Impacts of Pavement Condition on Fine Sediment Particle Load in Roadway Stormwater Runoff

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ABSTRACT: Pavement deterioration has not been recognized as a major source of fine sediment particles (FSP) that should be mitigated to help improve the clarity of Lake Tahoe. This study investigated impacts of asphalt pavement condition on FSP loads in roadway stormwater runoff in South Lake Tahoe. Stormwater samples were collected before and after pavement rehabilitation. Pavement condition index was improved from 29 (poor) to 99 (excellent) after the rehabilitation. Samples were analyzed for elements and organic markers (e.g., hopanes) to determine the contributions of FSP from major sources using a chemical mass balance model. Volume weighted mean concentrations and annual loads of FSP declined from 53.1 mg/L to 8.57 mg/L and from 293 kg to 36.7 kg, respectively, equivalent to 756 Lake Clarity Credits per 1 km^2 of pavement. Before pavement rehabilitation, pavement wear was the primary source of FSP in stormwater runoff. Volume weighted mean concentration of FSP from pavement wear, native surface soil, and traction abrasives declined from 22.4 mg/L to 2.12 mg/L, from 17.5 mg/L to 3.65 mg/L, and from 9.23 mg/L to 0.76 mg/L, respectively, indicating that pavement condition improvement should be considered for water quality management to restore the extraordinary clarity of Lake Tahoe.

KEY WORDS: Fine sediment particles, Source apportionment, Stormwater runoff, Pavement condition, Lake clarity credit

SYNOPSIS

Pavement condition improvement significantly reduced fine sediment particles in stormwater runoff and should be considered for water quality management in order to restore Lake Tahoe clarity.

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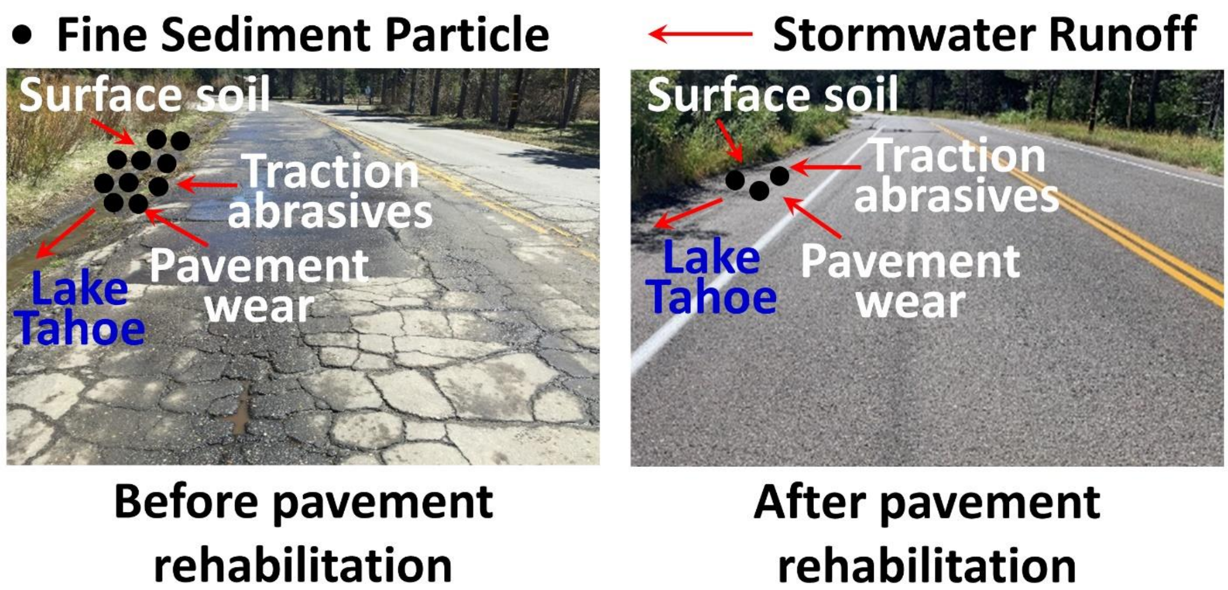

Fine Sediment Particle
Stormwater Runoff
Surface soil
Traction abrasives
Pavement wear
Lake Tahoe
Surface soil
Traction abrasives
Lake Tahoe
Pavement wear
Before pavement rehabilitation
After pavement rehabilitation

INTRODUCTION

Lake Tahoe, an alpine lake in the Sierra Nevada of the U.S., was designated as an Outstanding National Resource Water under the federal Clean Water Act's Antidegradation Policy because of its world-famous crystal-clear water. However, lake clarity has declined significantly over the last several decades (Figure S1). Secchi depth, a measure of water clarity, was nearly 30 meters when it was first measured in 1968 but has decreased to approximately 18 meters in 2020. One of the main reasons is an increase of fine sediment particles (FSP) smaller than 16 μm that account for 67% of the light scattered or absorbed in the Lake Tahoe water column.[1,2] To restore Lake Tahoe's historic water transparency to 30 meters by 2076, the Lake Tahoe Total Maximum Daily Load (TMDL) was adopted in 2010.[3]

Stormwater runoff from urban uplands was estimated to account for approximately 70% of the total FSP entering Lake Tahoe[3], suggesting that a reduction in FSP input from roadway runoff is a critical mitigation strategy for improving Lake Tahoe's famed clarity. In the last two decades, traction abrasives have received special attention as a dominant source of FSP in roadway stormwater runoff, and many efforts have been made by municipal jurisdictions in the Lake Tahoe Basin.[4, 5] For example, El Dorado County has reduced annual traction abrasive application by 60% since the early 2000s (Figure S2).[6] Additionally, traction abrasives (e.g., Washoe sand) are washed by the vendor prior to sale to remove FSP.[6] Despite these efforts, significant reductions in FSP loads in stormwater runoff and significant improvement of Lake Tahoe clarity have not been fully observed over the last 20 years (Figure S1), indicating that sources other than traction abrasives contribute a large fraction of the FSP in roadway stormwater runoff.

Previous studies found that asphalt pavement wear accounted for 20-25% of FSP in stormwater runoff collected from a site in the Lake Tahoe Basin.[7] Heavy machinery such as snow plows and rotary snow blowers equipped with steel cutting edges are expected to produce large amounts of FSP because they damage the asphalt pavement surface during removal of snow and ice from roads (Figures S3 and S4). However, the impacts of pavement surface condition on FSP loads in stormwater runoff have not been fully investigated in the Lake Tahoe Basin. As a result, both States of California and Nevada and local agencies have not considered generation of FSP from pavement deterioration and its impact on water quality as a factor in evaluating cost-effectiveness of road asset maintenance strategies or crediting associated with the Tahoe TMDL.

This study collected stormwater runoff samples from Elks Club Drive in South Lake Tahoe, California before and after the placement of new asphalt overlay to investigate the impacts of pavement condition improvement on FSP loads from major sources, including pavement wear, traction abrasives, natural soil from sidehills, and vegetation debris. A significant reduction in FSP in stormwater runoff was anticipated after the pavement rehabilitation through less contribution from pavement materials and less accumulation of traction abrasives in cracks from deteriorating pavement.

MATERIALS AND METHODS

Study Site. The County of El Dorado, California, USA installed new asphalt overlay (1.3 km) on Elks Club Drive in the summer of 2018 to improve road sweeping efficiency and reduce air pollution and stormwater pollution. This road surface rehabilitation provided an ideal opportunity to investigate the effects of pavement condition improvement on FSP load reduction in stormwater runoff. Reducing FSP loads is one of the objectives of the Lake Tahoe Environmental Improvement Program to restore the environmental health of Lake Tahoe.[8] Elks Club Drive is identified as a major collector road that traverses a residential neighborhood connecting Pioneer Trail to State Highway 50 in south of the City of South Lake Tahoe (Figure S5). Prior to completion of the overlay, pavement condition index (PCI) of Elks Club Drive was determined based on visual surveys of the types and severity of distresses on the pavement surface. PCI is a numerical value, ranging from 0 to 100, that represents the worst and best possible pavement conditions, respectively.[9] The pavement condition of Elks Club Drive was poor (Figure S6) with the PCI of 29 before placement of the new asphalt overlay. Significant portions of the pavement were covered in cracks and potholes. After the placement of the asphalt overlay, the pavement condition was changed to excellent with the PCI of 99 (Figure S6).

Total lengths of Elks Club Drive that contributed runoff to the sampling stations were 580 m and 520 m in years 1 (2017-2018) and 2 (2018-2019), respectively. The total width of Elks Club Drive was 10.4 m and 11.3 m in years 1 and 2, respectively. The tributary width includes pavement, shoulders on both sides of the pavement, and a ditch on the north side of the road. A pavement surface slope survey indicated that 70% of stormwater runoff ran toward the northern side where the sampling station was installed. Five side streets that feed into Elks Club Drive also contributed runoff to the sampling stations. The total length and width of the side streets that contributed runoff were 1.27 km and 9.1 m, respectively. Road rehabilitation was not performed on the side streets, and thus, surface area and pavement condition of the side streets were virtually equivalent in both years.

Sample Collection. Stormwater runoff samples were collected before (year 1: between October 2017 and May 2018) and after (year 2: between October 2018 and May 2019) pavement rehabilitation. Stormwater runoff samples were collected during 7 and 12 events in years 1 and 2, respectively (Table 1). Only runoff produced by precipitation was collected. Runoff produced by snowmelt was not collected because it was too clean for particle analysis. Snowmelt runoff is defined as runoff produced by melting snow accumulated on adjacent sidehills and/or emerging groundwater.

Automated sampling stations were installed in the drainage ditch on the north side of Elks Club Drive (Figure S7). The locations of the sampling stations in year 1 and year 2 were slightly different. In year 2, the sampling station was moved 60 m east of the point used in year 1. A Tracom (Atlanta, GA, USA) Palmer Bowlus fiberglass flume instrumented with a pressure transducer to measure water level, an FTS (Victoria, BC, Canada) DTS-12 digital turbidity sensor, and a Teledyne (Lincoln, NE, USA) ISCO 6712 automated sampler were installed in the drainage ditch. Stormwater runoff samples were collected using the ISCO sampler in twenty-four 1 L bottles. The ISCO sampler was programed to fill one bottle every 8,500 L or 14,200 L across the entire hydrograph for each runoff event sampled depending on the size of the storm. Sample collection duration, which is time between the first sample and the last sample, of each event ranged from 6 hours to 135 hours. Water level and turbidity of the runoff were measured on site every 5 minutes from October 1 to September 30 in both years. Water levels were converted to flow rates using an equation provided by flume manufacturer.

Source samples, including native surface soils and vegetation debris from hillside, traction abrasive, and pavement cores were collected for chemical analysis. Atmospheric dry deposition was not collected for this study. Trace element concentrations measured in atmospheric dry deposition samples collected previously at a site close to Elks Club Drive were adopted for this study.[7] The previous study reported that local atmospheric dry deposition accounted for less than 3% of FSP load in roadway stormwater runoff.[7]

Table 1. FSP concentrations (mg/L) in roadway stormwater runoff collected from Elks Club Drive before (year 1) and after (year 2) pavement condition improvement.

Year 1		Year 2	
Collection date	Concentration	Collection date	Concentration
11/15/2017	27.8	11/23/2018	3.21
1/6/2018	70.9	11/27/2018	8.52
3/13/2018	19.1	1/16/2019	5.45
3/20/2018	79.2	1/20/2019	9.42
4/6/2018	60.5	2/2/2019	12.1
5/24/2018	297*	2/13/2019	8.94
5/25/2018	26.9	3/5/2019	3.06
		3/27/2019	21.0*
		4/2/2019	9.35
		4/8/2019	6.40
		5/16/2019	1.70
		5/26/2019	1.54
Arithmetic mean	47.4	Arithmetic mean	6.34
Standard deviation	25.9	Standard deviation	3.60
Volume weighted mean	53.1	Volume weighted mean	8.57

*Outliers. Arithmetic mean concentrations were calculated without outliers.

Separation of Fine Sediment Particles. Stormwater runoff samples collected in plastic bottles were transported to the laboratory and passed through a stainless sieve (20 μm) to remove particles greater than 20 μm. Sieved water was combined in glass bottles (4 L) and kept unagitated at room temperature for at least 24 hours to ensure FSP settled to the bottom. A previous study showed that more than 99% of fine sediment particles settled to bottom when kept unagitated for 24 hours.[7] Supernatant was removed using a siphon. The bottom layer, enriched with FSP, was filtered through Whatman (Maidstone, UK) acid treated TCLP filter papers. The filter papers with FSP were dried in an oven (60 °C) for 24 hours and the weight of the filter papers were measured using a balance that can measure to 0.0001 g. A portion of the asphalt core top layer was dissolved in dichloromethane to separate binder and aggregates. Traction abrasive, pavement aggregate, and vegetation debris were gently ground and sieved using a stainless sieve (20 μm) to collect particles smaller than 20 μm. Surface soil from hillside was sieved using a stainless sieve (20 μm) without grinding. The filter papers and the sieved source samples were stored in a freezer (-20 °C) until chemical analysis was performed.

Chemical Analysis. Each glass fiber filter with FSP was split into two or four fractions to be analyzed for trace elements, including aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr) copper (cu), iron (Fe), lead (Pb), nickel (Ni), vanadium (V), and zinc (Zn), in the FSP. A fraction of the filter was placed in a polypropylene bottle (15 mL) and digested using concentrated nitric acid for 24 hours and digested again using hydrogen peroxide for 24 hours to extract trace elements from FSP. Sieved source samples (0.05 g) were also digested using the same procedure. Digested samples were then centrifuged, and an aliquot of supernatant was diluted 5 times using deionized water made by a Milli-Q ultrapure water system before instrumental analysis. Trace elements in the diluted water were analyzed and quantified using Agilent (Santa Clara, CA, USA) 7900 inductively coupled plasma-mass spectrometer.

One or more fractions of each glass fiber filter were placed in a Teflon tube (40 mL) and extracted with 35 mL of dichloromethane on a rotating tumbler for 24 hours and centrifuged at 2,000 rpm for 10 minutes to extract organic markers from the FSP. The top solvent layer was slowly transferred into a glass concentration tube. Extraction with dichloromethane was repeated twice more and solvent extracts were combined and concentrated down to 5 mL of hexane. Asphalt binder in small pieces of pavement was also extracted using dichloromethane and concentrated down to 5 mL of hexane. The other source samples were not extracted using dichloromethane because they don't contain target organic markers. The concentrated extract was filtered through a glass wool packed filter. The final volume of extract was adjusted to 5 mL, and an internal standard (d_{10}-pyrene) was added. Organic markers, including alkanes, hopanes, and steranes, were analyzed using Agilent (Santa Clara, CA, USA) 5977B gas chromatograph-mass spectrometer.

Each sample batch included a procedural blank, a filter paper blank and a sample duplicate. National Institute of Standards and Technology standard reference material (NIST SRM) 2709a (San Joaquin soil for trace element concentrations) was also included in each batch to validate the accuracy of trace element quantification. Recovery rates of trace elements were between 75% and 96% for all measured elements except Al, Cr, Pb, and V. Recovery rates observed in this study were very similar to those reported by NIST.[10]

Chemical Mass Balance Model. The contribution of FSP from each source was estimated using the chemical mass balance (CMB) model (Eq. 1),

$$C_i = \sum_{j=1}^{p} a_{ij} S_j, \; i = 1, n \qquad \text{(Eq. 1)}$$

where C_i is a concentration (mg/L) of a chemical i in stormwater runoff, a_{ij} is a concentration (mg/L) of chemical i in source j, S_j is a mass concentration (e.g., %) contributed by source j, p is number of sources, and n is number of chemicals with $n \geq p$. Concentrations of the organic markers were used to estimate the contribution from asphalt binder and concentrations of the trace elements were used to estimate the contribution from other sources. Although the contribution from tire, brake pad, tire weight balance wear particles was much less than 1%, these also included in the CMB model because these sources are highly enriched with Zn, Cu, and Pb.

RESULTS AND DISCUSSION

Runoff volume. Annual cumulative runoff volumes, including both stormwater and snowmelt, that passed through the sampling station were 11,410 m^3 in year 1 and 10,300 m^3 in year 2. Considering almost the same precipitation depth in both years (61 cm in year 1 and 62 cm in year 2) and a slightly shorter contributing pavement length in year 2 (580 m in year 1 and 520 m in year 2), pavement rehabilitation did not substantially influence total runoff volume. However, when the total runoff volumes were split into stormwater and snowmelt, significant differences were observed between years 1 and 2. Annual cumulative volumes of stormwater runoff were 5,720 m^3 and 3,150 m^3 in years 1 and 2, respectively, and annual cumulative snowmelt runoff volumes were 5,690 m^3 and 7,150 m^3 in years 1 and 2, respectively. This difference is likely attributable to different precipitation patterns between years 1 and 2. Ranges and patterns of ambient atmospheric temperature in year 1 and 2 were very similar. However, precipitation patterns were different. In year 1, about 30% (by volume) of the precipitation occurred between December 1 and March 31, when ambient temperatures are frequently cold enough to produce little to no runoff. In year 2, about 70% (by volume) of precipitation occurred between December 1 and March 31 (Figure S8). This difference in precipitation timing likely explains the 45 % lower stormwater runoff volume and the 25% greater snowmelt runoff volume in year 2.

In most cases, stormwater runoff volume correlates well linearly with precipitation and can be estimated by precipitation depth. However, this relationship in the Tahoe Basin can be influenced by other factors, such as precipitation type (e.g., rain, snow), interevent dry period length, precipitation duration, presence/absence of man-made hillsides (also called cut slopes) or naturally produced hillsides (also called native slopes), and slope and area of hillsides. For example, stormwater runoff volumes can be significantly greater than estimated volumes at a site with hillsides angling toward the road on one or both sides than at a site with no hillsides or hillsides angling away from the road. Hillsides are pervious, so stormwater runoff from hillsides does not start until surface soil on hillsides are saturated by rain. But, when surface soil on hillsides are saturated with rain, stormwater starts to run off the surface and mix with runoff from the road surface. Stormwater runoff from hillsides can also significantly increase FSP load.[7]

Stormwater volumes calculated from precipitation depth may overestimate the contribution from hillsides for events with longer precipitation durations and longer interevent dry periods. When interevent dry periods are longer, surface soils are dryer and it takes longer for runoff to occur. To minimize uncertainties from these factors, the following equation was developed to estimate stormwater runoff volume (V) from precipitation.

$$V = DA \times RF \times P \times C \times e^{-(k1 \times RD)} \times e^{-(k2 \times ID)} \qquad \text{(Eq. 2)}$$

where V is estimated volume (m^3) of stormwater runoff, DA is drainage area (m^2), RF is fraction of runoff that drains toward the side where the sampler was installed, P is precipitation depth (m) for an event, C is runoff coefficient, RD (runoff duration) is time (hour) from start to end of runoff, $k1$ is a constant of runoff duration, ID (interevent duration) is the dry period (days) between the previous and current precipitation events, and $k2$ is a constant of interevent duration. This equation was developed using data collected for the present study. Stormwater runoff drainage area (DA) was calculated by multiplying length and width (pavement plus shoulders) of the roads (Elks Club Drive and side streets) contributing runoff to the sampling stations. Runoff fraction (RF) was determined by identifying the crown of the road and calculating the fraction of surface runoff that would flow into drainage ditches that are connected to the sampling station.

Equation 2 does not incorporate the contribution from the adjacent hillside because it is difficult to estimate stormwater runoff volumes from hillsides that is highly influenced by slope, area, and surface condition of hillsides. Theoretical stormwater runoff volumes estimated using equation 2 were compared to runoff volumes measured at the sampling site to determine the influence of the adjacent hillside. If estimated volume is 2-fold lower than measured volume, it can be inferred that runoff from the adjacent hillside accounts for 50% of the measured runoff volume. When estimated volume to measured volume ratios are compared with precipitation depth, a strong negative correlation is observed in year 1 (Figure 1). This indicates that the contribution of stormwater runoff from the hillsides increased with increasing of precipitation. When precipitation was less than 2.5 cm, estimated to measured volume ratios were greater than 1 in year 1, indicating that the adjacent hillsides was not likely saturated by rain and unlikely

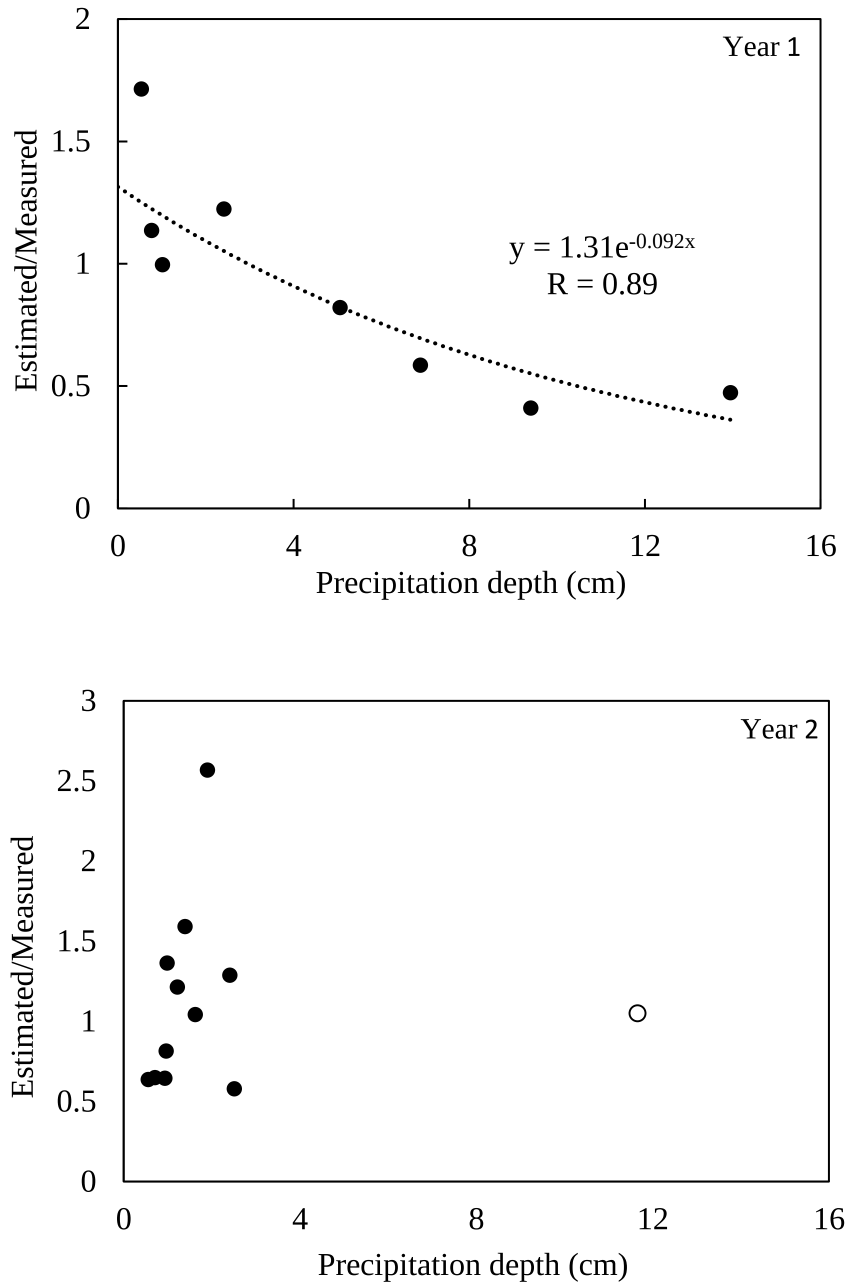

Figure 1. Comparison of estimated to measured stormwater runoff volume ratios and precipitation for stormwater runoff collected before (year 1) and after (year 2) pavement condition improvement. Open circle in year 2 indicates an outlier.

contributed to stormwater runoff measured at the site. But stormwater runoff from the adjacent hillsides accounted for about 50% of total volume when precipitation was greater than 8 cm. This pattern was not observed in year 2 because precipitation was less than 2.5 cm for all events except one.

FSP concentrations and loads. The significantly lower FSP concentrations observed in year 2 clearly show the benefit of pavement condition improvement in reducing FSP load in stormwater runoff. This indicates that pavement condition is an important factor to be included in managing FSP load in stormwater runoff especially in the Lake Tahoe Basin. FSP concentrations in stormwater runoff samples ranged from 19.1 mg/L to 297 mg/L in year 1 and 1.54 mg/L to 21.0 mg/L in year 2 (Table 1). These are within the range of FSP concentrations observed at other sites in the Tahoe Basin.[11] Arithmetic mean FSP concentration was 47.4 ± 25.9 mg/L in year 1 and declined to 6.34 ± 3.60 mg/L in year 2. If values were outside of upper or lower boundaries, they were regarded as outliers and not included in the calculation of arithmetic mean concentrations. The upper and lower boundaries were calculated by adding 1.5 times of interquartile range (IQR) to 75th percentile and subtracting 1.5 times of IQR from 25 percentile, respectively. IQR is the difference between 75th and 25th percentiles. The ANOVA test shows this reduction is statistically very significant ($p < 0.01$).

Volume weighted mean FSP concentration was 53.1 mg/L in year 1 and declined by 84% to 8.57 mg/L in year 2. The volume weighted mean FSP concentrations are 12% and 35% higher than the arithmetic mean concentrations in years 1 and 2, respectively. Arithmetic mean FSP concentration, which is an unweighted mean, may represent the overall FSP concentration less accurately because the FSP concentration for each event is weighted equally regardless of stormwater runoff volume. FSP concentrations in large and small events need to be weighted more and less, respectively, to calculate the overall FSP concentrations accurately.

FSP load delivered by stormwater runoff was calculated by multiplying FSP concentration and stormwater runoff volume of each event. FSP load ranged from 1.36 kg to 105 kg in year 1 and 0.05 kg to 1.08 kg in year 2 (Figure 2). Annual FSP loads calculated by multiplying the volume weighted mean FSP concentrations by annual total stormwater runoff volumes (5.72×10^6 L for year 1 and 3.15×10^6 L for year 2) were 303 kg in year 1 and 27 kg in year 2. For this study, however, stormwater runoff samples were collected for 7 and 12 events in years 1 and 2, respectively, that account for 70% and 50% (by volume) of all stormwater runoff in years 1 and 2, respectively. This means that FSP concentrations were not measured in 30% (year 1) and 50% (year 2) of stormwater runoff and 100% of snowmelt runoff. Therefore, some uncertainties may arise if the FSP concentrations measured from the collected stormwater samples are applied to the rest of the runoff.

As an alternative, FSP concentrations can be estimated using turbidity of stormwater runoff measured on site using digital sensors. Heyvaert et al.[11] compiled the results of the monitoring conducted in the Tahoe Basin between 1992 and 2012 and found that turbidity of stormwater runoff had a strong positive correlation with FSP concentrations expressed in mass (mg/L) and developed the following equation

$$\text{FSP concentration (mg/L)} = 10^{(-k + 1.08 \cdot \text{Log T})} \qquad \text{(Eq. 3)}$$

where *k* is a conversion constant and T is real-time turbidity (NTU) measured on site.

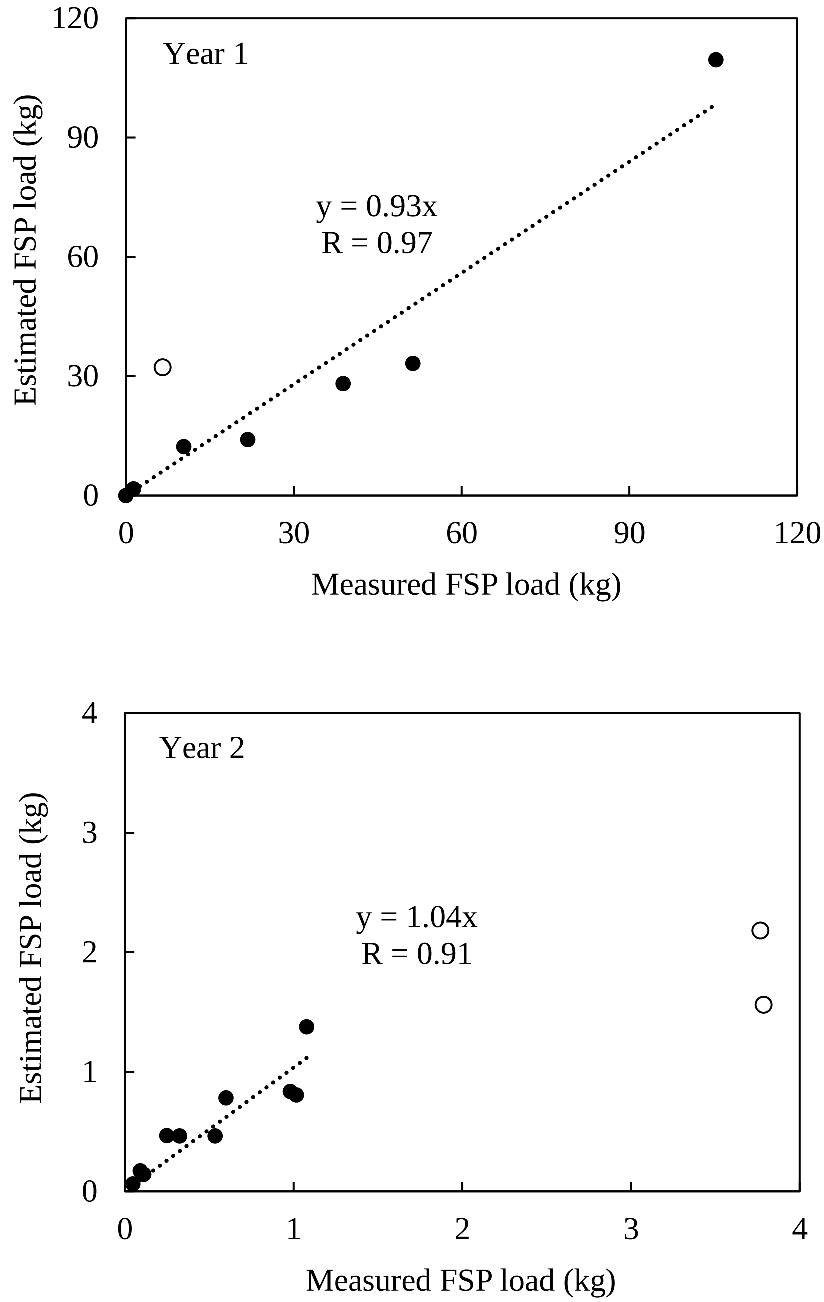

Figure 2. Comparison of measured and estimated FSP loads in stormwater runoff collected before (year 1) and after (year 2) pavement condition improvement. Outliers (open circles) were not included in the regression analysis.

The FSP loads estimated using the real-time turbidity measured every 5 minutes on site were compared to the gravimetrically measured FSP loads in runoff samples (Figure 2). They showed a very strong positive correlation for both years. This indicates that the annual FSP load estimated from continuous turbidity measured in-situ is reliable. For both years, outliers were not included in determining correlation coefficients. In a couple of events, large differences between the measured and the estimated FSP loads were observed (Figure 2). The most likely explanation is unexpected malfunctions of the turbidity sensor and the water flow sensor, which is often seen in continuous field sampling.

The continuous real-time turbidity measured on site was converted to FSP concentrations in stormwater and snowmelt runoff and then multiplied by real-time runoff volume to calculate FSP load, which was added up for the whole year to calculate the annual (October 1-September 30) cumulative FSP loads for years 1 and 2. The estimated annual cumulative FSP load delivered was 293 kg in year 1 and declined by 87% to 36.7 kg in year 2. Annual cumulative runoff volume in year 2 was only 5% less than year 1, indicating that the reduction in annual FSP load was associated with the reduction in FSP concentration in stormwater runoff.

Sources of fine sediment particles. The major sources of FSP in stormwater runoff were pavement materials (aggregates and asphalt binder), native soil, traction abrasives, and vegetation debris. These four major sources, combined, accounted for 96.1 ± 1.4% of the total FSP load in year 1 and 91.7 ± 1.8% in year 2 (Table 2). Pavement condition improvement contributed to significant reduction in FSP load from all these major sources. FSP load from these four sources, combined, declined from 291 kg in year 1 to 24.8 kg in year 2.

Table 2. Sources of FSP in stormwater runoff collected before (year 1) and after (year 2) pavement condition improvement.

	Year 1		Year 2	
	Contribution (%)	VWM* (mg/L)	Contribution (%)	VWM (mg/L)
Natural Soil	33.0 ± 6.8	17.5	42.6 ± 6.7	3.65
Pavement (aggregate + binder)	42.2 ± 9.4	22.4	24.8 ± 5.9	2.12
Traction abrasive	17.4 ± 5.4	9.23	8.9 ± 3.7	0.76
Vegetation debris	3.6 ± 2.4	1.89	15.5 ± 5.5	1.33
Atmospheric deposition	3.0 ± 1.4	1.59	4.9 ± 1.7	0.42
Tire	0.7 ± 0.2	0.37	3.2 ± 2.6	0.27
Engine Oil	0.2 ± 0.0	0.11	0.2 ± 0.0	0.02
Brake Pad and Drum	0.03 ± 0.02	0.02	0.12 ± 0.2	0.01
Lead tire balancing weight	< 0.0001	< 0.00001	< 0.0001	< 0.00001

*VWM: Volume weighted mean concentration

Before pavement rehabilitation, wear of asphalt pavement materials was the primary source of FSP in stormwater runoff. Asphalt pavement materials accounted for 42.2 ± 9.4% of the FSP load in year 1 and declined to 24.8 ± 5.9% in year 2. Changes in contribution percentages do not reflect actual changes in FSP loads from each source because the percentages are relative values. When converted to volume weighted mean concentration, pavement rehabilitation reduced FSP from pavement wear by 91%, from 22.4 mg/L in year 1 to 2.12 mg/L after pavement rehabilitation (Figure 3). Asphalt pavement materials consist of aggregates, which include crushed rocks, natural gravels, and sand-soil mixtures, and an asphalt binder, also known as bitumen, which is a general description for the adhesive or glue that is used to bind the aggregates together in pavements.[12, 13]

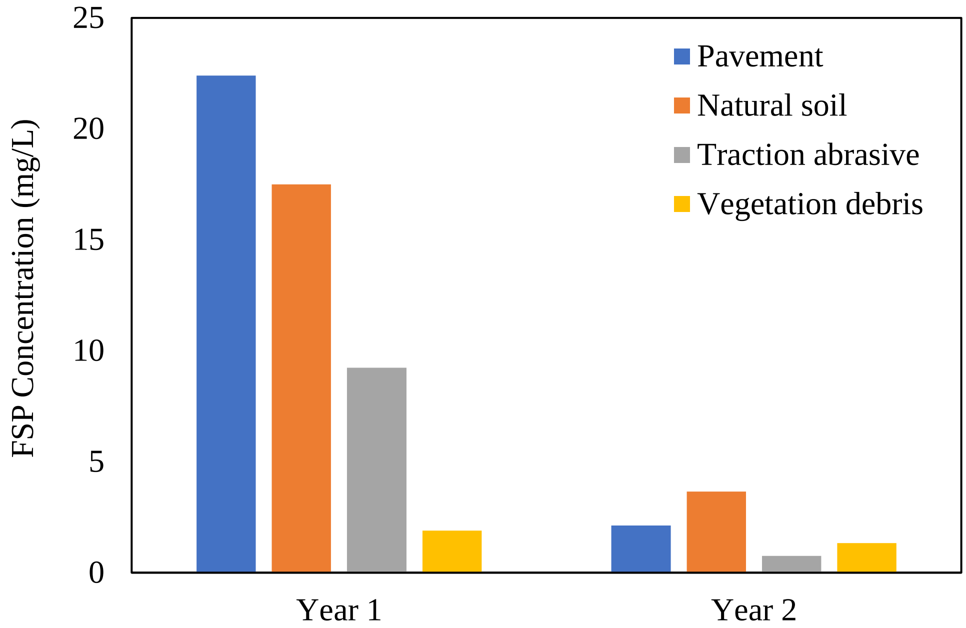

Figure 3. Volume weighted mean concentrations of FSP from major sources before (year 1) and after (year 2) pavement condition improvement.

Asphalt pavements constitute the surface layer of the majority of the roads in the Lake Tahoe Basin. The primary mechanism of FSP generation from the pavement surface is friction between pavement materials and vehicle tires with and without snow chains and steel blades mounted on snow removal equipment such as snow plows and snow blowers. Aging and damage from repeated loading and environmental stresses over time accelerate the release of FSP. As asphalt binder slowly ages, it becomes progressively stiffer and more brittle, and the pavement surface starts losing aggregates and the pavement becomes less durable.[12] Temperature also has an effect on asphalt binder. At low temperatures (e.g., below freezing) commonly observed in winter in the Tahoe Basin, asphalt binder becomes very stiff and less resistant to stresses.[13-15] These changes in the binder characteristics make the pavement surface experience a faster loss of binder and aggregates through weathering and cracking (Figure S9). Snow removal practices also damage the pavement surface substantially (Figures S3 and S4) and accelerate the generation of FSP from pavement materials. So, a greater amount of FSP is likely to be generated from older and more damaged pavements commonly observed in the Tahoe Basin. In El Dorado County, asphalt pavements in poor or fail condition with a PCI of 50 or lower account for more than 50% of all roads (Figure S10), indicating that improvement of pavement in poor or fail condition can significantly reduce FSP loads from pavements.

Percent contribution of traction abrasives was significantly reduced from 17.4 ± 5.4% in year 1 to 8.9 ± 3.7% in year 2. Volume weighted mean concentration of FSP from traction abrasives declined by 92% from 9.23 mg/L in year 1 to 0.76 mg/L in year 2. This reduction in FSP concentration cannot be explained by the amount of traction abrasives applied in years 1 and 2. The total annual amount of traction abrasives applied on the roads in the County of El Dorado were significantly greater in year 2 (450 tons) than in year 1 (318 tons), probably due to more precipitation between December and March in year 2 when the ambient temperatures were often below freezing. Therefore, this reduction in FSP originating from traction abrasives was likely associated with pavement condition improvement. Pavement in poor condition with many cracks and potholes, like Elks Club Drive in year 1, can retain greater amounts of FSP associated with traction abrasives. Additionally, road sweeping is less effective in removal of FSP on pavement in poor condition,[16, 17] so a significant fraction of FSP originating from traction abrasives was likely retained on the pavement and washed off by stormwater runoff in year 1.

Percent contribution of native soil increased from 33.0 ± 6.8% in year 1 to 42.6 ± 6.7% in year 2 after pavement habilitation. Again, this is just a proportional increase and does not mean that the FSP loads originating from native soil increased after pavement rehabilitation, as these are relative percentages. Volume weighted mean concentration of FSP from native soil declined by 79% from 17.5 mg/L to 3.65 mg/L. FSP associated with native soil originates from subgrade and narrow and partially vegetated hillsides with a gentle slope only on the north side of Elks Club Drive. Many roads in the Tahoe Basin have hillsides on one or both sides of roads because roads are constructed through hilly terrain. Road construction in hilly areas removes stabilized topsoil and exposes nutrient-poor subsoil, so cut slopes (man-made hillsides) are typically a bare or partially vegetated surface.[18] Erosion from bare cut slopes was nearly an order of magnitude greater than erosion from native slopes in the Lake Tahoe Basin.[19, 20] A four-year cumulative erosion study in forest cut slopes showed that bare slopes produced 5.5 times more sediment than slopes with native species vegetation.[21] Repeated freeze-thaw cycle is also one of the main disintegrating forces for soil aggregates, resulting in increased soil erosion.[22, 23]

A significant portion of the FSP was also likely originated from subgrade, a layer of compacted roadbed soil underneath of pavement, which can be disturbed by vehicles and winter road maintenance practices (e.g., snow removal). As subgrade is saturated by water and experiences freeze-thaw cycles repeatedly, subgrade loses compaction and becomes less consolidated. FSP contained in subgrade can then be quickly pumped to the pavement surface through cracks and potholes. This study, however, did not quantify the proportion of FSP in roadway stormwater runoff that originated from subgrade because it is difficult to differentiate hillside soil and subgrade using element composition.

Percent contribution of plant debris (e.g., leaves, cones, needles, twigs, stems and foliage of non-woody plants) increased from 3.6 ± 2.4% in year 1 to 15.5 ± 5.5% in year 2 after pavement habilitation. This also does not mean the FSP loads originating from plant debris increased after pavement rehabilitation. Volume weighted mean concentration of FSP from plant debris declined by 30% from 1.89 mg/L to 1.33 mg/L. This is the lowest reduction among the four major sources.

FSP can also be produced from plant debris that has fallen on the pavement surface or hillside. Plant debris on the pavement surface can be pulverized by tire abrasion. If pulverization by tires was the primary source of FSP originating from plant debris, the reduction percentage of FSP from vegetation debris should be similar to the reduction observed in traction abrasives that declined by 92%. The reduction (30%) observed in plant debris means that a much greater portion of FSP originating from plant debris was introduced from the hillside. Plant debris from the hillside can be transformed into FSP through microbial decomposition, mechanical breakdown, and chemical actions. Pavement condition does not influence washoff of FSP originating from plant debris from the hillside.

First Flush Phenomenon. It is common to observe the first flush phenomenon for pollutants in stormwater runoff from urban roadways in excellent/good condition.[24-26] Two different types of first flush phenomenon have been used to describe transport of pollutants by stormwater runoff. Concentration-based first flush can be defined as a disproportionally higher concentrations of pollutants in the early phase compared to the remaining phases of a rain event. Another type of first flush is mass-based first flush that can be defined as disproportionally higher load of pollutants in the early phase. Most groups dealing with FSP in stormwater runoff in the Lake Tahoe Basin prefer to use load rather than concentration. So, this study uses the term load-based first flush (LFF).

LFF can be presented by numerical ratios and/or graphs.[25, 26] The unitless LFF ratios can be calculated by dividing the cumulative fraction of FSP load by the cumulative fraction of runoff volume measured at the same time point. Different numerical cutoffs have been used to determine the presence of the first flush phenomenon. Some studies defined the first flush as an 80% or greater fraction of pollutants transported during the first 20% or 30% of runoff volume, which can be described as an 80/20 or 80/30 first flush.[24, 25] Other studies described the first flush as 50/25 or 40/20.[27] LFF ratios of 80/20, 80/30, and 50/25 are 4.0, 2.7, and 2.0, respectively. For this study, 40/20 or an LFF ratio of 2.0, was used as a cutoff to minimize influence of FSP from hillside on the presence of the first flush phenomenon. Because many roads in the Lake Tahoe Basin have hillsides or cut slopes on one or both sides, FSP from natural surface soil from hillsides or cut slopes can contribute significantly to the FSP load in stormwater runoff. Asphalt pavement is impervious, so stormwater runoff is created shortly after rain starts. However, hillsides are pervious, so stormwater runoff does not start until surface soils on hillsides are saturated by rain, and the contribution of FSP from hillsides is likely delayed compared to the contribution from pavement.

LFF ratios at 20% of runoff volume (LFF_{20} ratios) ranged from 1.07 to 3.97 in year 1 and 0.73 to 2.82 in year 2. The first flush phenomenon was observed more frequently in year 1. Different precipitation patterns in rain events are likely responsible for this wide range of the LFF ratios. The input of FSP from the hillsides can also contribute to the wide range of LFF_{20} ratios. Significantly higher LFF_{20} ratios were observed in year 1 (1.96 ± 1.13) than in year 2 (1.15 ± 0.65) probably because FSP loads from pavement were much higher and the contribution of FSP from hillside soils in the later phase of the rain events was relatively lower in year 1.

The first flush phenomenon can also be presented visually in graphs. The presence of the first flush can be illustrated when a data line representing the dimensionless cumulative FSP load against the dimensionless cumulative of runoff volume is significantly above a theoretical line representing a synchronistic cumulative increase in FSP loads at the same rate as runoff volumes (Figure S11). A data line close to the theoretical line indicates no presence of the first flush.

Lake Clarity Credit. In the Tahoe Basin, FSP reduction in roadway stormwater runoff is converted to Lake Clarity Credit under the TMDL Program's 65-year plan to restore Lake Tahoe's clarity to 33 m.[3] A 100 kg load reduction in FSP is equal to 1.1 credit.[3] Each municipal jurisdiction in the Tahoe Basin is required to earn a specific number of credits each year to meet the lake clarity goal established by TMDL. The results of this study facilitate an estimation of how many credits can be earned when pavements in poor condition are improved. The results of this study indicate that the reduction (256 kg) in annual FSP load from the study site (0.52 km of pavement) is equal to 2.8 credits or 5.4 credits per 1 km of pavement. A pavement surface slope survey indicated that 70% of stormwater runoff ran toward the side where the sampling station was installed. So, when combined with the FSP reduction associated with the remaining 30% of runoff that ran to the other side of the road, this pavement rehabilitation is estimated to provide 7.7 credits per 1 km of pavement in the first year after the pavement rehabilitation. The reduction in FSP load from the new asphalt overlay (1.3 km) installed for this pavement rehabilitation project is equivalent to 10 credits. Further evaluations are required to determine whether earning credit from pavement condition improvement can be blended into the Road Rapid Assessment Method (RoadRAM), a field observation and data management tool that has been implemented in the Tahoe Basin to rapidly assess relative pavement condition of large areas of roads.[28] As the new asphalt pavement ages, FSP loads are expected to gradually increase. But FSP loads from old asphalt pavement are likely to increase at a faster rate as pavement ages. Therefore, the same credit may be used for estimating FSP load reduction for many years following the installation of the new asphalt overlay.

CONCLUSIONS

This study provides clear evidence that pavement condition improvement is highly beneficial in reducing FSP in roadway stormwater runoff, suggesting that pavement condition and FSP load in stormwater runoff need to be included in cost-benefit analyses for pavement asset management. FSP load reduction associated with pavement condition improvement may also help jurisdictions earn Lake Clarity Credits. Until now, the impacts of pavement condition on FSP load in stormwater runoff has not received enough attention and there has been a lack of information robust enough to be used for more accurate cost-benefit analyses. Additional studies are required to determine what pavement condition index should trigger replacement of damaged roads. Effectiveness of sweeping in removing FSP from pavements with different condition indices also needs to be measured to estimate the maximum benefits of pavement condition improvement. Impacts of other factors such as strength of pavement materials (binder and aggregates) and road sweeping frequency on the reduction of FSP loads also need to be studied.

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SUPPORTING INFORMATION

Impacts of Pavement Condition on Fine Sediment Particle Load in Roadway Stormwater Runoff

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Description of Supporting Information

Figure S1. Historical changes in Lake Tahoe clarity. This image was retrieved from the website of Tahoe Environmental Research Center, University of California, Davis (www.terc.ucdavis.edu).

Figure S2. Annual usage of traction abrasives in El Dorado County since the winter of 2001. The dashed regression line represents a gradual decline of abrasive usage at a rate of 52 tons per year. Usage data was retrieved from Wigart and Ferry (2015).

Figure S3. Snow plow equipped with a metal blade (left) and rotary blades mounted on a snow blower (right), operated by El Dorado County to remove snow from roads.

Figure S4. Pavement damage caused by snow plows (left) and rotary blades (right). A mechanical pencil was placed to show the scale of the damage.

Figure S5. Aerial view of the study site and locations of sampling stations.

Figure S6. Pavement condition of Elks Club Drive before (left) and after (right) the installation of new asphalt overlay.

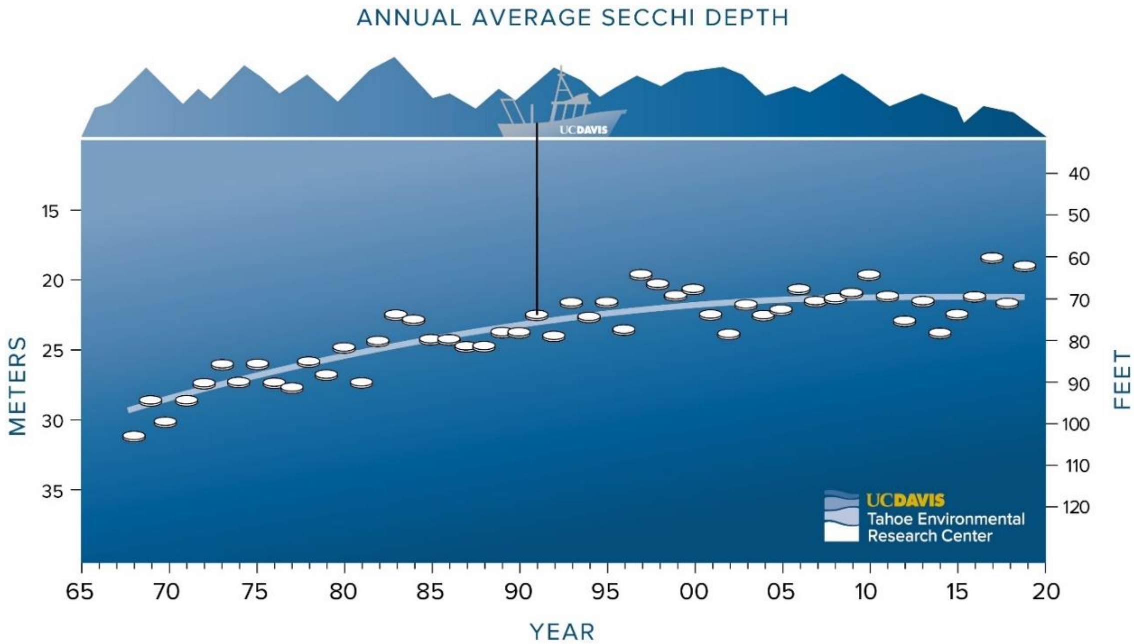
Figure S7. Sampling stations installed on Elks Club Drive for stormwater runoff collection before (year 1, left) and after (year 2, right) pavement rehabilitation.

Figure S8. Daily precipitation (rain and snow) and ambient atmospheric temperature recorded near the stormwater runoff collection site in year 1 (October 1, 2017-July 30, 2018) and year 2 (October 1, 2018-July 30, 2019).

Figure S9. Fatigue cracks (left) and severely enlarged cracks (right) developed on asphalt pavement surface on Elks Club Drive in County.

Figure S10. PCI of residential traffic roads in El Dorado County. Green, light green, orange, and red colors indicate roads in excellent/good (PCI: 70-100), at risk (PCI: 50-70), poor (PCI: 25-50), and failing (PCI: 0-25) conditions, respectively.

Figure S11. Comparison of the cumulative fractions of FSP load and runoff volume in stormwater runoff samples. Dashed line indicates theoretical synchronistic cumulative increases in FSP load at the same rate as runoff volume.



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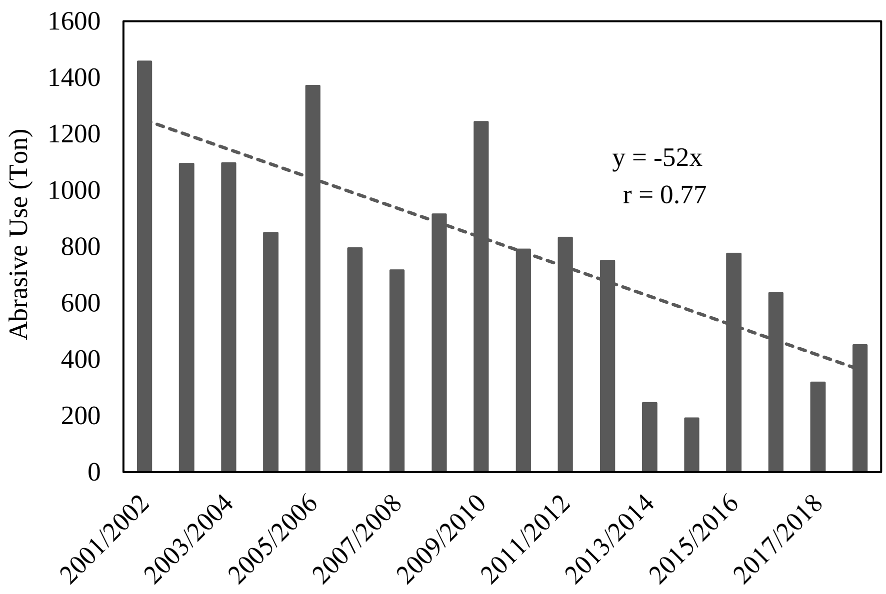

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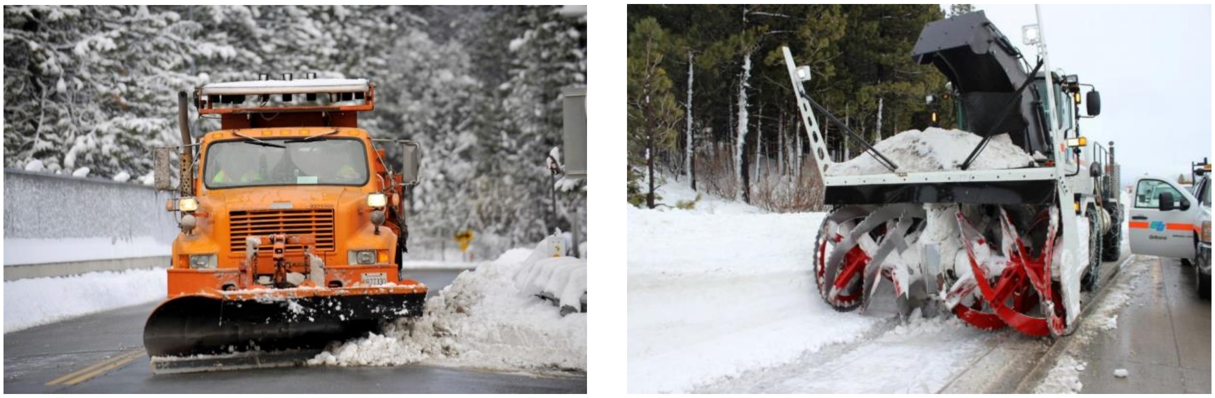

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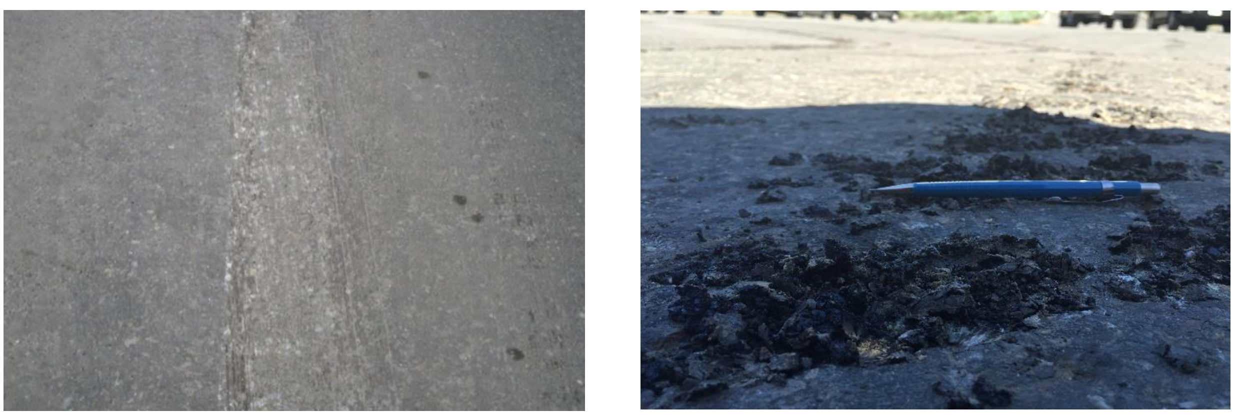

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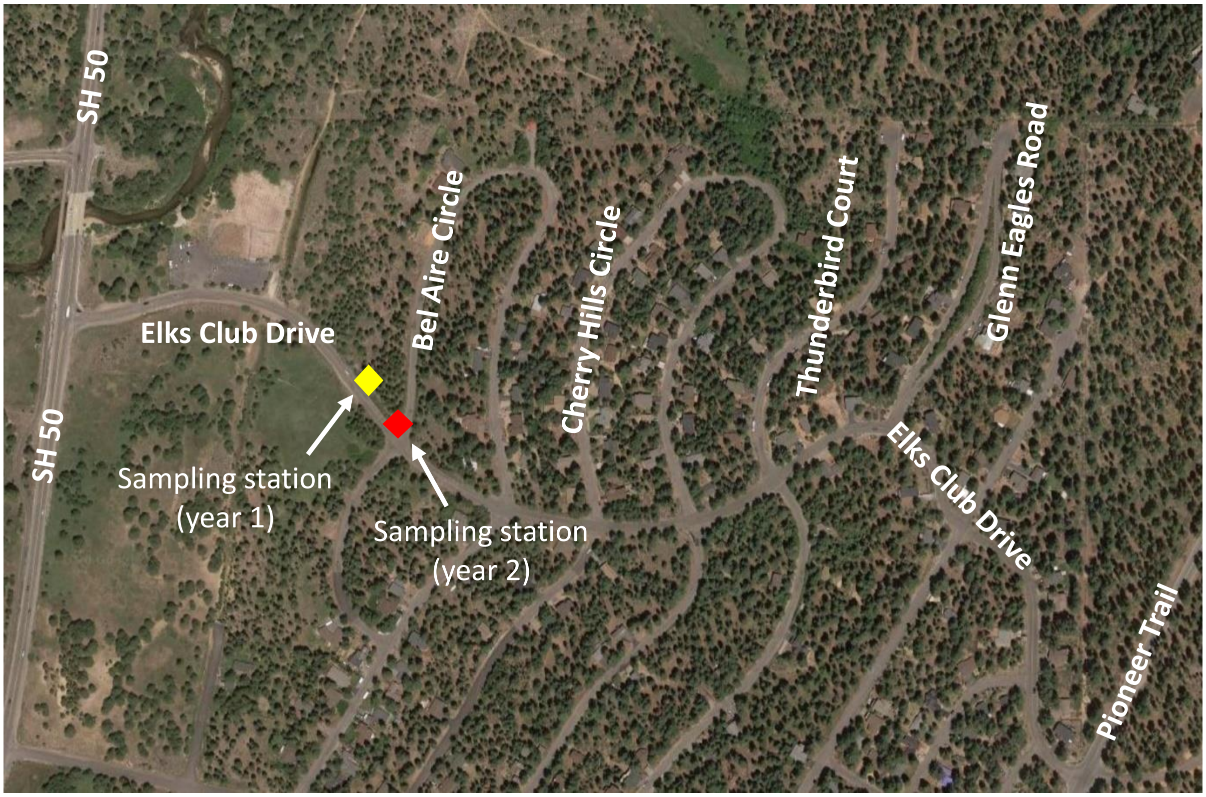

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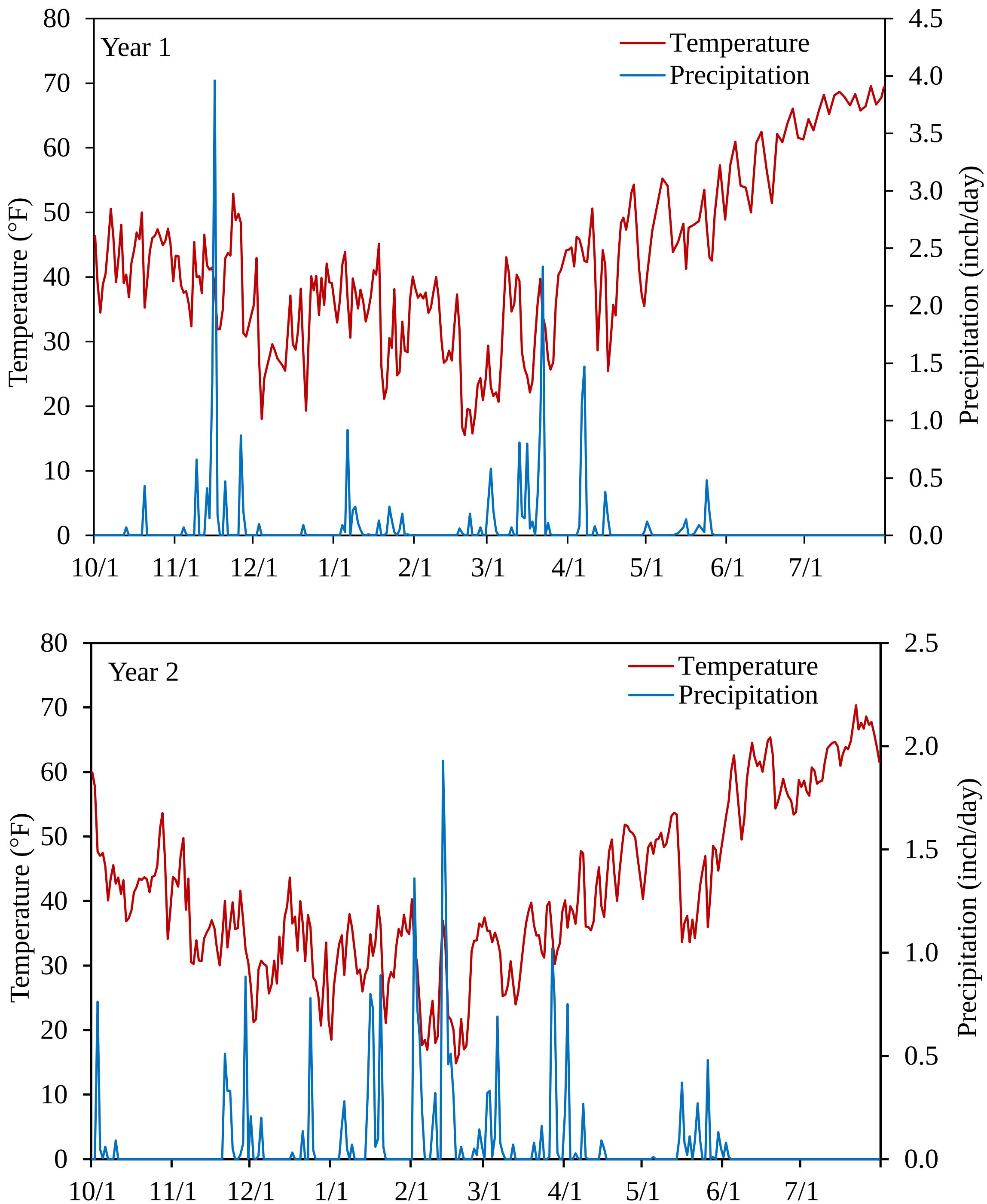

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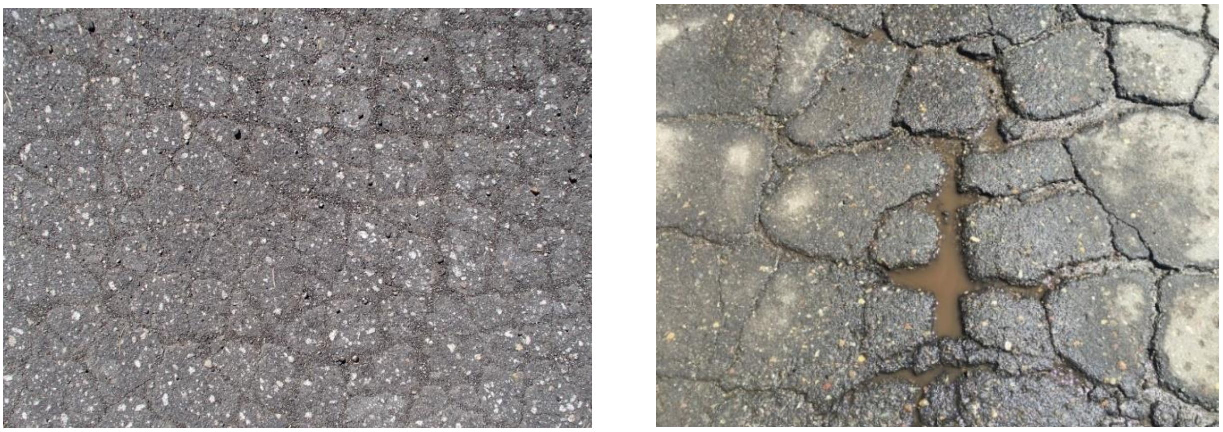

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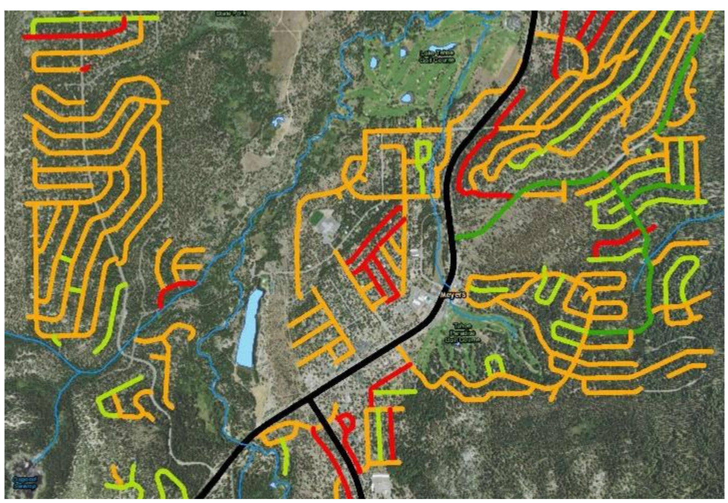

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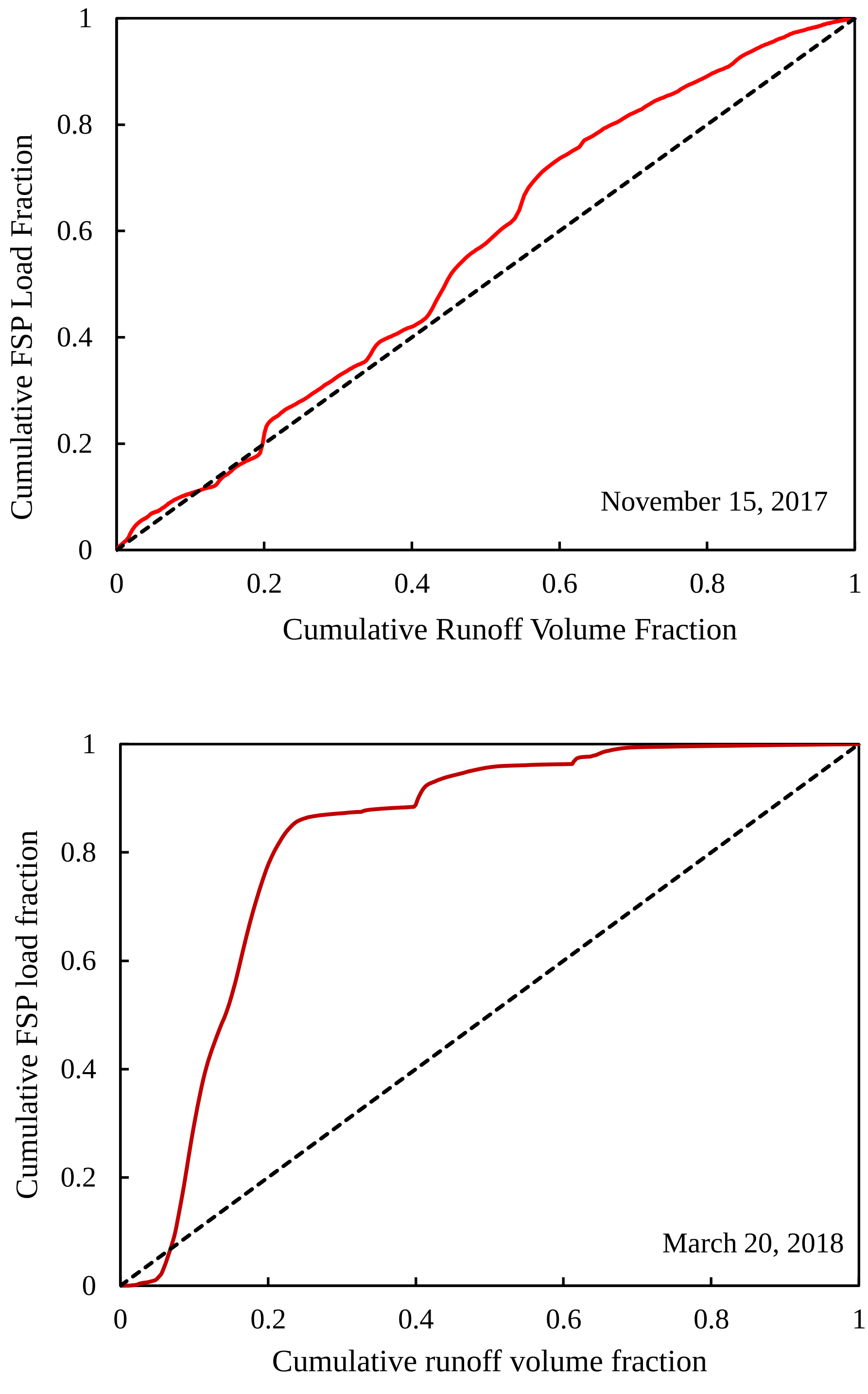

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