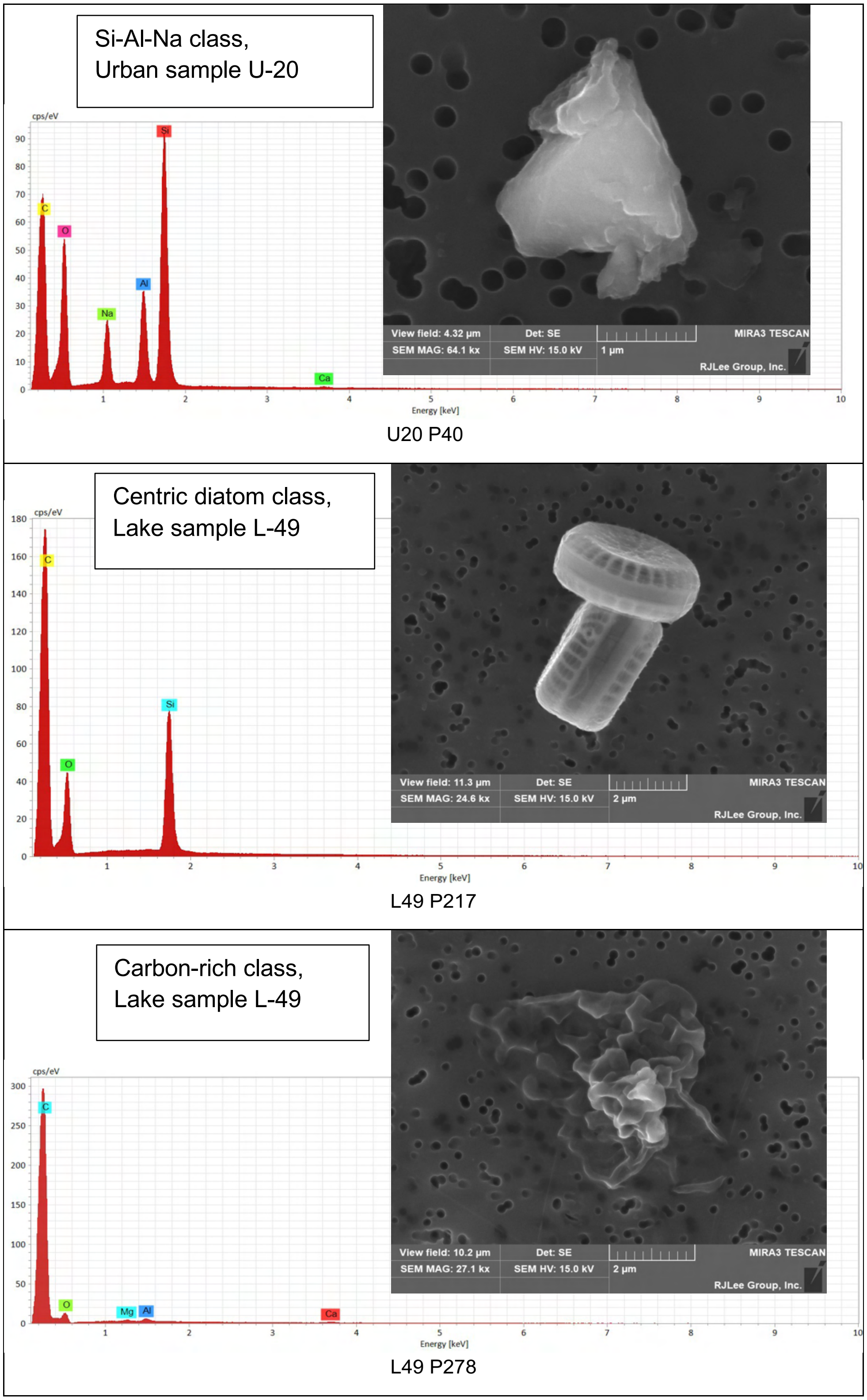


Figure 18. Field emission SEM images of common particle classes from lake, stream and urban runoff sources.

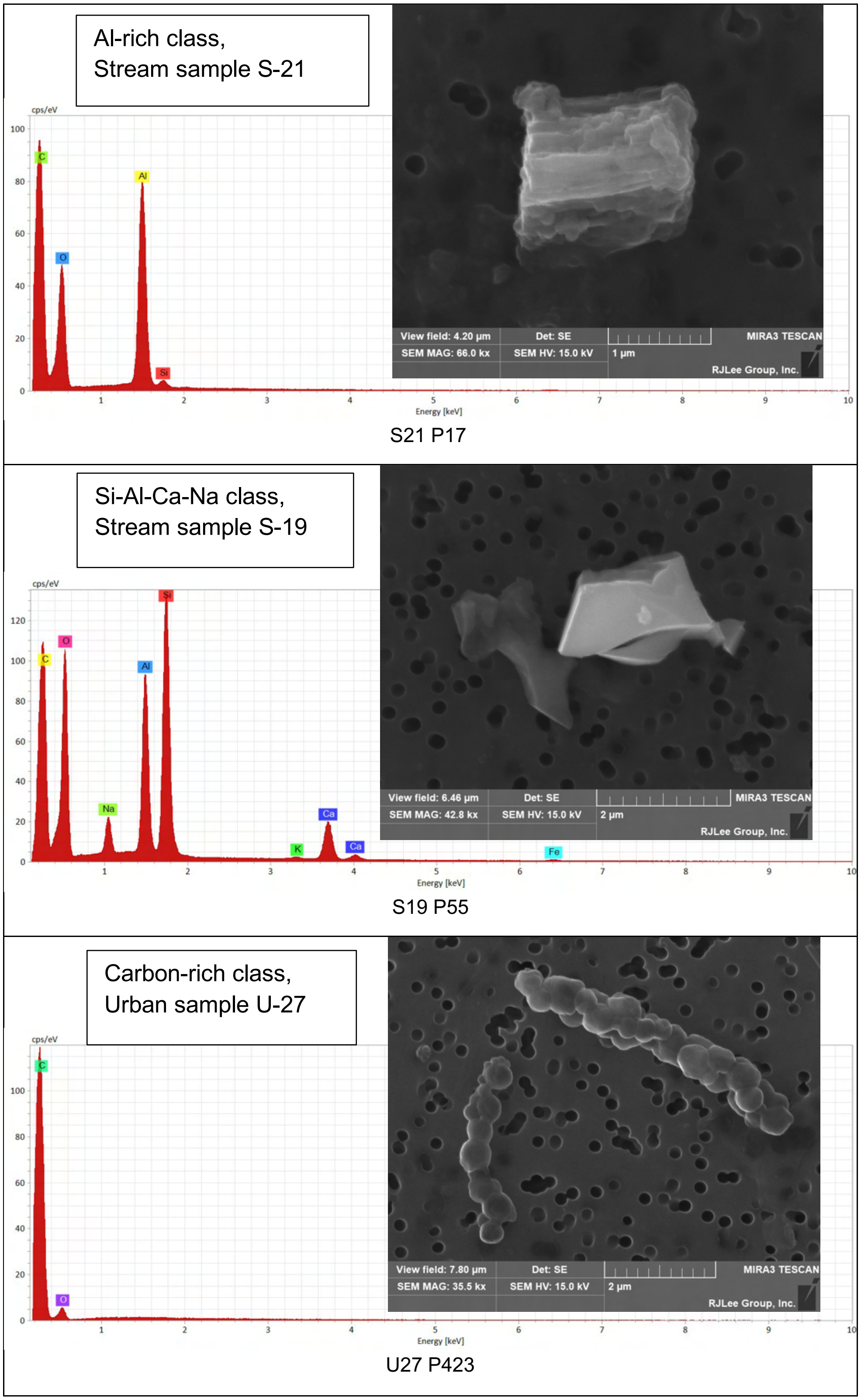
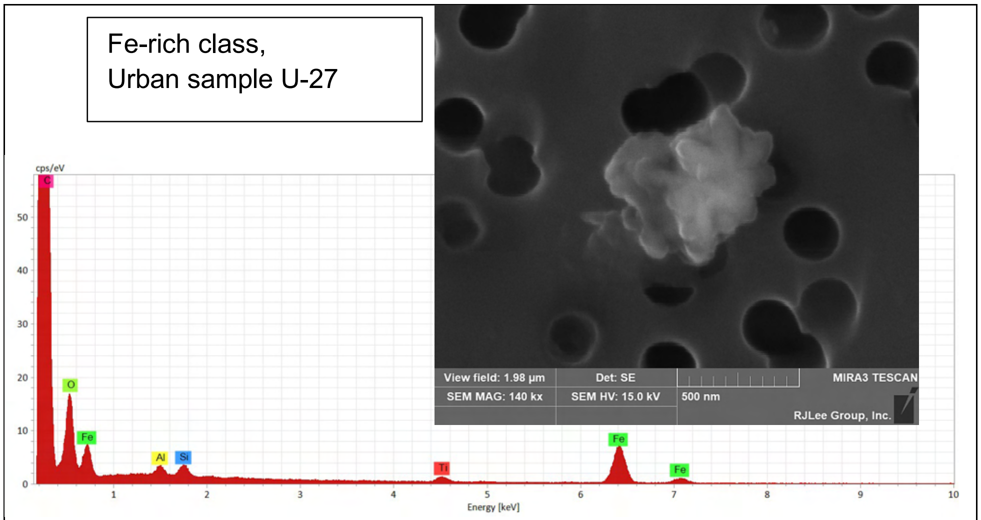
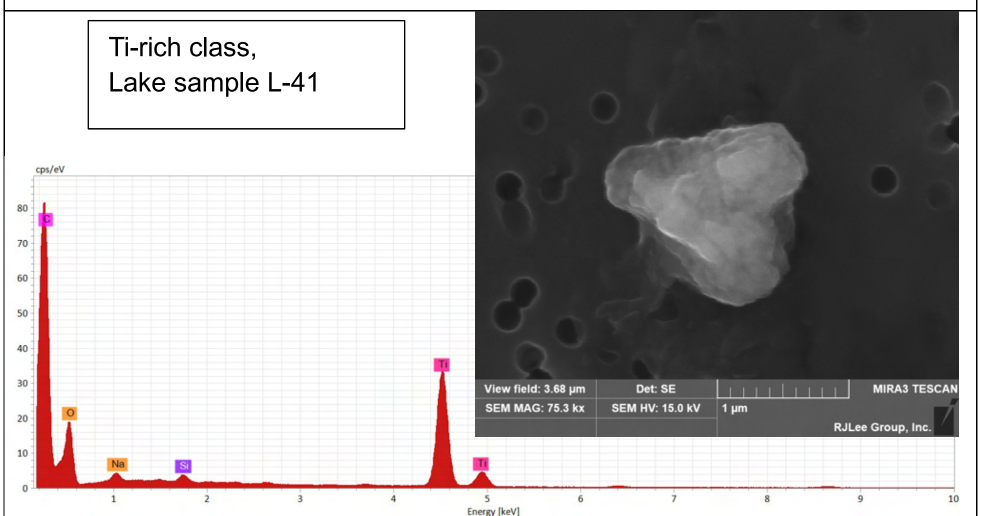


Figure 18, continued. Field emission SEM images of common particle classes from lake, stream and urban runoff sources.



U27 P598



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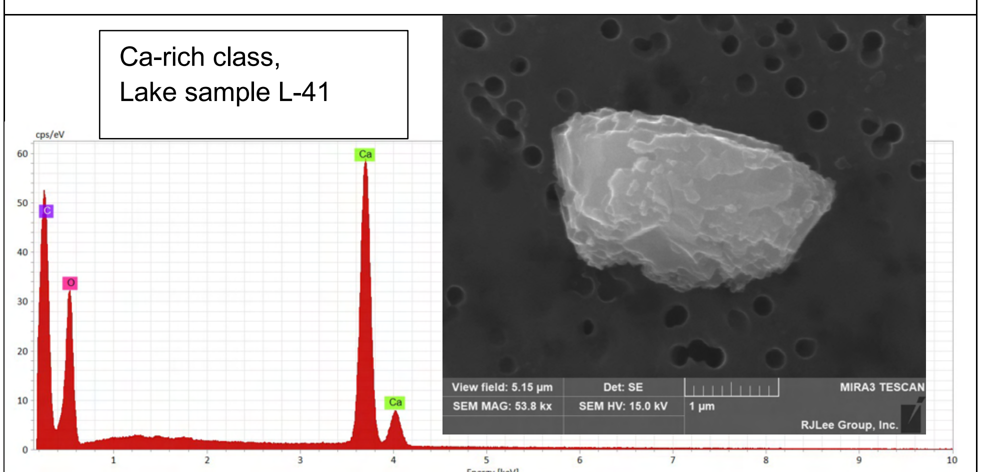

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Figure 18, continued. Field emission SEM images of common particle classes from lake, stream and urban runoff sources.

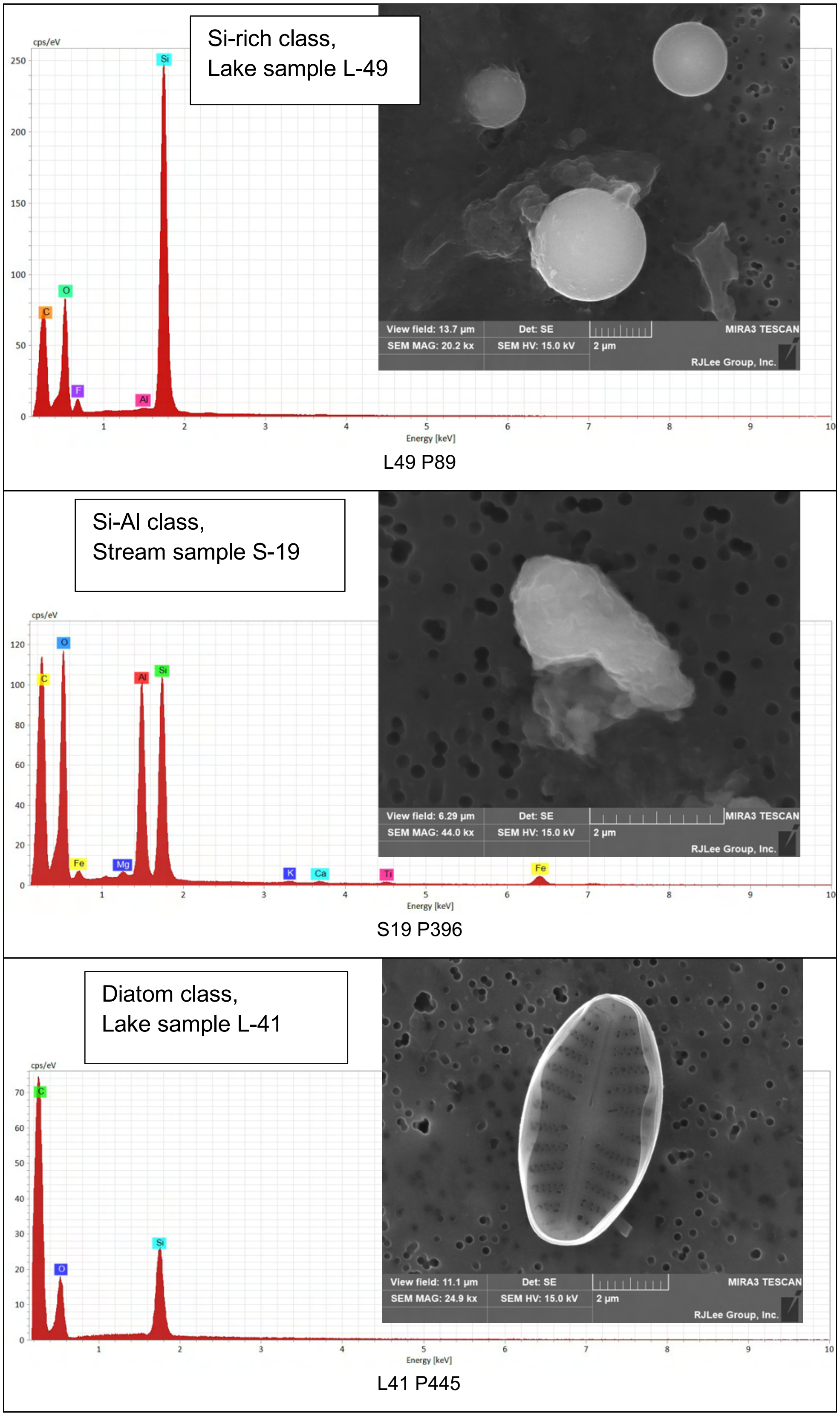

Figure 18, continued. Field emission SEM images of common particle classes from lake, stream and urban runoff sources.

Conclusions

Reduced loading of fine sediment particles (FSP <16 μm) is the primary focus of the Tahoe TMDL program to restore lake clarity. The objective of this Aquatic Particles Project was to use computer-controlled scanning electron microscopy with energy dispersive spectroscopy (CCSEM-EDS) analysis to assess the composition, relative concentrations and sources of fine particles contributing to clarity loss. As a proof-of-concept approach this project examined the characteristics of over 49,000 particles in 85 water samples collected from three source types: the water column of Lake Tahoe, seven watershed tributaries discharging to the lake, and runoff from eight urban stormwater sites flowing to the lake. Analysis of the samples collected from these sites was intended to provide a broad, basin-wide perspective on source-type particle contributions through the application of a uniform method for estimating particle concentrations and evaluating their characteristics.

On average, the median FSP concentrations in samples from urban sites (319,472 particles/mL) were about 13 times greater than the FSP concentration in stream samples (4,138,748 particles/mL). However, it should be noted that upland areas contributing to Tahoe basin streamflow and corresponding runoff volumes are much greater than from the urban landscape.

Median FSP concentrations in the lake estimated by SEM were much lower (5,331 particles/mL) than the stream and urban concentrations; and somewhat less than the concentrations measured at DRI with a LiQuilaz method (7,171 particles/mL).

Measurements of sample turbidity were more closely aligned with LiQuilaz data from lake and stream samples and with the Beckman Coulter laser diffraction data from urban samples than were the particle concentration data from SEM analysis. Continued refinement of these methods, however, will likely contribute to converging results over time.

The majority of FSP particle mass in lake, stream and urban runoff samples is in the 5–20 μm size range. However, it is the concentration (number) of particles that has the greater effect on clarity, and the majority of particles from all three sources are in the 1–5 μm size range.

Most of the particle mass in samples from all three sources was within the large size categories: 74–82% of particle mass was in the 5–20 μm range, compared to 17–25% of mass in the 1–5 μm size range. Particle concentrations, however, were predominately represented within smaller size classes: 48–52% of particles were in the 1–5 μm range, compared to 3–11% in the 5–20 μm range. Since the main factor contributing to Secchi depth clarity is the *number* of particles within a 1–5 μm range, one cannot simply use total mass of FSP captured or retained on the landscape as a metric for progress toward clarity restoration. Such data must always be adjusted for particle volumetric distributions across size classes.

Aluminosilicate and feldspar particles dominate in the 1–5 µm size range of stream and urban samples, followed by silica-rich particles (e.g. quartz). Silica-rich particles also make up about 34% of that 1–5 µm fraction in lake samples but automated CCSEM-EDS routines did not adequately distinguish diatoms (amorphous silica) from the mineral silica particles in these samples. Notably, post-analysis review of Si-rich particles in a test set of two lake samples decreased their representation in that class by about 75% when particles were correctly reclassified as diatoms.

Carbon-rich particles were common in the lake, as expected given biological production and accumulation there. However, C-rich particles were also present at significant quantities in the stream and urban runoff samples. Ultimately, although CCSEM-EDS analysis of these particles is useful for general classification purposes, the definitive identification of biological and C-rich particles requires more expertise.

The main advantage of using CCSEM-EDS for analysis of sample particle sizes, concentrations, and characterization lies in the large numbers of particles individually identified, imaged and measured for their size and composition. Additional fine-tuning of classification methods would improve performance, along with some post-process reviewing that can be done more efficiently with practice. This could be particularly useful for samples from the water column within Secchi depth ranges as part of routine lake monitoring.

Further research on methods that improve the characterization of particle size, composition and source estimates across lake, stream and urban stormwater samples will support the coordinated efforts toward lake clarity restoration.

Although this project was designed to give a broad proof-of-concept perspective on the use of CCSEM-EDS for particle characterization, further work could be done to assess other factors, such as the differences between specific sampling sites from streams and urban areas as well as distinctions associated with seasonal runoff periods and different lake depths. Continued application of this and related analytic approaches would yield improved results for particle class identifications and source characteristics, as well as better concentration estimates and important visual information not available by other methods.

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Appendix A

Particle concentrations from lake (L), stream (S), and urban runoff (U) samples analyzed on SEM filters, prescreened at 20 µm. Effective volumes filtered are the amount passed through a 0.2 µm nucleopore filter (35 mm effective diameter) to yield sufficient particles with adequate dispersion and minimal overlap for automated SEM counting purposes.

Sample	SEM 0.5–20 µm (#/cm^2)	SEM 0.5–15 µm (#/cm^2)	SEM 1.0–15 µm (#/cm^2)	SEM 1.0–5 µm (#/cm^2)	Volume Filtered (mL)	Conc. 0.5–20 µm (#/mL)	Conc. 0.5–15 µm (#/mL)	Conc. 1–15 µm (#/mL)	Conc. 1–5 µm (#/mL)
L-01	137,216	136,981	76,107	66,793	117.5	11,235	11,216	6,232	5,469
L-02	55,583	55,439	26,630	22,976	200	2,674	2,667	1,281	1,105
L-03	19,833	19,494	15,616	8,195	200	954	938	751	394
L-04	113,733	113,382	68,679	59,222	25	43,769	43,635	26,431	22,791
L-05	219,364	219,364	117,267	107,227	200	10,553	10,553	5,641	5,158
L-06	231,038	230,015	159,029	126,039	100	22,228	22,130	15,300	12,126
L-07	260,442	258,483	173,181	145,196	200	12,529	12,434	8,331	6,985
L-08	120,235	119,096	74,909	61,247	50	23,136	22,917	14,414	11,785
L-09-RP	112,583	112,465	73,104	61,184	50	21,663	21,641	14,067	11,773
L-10	51,929	51,929	37,985	29,393	100	4,996	4,996	3,655	2,828
L-11	66,149	66,149	50,405	40,850	100	6,364	6,364	4,849	3,930
L-12	82,776	82,370	56,481	48,354	200	3,982	3,962	2,717	2,326
L-13	185,130	183,712	117,303	95,140	100	17,812	17,675	11,286	9,153
L-14	35,740	35,469	23,703	18,226	200	1,719	1,706	1,140	877
L-15	77,808	77,047	53,502	45,781	200	3,743	3,706	2,574	2,202
L-16	83,859	83,756	43,088	38,691	200	4,034	4,029	2,073	1,861
L-17	108,058	107,861	60,724	54,034	200	5,198	5,189	2,921	2,599
L-19	151,134	150,917	94,003	81,656	100	14,541	14,520	9,044	7,856
L-21	258,116	258,116	136,232	124,737	100	24,834	24,834	13,107	12,001
L-23	41,637	41,511	36,763	31,284	100	4,006	3,994	3,537	3,010
L-25	223,236	222,761	146,017	129,080	400	5,369	5,358	3,512	3,105
L-27	74,832	74,358	51,429	42,648	400	1,800	1,789	1,237	1,026

Sample	SEM 0.5–20 µm (#/cm^2)	SEM 0.5–15 µm (#/cm^2)	SEM 1.0–15 µm (#/cm^2)	SEM 1.0–5 µm (#/cm^2)	Volume Filtered (mL)	Conc. 0.5–20 µm (#/mL)	Conc. 0.5–15 µm (#/mL)	Conc. 1–15 µm (#/mL)	Conc. 1–5 µm (#/mL)
L-29	99,430	98,924	67,357	48,642	400	2,392	2,379	1,620	1,170
L-31	78,880	78,665	43,627	38,942	100	7,589	7,568	4,197	3,747
L-33	67,078	66,951	42,676	36,699	100	6,454	6,441	4,106	3,531
L-35	130,056	129,993	51,376	47,912	100	12,513	12,507	4,943	4,610
L-37	90,297	90,297	42,282	37,937	100	8,688	8,688	4,068	3,650
L-39	47,232	46,909	34,189	26,431	400	1,136	1,128	822	636
L-41	48,978	48,745	30,083	24,994	400	1,178	1,172	724	601
L-42-Rev	141,798	141,551	82,685	71,202	190	7,180	7,168	4,187	3,605
L-43-Rev	230,496	229,883	119,003	108,832	220	10,080	10,053	5,204	4,759
L-44-Rev	77,587	77,120	52,419	40,519	190	3,929	3,905	2,654	2,052
L-45-Rev	122,432	121,894	74,369	64,370	220	5,354	5,331	3,252	2,815
L-46	128,528	128,171	79,856	66,086	220	5,621	5,605	3,492	2,890
L-47-RP	103,839	103,291	72,143	58,983	220	4,541	4,517	3,155	2,579
L-48-RP	64,526	64,049	42,896	35,872	190	3,267	3,243	2,172	1,816
L-49	90,095	89,434	60,798	50,803	190	4,562	4,529	3,079	2,573
L-50	84,828	84,574	50,600	44,370	210	3,886	3,875	2,318	2,033
L-51	59,232	59,032	30,466	26,574	210	2,714	2,705	1,396	1,217
L-52-RP	110,630	110,257	76,678	70,213	200	5,322	5,304	3,689	3,378
L-53-RP	111,878	111,728	70,610	61,763	200	5,382	5,375	3,397	2,971
S-01	595,425	594,866	282,795	269,382	5	1,145,732	1,144,657	544,161	518,351
S-02	552,046	552,046	276,786	261,805	5	1,062,262	1,062,262	532,598	503,771
S-03	281,613	281,193	145,423	141,501	5	541,887	541,078	279,826	272,280
S-04	179,260	179,260	96,047	89,996	5	344,937	344,937	184,815	173,173
S-05	392,429	391,326	211,886	201,077	5	755,122	752,999	407,716	386,918
S-06-RP	423,293	423,293	239,422	228,503	25	162,902	162,902	92,140	87,938
S-07-RP	649,923	647,285	336,449	310,076	25	250,120	249,105	129,481	119,331
S-08-RP	281,095	280,431	136,490	131,309	25	108,178	107,923	52,527	50,534

Sample	SEM 0.5–20 µm (#/cm^2)	SEM 0.5–15 µm (#/cm^2)	SEM 1.0–15 µm (#/cm^2)	SEM 1.0–5 µm (#/cm^2)	Volume Filtered (mL)	Conc. 0.5–20 µm (#/mL)	Conc. 0.5–15 µm (#/mL)	Conc. 1–15 µm (#/mL)	Conc. 1–5 µm (#/mL)
S-09-RP	714,049	713,768	342,089	330,597	25	274,798	274,690	131,651	127,229
S-10-RP	777,475	776,453	418,588	389,973	25	299,208	298,814	161,091	150,079
S-11	206,247	204,722	114,053	103,043	5	396,865	393,931	219,464	198,279
S-12	166,026	166,026	102,764	100,362	5	319,472	319,472	197,741	193,119
S-13	331,953	331,362	169,470	161,393	5	638,753	637,616	326,099	310,556
S-14	126,738	126,396	66,436	62,583	5	243,873	243,214	127,837	120,424
S-15	1,207,168	1,206,630	617,563	602,491	12.5	929,146	928,731	475,332	463,731
S-16	795,355	794,389	399,707	377,990	50	153,044	152,858	76,913	72,734
S-17	601,879	601,879	306,801	293,529	50	115,815	115,815	59,035	56,482
S-18	951,874	950,946	479,550	456,363	50	183,162	182,983	92,276	87,815
S-19	631,371	631,371	311,754	287,255	50	121,490	121,490	59,988	55,274
S-20	1,096,074	1,094,684	568,017	526,331	50	210,909	210,642	109,299	101,278
S-21	404,812	404,201	175,023	161,796	50	77,895	77,777	33,678	31,133
S-22	1,474,265	1,471,692	702,916	668,824	12.5	1,134,727	1,132,747	541,027	514,787
S-23	604,294	602,025	305,884	279,412	12.5	465,119	463,373	235,436	215,060
S-24	918,971	916,804	507,127	463,794	12.5	707,323	705,655	390,331	356,978
S-25	688,882	686,460	308,101	286,305	12.5	530,225	528,361	237,142	220,366
U-01	363,576	363,344	219,240	205,806	2.5	1,399,203	1,398,311	843,735	792,035
U-02	353,418	352,846	224,382	203,794	1	3,400,281	3,394,779	2,158,808	1,960,726
U-03	355,834	355,481	218,912	194,882	0.5	6,847,050	6,840,250	4,212,366	3,749,978
U-08	269,976	268,858	161,641	148,002	0.625	4,155,958	4,138,748	2,488,266	2,278,309
U-09	302,408	302,174	172,205	158,141	0.625	4,655,214	4,651,606	2,650,884	2,434,384
U-10	1,083,370	1,082,282	502,642	470,525	0.625	16,677,192	16,660,433	7,737,570	7,243,166
U-11	319,333	319,333	193,605	184,818	1.25	2,457,875	2,457,875	1,490,155	1,422,529
U-16	1,795,517	1,794,604	846,202	811,493	0.625	27,639,837	27,625,776	13,026,261	12,491,961
U-17-RP	1,443,226	1,443,226	730,167	697,382	5	2,777,092	2,777,092	1,405,005	1,341,920
U-18-RP	831,206	828,611	523,058	492,565	5	1,599,429	1,594,435	1,006,481	947,806

Sample	SEM 0.5–20 µm (#/cm^2)	SEM 0.5–15 µm (#/cm^2)	SEM 1.0–15 µm (#/cm^2)	SEM 1.0–5 µm (#/cm^2)	Volume Filtered (mL)	Conc. 0.5–20 µm (#/mL)	Conc. 0.5–15 µm (#/mL)	Conc. 1–15 µm (#/mL)	Conc. 1–5 µm (#/mL)
U-19	2,762,227	2,762,227	1,423,892	1,345,920	0.625	42,521,181	42,521,181	21,919,114	20,718,826
U-20	2,107,538	2,106,368	1,081,752	1,041,966	5	4,055,379	4,053,127	2,081,535	2,004,978
U-21	557,493	556,449	342,653	317,593	2.5	2,145,484	2,141,466	1,318,684	1,222,241
U-22	836,903	834,734	322,368	304,298	2.5	3,220,779	3,212,434	1,240,619	1,171,077
U-23	1,304,937	1,304,228	710,896	682,507	0.625	20,087,950	20,077,024	10,943,395	10,506,383
U-24	1,553,627	1,553,627	784,091	756,870	0.625	23,916,235	23,916,235	12,070,146	11,651,113
U-25	504,827	503,803	331,703	294,838	0.625	7,771,208	7,755,444	5,106,172	4,538,685
U-26	960,799	959,946	595,736	532,620	0.625	14,790,358	14,777,228	9,170,638	8,199,045
U-27	530,114	529,642	347,109	313,090	1.25	4,080,237	4,076,601	2,671,661	2,409,820

Appendix B

LTIMP Relationship between Turbidity and FSP Concentration

The U.S. Geological Survey has monitored discharge and collected discrete water-quality (QW) samples from seven tributaries in the Lake Tahoe Basin since the 1970's under the Lake Tahoe Interagency Monitoring Program (LTIMP). The goal of LTIMP is to assess suspended-sediment concentration (SSC) and nutrient inputs to Lake Tahoe from these watersheds. The USGS and the University of California-Davis (UCD) began analyzing these QW samples for fine-sediment particles (FSP) in 2002. This yields the number of particles per milliliter across 13 particle size bins from 0.5 to 16 µm. Real-time turbidity sensors were added to California LTIMP surface water gages in 2015 water year (WY, October to September), and Nevada LTIMP surface water gages in 2019 WY. At each gage, turbidity is measured using a YSI model 6136 turbidity sensor. The 6136 Turbidity Sensor has a range to 1,000 FNU and a reported accuracy of 0.3 FNU. Values of turbidity below 0.3 or above 1,000 are censored.

Continuous data (turbidity and discharge) are sampled at 15-minute intervals. These data are aligned with the QW collection time and averaged over the prior hour. All variables are log-transformed, then a multiple linear regression model is developed using WY as categorical variable and turbidity and discharge to predict Log(FSP). The continuous FSP predictions are bias corrected after log-transformation back to native units (number of particles per milliliter). This is a relatively recently method for relating turbidity to FSP concentration that the USGS has developed and continues to refine for improved estimation of FSP concentrations and loads in LTIMP streams.

RSWMP Relationship between Turbidity and FSP Concentration

Since the inception of the Regional Stormwater Monitoring Program (RSWMP) in water year 2014, each urban monitoring location has been equipped with an FTS-DTS in-situ continuous turbidimeter. To calculate estimated FSP concentration from continuous turbidity for a given period of flow, generally a storm runoff event, an equation established by 2NDNATURE (2NDNATURE 2014) has been applied to every 5 minute turbidity reading. The estimated FSP concentrations and associated flow volumes are then used to calculate an estimated FSP load for that runoff event. Additionally, a composite water sample made from individual samples collected across the hydrograph is analyzed for FSP concentration and a corresponding event FSP load is calculated by multiplying the resulting concentration by the flow volume for the period of flow. A comparison of loads using these two methods for the same period of flow often results in vastly different load values, which suggests that some changes in methods may be warranted.

The equations outlined in 2NDNATURE 2014 are not site specific, they are generalized for each quadrant of Lake Tahoe for each month of the year. Developing site-specific rating curves relating the turbidity sensor readings to discrete FSP concentrations could contribute to a better estimation of FSP loads from in-situ turbidity. This would require paired in-situ turbidimeter readings and measured FSP concentrations from individual samples to create, over time, site-specific regression curves in line with USGS practices. Creating this relationship would improve the quality of load estimates for FSP and justify maintaining the in-situ turbidimeters at each site. Over the longer term there may be a cost savings, if fewer samples need to be analyzed for both particle size distribution and suspended sediment mass (as SSC or TSS) to derive the FSP loads in terms of mass and number of particles per milliliter.

Creating site-specific relationships relating turbidity to FSP concentration would improve FSP load estimates and justify maintaining in-situ turbidimeters at each monitoring site.

Appendix C

Element atomic masses (u) and assumed oxide densities (g cm^{-3}) for the corresponding elements detected by SEM-EDS. Oxide densities were applied proportional to atomic percentages of particle element composition with particle dimensions determined by SEM imaging and volumes conforming to a prolate spheroid.

Element	Atomic Mass	Oxide Density (g/cm^3)
Na	22.990	2.54
Mg	24.305	3.58
Al	26.982	3.97
Si	28.085	2.29
P	30.974	2.30
S	32.070	1.96
Cl	35.450	3.49
K	39.098	2.23
Ca	40.080	3.25
Ti	47.867	4.36
Cr	51.996	5.21
Mn	54.938	4.96
Fe	55.840	5.37
Ni	58.693	6.67
Cu	63.550	6.20
Zn	65.400	5.61
C	12.011	1.80