Development of a Method to Measure the Impacts of Street Sweeping on Wet Weather Runoff Water Quality

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SOUTHERN CALIFORNIA STORMWATER MONITORING COALITION

SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT

Technical Report 1411

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Southern California Coastal Water Research Project, Costa Mesa, CA

January 2025

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ACKNOWLEDGEMENTS

We would like to thank SMC member agency, City of Long Beach, for coordinating access to the Junipero Beach parking lot, providing traffic control, and street sweeping services in support of this study. Supplemental funding from the City of Santa Barbara enabled analysis of novel contaminants including microplastics, neonicotinoid and fipronil pesticides, and an exploration of cell toxicity potentially resulting from neonicotinoid pesticides. We would also like to thank our colleagues Beate I. Escher, Jenny Braasch, Maria König, and Georg Braun at the Helmholtz Centre for Environmental Research-UFZ for performing the neurotoxicity screening assays.

Prepared as a deliverable for the Southern California Stormwater Monitoring Coalition.

This report should be cited as:

Fassman-Beck, E., E. Tiernan, D. Xin, A. Mehinto, V. McGruer, S Sauers. 2024. Development of a Method to Measure the Impacts of Street Sweeping on Wet Weather Runoff Water Quality. Technical Report 1411. Southern California Coastal Water Research Project. Costa Mesa, CA.

Keywords:

Street sweeping; non-structural BMP; rainfall generator; runoff; water quality; SMC

Executive Summary

Street sweeping is a non-structural stormwater best management practice (BMP) implemented as part of every Southern California Stormwater Monitoring Coalition (SMC) member agency's current National Pollutant Discharge Elimination System (NPDES) municipal separate storm sewer (MS4) permit and related watershed management plans. To improve progress towards achieving water quality goals, SMC agencies seek to generate scientifically-defensible quantitative evidence of the difference in runoff water quality between unswept and swept street surfaces. The research documented herein develops a reliable method to measure the effects of street sweeping at a single location, that subsequently informs a scope in a future study for application across multiple locations around southern California. The current study scope does not seek to statistically evaluate differences in unswept and swept water quality data generated herein.

The approach adopted for field-scale testing isolates runoff from unswept and swept asphalt surface segments using simulated storm events. The approach, derived through consultation with a technical working group (TWG) of staff from SMC member agencies, was designed to overcome the measured variability compromising conclusive data interpretation in previous field studies in the literature on street sweeping water quality impacts. In the study design, applying consistent, uniform simulated rainfall eliminates sources of environmental variability such as antecedent dry period and rainfall characteristics such as intensity and duration. Limiting the rainfall application to only paved segments isolates runoff to the area over which street sweeping operates (and thus might influence runoff quality), eliminating the confounding effects of runoff from a wider catchment. Finally, only sweeping by advanced technology sweepers is considered as the benefits for debris capture over mechanical sweepers is well documented in the literature. The key elements of the research thus include developing an apparatus to deliver simulated rainfall and testing its application in the context of measuring street sweeping impacts on a range of runoff water quality parameters. The scope of this pilot study is to develop the method for testing, in anticipation of a separate study to establish statistically-defensible data sets quantifying differences in runoff quality from unswept and swept pavements.

SCCWRP developed a Norton ladder-style rainfall generator (RFG) that successfully produces repeatable, uniform rainfall (coefficient of uniformity of 0.73) with the kinetic energy of drop impact required to mobilize pollutant wash-off. Measured concentrations in runoff from unswept pavements are consistent with event mean concentrations (EMCs) reported in the literature for conventional stormwater pollutants including total suspended solids (TSS), total zinc, total copper, total lead, and total coliforms from the simulated storms, while nutrients (total nitrogen [TN] and total phosphorus [TP]) were higher. The simulated rainfall is

representative of kinetic energy reported in the literature for Mediterranean climates and natural storm intensity in southern California, although intensity is less relevant to pollutant wash-off than kinetic energy. Altogether, the SCCWRP RFG satisfies all design criteria established for the intended SMC application.

Repeated testing at the Junipero Beach parking lot (City of Long Beach) indicates that street sweeping on average reduces the concentrations of a range of conventional, common stormwater quality parameters including TSS, TP, TN, total PAHs, total coliform, total zinc and total copper, as well as Fipronil pesticides compared to runoff from unswept pavement. The difference in average TSS concentrations between unswept and swept pavements was 13%. The difference in measured concentrations on average for other pollutants ranged from approximately 20-50%, suggesting the possibility that street sweeping may provide greater benefit than the 5-10% reduction assumed in many current NPDES MS4 permits, acknowledging this pilot test is only a first step towards a comprehensive study. It is also noted that the reduction in some instances was allowed for all minimum control measures implemented collectively. Results are the average of 3 tests comparing unswept and swept pavement runoff concentrations generated after 2 weeks' antecedent dry period and one pass of a regenerative air sweeper over the designated swept pavement area. Each test was conducted over an area of approximately 19.5 m^2 (210 ft^2) and reflects runoff from 8 mm (~0.32 in) of rainfall occurring in 15 min.

The research also explored the potential impacts of street sweeping on emerging contaminants including neonicotonoid pesticides and microplastics, as well as the potential toxicity from chemical mixtures. Pesticide detection was limited for both pavement conditions, but positive differences between unswept and swept concentrations were measured for several specific compounds in all 3 tests. Similar patterns were observed using the rapid toxicity screening assays. Results of the three bioassays applied indicated that bioactivity caused by mixtures of PAHs, pesticides and other unknown chemicals were reduced due to street sweeping. Microplastics smaller than 125 μm are likely to be removed by street sweeping, while particles larger than 355 μm are not, based on the single sample successfully collected.

Practical lessons on the method of generating and capturing runoff emerged, and are relevant to develop a scope for future testing. For example, variability in results amongst testing locations even in the same parking lots indicates the importance of generating runoff from a "large enough" area. The size of the testing area needs to be balanced with the expected number of event pairs to occur in a single testing day. Logistics of testing, including set-up, generating rainfall and collecting runoff, sample collection, refilling the water supply with a hose, and break-down suggest that up to 4 tests at a single location can be conducted in a 14-hr day. The size of the test area could be increased if a more efficient water supply, such as a water truck or hydrant, were provided.

A minimum of 4 tests each on unswept and swept pavement conditions is required at each location to likely generate statistically defensible differences in measured runoff water quality. Additional tests will be necessary if the event-to-event variability exceeds the observations at the Junipero Beach parking lot.

Members of the SMC TWG concur that the RFG and its application provided a successful pilot test and proof of concept for a method to measure water quality in swept and unswept conditions, and acknowledge the ability to detect statistical differences in constituent concentration is not guaranteed within the existing scope of application. The TWG prioritized scoping future testing to evaluate water quality differences according to (in order) average daily traffic, road surface condition/level of service, sweeping and rainfall frequency, sweeper operation (number of passes and vehicle speed), noting that many additional factors were identified as possible influences of interest. The analytes measured herein were of continued interest, in particular TSS, metals, nutrients, FIB, and microplastics, while particle size distribution for the sample as a whole should also be measured.

Identifying testing locations requires detailed investigation, planning, and cooperation. To develop a practical work plan for testing at multiple locations and addressing identified priorities to evaluate, SMC member agencies should first collate an inventory of their existing street sweeping programs (e.g., existing coverage, responsible departments, etc.) cross-referenced to pavement maintenance programs. Available street sweeping equipment should be investigated, although it is acknowledged that some vendors offer sweeper rental programs.

Altogether, the research successfully achieved the objectives of developing a reliable method to measure unswept and swept pavement water quality, and established proof-of-concept comparisons suggesting that street sweeping with an advanced sweeper technology likely improves runoff water quality concentrations for a variety of constituents. Representative, field-scale urban runoff water quality studies are now able to be conducted on a prescribed schedule, at a wide range of locations across the SMC. The testing system developed herein is ready to be deployed for a future multi-location initiative.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ACRONYMS

BMP	best management practices
CuC	Christiansen uniformity coefficient
EMC	event mean concentration
MAG	microplastic-analysis-grade
MS4	municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
NSQD	National Stormwater Quality Database
RFG	rainfall generator
SMC	Southern California Stormwater Monitoring Coalition
TWG	technical working group

Note: pollutant names/acronyms are excluded from this list

INTRODUCTION

The Southern California Stormwater Monitoring Coalition (SMC) is pursuing research to quantify the positive impact of street sweeping on pollutant loading and concentrations from roadways through field monitoring. The current assumption by many SMC member agencies that street sweeping reduces pollutant loads from 5-10% is historically derived from best professional judgement. SMC member agencies seek quantitative evidence to support or refute the assumed load reductions to improve watershed management plans and achieve water quality objectives.

Several studies in the literature have documented pollutant masses collected by street sweeping (City of San Diego 2010-2015; Lloyd et al. 2019; Muhammad et al. 2006; Schueler et al. 2016; Seattle Public Utilities and Herrera Environmental Consultants 2009), which often show measurable masses of pollutants in road debris. There is no generally accepted method to translate loads captured by street sweepers during dry weather into reductions in urban runoff event mean concentrations (EMCs). No study identified to date has shown an effect of street sweeping on downstream water quality, e.g., at storm sewer outfalls, nor has any study definitively quantified differences in stormwater runoff concentrations between swept and unswept streets (Kang et al. 2009; Kang and Stenstrom 2008; Muhammad et al. 2006; Pearson et al. 2018). High event-to-event variability in pollutant build-up and wash-off has been identified as a challenge in measuring downstream benefits (or lack thereof). Study designs may have also prevented conclusive findings at outfalls, since the roadway is often only a fraction of the total contributing catchment. The most common factors used to characterize study conditions include land use in the surrounding catchment, average daily traffic (or other indicator of road usage), and street sweeping frequency. An annotated literature review of street sweeping studies is provided in Appendix A.

The primary focus of this project is to develop a reliable method to measure differences in runoff water quality between swept and unswept pavements. The SMC embarked on this pilot study as a first step towards developing quantitative evidence on pollutant removal to support NPDES permitting. The study design adopted an approach of isolating runoff from heavily trafficked asphalt surface segments using simulated storm events because:

- Heavy traffic is presumed to create greater particulate pollutant loads, which are also more likely to be removed by street sweeping.
- The majority of road surfaces subject to street sweeping in southern California are asphalt. Concrete road surfaces are typically found on highways.

- Street sweepers only service trafficked areas (roads, parking lots, etc.).
- Sampling isolated runoff avoids confounding factors associated with sampling flows at outfalls that would likely include runoff from other land-uses across the catchments, which might mask the effect of street sweeping.
- Controlled testing using simulated rainfall limits confounding effects of storm-to-storm variability in rainfall that limits potential pollutant build up (i.e., antecedent dry period relative to sweeping) and drives the wash-off process (i.e., rainfall characteristics mobilizing pollutants).

The recommended method was derived through consultation with a technical working group (TWG) of SMC member agencies (Table 1), informed by an extensive literature review that ultimately concluded that the multiple confounding effects reflected within catchment-scale studies (e.g., sampling at outfalls) preclude measuring effects of a street-scale non-structural best management practice (BMP) such as street sweeping (Appendix A). The TWG recognized that factors such as climate, road usage, road surface type, and street sweeping frequency (Table 2) are potentially influencing factors on EMCs, but prioritized study design elements herein to focus on test method development as a cautious first initiative in light of the potential challenges and costs associated with a large-scale field monitoring campaign.

The key elements of this project include developing an apparatus to deliver simulated rainfall and testing its application in the context of measuring street sweeping effectiveness. This report first describes the design criteria and testing of a mobile rainfall generator (RFG) to overcome limitations in drawing conclusions on the impacts of street sweeping on runoff water quality in previous street sweeping studies (Appendix A). The second part of this report details the method and results of repeatedly applying simulated rainfall on a single parking lot subject to swept and unswept conditions. Data from the application are evaluated to determine if the RFG generates representative urban runoff quality and the potential for successfully quantifying differences in water quality from unswept and swept pavements. A range of conventional stormwater pollutants (sediments, nutrients, heavy metals, polycyclic aromatic hydrocarbons [PAHs]) and emerging contaminants including microplastics and neonicotinoid pesticides are measured. Experimental cell bioassays are explored to evaluate whether neonicotinoid pesticides cause concern for runoff toxicity. Priorities for a future study are suggested.

Table 1. Technical Working Group members.

Representative	SMC Member Agency
James Fortuna	County of Orange
Matt Yeager	Riverside County Flood Control and Water Conservation District
Laura Barret / Jaime Milani	County of San Diego
Hamzah Ramadan	Caltrans
Jill Murray	City of Santa Barbara
Gerhardt Hubner	SMC at large
Wayne Chiu	Region 9 Waterboard
Ivar Ridgeway	Region 4 Waterboard

Table 2. List of factors potentially influencing the impacts of street sweeping on runoff water quality from street sweeping.

Factor	Variables
Climate	Rainfall depth Rainfall intensity Rainfall duration
Road Use	Average Daily Traffic Number of lanes Light duty vs heavy duty vehicles Road classification*: interstate, arterials, collectors, local roads
Road Surface	Material of construction Level of service
Sweeper Frequency	Static frequency Time since rainfall

*https://safety.fhwa.dot.gov/speedmgt/data_facts/docs/rd_func_class_1_42.pdf

Rainfall Generator (RFG) Development

Background

The primary reason to employ an RFG to support research is to reliably produce data from variable-intensity rainfall that researchers otherwise may need to wait years to collect (Hermsmeier & Mutchler 1965; Sousa Júnior et al. 2017; Tiefenthaler et al. 2001). An RFG enables study designs to proceed expeditiously with regards to climate variables (Gershunov et al. 2019), and to isolate a specific land use for runoff characterization (Egodawatta 2007; Litt et al. 2020). Many varieties of RFG, and an American Society for Testing and Materials (ASTM) standard, exist for soil erosion applications (Kibet et al. 2014; Lascano et al. 2019; Ricks et al. 2019; Zambon et al. 2021), but fewer RFGs exist for general purpose studies such as field-scale BMP effectiveness or land-use runoff characteristics (Abudi et al. 2012; Herngren et al. 2005; Sousa Júnior et al. 2017). Most commercially available RFGs tend to be tabletop drip simulators (Cottenot et al. 2021; Davis 2023; Rončević et al. 2022), whereas field-scale RFGs tend to be the domain of a handful of interested research agencies in the agricultural sector, including the USDA (Esteves et al. 2000; Lascano et al. 2019; Miller 1987; Paige et al. 2004).

Two common types of research RFGs prevail, referred to herein as inverse generators and Norton-ladder type generators. Inverse generators cast a fountain of water droplets skyward that then fall by gravity back to earth (Abudi et al. 2012; Esteves et al. 2000; Ricks et al. 2019). Norton-ladder type simulators, by contrast, use a pressurized water delivery system to spray water droplets directly downwards from some height (Egodawatta 2007; Herngren et al. 2005; Miller 1987; Navas et al. 1990). Inverse generators tend to produce highly uniform simulated rainfall (Abudi et al. 2012; Ricks et al. 2019) that falls from a sufficient height to ensure terminal velocity (Esteves et al. 2000). The advantage of Norton-ladder type generators is related to field portability and resilience to windy conditions (Blanquies et al. 2003; Herngren et al. 2005; Iserloh et al. 2010). RFG technology has been roughly the same for decades (Hermsmeier & Mutchler 1965), though improvements to instrument precision were brought about by the computerization of pressure and oscillation components by Miller (1987), Navas et al. (1990), and Ricks et al. (2019).

Design Criteria

Developing the SCCWRP RFG for a street sweeping study gave rise to three design criteria. The SCCWRP RFG must:

1. Be field scale, constructed from low-cost, commercially available components;
2. Enable rapid, mobile deployment for use at a wide range of locations;
3. Generate near-natural rainfall conditions endemic to southern California. Near-natural rainfall is defined by Blanquies et al. (2003) to be simulated rainfall that has:
    a. Representative kinetic energy
    b. Reproducible intensities
    c. Uniform intensity and application
    d. Vertical angle of impact

The first two criteria drive decisions related to the selection and configuration of physical components of the apparatus that do not necessarily require testing. Success in the third criteria requires iterative testing and calculation once the physical apparatus is constructed.

Kinetic energy drives pollutant mobilization and wash-off (Kibet et al. 2014; Nearing et al. 2017; Rončević et al. 2022), and is therefore perhaps the most important design criteria for the street sweeping effectiveness study. Repeatable rainfall intensities are necessary to generate consistent simulated storm conditions, promoting statistically defensible data sets. A uniform intensity over the footprint of the simulated rainfall is required to ensure equal opportunity for pollutant wash-off. The vertical angle of impact influences the calculation of terminal velocity at the impact of raindrops to the ground surface, and therefore influences the kinetic energy.

Overall Description

The principal components of an RFG are the frame, the water delivery system, and the spray nozzles. While the nozzles themselves are perhaps the most important component (as they are responsible for producing water spray that resembles natural rainfall), the frame and water delivery system drive the overall scale and cost of the RFG.

Figure 1 outlines the water delivery system, composed of the water supply reservoir, pumps, pressure regulators, and plumbing to the individual nozzles. The water supply reservoir was served by a 1,000 L intermediate bulk container (IBC) tote. A cistern pump (powered by a gas generator) is used to deliver water from the IBC tote into a well tank, which maintains a stable operating pressure for the RFG. The pressurized water from the well tank is routed through a water separating manifold into eight flexible PEX (cross-linked polyethylene) conduits that deliver the water to the spray nozzles. Individual pressure regulators on the water separating manifold eliminate the need for tweaking water pressure in the field. The PEX material was selected for the plumbing due to its flexibility, ability to operate under pressure, and readily available connectors/fittings. The PEX plumbing to individual nozzles was color-coded for rapid assembly.

The operating pressure for the well tank is between 275 - 400 kPa (40-60 psi), while the water separating manifold also contains pressure regulators set to 275 kPa (40 psi) that ensure the spray nozzles each receive the same pressurized flow. The spray nozzles are attached to battery-powered oscillating arms that horizontally translate the nozzles over a larger surface area. Oscillating the banded spray (i.e., conical spray where the length of the base is much greater than the width) is critical to promote a more uniform application of simulated rainfall.

As a Norton-ladder type RFG where the generated rainfall is directed downwards from a supporting platform, the footprint of the frame dictates the wetted area of the simulated rainfall. The SCCWRP RFG uses telescoping gantries spaced 2.5 m apart and an aluminum frame spanning between them to create a uniform rainfall footprint area of 6.5 m^2. Developed to support urban runoff studies, the SCCWRP RFG is designed to span approximately one travel lane (~4.3 m total) and be maneuverable on paved surfaces. Adjustable gantries were strongly favored for improved access to the RFG water delivery system at low height. The hoist capabilities of the 0.5-ton telescoping gantries exceed the RFG demands; however, it was the smallest model mobile gantry that was readily available.

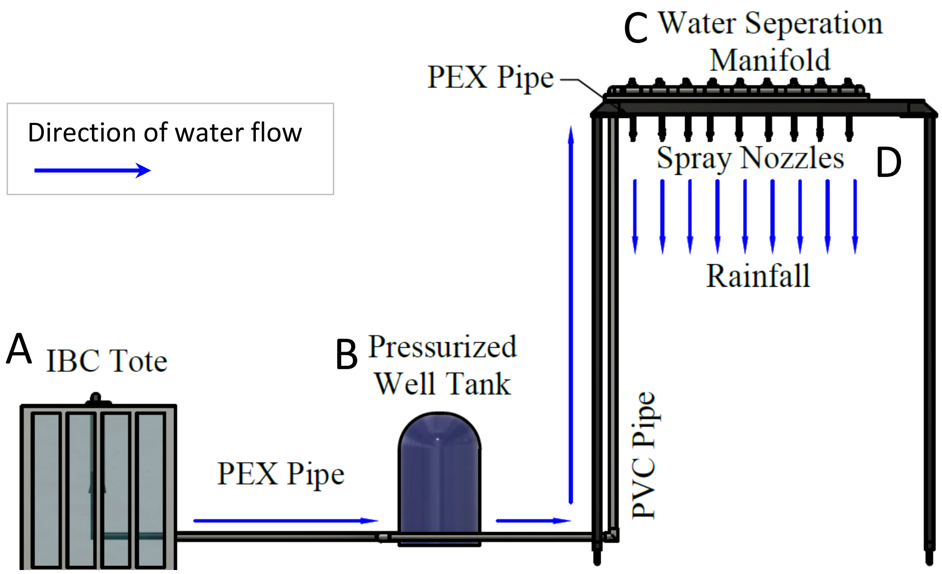


Figure 1. Schematic of SCCWRP RFG water delivery system, A) Water storage reservoir; B) Well tank; C) Water Separating Manifold; D) Banded-spray nozzles.

The principal components of the SCCWRP RFG are detailed in Table 3. The components overall were constrained to fit into SCCWRP's existing 3 m x 4.25 m towing trailer, so that it could be deployed around all SMC agencies. Additional information about the design, construction, and assembly of the SCCWRP RFG are available on the Open Science Framework (OSF) platform (https://osf.io/2b4vh/, Tiernan et al. 2023).

A rudimentary wind screen was developed to shield the SCCWRP RFG. The wind screen was composed of a 3 x 4 m weather-resistant plastic tarp supported lengthwise by vertical aluminum extrusions. The wind screen was secured with guy wires to anchors composed of concrete in plastic 5-gal buckets. The height and width of the windscreen protected the RFG from one prevailing wind direction; dollies were eventually used to adjust the windscreen as needed.

Table 3. SCCWRP RFG Principal Components.

RFG Component	Function
Spraying Nozzles	The spraying nozzles transform a constant pressure flow feed into a banded spray of droplets. The spray droplets resemble natural rainfall in terms of the drop size distribution and volume flux (i.e., rainfall intensity).
Oscillating Arms + Motors	The oscillating arms move the spraying nozzles to physically distribute the cone of droplets uniformly across the footprint of the RFG. Rotating worm gear motors and 12V batteries power the oscillating arms.
Water Separating Manifold + PEX Tubing	The water separating manifold is a linear flow-divider apparatus open to a constant high-pressure flow feed on one end and closed on the other end. Pressure regulators at 0.2 m intervals and consistent length PEX tubing are used to deliver constant pressure flow feed to the spraying nozzles.
Well tank	The well tank is an intermediate storage component that allows for constant high-pressure flow feed delivery to the manifold. The well tank pressure is set to at least 275kPa to ensure equal pressure flow reaches the individual pressure regulators and spraying nozzles.
IBC Tote + Cistern pump	The IBC tote is the water storage reservoir. The cistern pump is used to deliver feed water from the tote to the well tank.
Adjustable Gantries + Frame	The adjustable gantries are used to raise and lower the RFG frame between maintenance and operational heights. The maintenance height is roughly 2m that allows for easier ground access; the operational height is roughly 3m that allows produced droplets to accelerate before impact. The RFG frame is a lattice of aluminum extrusions that physically supports the PEX tubing, oscillating arms, and spraying nozzles.
Wind Screen	The wind screen is a plastic tarp stretched between two vertical aluminum extrusions set in concrete blocks. The wind screen protects the RFG from the primary wind direction, improving the accuracy of uniformity and intensity measurements.
Power Supply	The cistern pump is powered by a gasoline generator.

Deployment

A critical design feature of the SCCWRP RFG intended for use to measure street sweeping effects on runoff water quality was the ability to be rapidly deployed and field mobile. Urban runoff study designs often require repeated trials to increase the statistical power of the results; the SCCWRP RFG must arrive on site, be assembled, run multiple events, be disassembled, and returned to storage within one reasonable working day.

Modular RFG components promote quick assembly. The adjustable gantries are kept at 2 m height for travel and assembly, only being raised to 3 m to generate simulated rainfall. The motorized oscillating arms and nozzle heads are bolted to the supporting aluminum frame at specified locations determined by uniformity testing. The flow-separating manifold is attached to the gantry with access to the pressurizing well tank. The assembly of the SCCWRP RFG requires a team of two and typically takes less than 30 minutes for an experienced team; a greater logistical concern in the field, in fact, is how quickly can a hose fill the 1,000 L IBC Tote. Once assembled, the SCCWRP RFG can be maneuvered in the field by carefully pushing the two gantries. To improve the mobility of the SCCWRP RFG over rougher surfaces, the factory-supplied 5 cm steel gantry wheels were upgraded to 10 cm lockable rubber wheels. The SCCWRP RFG has been tested on paved surfaces of various conditions; it can handle a mild pothole, but unpaved surfaces will present a challenge to the current design.

Figure 2 shows a photograph of the SCCWRP RFG fully assembled and deployed on a logistical testing field visit to San Diego in Aug. 2024, and during testing of street sweeping effectiveness with the wind screen deployed in Long Beach in Dec. 2024.

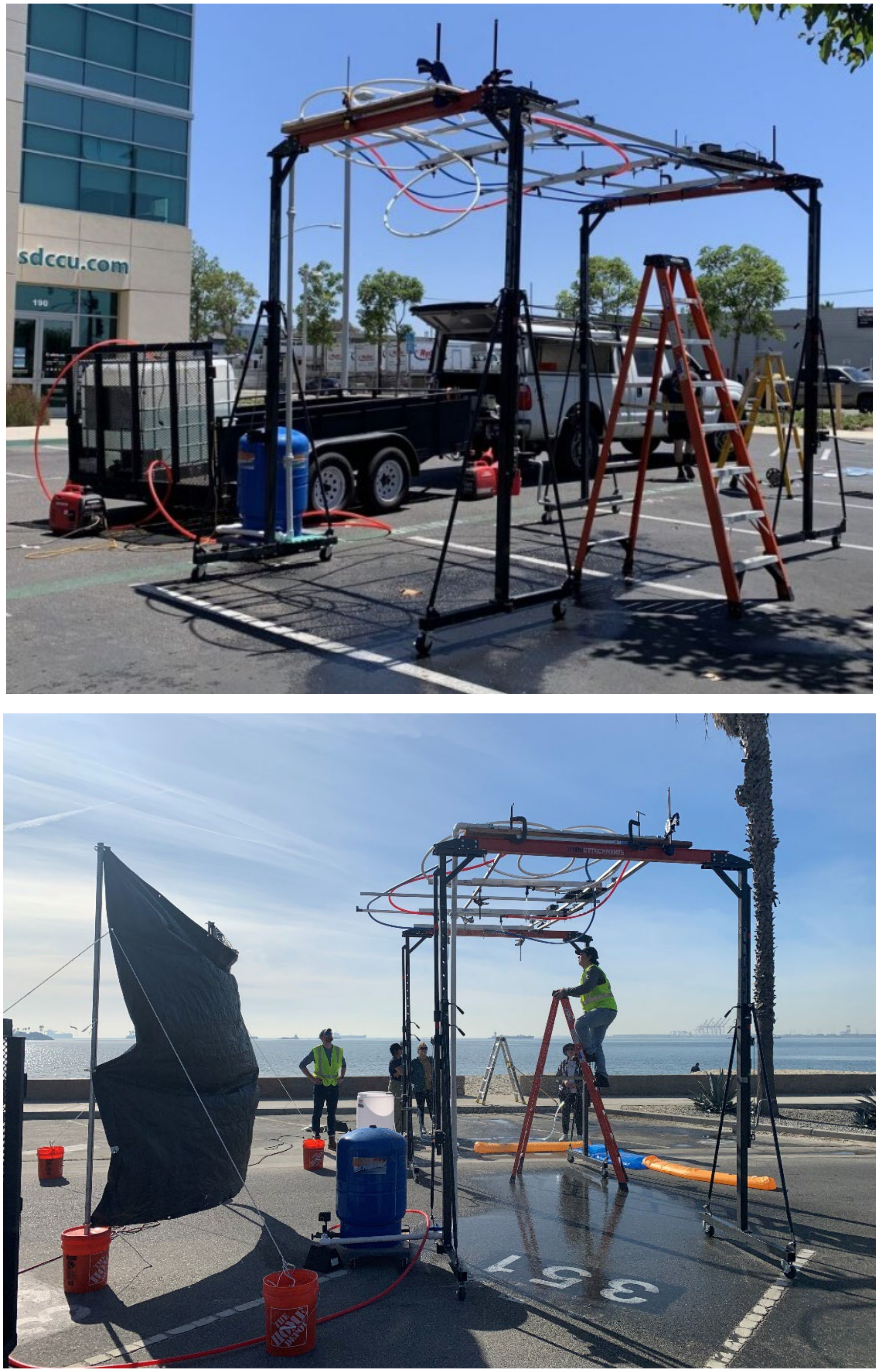


Figure 2. (a) The SCCWRP RFG during shake-down testing showing the full assembly at operational height and with trailer. (b) A windscreen (photo left) was later added to the overall set-up. Ladders are for assembly/disassembly.

Testing For Near-Natural Rainfall

Kinetic energy, rainfall intensity and uniformity of rainfall are intricately linked through nozzle selection, operating pressure, and positioning within the frame of the RFG. Commercial availability of nozzles limits alternatives, thus an ability to simulate the kinetic energy of rainfall characteristic of southern California was prioritized. An air-induction (AI) spraying nozzle from TeeJet Technologies (TeeJet 2014) was selected to produce a coarse droplet at a relatively low flowrate. The nozzle produces 0.57 liters per minute (0.15 GPM) at 275 kPa (40 psi).

Methods

The kinetic energy of a falling raindrop is related to the mass of the droplet and the speed at which it falls, where smaller drops have a lower terminal velocity. Natural rainfall occurs as a distribution of drop sizes; the ability of the nozzles to replicate the distribution was determined herein using a “flour method.” The flour method involves briefly exposing uncompacted wheat flour to the simulated rainfall to create pellets that, when dried, sieved, and weighed, relate back to the size of the droplet that produced them (Egodawatta 2007; Hudson 1963; Kathiravelu et al. 2016; Mazon & Viñas 2013). The terminal velocity for each drop size was calculated using equations for the velocity of the drops exiting the nozzle, acceleration, and drag force.

Rainfall intensity and uniformity were tested by iterative measurement and adjustment (Figure 3). An array of graduated cylinders was set up beneath the spraying nozzles with 30 cm x 30 cm resolution. The total size of the grid was 5 m x 3 m. Graduated cylinders were pre-wetted to mitigate water losses to surface tension on the cylinders. The SCCWRP RFG rained for 5-minutes on the graduated cylinders before recording the accumulated rainfall volume. The average rainfall intensity at each location was determined by dividing the collected volume by the area of the cylinder mouth. Data are applied to calculate the Christiansen Uniformity Coefficient (CuC) as per methods described in Appendix B (Christiansen 1942). The CuC is a spatial metric of simulated rainfall variability. Natural rainfall is largely uniform within a localized area, so the simulated rainfall should also be applied uniformly. Partial uniformity tests were conducted iteratively as part of the SCCWRP RFG development, e.g., the placement of the nozzles and oscillating arm lengths were determined by observing the water volume in each cylinder.

Visual observations coupled with manufacturer-provided information on nozzle operation enabled assessment of the vertical angle of impact.

Additional details of conducting testing and calculations to determine the kinetic energy flux, rainfall intensity, uniformity, and vertical angle of impact are found in Appendix B.

Figure 3. Iterative testing of nozzle position and operating pressure to evaluate simulated rainfall intensity and uniform application (Sept. 2023).

Results and Discussion

The critical design objective for the RFG was to produce near-natural rainfall characteristic of southern California. The AI-TeeJet nozzles operating at 40 psi deliver a constant rainfall intensity of 32 mm/hr with an estimated kinetic energy flux of 29.8 J/m^2mm. The kinetic energy flux is approximately 18% greater than the estimated kinetic energy flux from natural rainfall at 32 mm/hr, which is considered very good agreement compared with RFGs in the literature (Abudi et al. 2012; Egodawatta 2007; Esteves et al. 2000; Grismer 2012).

The delivered intensity (32 mm/hr [1.25 in/hr]) is similar to a 25-year, 60-min storm event in Los Angeles County (NOAA 2017), which is on the very low end of what rainfall generators are typically capable of producing (Ricks et al. 2019). The design issue with simulating low-intensity rainfall is that nozzles capable of restricting flow rate tend to produce very fine “misty” droplets that do not represent natural raindrops. The misty drop effect can be ameliorated by reducing the operating pressure of the RFG, but upgrading pressure regulating components would dramatically increase cost[1]. Small-droplet simulated rainfall will underestimate the kinetic energy of the natural rainfall at the same intensity (Abudi et al. 2012). Misty-rain is also highly susceptible to wind, compromising uniformity and the angle of impact. The intended RFG application for the street sweeping water quality study emphasizes the characteristics of adequate kinetic energy to mobilize pollutants and adequate duration for representative wash-off, whereas rainfall intensity and duration dictate the total volume of rainfall, which is a lower priority herein since street sweeping does not offer any function that should influence runoff hydrology.

The uniform footprint of the SCCWRP RFG is drawn such that the average intensity within the footprint is equal to the target intensity (in this case, 32 mm/hr, Figure 4). The CuC score of 0.73 was calculated from the intensity values within the footprint. According to the literature, RFGs should have uniformity coefficients greater than about 0.75 (Blanquies et al. 2003; Herngren et al. 2005; Navas et al. 1990). Banded spray Norton-Ladder type simulators such as the SCCWRP RFG tend to have lower CuC scores than conically spraying inverse simulators (Abudi et al. 2012; Esteves et al. 2000). The SCCWRP RFG CuC score of 0.73 was deemed adequate for the purposes of the current application, since the full uniformity test on the 5 m x 3 m grid with 5-minute simulated events requires 12 hours of rainfall to complete. Further adjustments to nozzle placement are recommended should the method developed herein be implemented for wide-scale testing of the effectiveness of street sweeping on runoff water quality.

Ultimately, the kinetic energy of the raindrops achieved with the SCCWRP RFG provides good agreement with the literature for mediterranean climates (Cerdh 1997; Petan et al. 2010). The final test of the suitability of the RFG emerges from the repeated testing for the street sweeping application, and determining whether the measured runoff water quality from unswept streets is consistent with expectations.

[1] Improving the pressure control required custom or not commercially available components.

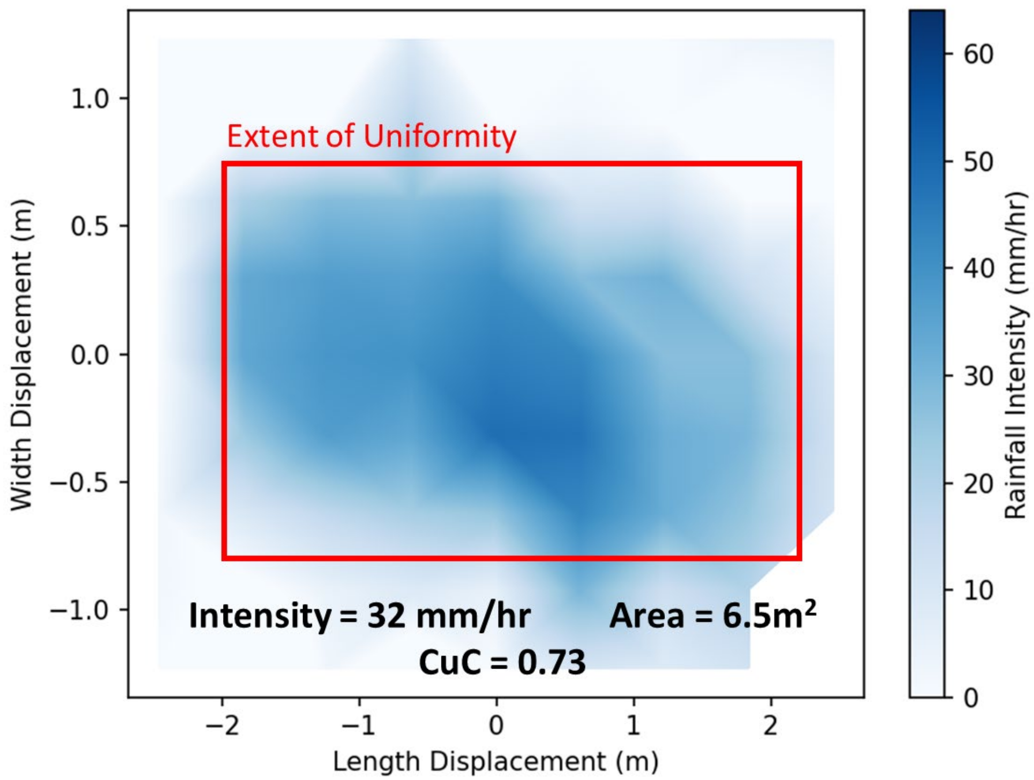


Figure 4. SCCWRP RFG uniform footprint. The average intensity within the red-outlined area is 32 mm/hr with a CuC score of 0.73.

Street Sweeping Effectiveness Field Testing

Site Selection

The scope of field testing in this project entailed repeatedly generating and capturing surface runoff at one location in unswept and swept conditions. Criteria for site selection included:

- Heavy use asphalt surface
- Ability to isolate segments of pavement with clear drainage pathways
- Ability to control (limit) access for a full day
- On-site water supply source to fill the rainfall generator
- Ability to control street sweeping schedule and coverage area
- Availability of an advanced technology street sweeper.

The current project scope specifically limited the scope to only applications where sweeping is accomplished with an advanced technology street sweeper, such as a regenerative air sweeper. The literature review revealed that the amount of debris collected by street sweeping technologies that include vacuum suction, pressure washing, or both while sweeping collect substantially more material than mechanical broom sweepers. The more effective sweeper technologies were prioritized for testing herein again to promote the likelihood of measuring a difference between swept and unswept pavements.

Candidate test sites were identified by SMC member agencies. Sanitation yards within the City of Los Angeles, street segments within the County of Orange, and areas within the Ports of Los Angeles were considered. Coordination often required conversations and meetings with multiple staff members from different teams within an agency. Site visits were conducted by SCCWRP staff. Potential liability precluded testing at several locations, either from having SCCWRP staff operating somewhat unknown equipment for an extended duration, and/or an inability to share resources such as advanced sweepers between City and County agencies. Few SMC agencies represented in the TWG had access to advanced sweeper technologies.

Ultimately, the City of Long Beach identified a site that satisfied the selection criteria in the parking lot of Junipero Beach (33.762326, -118.163556), had a visible sediment load on the surface, and provided all of the requisite resources to enable testing.

Figure 5. Junipero Beach parking lot aerial view. The test location is highlighted in red, on the south end of the parking lot. Image source: Google Maps.

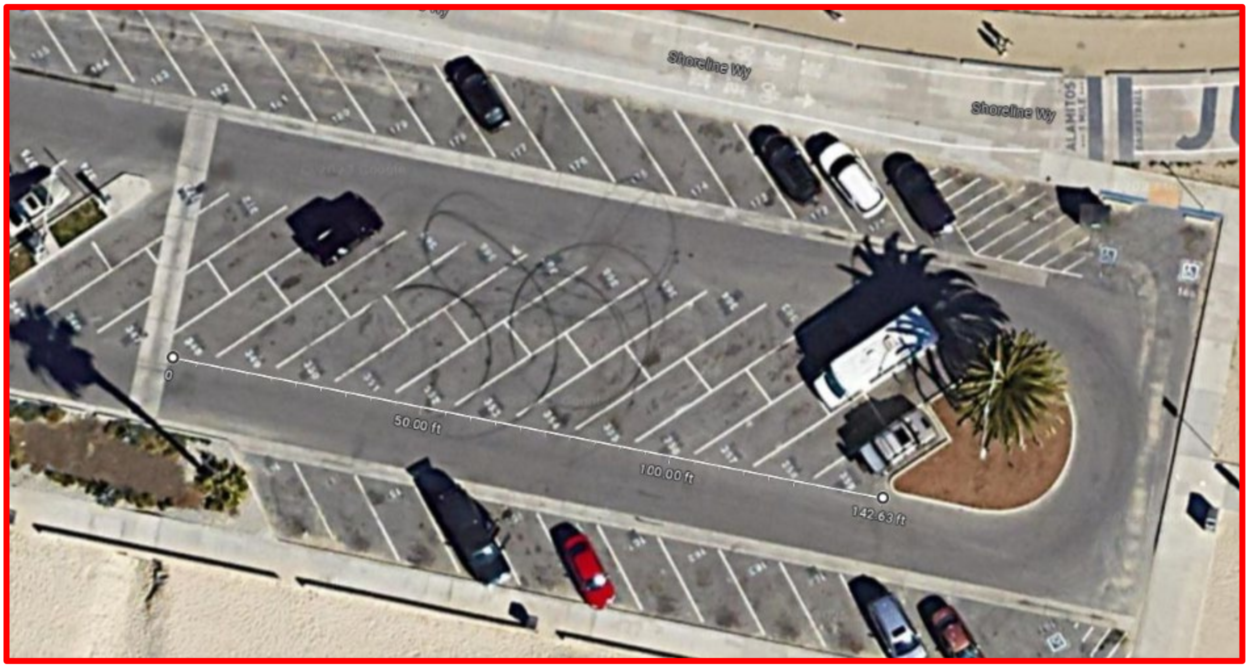


Figure 6. Close up aerial view of Junipero Beach parking lot testing area. Image source: Google Maps.

METHODS

Three simulated rainfall tests were conducted at Junipero Beach for each pavement condition: unswept and swept. The City of Long Beach organized parking lot closure with traffic cones and signage on behalf of the SCCWRP field team. They also coordinated a city-owned street sweeper to arrive on site at approximately 7 am. Fortunately, the parking lot was already on a bi-weekly schedule for sweeping, thus the SCCWRP team coordinated field testing for existing days of sweeping. On test days, an AT Tornado regenerative air sweeper (https://schwarze.com/en/product-catalog/a7-tornado/) conducted one full pass of the designated "swept" side of the parking lot (the inland side) (Figure 6 and Figure 7).

The sweeper operator was instructed by the SCCWRP team to conduct sweeping "as usual" in the parking lot, with the exception of not sweeping the designated "unswept" side of the parking lot. Sweeper operations were not a component of the experimental design in this pilot study. The designated test areas did not include areas with curbs (Figure 9). The lack of a curb and gutter system typical of municipal streets may influence the results herein. Debris is known to accumulate along the curbline in municipal streets, and typical street sweeping may be limited to the lane along the curbline in a street.

Figure 7. AT Tornado street sweeper provided by SMC member agency, City of Long Beach.

Figure 8. Before (left) and after (right) one pass of the AT Tornado street sweeper on the designated "swept" side of the Junipero Beach parking lot.

Each day of testing included:

- On-site assembly of the RFG
- Sweeping of the designated side of the parking lot by the City of Long Beach
- Applying simulated rainfall to unswept and swept pavement segments, and collecting and aliquoting runoff samples
- Collection of a range of field blanks

- Disassembly of the RFG
- Transportation of samples to SCCWRP for subsequent distribution for analytical services on the following day.

Applying the RFG consecutively over three adjacent pavement segments is considered a unique test event per pavement condition (Figure 8). Simulated rainfall was applied for 15-min each over each segment. The duration of rainfall was determined as a balance between providing adequate time for pollutant wash-off, an ability to test multiple segments to constitute a single event for a pavement condition, and testing multiple event pairs in a single day. A Schiff et al. (2016) study of pollutant dynamics in runoff concluded that peak runoff concentrations were observed 10-20 min from the onset of rainfall, while the August shake-down test in San Diego found that a 60-min duration test diluted runoff concentrations compared to a 30-min test (Appendix C).

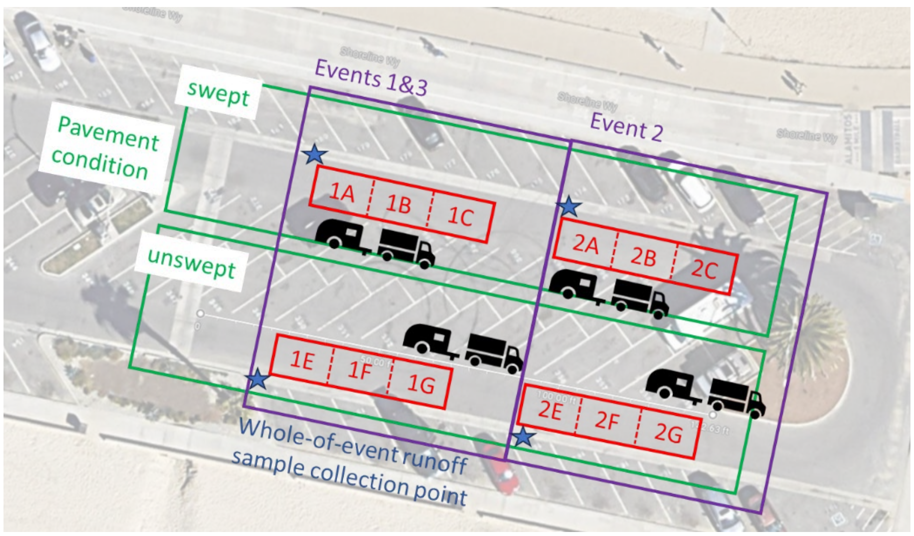


Figure 9. Field testing procedure. An event "pair" is considered the runoff from simulated rainfall applied for 15-min consecutively over three adjacent unswept pavement segments captured in a whole-of-event composite and over three adjacent swept pavement segments captured in a whole-of-event composite. Segments A, B, C in the figure contribute to the total rained-on area per event per pavement area identified by the solid red outline.

The RFG was positioned over a pavement segment such that the downstream end was as close as possible to the parking lot's gutter pan (Figure 9). Close proximity of the sample collection point to the area of runoff generation was necessary to prevent pollutants from re-depositing as it flowed downhill over rough pavement. Gutter pans were broom-swept prior to initiating testing. Water-filled plastic dams were positioned downstream of the segment being tested and around the gutter pan to pool runoff for collection using a peristaltic pump. Captured runoff was collected in a clean, white 200-L polypropylene barrel.

Runoff was generated from each pavement segment consistently within approximately 2-min of initiating rainfall. After 15-min of rain over a segment, the entire RFG and pump assembly was walked to the adjacent segment, without halting operation (Figure 10). Water dams were also shifted as soon as runoff collection was deemed complete at the previous location. A multi-channel peristaltic pump enabled runoff collection from multiple positions, enabling capture at the appropriate positions for the few minutes of transition between pavement segments of the same condition.

Three paired unswept and swept pavement tests were conducted at the Junipero Beach parking lot. Events 1 & 2 were conducted on Dec. 4, 2023. Event 3 was conducted on Dec. 18, 2023. Equipment malfunctions delayed the start of testing on Dec. 18 such that there was time to conduct only 1 pair of tests.

The total rainfall applied for each test is approximated assuming a uniform rainfall intensity of 32 mm/hr (1.25 in/hr) delivered for 15 min over three 6.5 m^2 (70 ft^2) pavement segments. These assumptions result in a rainfall depth of approximately 7.9 mm (0.31 in), and a total rainfall volume of approximately 466 L (123 gal). Approximately 125 – 136 L (33-36 gal) of runoff was collected during each test, of which approximately 98 – 117 L (26-31) gal was filtered for microplastics analysis after aliquots for all other analytes had been subsampled.

Figure 10. The rainfall generator is positioned close to a gutter pan to facilitate runoff collection. Water-inflatable plastic dams are positioned to promote runoff capture using a multi-channel peristaltic pump. Runoff is collected in a clean 200-L polypropylene barrel.

Figure 11. After 15-min of rainfall, the entire RFG and pump assembly are "walked" to the adjacent pavement segment.

Runoff Sample Compositing, Aliquoting, and Handling

Runoff from three adjacent pavement segments was captured in the same vessel to create a "whole-of-event" composite for a pavement condition per event. The whole-of-event composite was subsampled for specific analyte analysis and cell-based toxicity screening (Table 4). The composite sample was continually mixed manually using a clean PVC tube during subsampling. Subsamples were extracted using a peristaltic pump that was continually and rapidly moved vertically through the water column, while stirring, to ensure subsamples were representative. The August shake-down test indicated there was less than 10% difference in concentrations between multiple sets of field duplicates generated using this depth-integrated sample aliquoting procedure (Appendix C). Individual bottles were filled with subsamples for analysis of the parameters listed in Table 4.

Bottles were provided by Physis Laboratories (Physis) for TSS, nutrients, hardness, heavy metals, and PAHs. A trace amount of sulfuric acid was added to bottles for total nitrogen (TN) measurements to prevent ammonia loss. Samples were stored in coolers with ice until transportation to SCCWRP. Samples were delivered to Physis for analysis the day after collection.

Samples for fecal indicator bacteria (FIB) analysis were collected in glass jars and immediately placed inside a cooler with ice. Approximately 1.5 hrs elapsed between the time of the start of each pair of unswept and swept tests. FIB sample analyses were initiated within 12-18 hr of collection[2].

Samples for neonicotinoids and fipronils analysis were collected in two 250-mL samples HDPE bottles containing 25 mg sodium thiosulfate as a preservative. After collection, the samples were kept on ice until transported to the SCCWRP laboratory, where they were immediately frozen. The samples were then shipped on ice to SGS AXYS Analytical Services for analysis.

Samples for cell bioassay screening were collected in 4L amber glass jars containing 1 g sodium azide and 50 mg ascorbic acid and filled to the top. The samples were immediately placed in the dark on ice and transported to SCCWRP laboratories. Samples were stored in the refrigerator at 4°C and processed within 48 hours.

Water samples collected for microplastics analysis (70-120L) were processed in the field to reduce the sample volume for easier transportation and to separate the runoff into different size fractions. To do so, a peristaltic pump was used to transfer runoff from the collection barrel through a stack of sieves with mesh opening sizes of 500 µm, 355 µm, 125 µm, 63 µm, and 20 µm. The runoff was continually mixed during sieving, and the pump intake was continually and rapidly moved vertically through the water column. Each sieve was rinsed into 1-L sampling jars using microplastic-analysis-grade (MAG) water and transported back to the SCCWRP laboratory for further processing and analysis.

[2] Field days were approximately 12-14 hrs' duration. FIB sample processing commenced at the start of the day immediately after testing. FIB data are used herein only for relative comparison between pavement condition.

Figure 12. A whole-of-event composite sample is continually mixed while using a peristaltic pump to sieve through a sieve stack to separate particles according to size fraction for microplastics analysis.

Figure 13. MAG water is used to wash captured particles into a glass jar (1 jar per size fraction) for transportation to SCCWRP and storage until analysis.

Table 4. Water quality analyses performed for unswept and swept pavement runoff.

Water Quality Indicators			Test Method*	Analytical Lab
Total suspended solids (TSS)			SM 2540 D	Physis
Total phosphorus (TP)			SM 4500-P E	Physis
Total nitrogen (TN)			SM 5310 B-N Module	Physis
Total hardness			SM 2340 B	Physis
Total and dissolved heavy metals	Aluminum (Al) Arsenic (As) Cadmium (Cd) Chromium (Cr) Copper (Cu) Iron (Fe)	Lead (Pb) Mercury (Hg) Nickel (Ni) Selenium (Se) Silver (Ag) Zinc (Zn)	EPA 200.8	Physis
Polycyclic aromatic hydrocarbons (PAHs)	1-Methylnaphthalene 1-Methylphenanthrene 2,3,5-Trimethylnaphthalene 2,6-Dimethylnaphthalene 2-Methylnaphthalene Acenaphthene Acenaphthylene Anthracene Benz[a]anthracene Benzo[a]pyrene Benzo[b]fluoranthene	Benzo[e]pyrene Benzo[g,h,i]perylene Benzo[k]fluoranthene Biphenyl Chrysene Dibenz[a,h]anthracene Dibenzothiophene Fluoranthene Fluorene Indeno[1,2,3-cd]pyrene Naphthalene Perylene Phenanthrene Pyrene	EPA 625.1	Physis
Fecal indicator bacteria (FIB)	*Enterococci* *E. Coli* Total coliforms		SM 9230D SM 9223B SM 9223B	SCCWRP
Microplastics			Thornton Hampton et al. (2023); Lao et al. (2024)	SCCWRP

Neonicotinoid and fipronil pesticides	Acetamiprid Acetamiprid-N-Desmethyl Thiacloprid Thiacloprid-amide Thiamethoxam Clothianidin Imidacloprid 5-OH-Imidacloprid Imidacloprid urea Imidacloprid olefin Desnitro-imidacloprid Dinotefuran Nitenpyram	Imidaclothiz Sulfoxaflor A Sulfoxaflor B MGK 264 A MGK 264 B Pipernonyl butoxide Flupyradifurone Fipronil Fipronil sulfide Fipronil sulfone Fipronil desulfinyl Fipronil detrifluoromethylsulfinyl	Internal methods	SGS AXYS Analytical Services
Cell bioassay screening	Aryl hydrocarbon receptor (AhR) activity Antioxidant response element (ARE) activity	Neurite outgrowth inhibition	Mehinto et al. 2021 (AhR) Lee et al. 2022a (neurite outgrowth)	SCCWRP

* SM = Standard Methods for the Examination of Water and Wastewater; EPA = US Environmental Protection Agency

Field Quality Assurance Sample Collection

Runoff sample duplicates were collected from the whole-of-event composite from every event and pavement condition for TSS. One swept pavement runoff sample duplicate per test day was collected from the whole-of-composite sample for all other analytical parameters. Composites were field-split using the subsampling methods described previously to create field duplicates. Field duplicates for microplastics analysis were created during the in-situ sieving procedure. Approximately half of the available volume was sieved and transferred to a set of 1-L glass jars (1 jar per size fraction). The sieve stack was washed with MAG water before sieving the remaining runoff into another set of 1-L glass jars.

Equipment blanks were created at the end of each day of testing by collecting rainfall emerging from the RFG (Figure 14). Rainfall was collected by placing the nozzles directly over a clean 200-L collection barrel. The blank was extracted using the peristaltic pump.

Additional blanks were collected for microplastics analysis only:

- A tap blank was created by collecting samples directly from the spigot used to fill the RFG supply tanks. Tap water was sieved through a stack of sieves at a flow rate of

6.5 L/min for 32 min, totaling 208 L of sieved tap water. A measurable difference in microplastics content between tap and equipment blanks would indicate if the RFG and sample collection components contributed to measured concentrations. The tap blank was collected at the end of Event 3.

- A sieve blank was collected to capture microplastics sourced from atmospheric deposition. A clean sieve stack was placed in open air for the duration of the rainfall-runoff tests and composite subsampling. Sieves were washed with MAG water into glass jars according to size fraction, following the same procedures as the runoff samples. Sieve blanks were collected on both testing days.

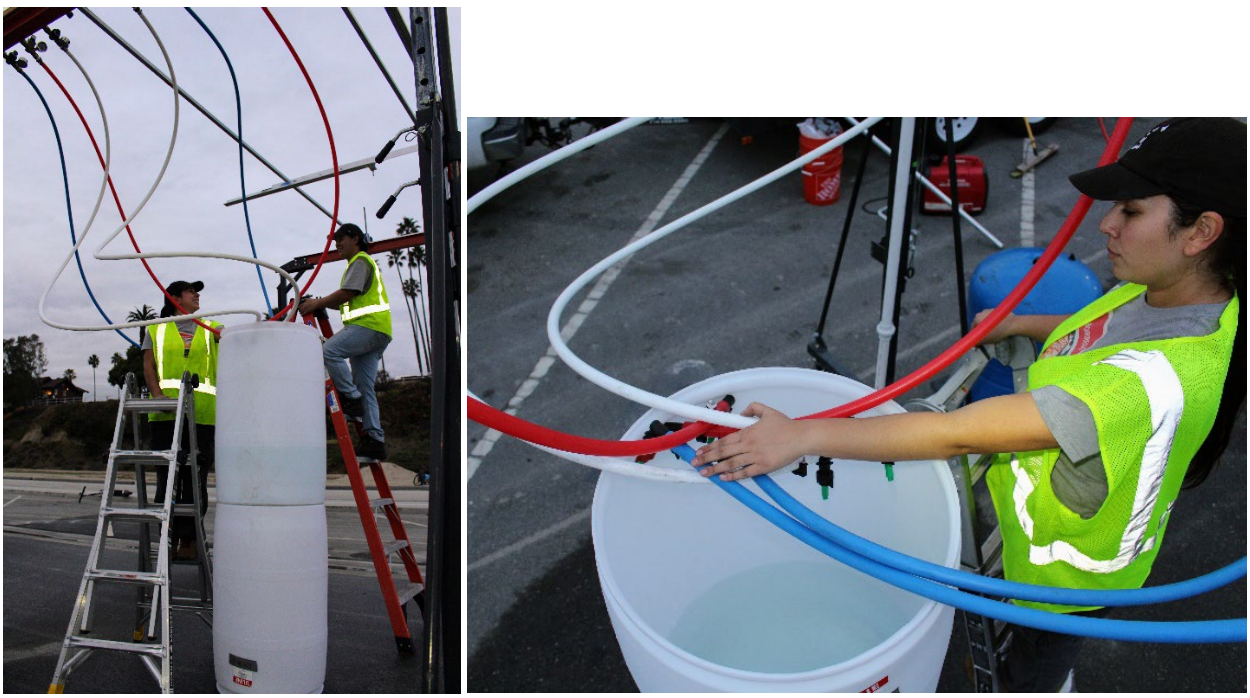


Figure 14. Equipment blank sample collection.

Laboratory Analysis

Analysis methods are presented in Table 4. Conventional stormwater pollutants (sediments, nutrients, heavy metals, and PAHs) were analyzed by a commercial laboratory (Physis) according to their published standard operating procedures. Detail is provided herein for all other analytes either analyzed at SCCWRP and/or for those that do not yet benefit from an established standard method, such as microplastics, neonicotinoid pesticides, and the cell bioassays.

FIB samples were analyzed at SCCWRP. Cultivable *Enterococcus* was quantified by using Enterolert with the Quanti-Tray 2000*TM* system (IDEXX, Westbrook, ME, United States), as per the manufacturer's instructions. Cultivable *E. coli* and Total Coliforms were quantified using Colilert-18 with the Quanti-Tray *2000TM* system (IDEXX, Westbrook, ME, United States), as per the manufacturer's instructions.

Microplastics samples were analyzed at SCCWRP according to Thornton Hampton et al. (2023) and Lao et al. (2024)[3]. Contents of each glass jar containing size-fractionated, concentrated microplastic samples underwent extraction, counting, and polymer identification. Extraction included a filtration step to remove excess water, followed by digestion using an acid/alkaline method (Lao et al. 2024) to eliminate organic, non-polymer particulates. If interference from sediments persisted, density separation was performed as a final extraction step. The extracted particles were counted using microscopy and identified using Fourier-Transform Infrared Spectroscopy (FTIR) (Nicolet iN10 MX Infrared Imaging Microscopy. Thermo Scientific, Madison, WI, USA). Samples were quantified for microplastics concentrations (by mass and particle count) and type of polymer in each size fraction.

Internal methods by SGS AXYS Analytical Services were used to measure concentrations of 25 neonicotinoids and fipronil plus select metabolites. Briefly, each sample was spiked with isotopically labeled surrogate and internal standards, then extracted and cleaned up using solid phase extraction (SPE). Extracts from duplicate samples were analyzed by ultra-performance liquid chromatography/ electrospray ionization/ tandem mass spectrometry (UPLC-ESI-MS/MS) in multiple reaction monitoring (MRM) mode, with positive and negative ionization, respectively. In the positive mode, 20 analytes (listed in the left column of Table 4) were targeted, while in the negative mode, 5 analytes (listed in the right column of Table 4) were targeted. Final sample concentrations were determined using isotope dilution/internal standard quantification.

Two cell bioassays purchased from ThermoFisher Scientific were applied to estimate the removal of known and unexpected chemicals, with analyses completed in the SCCWRP laboratory. The Cell sensor-CYP1A bioassay measures the presence of dioxin-like chemicals (e.g., PAHs and PCBs) and other carcinogens capable of activating the aryl hydrocarbon receptor (AhR). The terms AhR and carcinogenity are used interchangeably in results and graphics below. The Cell sensor-ARE bioassay measures the presence of chemicals activating oxidative stress response via the antioxidant response element (ARE). Sample extraction and laboratory analysis procedures are described in (Mehinto et al. 2016). Data quality was

[3] A standard method for microplastics analysis was developed by SCCWRP for drinking water samples. The same methods were followed herein, with the exception of substituting a 63 mm sieve for the standard 50 mm sieve. The substitution was made to maintain relevance for BMP performance interpretation. 63 -74 mm is considered the distinction between sand and silt size fractions in several common soil classifications.

validated against a set of performance-based quality assurance/quality control (QA/QC) parameters as detailed in Mehinto et al. 2024. Cell bioassay results were expressed as bioanalytical equivalent concentrations relative to a known reference chemical: 2,3,7,8-tetrachlorodibenzodioxin equivalent (ng TCDD/L) for AhR and tert-butylhydroquinone equivalent (ng TBHQ/L) for ARE. To screen for neurotoxic chemicals, a neurite outgrowth assay was also used. This assay recently developed in the Escher laboratory (Lee et al. 2022a) could potentially be used to screen for pesticides including neonicotinoids, which are known to produce neurotoxicity (Sánchez-Bayo et al. 2016; Zhao et al. 2020). The neurite outgrowth results were adjusted by subtracting the solvent control.

Data Analysis

EMCs for conventional pollutants resulting from laboratory analysis of the whole-of-event composite samples are compared against data from the National Stormwater Quality Database (NSQD v. 4.02, [Pitt et al. 2018]) to assess whether the SCCWRP RFG generates pollutants typical of urban runoff. Data from the land-use category of "freeways" is used for comparison as it is the closest single land use to streets and parking lots in the NSQD.

Differences between unswept and swept runoff water quality concentrations are calculated according to Equation 1.

$$\% \boldsymbol{Difference} = \frac{(\boldsymbol{Uns} - \boldsymbol{Swept})}{\boldsymbol{Uns}} \times \mathbf{100}\% \qquad \textbf{Equation 1}$$

Where *Uns* = event mean concentration from unswept pavement runoff and *Swept* = event mean concentration from swept pavement runoff, and *Uns* and *Swept* have the same units for a given analyte. Data analysis of measured runoff concentrations herein is intentionally limited. The study scope is to establish a method for testing, and investigate initial comparisons between unswept and swept pavement water quality to inform whether larger-scale study is warranted. This study scope does not aim to establish statistically evaluated %-differences. Should a larger-scale study be pursued, the data collected herein could contribute to a statistical evaluation.

Data for dissolved metals were deemed unreliable as filtration occurred post-collection in the laboratory, rather than in the field at the time of sample collection.

Analyses related to neonicotinoid pesticides are considered primarily exploratory. There is very little literature documenting untreated runoff concentrations of these compounds, thus data are intended to contribute to an initial body of knowledge and inform decision-making on whether these compounds should be considered in future monitoring of street sweeping runoff quality. Chemistry results are also investigated from the standpoint of presence or absence of pesticides, and are used to support interpretation of the exploratory cell bioassays.

Pollutant load differences are not expressly calculated as there was no measurable difference in runoff volume from equal rainfall occurring over equal areas of pavement for each test. The act of street sweeping does not introduce a mechanism to influence runoff volume. Testing side-by-side unswept and swept pavement segments should also not impose a difference in runoff volumes for the paired samples since the pavement's level of service is consistent.

RESULTS AND DISCUSSION

Conventional Pollutants

Event mean concentrations (EMCs) from laboratory analysis of the whole-of-event composite samples are presented for selected analytes in Figure 15. The simulated rainfall generates runoff with water quality concentrations reasonably representative of urban runoff for commonly considered stormwater pollutants. Unswept runoff concentrations are consistent with the 25th to 75th percentile concentration range for "freeways" in the National Stormwater Quality Database (NSQD v. 4.02, [Pitt et al. 2018]). It is noted that the mean NSQD concentrations exceed the interquartile range for most parameters; this is because of an underlying skewed data set. Total nitrogen and total phosphorus in unswept pavements from the Junipero Beach parking lot had notably higher concentrations than the NSQD. Data are not available for total PAHs from the NSQD.

Event-to-event concentration variability for a given pavement condition is attributed to the spatial heterogeneity inherent in urban runoff (Events 1 and 3 were conducted in the same location on different days, whereas Events 1 and 2 were conducted on the same day, in different locations, Figure 9). Most total heavy metals, as well as TSS and TP demonstrate a slightly higher concentration in Event 2 swept samples compared to the unswept samples. Variability in concentrations for the same pavement condition and location (i.e., comparing Events 1 and 3) is indicative of the natural variability of pollutant accumulation, noting that all tests were performed after a 2-week antecedent dry period. The variability highlights the importance of generating runoff from a representative area, i.e., combining runoff from simulated rainfall over several adjacent pavement areas, and sampling multiple rain events at the same location.

Comparison of unswept and swept pavement runoff concentrations suggests that the testing method is able to detect measurable differences in water quality due to street sweeping (Figure 17). Average runoff concentrations from swept pavements were lower (i.e., a positive %-difference per Equation 1) for TSS, TP, TN, total PAHs and Total Coliform, as well as for 6 of the total heavy metals considered (As, Cd, Cu, Pb, Ni, Se, Zn). Differences in TSS in unswept and swept runoff was 13% on average. Evaluation of particle size distributions in future testing might provide insight into why average TSS removal was lower than many other analytes. In most cases, the average difference for other analytes exceeds 10%. Sand was visible on the parking lot, even after the single pass of the street sweeper (Figure 9). Zanders (2005) identified that copper and zinc are preferentially sorbed to particles smaller than 250 μm. These smaller particles offer relatively lower proportion of a sample's total particulate mass, and thus their absence if picked up by the sweeper might not be detected well when measuring the mass of TSS (Brown et al. 2012).

Of the remaining heavy metals, the difference between unswept and swept pavement runoff for total Cr and total Ag appears close to zero. The higher concentration in swept samples in Event 2 is most notable for total Al, Fe, and Hg rendering the mean %-difference close to zero or negative (i.e., average swept concentration is higher than unswept) for these analytes. Samples analyzed for Al and Pb were mostly or entirely reported below the method detection limit.

The only FIB consistently measured above the detection limit in unswept and swept pavement conditions was Total Coliform. Average Total Coliform concentrations differed by 79% between unswept and swept conditions. *Enterococci* was measured just above the detection limit for only the unswept condition at concentrations of 20 MPN in both Events 2 and 3.

Total PAHs are determined from the sum of individual PAHs; data for individual PAHs are presented in Appendix D. Average total PAH concentrations differed by 30% between unswept and swept conditions.

Total hardness averaged 209, 221, and 161 mg/L as $CaCO_3$ for Event 1, 2, and 3, respectively, while equipment blanks were 171 and 119 mg/L as $CaCO_3$ on the different days of testing. Results indicate the flow over asphalt and/or the concrete gutter pan was enough to increase hardness, despite the limited flow path length over the surface. Hardness was measured herein for completeness, as it is typically needed in order to assess potential toxicity of heavy metals.

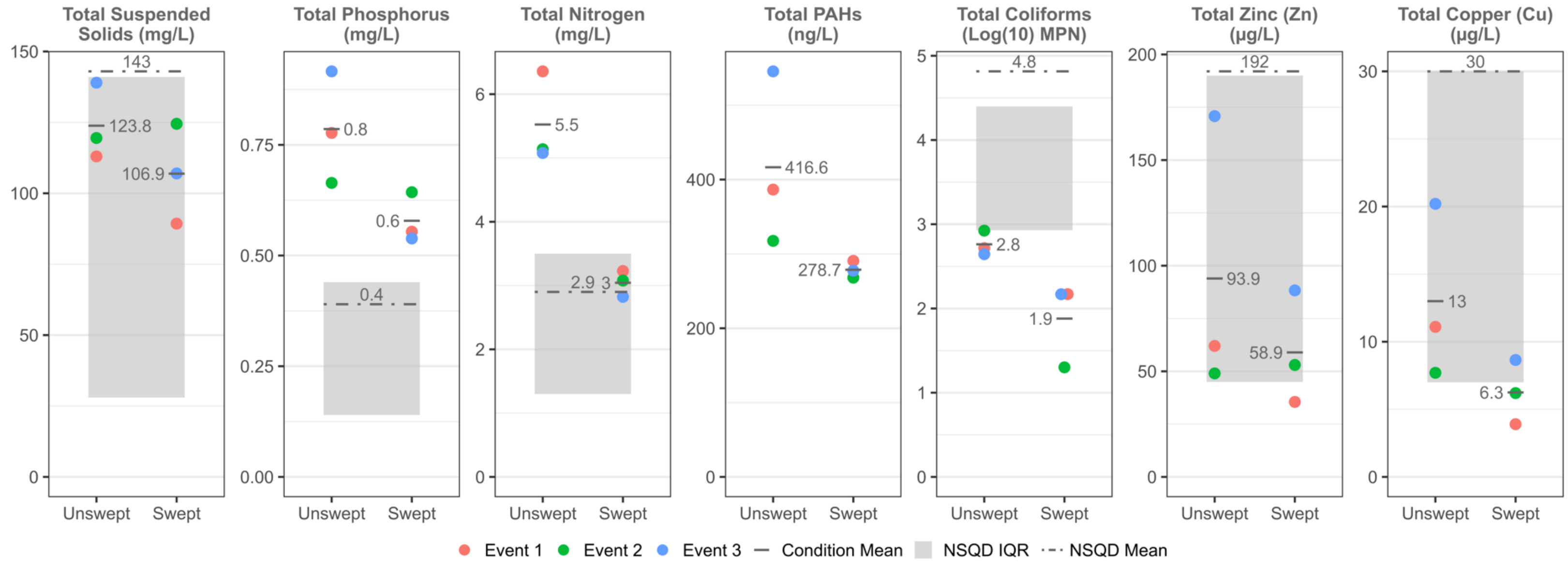


Figure 15. Event mean concentrations measured during field testing of common urban runoff pollutants.

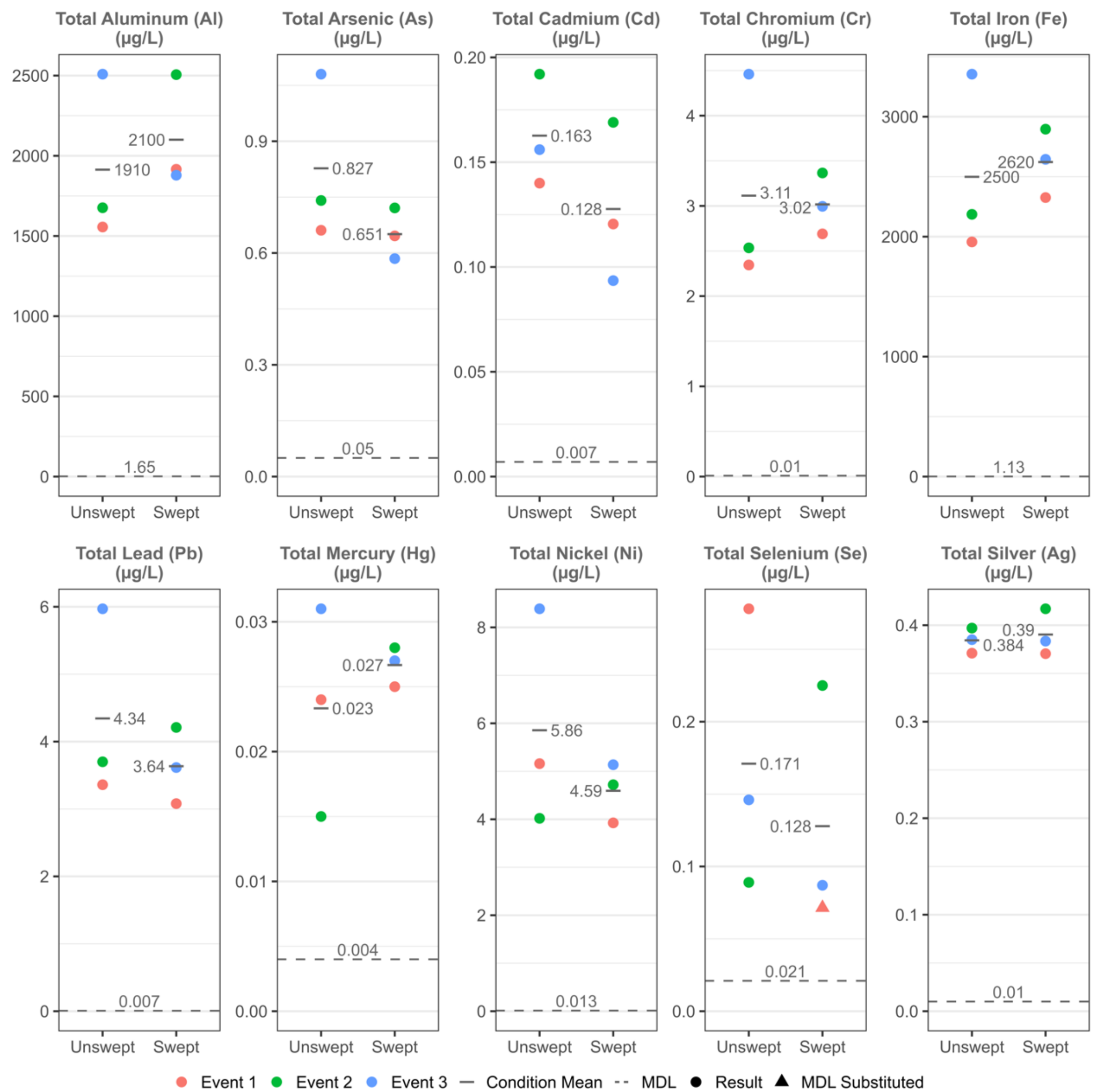
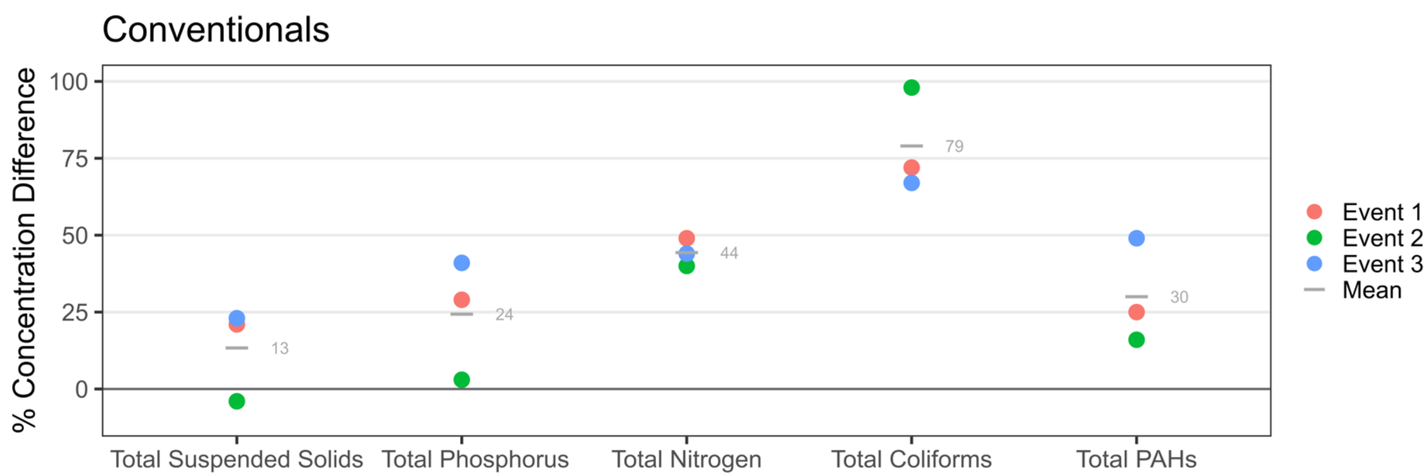
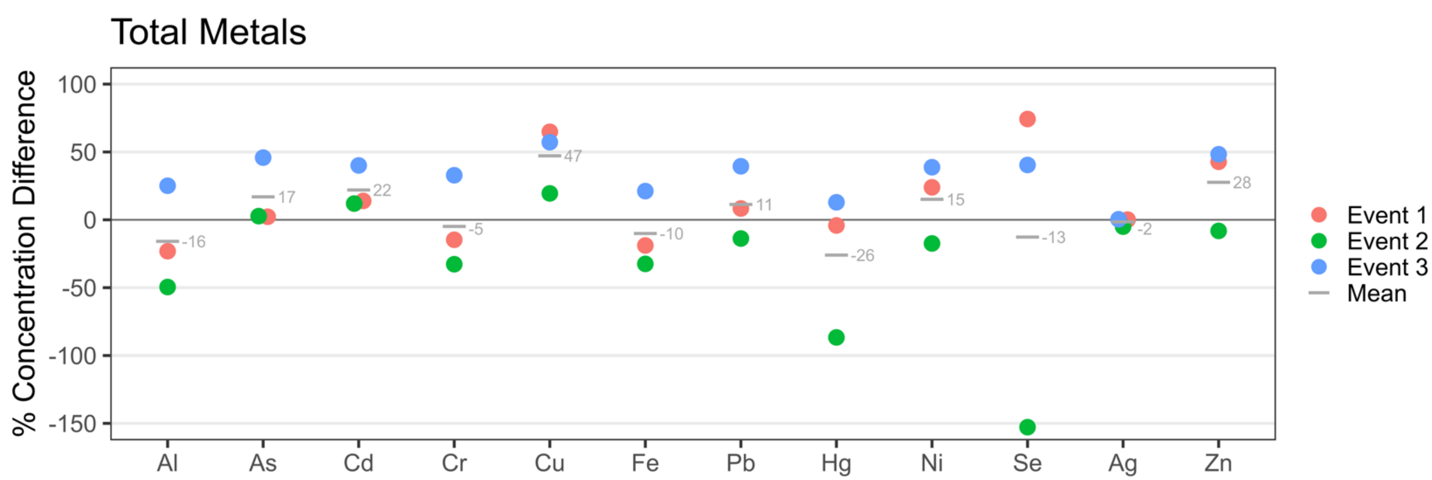


Figure 16. Event mean concentrations for total heavy metals other than copper and zinc.



(a)



(b)

Figure 17. Concentration differences between unswept and swept pavement runoff: (a) TSS, nutrients, FIB, and total PAHs; (b) total heavy metals. Data points above zero indicate higher concentrations in unswept pavement runoff.

Developing Statistical Confidence in Measured Differences

The SMC's interest in developing a viable study method is to evaluate whether there is a statistically defensible, measurable benefit of street sweeping in reducing runoff pollution. The method development and application at Junipero Beach provides successful proof-of-concept results. Statistical power analysis was applied to the Junipero Beach results to provide an estimate of how many event pairs might be necessary to establish a statistically representative data set. The analysis was arbitrarily performed for TSS, TP, and total PAHs, balancing considerations as representative pollutants and project cost.

Power analysis is a statistical test that estimates the minimum sample size needed to detect a treatment effect. In this case, the "sample size" refers to the number of paired unswept-swept runoff concentrations measured. The treatment effect is the difference between the measured concentrations in a sample pair (Table 5), rather than the relative difference that is expressed by the %-difference (Equation 1). In the application to the Junipero Beach data, the measured concentration differences (Figure 15) are subsequently compared to the associated %-differences (Equation 1) to extrapolate results for practical purposes.

The power analysis was performed to satisfy a statistical power of p= 80% at a significance level of α = 5%[4]. The outcome of power analysis depends on an accurate estimate of data variability . A larger number of sample pairs typically decreases the variance. Achieving confidence in smaller magnitude of effects (the measured concentration differences) always requires more samples than larger differences.

The results of the power analysis are presented graphically in Figure 18. The blue arrows in the TSS and TP graph approximately identify the measured concentration differences in Events 1 and 3 on the horizontal axis, while the connection to the vertical axis indicates the number of paired events (i.e., sample size) that is estimated to be needed to provide a statistical confidence at α = 0.05 of the measured difference. For example, 4 sample pairs would be needed to provide confidence in a measured difference of approximately 32 mg/L of TSS, while 6 sample pairs would be needed to provide confidence in a measured difference of approximately 24 mg/L (Figure 15). In Events 1 and 3, these differences corresponded to a calculated %-difference between unswept and swept pavement conditions of 21 and 23%, respectively (Equation 1). Thus, it is estimated that 4-6 event pairs at Junipero Beach would provide statistical confidence of an approximately 20% difference between unswept and swept pavement TSS EMCs. Likewise, 4-6 sample pairs are likely required to estimate a 29-41% difference in TP EMCs, based on measured concentration differences of approximately 0.2-0.4 mg/L. The blue arrows in the total PAH graph indicates that 6 sample pairs would likely be

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[4] The statistical power is the likelihood that a test will detect an effect of a certain size if there is one (here, the mean concentration difference between swept and unswept pavements), while the significance is the maximum risk of a Type I error (rejecting a true null hypothesis).

required to provide statistical confidence in an average 30% EMC difference (Figure 14), based on an average EMC difference of 138 μg/L measured between unswept and swept pavements.

Table 5. Test statistics contributing to power analysis

Parameter	Units	Concentration Differences Among Event Pairs (Unswept-Swept)	
		Mean Measured Difference	Standard Deviation of Differences
Total PAH	ng/L	137.8	115.2
Total Phosphorus	mg/L	0.21	0.18
Total Suspended Solids	mg/L	16.9	19.4

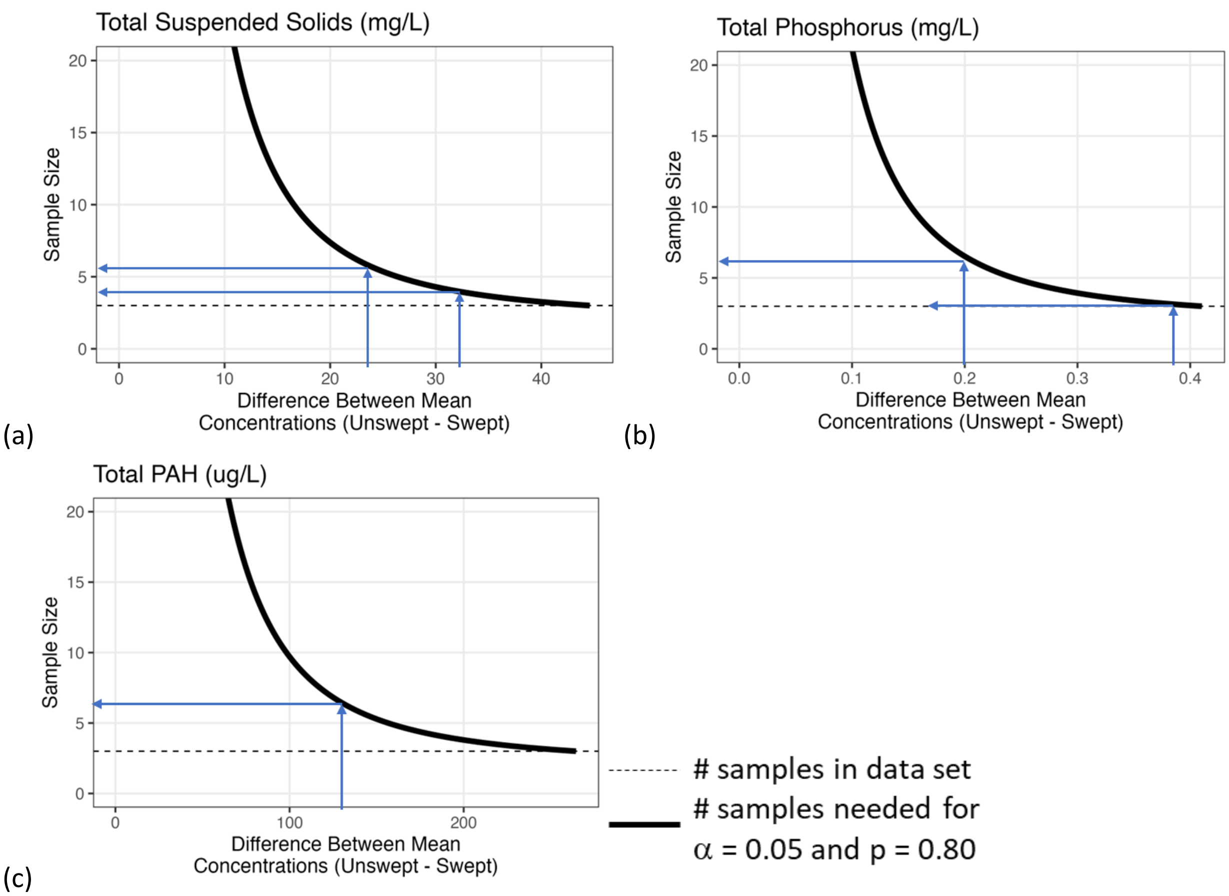


Figure 18. Power analysis to estimate the number of paired unswept-swept samples at Junipero Beach needed for statistical confidence in the mean measured concentration difference. For reference to the measured differences at Juniper Beach, blue arrows indicate the measured concentration difference for Events 1 and 3 for (a) TSS and (b) TP, and the average concentration difference for (c) total PAHs.

Neonicotinoid and Fipronil Pesticides

The results for pesticide analytes detected in runoff samples from all three events and pavement conditions are summarized in Figure 19. Out of the 25 analytes, 9 were detected above the reporting limit, while the remaining 16 were not detected in either swept or unswept across all three events. Fipronils, Imidacloprid, and Piperonyl butoxide concentrations measured in this study were the only analytes that were consistently above detection limits for all tests and pavement conditions. Among the detected analytes, Imidacloprid was found at 6.82 ng/L in one of the equipment blanks, and piperonyl butoxide [5] was detected at 3.4-4.14 ng/L in both equipment and tap water blanks. These results are consistent with a previous study by the City of Santa Barbara (2017), where Imidacloprid was detected in 8 of 12 samples, with detected concentrations ranging from 4-28 ng/L. These data contribute to a growing body of knowledge on the occurrence and prevalence of compounds that are infrequently monitored in urban runoff, yet pose an ecotoxicological threat in streams (Weston et al. 2014, 2015).

Concentration differences for analytes and data pairs above detection limits are summarized in Figure 20. Fipronils in swept pavement runoff were consistently less than unswept pavements, with 27-40%-differences observed as falling in a similar range as conventional pollutants.

[5] Noted this compound is a synergist, rather than a pesticide itself.

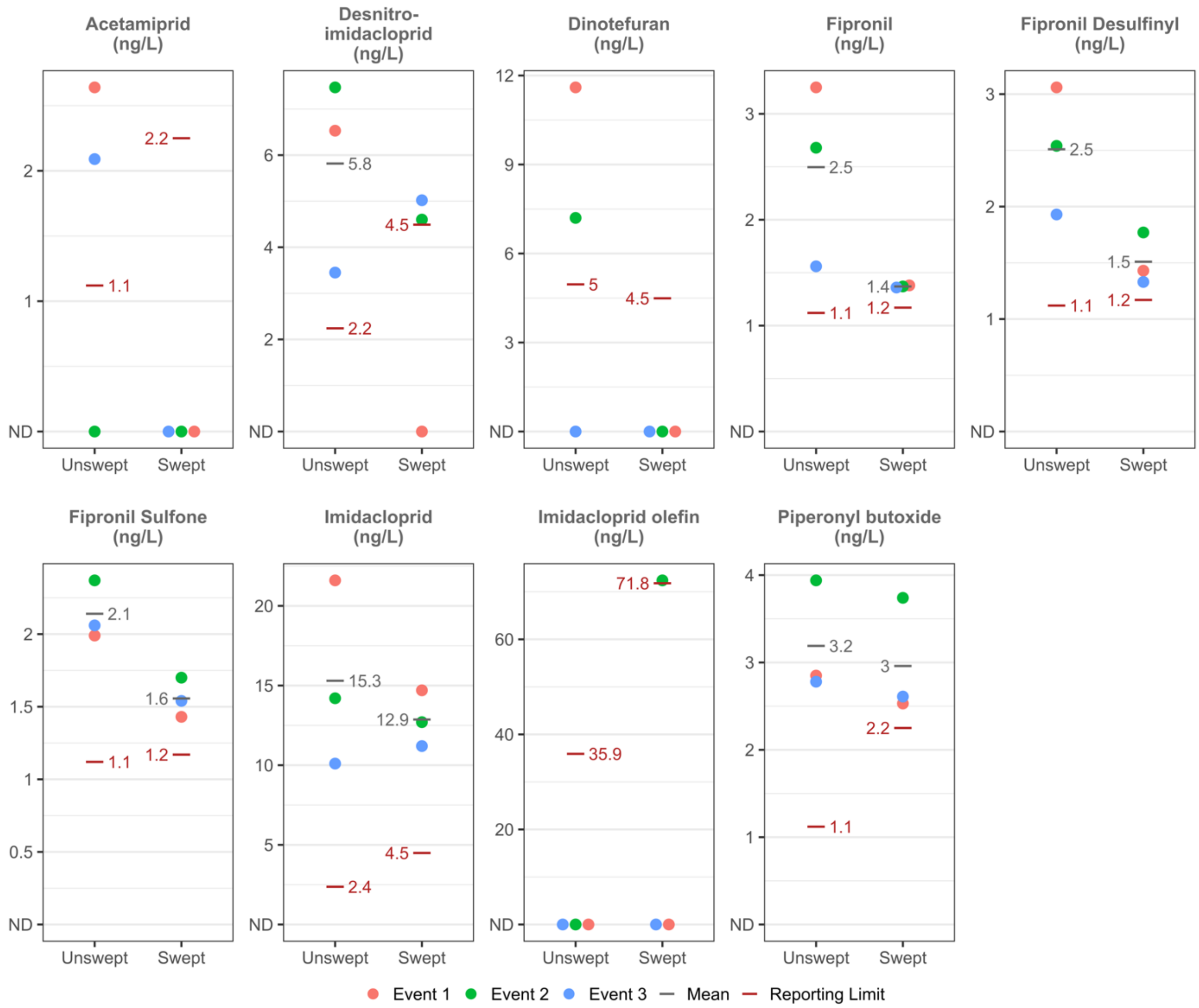


Figure 19. Summary of neonicotinoids detected in runoff samples from all three events, both from swept and unswept segments. Mean values are shown only when results from all three events exceed laboratory reporting limits. Analytes for which all six results were below the reporting limit are not included.

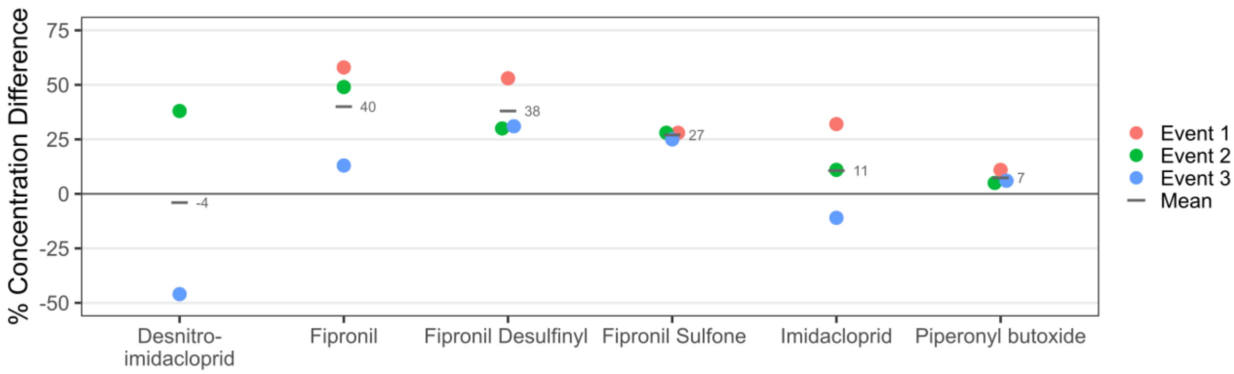


Figure 20. Concentration differences for neonicotinoids between unswept and swept pavement runoff. Only paired results (both unswept and swept) with concentrations above the reporting limit are included. Data points above zero indicate higher concentrations in unswept pavement runoff

Cell Bioassays

Cell bioactivity was measured in all runoff samples collected for unswept and swept pavements (Figure 19). AhR bioassay responses ranged between 0.25 and 0.66 ng TCDD equivalent/L, indicative of the presence of PAHs and other dioxin-like chemicals. ARE bioassay responses, that inform the presence of oxidative stress-inducing chemicals, were between 113 and 489 µg tBHQ equivalent/L. Neurotoxicity bioassay responses indicated inhibition of neurite outgrowth at concentrations equivalent to 421 to 1290 ng narciclasine equivalent/L. Bioactivity levels were within the range of cell bioassay data reported in previous California watersheds and elsewhere. A SMC-funded study showed that over half of the water samples from urban sites had AhR bioactivity levels between 0.2 and 1 ng TCDD eq/L (Mehinto et al. 2017). Tang et al. (2013) observed the highest levels of AhR bioactivity (> 10 ng TCDD eq/L) and ARE bioactivity (up to 400 µg tBHQ eq/L) at the study site characterized with major roads and heavy traffic. Lee et al. (2022b) found inhibition of neurite outgrowth (28 to 6038 ng narciclasine eq/L) in surface water samples collected in agricultural areas during rain events.

Bioassay results were also used to assess the removal efficiency of chemical mixtures, knowns and unknowns. Events 1 and 3 showed an average reduction of 25% in AhR bioactivity, 40% reduction in ARE bioactivity, and 46% reduction in neurotoxicity. Event 2, however, produced inconsistent results with a mean 14% increase in AhR bioactivity, 10% reduction in ARE bioactivity, and no change in neurotoxicity between unswept and swept pavements (Figure 20). The response patterns were consistent with the targeted chemistry results (Figure 15). Both chemical and bioscreening data showed high pollutant reduction in Event 3, while the effectiveness of street sweeping during Event 2 was more variable.

A positive correlation was observed between the AhR bioassay and concentrations of select PAHs (Figure 15) (Pearson correlation R^2= 0.88). However, the specific PAH congeners measured explained only 2 to 7% of the cell bioactivity detected. This indicates that most co-occurring chemicals with toxicity potential were not measured in these runoff samples. Similarly, the targeted chemistry data did not explain the levels of oxidative stress and neurotoxicity measured. This is not surprising as the ARE bioassay is sensitive to a variety of chemical classes including personal care products, pesticides, and transition metals (Liang et al. 2024). The neurite outgrowth bioassay showed promise as a general neurotoxicity screen but did not show a strong sensitivity to fipronils or neonicotinoids targeted. The other published study for this bioassay reported that 0 to 4% of the bioactivity could be attributed to detected environmental chemicals (Lee et al. 2022b). In conclusion, all three bioassays provided a more comprehensive screen of known and unknown bioactive chemicals for unswept and swept pavements. However, additional analysis would be needed to identify the specific chemicals of concern.

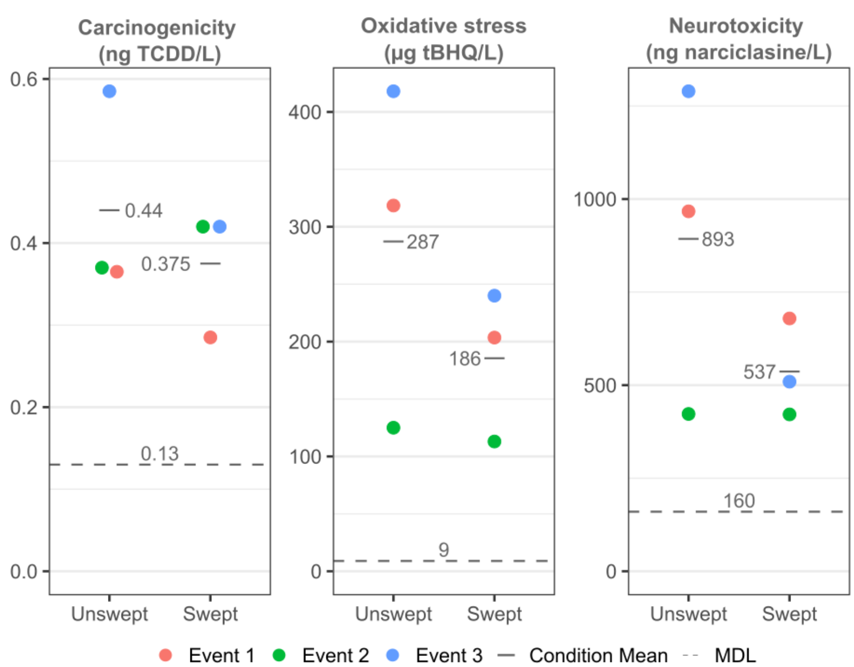


Figure 21. Event mean carcinogenicity (AhR), oxidative stress (ARE), and neurotoxicity cell bioassays responses.

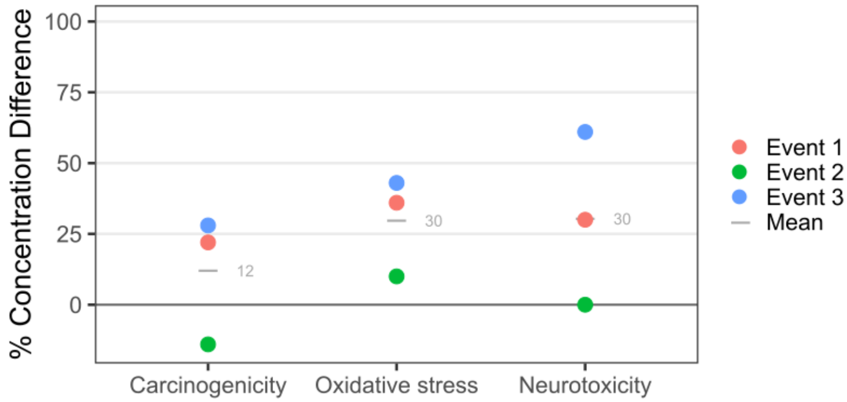


Figure 22. Differences in cell bioassay responses between unswept and swept pavement runoff. Data points above zero indicate higher response in unswept pavement runoff.

Microplastics

Few studies quantifying microplastics in urban runoff have been published to date, and each study adopts a different approach to sample collection, analysis and reporting (Österlund et al. 2023). In the spirit of consistency with the only known microplastics standards, which were developed for drinking water analysis and reporting, the current effort initially adopted the approach of determining and reporting particle counts, concentrations, and polymer identifications by size fractions (Thornton Hampton et al. 2023). The substantially greater abundance of microplastics in the Junipero Beach runoff created herein compared to drinking water resulted in several adaptations for reporting results herein.

Meaningful analytical results were only obtained for Event 3, despite sample collection during all events. Particles in larger size fractions (≥ 355 µm) were analyzed and are reported as counts, concentrations, and with identifications for Event 3 (Table 6 and Figure 20). Particles from smaller size fractions (125 µm, 63 µm, and 20 µm) were present in such high concentrations (Figure 19) that individual counting was not feasible. Consequently, these results are reported as mass of total microplastics.

The results from the single paired sample in Event 3 might suggest that street sweeping is effective only for smaller size fractions, with a 55% reduction in microplastics particle mass for size fractions <355 µm (Table 7). Among <355 µm fractions, the particle composition predominantly consisted of blue fragments, identified as polypropylene. Extensive photo documentation from the testing on the day of Event 3 did not reveal a likely source of blue polypropylene. No difference was observed in particle counts or concentrations for size fractions ≥355 µm; however, the composition of the types of microplastics showed a dramatic difference where 44% were identified as polyethylene in the unswept samples but 59% were rayon in the swept samples.

Samples from Events 1 and 2 revealed a high concentration of orange particles, visible to the naked eye (Figure 21). The source of the particles was traced to the concrete-filled plastic buckets used to anchor the windscreen, which was shifted by hand as needed throughout the day to continually face upwind of the RFG set-up (Figure 3b). Although the buckets were never directly rained upon, the windscreen was inadvertently moved upwind as the RFG was shifted amongst pavement segments, meaning that particles were shed over pavements that were subsequently subjected to rainfall. These samples were not considered representative of the pavement condition, thus analyses were not completed. In Event 3, the buckets were placed atop furniture dollies to facilitate repositioning, and avoiding contact with the pavement, and providing important procedural considerations for future studies.

Table 6. Summary of microplastics (MP) concentrations in >355 µm size fractions.

Street Condition	Sieved Sample Volume (L)	Microplastic Count (# of plastic particles)	Microplastic Concentration (MP/L)
Unswept	106	89	0.84
Swept*	59	50	0.85

*The swept pavement condition was field-sieved into split, duplicate samples. The total volume of sample sieved for the swept pavement condition was 117 L. Analytical results are averaged.

Table 7. % Difference of microplastics concentrations between swept and unswept samples in <355 µm size fractions.

Size Fraction	Unswept Concentration (mg/L)	Swept Concentration* (mg/L)	% Difference
125 µm	0.224	0.064	71
63 µm	0.041	0.059	-44
20 µm	0.068	0.027	60
All	0.33	0.150	55

* Average of sample duplicates

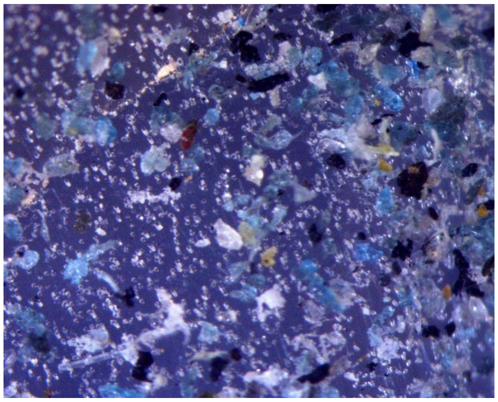
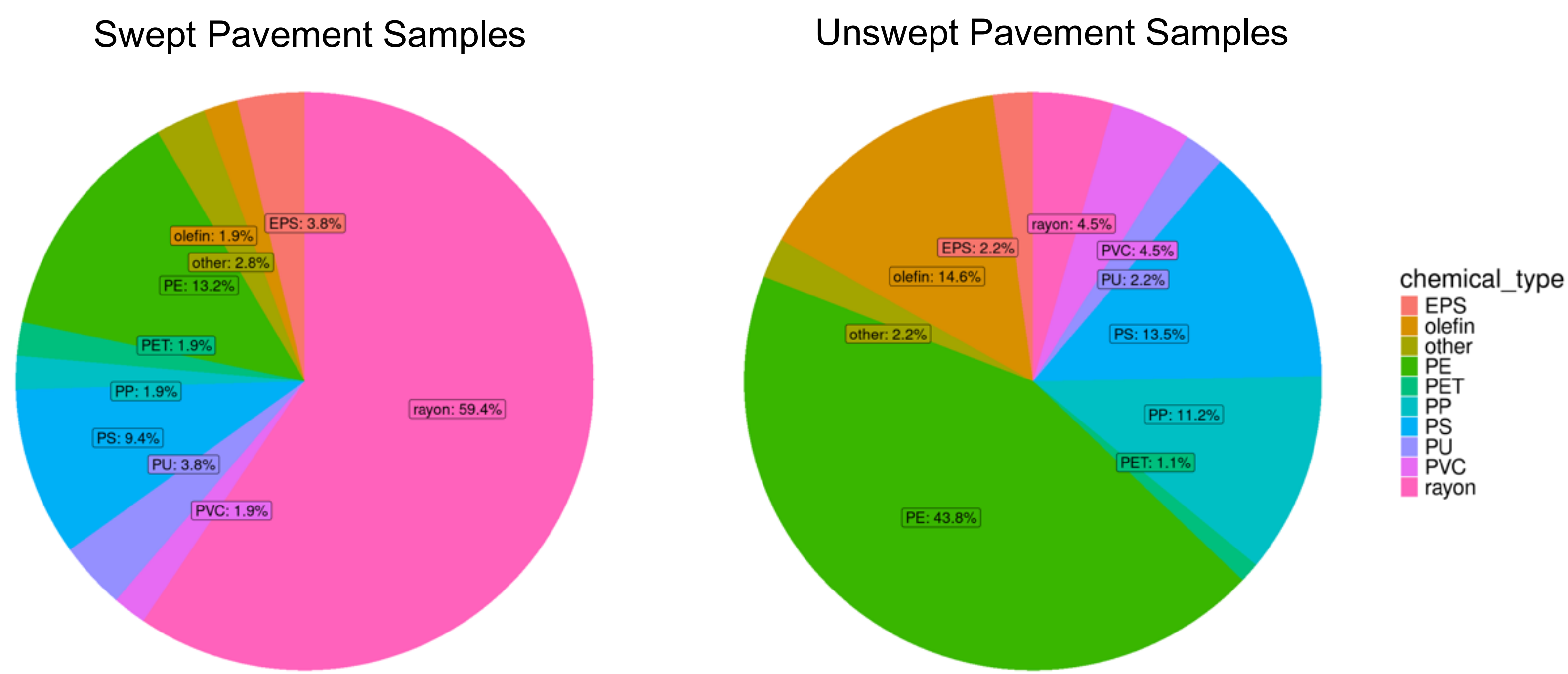


Figure 23. Extremely high polypropylene content in all Event 3 samples with size fractions ≤ 125 μm inhibited discrete quantification and polymer identification using typical methods. The photo was captured during microscopy of the 63 μm fraction.

As sampling and analysis of microplastics is a novel undertaking, useful lessons learned warrant documentation for future field work include:

1. Multiple sieve stacks should be available on each day of testing. Ideally, it is recommended to have at least one stack of sieves available for each runoff sample, and potentially an extra sieve for the smaller size fractions. Sieve cleaning in-situ is feasible, but extremely time consuming. This was a limiting step in the overall logistics of each day of testing. Additionally, extra sieves for smaller size fractions can help replace clogged sieves, further saving time by avoiding having to clean them mid-processing.
2. All plastic equipment used in the field should be tested in advance for microplastic shedding to prevent contamination. The RFG assembly was evaluated for microplastics' shedding during development without the windscreen. This resulted in identifying a critical logistical step requiring the assembly to be completely emptied of water between uses. Residual water was shown to have measurable microplastics counts when later flushed out of the assembly. Alternatively, a flush of the RFG assembly prior to setting into testing position is recommended. Plastics are largely unavoidable in creating a cost-effective RFG. Comparison of tap and equipment blank samples (Appendix E) suggests that despite precautions, the assembly does shed very small microplastics, as indicated by particle counts (especially those ≤ 20 μm). Nevertheless, the abundance of the blue polypropylene particles (Figure 19) substantially exceeded the minimum detectable number required for valid analysis and interpretation (Table E1).
3. Plastic particle deposition is ubiquitous. Any plastic materials used in the deployment must be lifted when moved, never dragged, or is ideally never brought into contact with the pavement.



Abbreviation	Polymer Name
EPS	Expanded polystyrene
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride

Figure 24. Polymer identification for ≥ 355 µm fraction microplastics from Event 3.

(a)  (b) 

Figure 25. (a). Orange particles suspended in MAG water following extraction and (b) after filtration.

Conclusions and Recommendations for Future Study

The primary study objective was to develop a viable field method to measure potential differences in runoff water quality from unswept and swept pavements. The approach adopted was to develop an RFG to apply simulated events over unswept and swept pavements in close proximity to each other, collect runoff from each condition, and compare water quality for a range of analytical parameters. The method was repeated over three events in the same parking lot at Junipero Beach (City of Long Beach), each following a 2-week antecedent dry period and time since last sweeping.

Does the SCCWRP RFG produce repeatable rainfall conditions that generate representative runoff water quality?

Yes. The RFG developed successfully produces repeatable, uniform rainfall with a kinetic energy similar to values in the literature for Mediterranean climates similar to southern California. The runoff generated mobilizes pollutants and creates runoff water quality representative of "freeways" (Figure 15).

Does the method developed herein provide evidence to suggest that street sweeping reduces pollutant concentrations in runoff? Is further study warranted?

Yes. Results indicate that street sweeping on average reduces the concentrations of a range of conventional, common stormwater quality parameters including total suspended solids, total phosphorus, total nitrogen, total PAHs, and total coliform, as well as some emerging contaminants of concern including neonicotinoid pesticides. The difference in measured concentrations on average ranged approximately 20-50% for most conventional pollutants considered and fipronyls (Figure 17 and Figure 20). The difference in average TSS concentrations between unswept and swept pavements was 13% for the three events. Microplastics smaller than 125 μm were removed by street sweeping (Table 5), based on a single sample. Altogether, pilot data indicate that street sweeping likely reduces pollutant concentrations. Additional field testing would be required to determine the crediting amount for NPDES MS4 permits.

Quantitative results obtained in the parking lot herein may differ from testing in a municipal street due to elements of the pilot study design. The parking lot lacks a typical street's curb and gutter system, where debris is known to accumulate. The full area over which the RFG was applied was swept, whereas typical street sweeping may be limited to the lane along the curbline in a street, excluding some lanes of traffic. Future applications should be designed to account for these differences if/where they occur.

What water quality parameters should be measured in future testing?

The TWG generally concurred that the analytes considered herein were of continued interest, in particular TSS, metals, nutrients, FIB, and microplastics. Other analytes such as emerging contaminants and cell assays are easily included in a scope when they do not impose burdensome sampling methods, such as the pesticides and toxicity measured herein. Results from microplastics and TSS analysis indicate that particle size distribution for the sample as a whole should also be measured. Measuring particle size distribution is anticipated to provide insight into sweeper technology effectiveness as well as potential influences of the surrounding catchment (e.g., the high sand load at Junipero Beach minimizing measured TSS removal compared to what might be measured in catchments with finer soils that may exhibit greater air entrainment from neighboring properties and subsequent deposition on pavements).

What is the effort required to conduct testing?

The size of the testing area needs to be balanced with the expected number of events to occur in a single testing day. Runoff was generated herein from approximately 19.5 m^2 (210 ft^2) per pavement condition, per event. This was achieved through applying 15-min of simulated rain consecutively on adjacent pavement segments, i.e., a total of 45-min of rainfall per pavement condition, per event. The size of the testing area, rainfall duration, and all other logistics required for set-up, operation, sample collection and equipment break-down enabled at most 4 total tests per 14-hr day.

Two modifications are suggested that might improve logistics. A significant time limitation arose from the need to refill the IBC tote with a garden hose. The size of the test area could be increased if a more efficient water supply were available, for example water truck delivery to the testing location. A second improvement would be to modify the RFG to rain over a larger footprint, or to operate multiple RFGs concurrently. Either modification to the RFG operation would also require a larger water supply.

How many tests should be conducted per location?

Statistical power analysis of representative pollutants suggests that 4-6 sample pairs would be needed at Junipero Beach to provide statistical confidence in the measured differences in runoff water quality between unswept and swept pavements. This estimate is unique to the Junipero Beach location, because power analysis is valid only for the measured variance – if or where other locations show greater variability between replicated tests, they might require more event pairs to generate statistical confidence in results. However, a minimum of 4-6 sample pairs was identified for three different pollutants to establish concentration differences between 20 and 40%, and thus suggests a good starting point for future testing.

How many locations should be tested?

Identifying testing locations requires detailed investigation and planning. Critical elements limiting site identification were the availability of a water supply in close proximity and perhaps more importantly, availability of an advanced sweeper technology such as those that employ a vacuum and/or pressure washing. Mechanical broom sweepers were excluded from consideration due to repeated studies that identified inferior debris collection compared to advanced technologies (Appendix A). Availability of a water truck to deliver water to a testing site would open up wider possibilities for future site selection.

For many member agencies, TWG representatives discovered that various aspects of their street sweeping program fell under the responsibility of multiple departments. Few, if any member agency was easily able to identify the extent or specific locations where street sweeping currently occurs. To develop a practical work plan for testing at multiple locations and addressing identified priorities to evaluate, SMC member agencies should first collate an inventory of their existing street sweeping programs (e.g., existing coverage, responsible departments, etc) cross-referenced to pavement maintenance programs. Available street sweeping equipment should be investigated, although it is acknowledged that some vendors offer sweeper rental programs.

What potential influences on street sweeping effectiveness should be incorporated into future study designs?

The TWG identified at the study outset a broad range of environmental, site, and sweeper conditions that might influence the effectiveness of street sweeping (Table 2). Recognizing the practical implications of a large scale study, and the outcomes from the literature review (e.g., effectiveness of advanced sweeper types compared to mechanical broom sweepers in accumulating debris), the TWG further prioritized factors to investigate in a larger scale, multi-location study in order as:

1. Average daily traffic (ADT)
2. Road surface condition/level of service
3. Sweeping and rainfall frequency (this pilot study tested bi-weekly sweeping and "rainfall")
4. Sweeper operation - # passes
5. Sweeper operation – vehicle speed

Other factors were considered, but did not rank highly as a group prioritization. These factors included:

- Land use in the surrounding catchment, because of the potential for pollutant deposition onto the street.
- Road classification or level of use, implying loading is attributed to the types of vehicles most often using the road.
- Pavement material, e.g., asphalt vs. concrete
- Sweeper type, by manufacturer or operation

To focus the scope and cost of a future study, the specific methods and assumptions supporting existing pollutant load reductions in permits should be reviewed – i.e., the SMC should determine if these influences aligned with permit assumptions, and thus confirm priorities for testing, or explore whether an alternative approach is scientifically warranted.

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Weston, D.P., and M.J. Lydy. 2014. Toxicity of the Insecticide Fipronil and Its Degradates to Benthic Macroinvertebrates of Urban Streams. *Environmental Science & Technology* 48, 2 (2014): 1290–97. https://doi.org/10.1021/es4045874.

Zambon, N., L.L. Johannsen, P. Strauss, T. Dostal, D. Zumr, T.A. Cochrane, and A. Klik. 2021. Splash erosion affected by initial soil moisture and surface conditions under simulated rainfall. *CATENA*, *196*, 104827. https://doi.org/10.1016/j.catena.2020.104827

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APPENDIX A. ANNOTATED LITERATURE REVIEW – PUBLISHED STREET SWEEPING STUDIES

Appendix A

Annotated Literature Review of Non-Structural Best Management Practices

Introduction

The annotated literature review herein focuses on documenting studies that link the implementation of a non-structural best management practice to urban runoff or in-stream water quality impacts, if/where feasible. The literature was sourced from published journal papers and limited gray literature (i.e., reports conducted by municipal or regional agencies found online). Empirical studies conducted at field scale were prioritized for review. Uncalibrated model studies were excluded.

Studies are organized categorically as

Within each category, studies are reviewed in reverse chronological order. This may be particularly relevant for street sweeping studies, since street sweeper technology has changed.

Public Education / Outreach / Participation

Gray, S.S., Brown, C., Haimann, R., Quinn, A. (2015). Non-Structural Best Management Practice Pollutant Load Reduction Estimation Method. WEFTEC2015, Chicago, IL, Sept. 26-30.

Study objective

Quantify the pollutant loading reduction that may arise from outreach and education to be applied to TMDL wasteload allocations in five San Diego watersheds.

Methods

- Best professional judgement based on literature review, practical experience, and stakeholder input.
- A framework was developed for calculating the effect of behavior change based on the literature review, which included studies on public perceptions and behavioral change and several Center for Watershed Protection studies (including analogies between qualitative non-structural BMP recommendations and quantitative structural BMP assessments).
    - The framework adjusts factors depending on scope of education and outreach program, assigns high-medium-low- or no pollutant removal potential, and the extent to which each BMP has the potential to control a polluting behavior.
    - The pollutant removal potential for each non-structural BMP was considered for specific pollutants, for example, pet waste programs were assumed to influence only bacteria and nutrients.

Main Findings

- The framework was applied to 80 nonstructural BMPs under consideration for the City of San Diego's Water Quality Improvement Plans for five watersheds.
- Public education and outreach primarily promotes problem awareness, which is the largest component in the path towards behavior change, after "intention" to undertake a behavior. Problem awareness is attributed to a potential for 18% behavior change.
- The framework represents a quasi-subjective assessment derived from mostly reasonable assumptions and a process described that results in quantitative values.
- The authors specifically call-out a need for direct measurement.

Limitations

- Considered water chemistry only, excluding physical or biological benefits of nonstructural BMPs.
- The heavy influence of professional judgement suggests that a qualitative or categorical approach for ranking pollutant removal may have been more appropriate, recognizing that the objective was to develop quantitative outcomes for use in wasteload allocations.
- A list of assumptions and limitations are provided.

Other Comments

- Substantial literature exists on behavior change applied across many different fields.
- Behavior or attitude change itself may not always directly translate to water quality improvement, but can lead to support for institutional programs or policies that do.

Penn, J., Hu, W., Cox, L, Kozloff, L. (2014). Resident and Tourist Preferences for Stormwater Management Strategies in Oahu, Hawaii. *Ocean & Coastal Management* 98(2014) 79-85. http://dx.doi.org/10.1016/j.ocecoaman.2014.06.002

Study objective

Measure residents' and tourists' preferences and willingness to pay for different approaches to stormwater management in Hawaii.

Methods

- Choice experiment (survey) that included broad categories of non-structural BMPs, structural BMPs, warnings & advisories, water quality testing, and education. Some examples of what activities fall under each category were given in the survey. Information on stormwater pollution and its connection to beach recreation were also provided to participants. Willingness to pay was presented as a household wastewater fee for residents, and an airport transit fee for tourists.
- A limited cost-benefit analysis of augmenting water quality strategies was conducted. The costs were determined through consultation with individuals in the local government. Benefits were based on willingness to pay by respondents, rather than water quality improvement potential.

Main Findings

- Residents and tourists rank water quality testing and education as 1 & 2, respectively.
- The survey results indicate value of information sharing to garner and maintain public support because the authors acknowledge that structural and non-structural BMPs are more effective for water quality improvement.

Limitations

- Very limited detail on cost-benefit analysis.

Other Comments

N/A

Kaplowitz, M. and Lupi, F. (2012) Stakeholder Preferences for Best Management Practices for Non-Point Source Pollution and Stormwater Control. *Landscape and Urban Planning*, 104 (2012) 364-372. doi:10.1016/j.landurbplan.2011.11.013

Study objective

Measure residents' preferences for a variety of mostly structural BMPs, and identify BMP combinations likely to be supported by local stakeholders in a Michigan watershed.

Methods

- Choice experiment (survey) amongst six types of BMPs, applied to specific landscape zones. Only the "streambank" landscape included nonstructural BMPs of streambank naturalization and /or rip rap armoring. The remaining BMPs included dry basins, wet ponds, wetlands, and filter strips for uploadn and lowland areas.
- All BMPs were assumed equally effective for water quality treatment.

Main Findings

Streambank naturalization was preferred by far by residents over rip rap.

Limitations

All BMPs were assumed to provide equal water quality treatment.

Other Comments

- An extensive literature review provided on the topic of engaging the public or stakeholders in decision-making, and how to measure stakeholder preferences for BMPs.
- The literature seems to be plentiful on how to influence and measure behavior change.

May, C.W. and Horner, R.R. (2004). The Limitations of Mitigation-Based Stormwater Management in the Pacific Northwest and the Potential of a Conservation Strategy based on Low-Impact Development Principles. 9th International Conference on Urban Drainage, Portland, Oregon September 8-13, 2002.

Study objective

Discussion paper on conservation practices as non-structural BMPs.

Methods

Undocumented discussion paper based on authors' professional experience.

Main Findings

- The paper presents limited data on the index of biological integrity via citations (not new work).
- Retention of native forest & wetland cover, minimizing impervious surfaces, and wide continuous riparian buffers are important practices for maintaining / protecting biological integrity in streams in the Pacific Northwest.

Limitations

- No data nor discussion on water chemistry.
- The existing level of development in southern California renders the discussion of limited practical value for most SMC member agencies.

Other Comments

N/A

Keller, Brant D. (1999). Griffin, Georgia's Stormwater Utility "A Non-Structural Best Management Practice (BMP)". Proceedings of the 1999 Georgia Water Resources Conference, Athens, Georgia, March 30-31, 1999.

Study objective

Describe the successful creation of a stormwater utility in City of Griffin, GA, to ensure funding for future stormwater improvements, in anticipation of NPDES Phase II.

Methods

The process to develop the utility including preparation (identifying the city's infrastructure needs with respect to stormwater), concept development (feasibility study), detailed analysis (policy and financial analysis), data and systems implementation (logistics of calculating charges, invoicing and receiving payments), and public information and education (supporting implementation).

Main Findings

Forward-looking paper outlining what the utility will accomplish at a high level.

Limitations

The paper is about funding the utility, not measuring water quality benefits.

Other Comments

N/A

Street Sweeping

Lloyd, L.N., Fitch, G.M., Singh, T.S., and Smith, J.A. (2019). Characterization of Environmental Pollutants in Sediment Collected During Street Sweeping Operations to Evaluate its Potential for Reuse. *Journal of Environmental Engineering* 145(2): 04018141.
https://doi.org/10.1061/(ASCE)EE.1943-7870.0001493

Study objective

Measuring sediment-attached concentrations of heavy metals, PAHs, and oil & grease in road-deposited sediments to consider alternatives for reuse or limitations on disposal.

Methods

- 79 sampling locations throughout Virginia, organized by ADT and land cover in the catchment. Only samples from the higher ADT locations were sieved for pollutant attachment according to particle size. PAH analysis was conducted for samples from 27 locations.
- Vacuumed road sediment during dry weather after at least 2 antecedent dry days. The vacuum was a 5-gal, 4.5 hp wet/dry vacuum with removal efficiency claimed equivalent to a regenerative air sweeper.
- Samples analyzed for metals, PAHs, and O&G.

Main Findings

- Concise tables of average heavy metals concentrations and PAHs from this and other studies.
- ADT cannot be used as predictor of heavy metals, PAHs, or O&G concentrations.
- Land use in a catchment is not a consistent predictor of heavy metals or PAHs, but is reasonable for O&G.
- Increasing concentrations with decreasing particle size were measured for heavy metals and PAHs.

Limitations

- The sampling method may not capture all particles < 75 um.
- Runoff concentrations were not measured.

Other Comments

- Largest sampling effort for a single study noted amongst the literature.
- Tables summarizing this and previous study outcomes are well presented if/when sediment-attached pollutant concentrations are of interest.

Pearson, B.J., Chen, J. and Beeson, R.C. (2018). Evaluation of Storm Water Surface Runoff and Road Debris as Sources of Water Pollution. *Water Air Soil Pollution* (2018) 229:194.
https://doi.org/10.1007/s11270-018-3793-2

Study objective

1. Quantify road debris as a source of nitrogen (N) and phosphorus (P)
2. Quantify N and P in stormwater
3. Determine if street sweeping influences N and P in stormwater

Methods

- 6 sampling locations amongst three community types in Florida: 3 new (< 10 yrs) residential, 2 established (> 10 yrs) residential, and 1 established mixed-use commercial/high density residential
- Monthly street sweeping occurred on one side of a street using a Pelican, Elgin sweeper. Sampling of road debris was also performed monthly using a hand-held vacuum along a one-meter segment of swept and unswept sides of the street.
- First-flush samples collected from 36 catch basins on swept and unswept sides of the same street. Rainfall samples were collected once in each location. Multiple storm events were collected from each location.
- Samples were analyzed suite of nitrogen and phosphorus forms.

Main Findings

- Street sweeping effectively reduced the volume of roadway debris, but did not find that it reduced nitrogen or phosphorus in stormwater.
- There was no significant differences between swept and unswept runoff samples collected at catch basin inlets, nor when samples were grouped by community type.
- The mean and standard deviation runoff concentrations from each of the six communities monitored is presented in tabular form. Swept and unswept runoff data are pooled. Ranges amongst the six communities monitored are:
  - 1.23 mg/L $\leq$ TKN $\leq$ 3.69 mg/L
  - 0.19 mg/L $\leq$ NO_x $\leq$ 1.00 mg/L
  - 0.40 mg/L $\leq$ TP $\leq$ 0.93 mg/L
  - 0.16 mg/L $\leq$ Ortho-P $\leq$ 0.61 mg/L

Limitations

- Whether areas other than the roadway contributed runoff to the catch basins was not reported.
- The timing of sample collection with respect to street sweeping was not reported.
- The leaching potential of sediment-attached nitrogen and phosphorus should be measured to associate effectiveness of street sweeping with the potential to reduce pollutant loads.
- Differences were not found between mean precipitation and runoff concentrations, except for two ortho-phosphorus from two communities. It is considered unusual that nutrient concentrations in precipitation would not differ from urban runoff at a catchment scale.

Other Comments

The literature review presents many citations on the concentrations of contaminants attached to road debris.

Schueler, T., Giese, E., Hanson, J., Wood, D. (2016). Recommendations of the Expert Panel to Define Removal Rates for Street and Storm Drain Cleaning Practices. Report to the Center for Watershed Protection.

Study objective

An expert panel developed recommendations for consideration by the Chesapeake Bay Program on how sediment and nutrient removal credits are calculated for street and storm drain cleaning based on a combination of the most recent 10 yrs' publications and modeling with WinSLAMM.

Methods

- The expert panel reviewed new research conducted over the previous ten years on (a) nutrient and sediment loading from streets, roads and highways (b) the particle size distribution and nutrient, carbon and toxic enrichment of urban street dirt and sweeper waste, and (c) ten recent research studies that evaluated the effect of different street sweeping scenarios on different street types across the USA.
- A modeling approach using WinSLAMM was adopted to derive sediment and nutrient reduction rates for street sweeping, given the absence of studies with empirical evidence supporting measurable differences between water quality from swept and unswept streets. WinSLAMM was selected in part because it has been calibrated using empirical data on street solid build-up and wash-off.

Main Findings

- Road runoff has moderately higher nitrogen concentrations than other forms of impervious cover.
- The accumulation rate, particle size distribution and pollutant content of street solids follows a relatively consistent and uniform pattern across the USA. These relationships provided an empirical basis for modeling how solids are transported from the street to the storm drain.
- Street cleaning may be an "excellent" strategy to reduce the toxic inputs from urban portions of the Chesapeake Bay watershed, given the high level of toxic contaminants found in both street solids and sweeper wastes.
- The water quality impact associated with street cleaning will always be modest, even when it occurs frequently. Mechanical broom sweepers have little or no water quality benefit. Advanced sweeping technologies, however, show much higher sediment reduction potential.
- Street parking and other operating factors can sharply reduce sweeper pick-up efficiency.
- The adjacent tree canopy influences the organic and nutrient loads on the street on a seasonal basis, but the management implications for this phenomenon are unclear.
- The ten sweeper studies 2006-2016 have produced a lot of quantitative data on the sediments and nutrients that are picked up by sweepers, but none were able to measure a detectable water quality change within storm drains that can be attributed to upland street cleaning. One key reason is the high variability that often occurs in street runoff can outweigh a measurable signal due to street cleaning. To date, researchers have been unable to collect enough paired stormwater samples to detect a statistically significant difference due to treatment. Consequently, most researchers now rely on simulation or mass balance models to quantify the impact of street cleaning.

- A spreadsheet tools was developed to consolidate results for removal rates for different street cleaning practices (primarily technology type and cleaning frequency). Additional credits were developed for catch basin cleaning.

Limitations

No new data collected.

Other Comments

The panel also recommended a long term research strategy to provide managers with the better data to improve the effectiveness of future street and storm drain cleaning programs.

City of San Diego. (2010-2015). Street Sweeping Pilot Study. Phase I – V. Individual reports accessible online: https://www.sandiego.gov/stormwater/pilot-projects/streetsweeping

Study Objective

The City of San Diego undertook a 5-phase pilot study to

Method

Main Findings

- **Frequency of sweeping**: Increased sweeping frequency using vacuum-assisted sweepers provided a linear increase in debris removal benefit. That is, additional sweeping with the vacuum-assisted sweeper resulted in similar debris removal rates at both the once-per-week and twice-per-week sweeping frequencies. Mechanical sweepers were less effective at debris removal on a weight-of-debris-removed-per-mile-swept basis when sweeping was conducted twice per week as opposed to the standard once-per-week frequency.
- **Sweeper types:** Vacuum-assisted sweepers are generally more effective than the regenerative air and mechanical sweepers at removing debris and especially fine particulates. Site-specific variations in roadway surface condition, roadway grade, and presence of a curb and gutter may have limiting impacts on vacuum-assisted machine performance. Vacuum-assisted sweeper performance declines on sloped streets.
- **Median sweeping:** Initial median sweeping event collected three to five times more debris than subsequent three-week-interval sweeping events. This suggests that a significant buildup of roadway debris occurs within and adjacent to median areas. The results also indicate that debris collected from median areas is similar in pollutant concentrations to the curb and gutter areas on the shoulder edge of the roadway surface.
- **Speed efficiency** study indicate that the operational speed of mechanical street sweepers has little impact on the weight of debris collected in the field.

Limitations

Other Comments

Seattle Public Utilities and Herrera Environmental Consultants. (2009) Seattle Street Sweeping Pilot Study. Accessed online 05.30.2022:
https://www.worldsweeper.com/Street/Studies/Seattle2009/SPU2009Study.pdf

Study Objective

Evaluate whether street sweeping can significantly reduce the mass of pollutants discharged to area receiving water bodies while reducing the frequency of catch basin cleaning.

Methods

- Mass balance approach measuring debris remaining on streets after sweeping (street debris), debris removed by the sweeper (sweeper waste), debris accumulated in catch basins (catch basin sediment), and thus estimating debris exported off site via urban runoff (mass balance result).
- Street sweeping conducted bi-weekly (alternate side of the street sweeping means half of each street is swept weekly). Sweeping was suspended in control sites for the duration of the study. Sweeping was conducted by a regenerative air sweeper at ~5-7 mph.
- Field measurements conducted approximately every 4 weeks.
  - Street debris collected using an industrial vacuum on swept and unswept sides of the street 1-2 days prior to street sweeping.
  - Sweeper waste stored in dumpsters unique to each location, and weighed on an industrial scale after dewatering. Materials > 2 mm removed and tracked separately.
  - Sediment accumulation in 12 catch basins was determined by measuring down from the rim of the maintenance hole to the surface of the sediment.
  - Debris samples from each component composited quarterly for analysis.

Main Findings

- Street sweeping did not result in a measurable difference in catch basin accumulation, but catch basins were all less than 10% full at the time of the study.
- Street sweeping removed ~2200-3100 lb/acre/yr.
- Median monthly street debris yield at swept sites was 48-90% less than control (unswept) sites.
- The mass balance indicates street sweeping can reduce the amount of pollutants discharged to receiving waters.
- Cost estimates of street sweeping vs. cost of constructing regional facilities leans strongly in favor of increasing the frequency and coverage of street sweeping for per kilogram of dry sediment removed.

Limitations

Runoff water quality was not measured specifically citing previous studies that struggled to produce a measurable difference, and the estimated effort required according to a statistical power analysis.

Other Comments

N/A

Kang, J-H., Debats, S., and Stenstrom, M.K. (2009). Storm-Water Management Using Street Sweeping. *Journal of Environmental Engineering,* 135(7):479-489 https://doi.org/10.1061/(ASCE)0733-9372(2009)135:7(479)

Kang, J-H. and Stenstrom, M.K. (2008). Evaluation of Street Sweeping Effectiveness as a Stormwater Management Practice Using Statistical Power Analysis. *Water Science & Technology,* 57 (9): 1309–1315. https://doi.org/10.2166/wst.2008.270

Study objective

Use previously published data to determine if there is a statistical difference in outfall water quality between swept and unswept catchments.

Methods

- Conducted a post-hoc statistical power analysis of previously published data. The null hypothesis tested was *street sweeping does not cause reduction in EMCs at outfalls.*
- The investigation included 15 outfall EMC data sets for total suspended solids (TSS), suspended sediment concentration (SSC) or chemical oxygen demand (COD) in 13 locations from 4 previous street sweeping studies (NURP 1983; Austin, TX 1995; Boston & Milwaukee 2002). The original analysis of data from Austin, TX did find statistically significant differences in TSS at $\alpha = 0.01$.
- Compared end of pipe samples from swept and unswept catchments (either paired catchments or before-and-after samples)
- Treatments also considered type of street sweeper (mechanical broom vs vacuum assisted).

Main Findings

- No differences were detected between swept and unswept observations with statistical power.
- Results were attributed to a high coefficient of variation in the underlying data and overall small sample set.

Limitations

The newest data set considered is 20 yrs old.

Other Comments

- "…numerous studies to evaluate sweeping efficiencies, little evidence has been documented that street sweeping directly improves storm-water quality"
- Extensive literature review on the motivation for street sweeping and the debate over effectiveness, including a summary table of studies published 1972-2005, with main findings.

Muhammad, N. and Hooke, A.M. (2006). Diffuse Pollution in Oxford (Ohio, USA) Watershed and Performance of 'Street Sweeping' as a 'Best Management Practice' (BMP). *Journal of Water and Health,* 4 (3): 357–364. https://doi.org/10.2166/wh.2006.020b

Study objective

Measure outfall concentrations & street sweeper (sediment-attached) concentrations.

Methods

- Wet weather samples collected from 3 outfalls (representing residential, commercial, and high-traffic zones) in a single watershed in Ohio. 14 outfall sampling events; 3 grab samples collected at each outfall and composited.
- Street sweeping performed weekly. 4 street sweep sediment sampling events collected from the dump area of the sweepers
- Runoff and collected road debris were analyzed for total coliform, fecal coliform, fecal streptococci, heavy metals, BOD, COD, total and volatile solids.

Main Findings

- Outfalls showed the highest fecal indicators from the residential area and in spring. The outcome was hypothesized as due to lower vegetation cover. Swept debris contained high concentrations of indicator organisms, suggesting street sweeping was a useful preventative measure from pollutants entering surface waters.
- Heavy metals are predominantly sediment-attached (by far). Street sweeps showed significant accumulation, and thus an important removal mechanism. Outfall concentrations were considered low overall.
- BOD/COD and TS/VS data were less rigorously analyzed. The authors concluded that non-degradable organic matter was dominant in outfalls.

Limitations

- The fraction of each catchment that is roadway was not presented.
- Most explanations are hypotheses, e.g. more pets in residential zones, effects of colder or warmer temperatures.
- Lack of replication brings to question transferability of results (3 outfalls sampled, each with a different land use, albeit with 14 sampling events at each)
- A subjective interpretation of effectiveness of street sweeping is offered. Comparisons were not made against water quality standards or other benchmarks. A control catchment was not monitored.

Other Comments

Older studies of street sweeping may no longer be applicable as sweeper technology has evolved.

Street Cleaning

Gasperi, J., Rocher, V., Moilleron, R., Chebbo, G. (2005). Hydrocarbon Loads from Street Cleaning Practices: Comparison with Dry and Wet Weather Flows in a Parisian Combined Sewer System. *Polycyclic Aromatic Compounds*, 25:169-191, 2005.
https://doi.org/10.1080/10406630590930734

Study objective

Quantify street washing as a dry weather pollutant source.

Methods

- Evaluated water quality of wash water when using a pressurized water jet street cleaning procedure. All wash water was collected in a catch basin.
- 3 sampling campaigns occurred at two mixed use sites (high density residential with some commercial) in Paris, France.
- Samples were analyzed for a range of dissolved and particulate PAHs, *n*-alkanes, and unresolved complex mixture hydrocarbons (UCM).

Main Findings

- Street washing flushes more PAHs into the storm sewer compared to wet weather runoff events; however, it is less efficient in removing *n*-alkanes and UCM, based on comparison to previous studies at similar locations.
- Street washing did not fully remove available PAHs, but is considered a significant source of dry-weather PAHs.

Limitations

N/A

Other Comments

Street washing is not a relevant practice for southern California.

Catch Basin / Inlet Cleaning

Two reports in the Street Sweeping section (Center for Watershed Protection 2016, Seattle Public Utilities 2009) also include limited assessment of catch basin /inlet cleaning. The information is not repeated here.

Morgan State University and Center for Watershed Protection (2018). What's in Your Storm Drain Inlet? A Study to Characterize the Loads from Inlet Cleaning. Accessed online 02/28/2022 https://www.cwp.org/whats-in-your-storm-drain-inlet-a-study-to-characterize-the-loads-from-inlet-cleaning/

Study Objectives

Quantify the amount of nitrogen, phosphorus and sediment loads associated with material removed from catch basin inlets.

Methods

- 97 inlets were cleaned using a Vactor Truck 2100 Series over eleven sampling events on Maryland highways.

Main Findings

- Accumulation in catch basins is variable. Overall, the average composition of sediment, organic material and trash was 67%, 31%, and 4%, respectively (based on dry weight).
- Different densities of materials (vegetation vs trash vs sediment) makes it difficult to compare relative accumulation.
- Fewer than half of catch basins inspected required cleaning, operationally defined as when the pipe or chamber was > 25% full.
- Materials begin to accumulate once pipes in self-cleaning inlets become clogged.
- Seasonality of materials' accumulation provides opportunities to optimize maintenance scheduling that may yield increase in load reductions.
- Approximately 5 lbs of trash is removed each time an inlet is cleaned.

Limitations

The full project report was not accessible. Information here is pulled from the online summary.

Other Comments

N/A

Disconnected Impervious Area

Since Impervious Area Disconnection is uncommon in southern California water quality improvement plans and watershed management plans, only main findings from these studies are presented.

Epps, T. H. P. D. and J. M. P. D. Hathaway (2021). Inter-Event Water Quality Variability and Intra-Event Pollutant Dynamics in Context of Effective Impervious Area. *Journal of Sustainable Water in the Built Environment* 7 DOI: 10.1061/JSWBAY.0000953.

Main Findings

Effective impervious area a.k.a. directly connected impervious area is an indicator of urban stream health

- Disconnecting impervious area to allow infiltration and evapotranspiration decreases runoff rate and volume, and delays the timing off-site hydrographs at the site scale.
- Variability in pollutant loads to 3 urban streams is partially attributed to effective impervious area for multiple pollutants

Baruch, E. M., K. A. Voss, J. R. Blaszczak, J. Delesantro, D. L. Urban and E. S. Bernhardt (2018). Not all pavements lead to streams: variation in impervious surface connectivity affects urban stream ecosystems. *Freshwater Science* 37(3): 673-684.

Main Findings

Macroinvertebrate community composition and the tissue concentrations of Cu, Pb, and Zn in 3 stream invertebrate taxa (*Cambaridae, Tipulidae, and Hydropsychidae*) found across 7 urban stream sites were correlated with watershed hydrologic connectivity

Mueller, G. D. and A. M. Thompson (2009). The Ability of Urban Residential Lawns to Disconnect Impervious Area from Municipal Sewer Systems. *Journal of the American Water Resources Association* 45(5).

Main Findings

Runoff reduction tests and steady-state infiltration testing was successfully used to calibrate a model that predicted substantial stormwater management from urban residential lawns

Walsh, C. J., T. D. Fletcher and A. R. Ladson (2009) Retention Capacity: A Metric to Link Stream Ecology and Storm-Water Management. ***Journal of Hydrologic Engineering*** **14, 399-406 DOI: 10.1061/(ASCE)1084-0699(2009)14:4(399).**

Main Findings

Effective impervious area a.k.a. directly connected impervious area is an indicator of urban stream health.

Shuster, W. D., E. Pappas and Y. Zhang (2008) Laboratory-Scale Simulation of Runoff Response from Pervious-Impervious Systems. ***Journal of Hydrologic Engineering*** **13, 886-893 DOI: 10.1061/(ASCE)1084-0699(2008)13:9(886).**

Main Findings

Differences measured in runoff rate ratio between 0 and 25% impervious area connectivity, at the beginning of synthetic storms during laboratory experiments.

No additional benefits were observed with 50% impervious area connection

Appendix B. Rainfall Generator Testing to Satisfy Design Criteria

An air-induction (AI) nozzle from TeeJet was selected as the spraying nozzle for the SCCWRP RFG to produce a coarse droplet at a relatively low flowrate (Teejet 2014). The SCCWRP RFG was tested to ensure that the AI-TeeJet nozzle delivered near-natural rainfall characteristics according to Blanquies et al. (2003).

Kinetic Energy

The kinetic energy of simulated rainfall is important for representative pollutant mobilization; raindrops that impact the ground with more energy are more likely to erode soils and mobilize surface pollutants into runoff (Kibet et al. 2014; Nearing et al. 2017; Rončević et al. 2022). The kinetic energy of a falling raindrop is related to the mass of the droplet and the speed at which it falls, where smaller drops have a lower terminal velocity. From this, the issue with misty droplets is explained: the small-droplet simulated rainfall will underestimate the kinetic energy of the natural rainfall at the same intensity (Abudi et al. 2012). The kinetic energy from natural rainfall has been studied in depth, with a universal relationship with intensity given by Van Dijk et al. (2002).

$$\boldsymbol{e_{NR} = 28.3(1 - 0.52e^{-0.042*I}})$$

Equation B1

where e_{NR} is technically the kinetic energy *flux* [Joules per m^2 per mm of rainfall] and I is the rainfall intensity [mm/hr]. The kinetic energy flux of 32 mm/hr natural rainfall is estimated to be 24.5 J/m^{2}mm.

For simulated rainfall, the kinetic energy flux is typically estimated from Newtonian mechanics (Mineo et al. 2019; Petan et al. 2010) as

$$e_{RFG} = \frac{1}{2}\rho_{mm}\sum f_i {V_i}^2$$

Equation B2

where ρ_{mm} is the density of water in kg/m^{2}mm, commonly taken to be 1.0 (kg/m^{2}mm), f_i is the mass fraction in each drop size category, and V_i is the drop impact velocity (m/s). The impact velocity, often assumed to be the terminal velocity, of a spherical drop is related to the diameter (Foote & du Toit 1969). The kinetic energy flux of the SCCWRP RFG, then, is related to the drop size distribution (DSD) of water droplets produced by the AI-TeeJet nozzles. The "flour method” described in the subsequent section, was used to determine the DSD, while a drag-model for velocity was adopted to estimate the impact velocity of initially fast-moving droplets.

Flour Method

The flour method involves briefly exposing uncompacted wheat flour to the simulated rainfall to create pellets that, when dried, sieved, and weighed, relate back to the size of the droplet that produced them (Egodawatta 2007; Hudson 1963; Kathiravelu et al. 2016; Mazon & Viñas 2013). Steps in conducting the test at SCCWRP are shown in Figure 26.The cumulative distribution function (CDF) derived from two flour tests of the AI-TeeJet nozzle are shown in Figure 27.

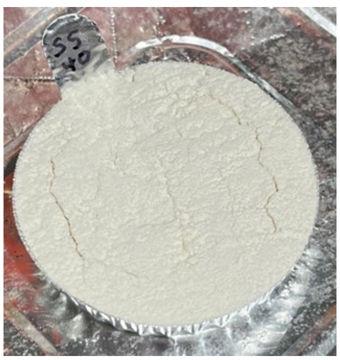
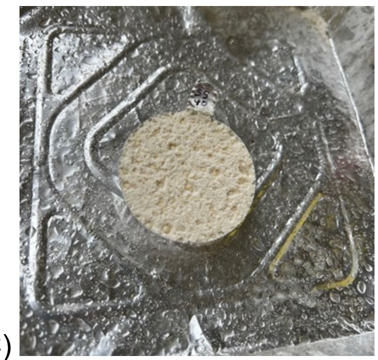
A)  B)  C) 

Figure 26. A) Uncompacted flour tray; B) Exposing the flour tray to the simulated rainfall for ~1s; C) Droplets’ shape preserved as flour pellets to be dried, sieved, weighed, and counted.

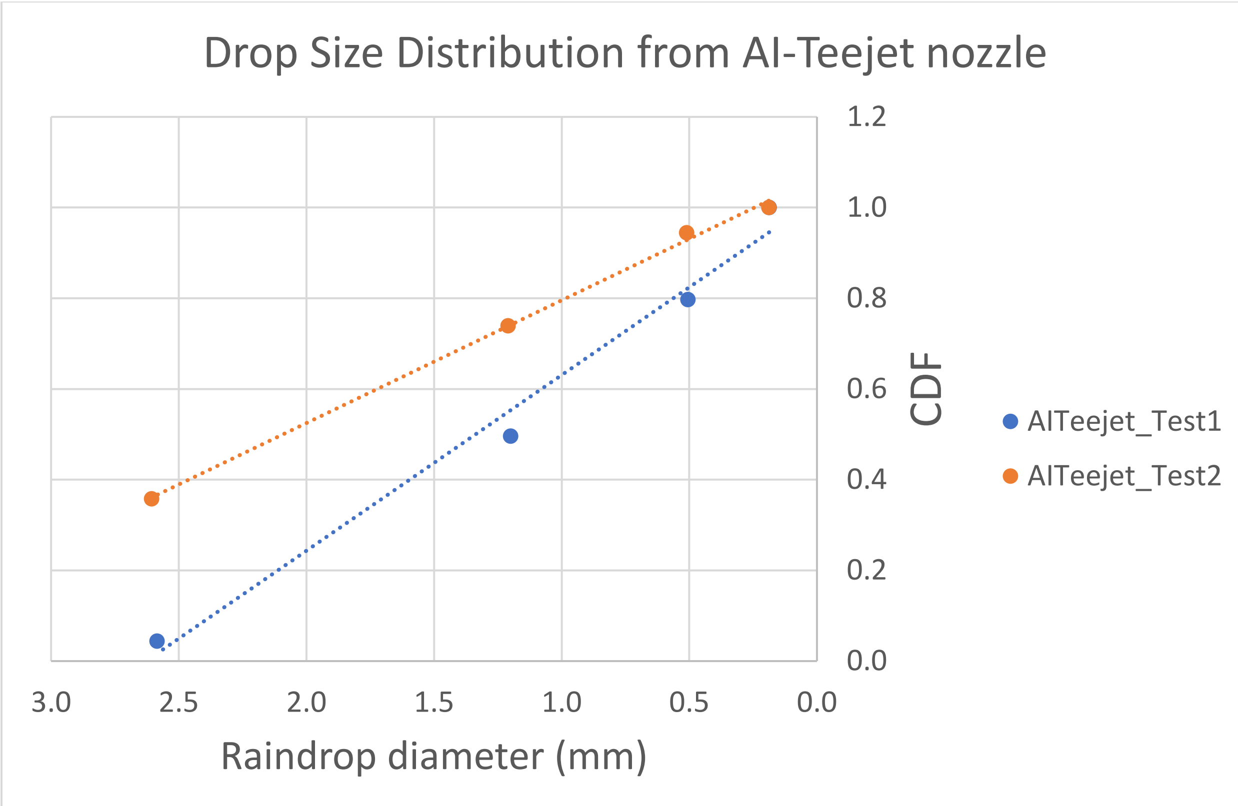


Figure 27. Cumulative distribution function (CDF) simulated raindrops produced by the AI-TeeJet nozzle during two tests.

Drag-Model for Velocity

Natural rainfall from clouds in the upper troposphere can be reasonably assumed to impact the ground at terminal velocity. However, this assumption may not hold for droplets ejected from spraying nozzles, with implications for the kinetic energy flux estimate from Equation B3.

The exit velocity of the water from the nozzle tip can be calculated using the operating pressure and the *vena contracta* equation. The operating pressure at the nozzles is 275 kPa, equivalent to 28.0m of head. The contraction coefficient, *C*, is about 0.7 (Jiang et al. 2019).

$$V_0 = C\sqrt{2 * g * h} = 0.7 * \sqrt{2 * 9.81 \, {}^{m}/_{s^2} * 28.0m} = 16.4m/s$$

Equation B3

The acceleration of the droplet upon ejection from the nozzle can be determined by balancing the drag force and gravitational acceleration acting on the droplet.

$$a(t) = \frac{F_d(t)}{m} - g$$

Equation B4

where $F_d(t)$ is the drag force, m is the drop mass, and g is the gravitational constant of acceleration. The drag force is calculated by,

$$F_D(t) = \frac{c_D\ \rho_{air}\ A}{2} V(t)^2$$

Equation B5

where C_D is the coefficient of drag for a sphere (taken as 0.5), ρ_{air} is the density of air, A is the cross-sectional area of the droplet sphere, and $V(t)$ is the instantaneous velocity of the droplet. By combining Equations B4 and B5 with the initial condition given by Equation B3, the impact velocity for each drop size class can be calculated. Table B1 summarizes the drop size diameter and average proportion from Figure 27 and reports the impact velocity of that drop size from the 3 m SCCWRP RFG operating height.

Table B1. AI-TeeJet nozzle drop size distribution and impact velocity from 3 m initial height.

Diameters (mm)	Mass Fraction	Drop Impact Velocity from 3 m (m/s)
0.19	0.09	1.99
0.51	0.23	3.44
1.20	0.40	7.05
2.58	0.29	11.33

Applying Equation B2 to the data from Table B1 yields an estimate of the kinetic energy flux of the SCCWRP RFG to be 29.8 J/m^2mm. The calculated kinetic energy flux from the SCCWRP RFG exceeds the estimated kinetic energy flux from natural rainfall at 32 mm/hr by about 18%, which is very good agreement compared with RFGs in the literature (Abudi et al. 2012; Egodawatta 2007; Esteves et al. 2000; Grismer 2012).

Reproducibility

The SCCWRP RFG delivers a constant rainfall intensity of 32 mm/hr. The well tank and individual pressure gauges on nozzles are the key components of the overall design to ensure reproducible rainfall simulation. The cistern pump is periodically activated to maintain an operating pressure for the well tank between 275 – 400 kPa (40 – 60 psi) while the individual pressure regulators are set to 275 kPa (40 psi) on the water separating manifold. The incremental pressure regulation, along with a constant length of PEX pipe between the manifold and nozzle ensured a constant head at the spraying nozzles. If the cistern pump is active for too long, the pressure in the well tank will become dangerously elevated; if the cistern pump is inactive for too long, the pressure in the well tank will continuously decrease until there's not enough pressure head to drive flow through the individual pressure regulators on the manifold. At this point, the RFG dribbles to a halt.

The capacity of the IBC tote is 1000 L. Each of eight AI-TeeJet nozzle produces 0.57 liters per minute (0.15 GPM) at 275 kPa (40 psi). Thus, when operated correctly the SCCWRP RFG can produce a constant 32 mm/hr intensity rainfall event (or series of constant intensity events) where the cumulative duration is about 3.5 hours.

Uniformity

The application of simulated rainfall should be nearly uniform across the wetted footprint from the RFG. The uniform footprint of the SCCWRP RFG was determined by measuring the volume of rainfall collected by a matrix of 250 mL graduated cylinders during a 5-minute test. The metric of uniformity typically used in rainfall generators is the Christiansen Uniformity Coefficient (CuC); our target CuC score is greater than 0.7, which has been shown to be acceptable for field-scale RFGs (Egodawatta 2007; Esteves et al. 2000; Herngren et al. 2005).

The CUC can be expressed as:

$$CUC = 100\% * \left(1 - \frac{\sum_i^N |X_i - \bar{X}|}{\bar{X}}\right)$$

Equation B6

where X_i is the intensity at a given grid value, and $\bar{X}$ is the average intensity over the given surface area. Measured volumes from the graduated cylinders are converted into intensities by dividing by the area of the cylinder mouth and the test time.

Figure 28 shows the spatial variability of intensity from the SCCWRP RFG. The red outline corresponds to the uniform footprint, wherein average intensity is equal to the target intensity of 32 mm/hr and the CuC score is greater than 0.7. The surface area of the uniform footprint is 6.5 m^2. Some RFG designs seek to capture the excess rainfall outside the uniform footprint (Blanquies et al. 2003; Iserloh et al. 2010), but that capability was not included in this version of the SCCWRP RFG.

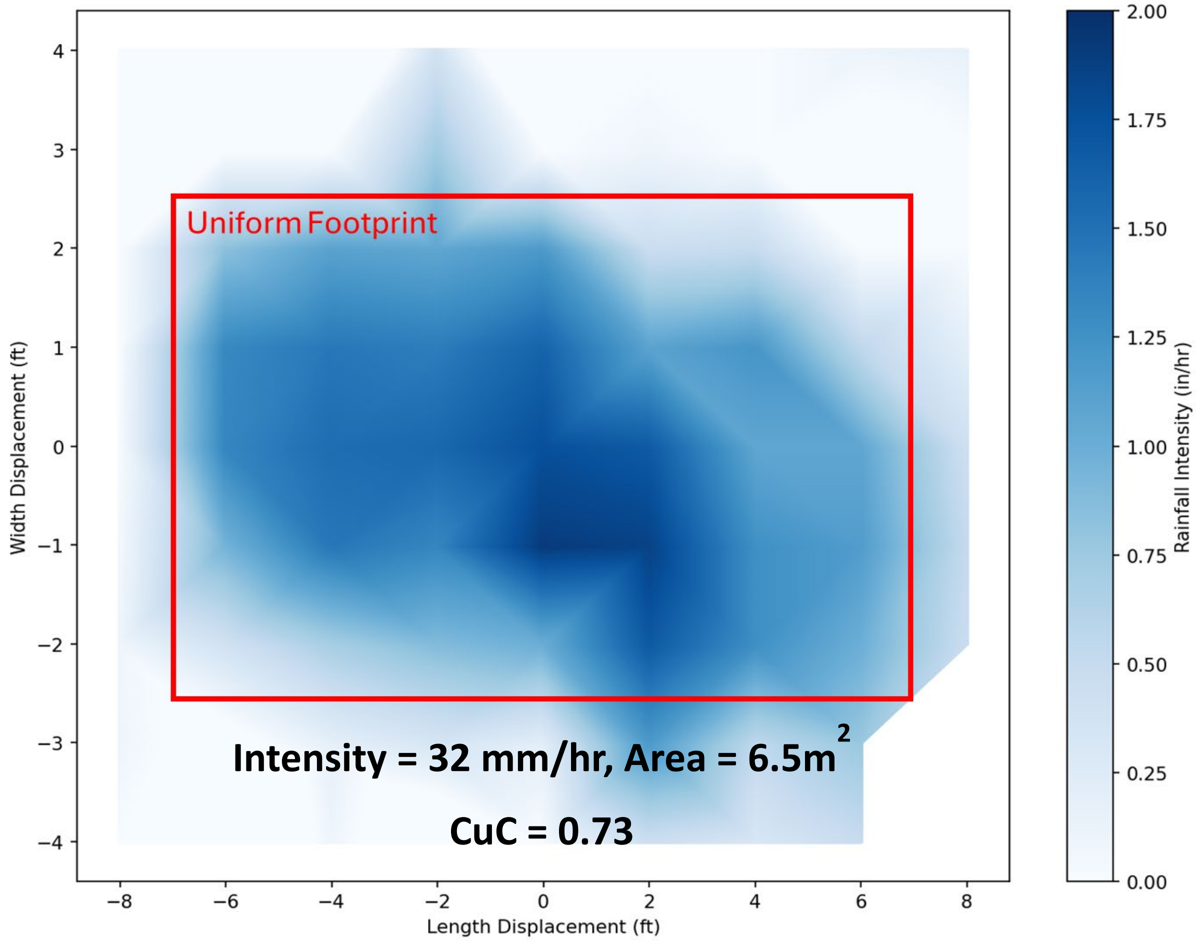


Figure 28. Visualization of intensity from graduated cylinder uniformity test.

Verticality of Impact

The banded spray from the AI-TeeJet nozzles used herein initially have a dispersion angle of 80˚ 2014). A droplet on the far edge of the banded spray (seen in Figure 29) is initially ejected at 40˚ angle relative to vertical. Initial deceleration in the horizontal direction predicted by the drag-model plus vertical acceleration due to gravity reorients the water droplet to near vertical by the time the drop is impacting the ground 3 m below.

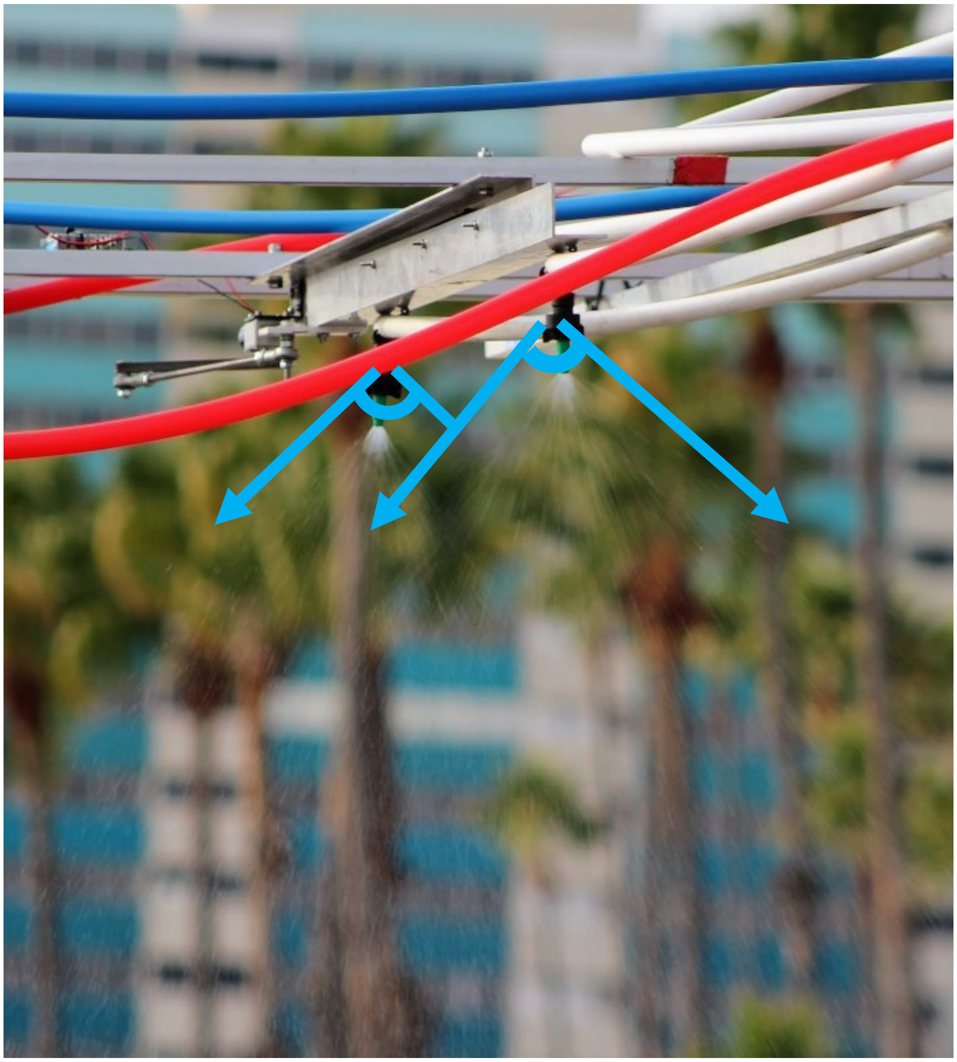


Figure 29. Photograph of AI-TeeJet nozzle spray on the RFG. Spray angle and extents annotated in light blue.

Appendix C. Shake-down Test Lessons Learned

A shake-down test of the anticipated field deployment in a parking lot within the County of San Diego's campus was conducted on Aug. 6, 2023. The test provided practical insights into the time required for set-up and break-down off-site (i.e., not at SCCWRP), the positioning of the RFG relative to the sampling location, equipment required to fill the supply tank from an unknown spigot, the duration of simulated rainfall to test, the number of field crew needed for conducting testing, and safe system deployment in the field. Only unswept pavement was tested. Overall runoff concentrations for key analytes including total suspended solids (TSS) was considered low compared to expectations from the National Stormwater Quality Database (NSQD V. 4.02) (Pitt et al. 2018). Combined with the absence of an advanced sweeper technology available from the County, the location was abandoned for further testing. The decision was confirmed during a review with the TWG. A summary of the shake-down test approach and results are documented herein as slides from a meeting of the TWG to review the results of the test.

Southern California STORMWATER MONITORING Coalition

Non-structural BMP Effectiveness Street Sweeping – Field Pilot Testing Status Update

SCCWRP Established 1969

09/19/2023

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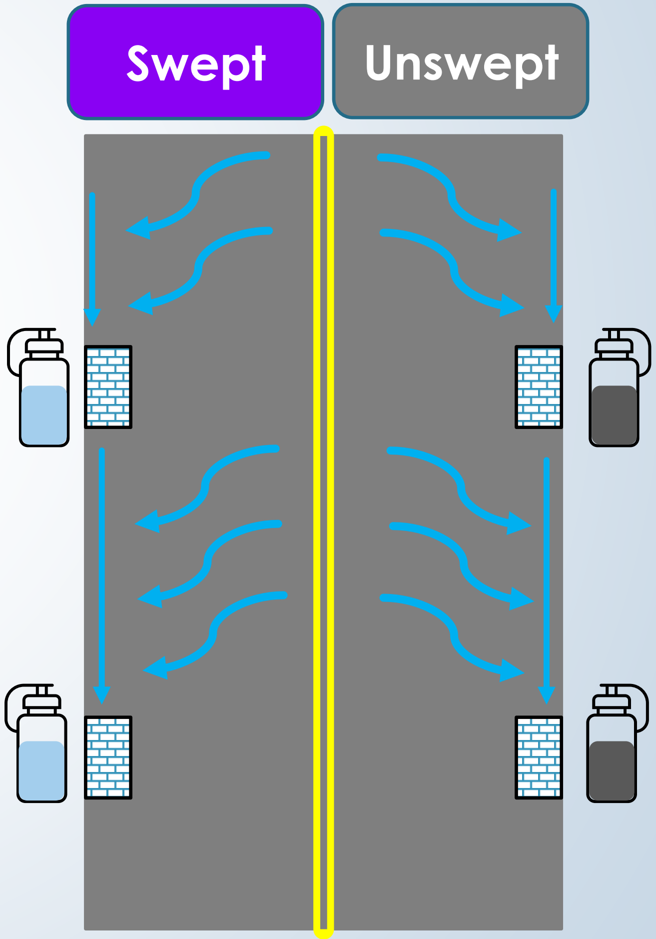
Technical Working Group Members

- James Fortuna – County of Orange
- Matt Yeager – Riverside County Flood Control & Watershed Protection District
- Wayne Chiu – Region 9 Water Board
- Ivar Ridgeway – Region 4 Water Board
- Hamzeh Ramadan – Caltrans
- Jill Murray – City of Santa Barbara
- ~~Lara Barrett – County of San Diego~~
- **Jamie Milani – County of San Diego**
- **Gerhardt Hubner – SMC administrative officer**

Project Overview

- Overall goal: Can we measure a difference in runoff water quality between swept and unswept pavements?
- Scope: One pavement, 2 conditions (swept & unswept)
- Progress:
    - Completed construction on synthetic rainfall generator June 2023
    - Candidate site identified by San Diego County
    - Today: Pilot Test Update



Synthetic Rainfall Generator

SCCWRPer Soaker

Rainfall Intensity
–> 1.25 in/hr

Uniform Footprint
–> 14ft x 6ft

Pilot Test

- Primary Goals – Logistics Shakedown
  1. Beta-test rainfall and sample collections method
  2. Confirm rainfall duration
  3. Determine if location generates an adequate pollutant load
- Approach
  - Build apparatus and conduct pilot test
  - Solids, nutrients, and trace metals analyses on collected samples
- Anticipated Outcomes
  - Proof of concept on experimental methods
  - Pilot site as a candidate for experiment

Questions we hope to answer today

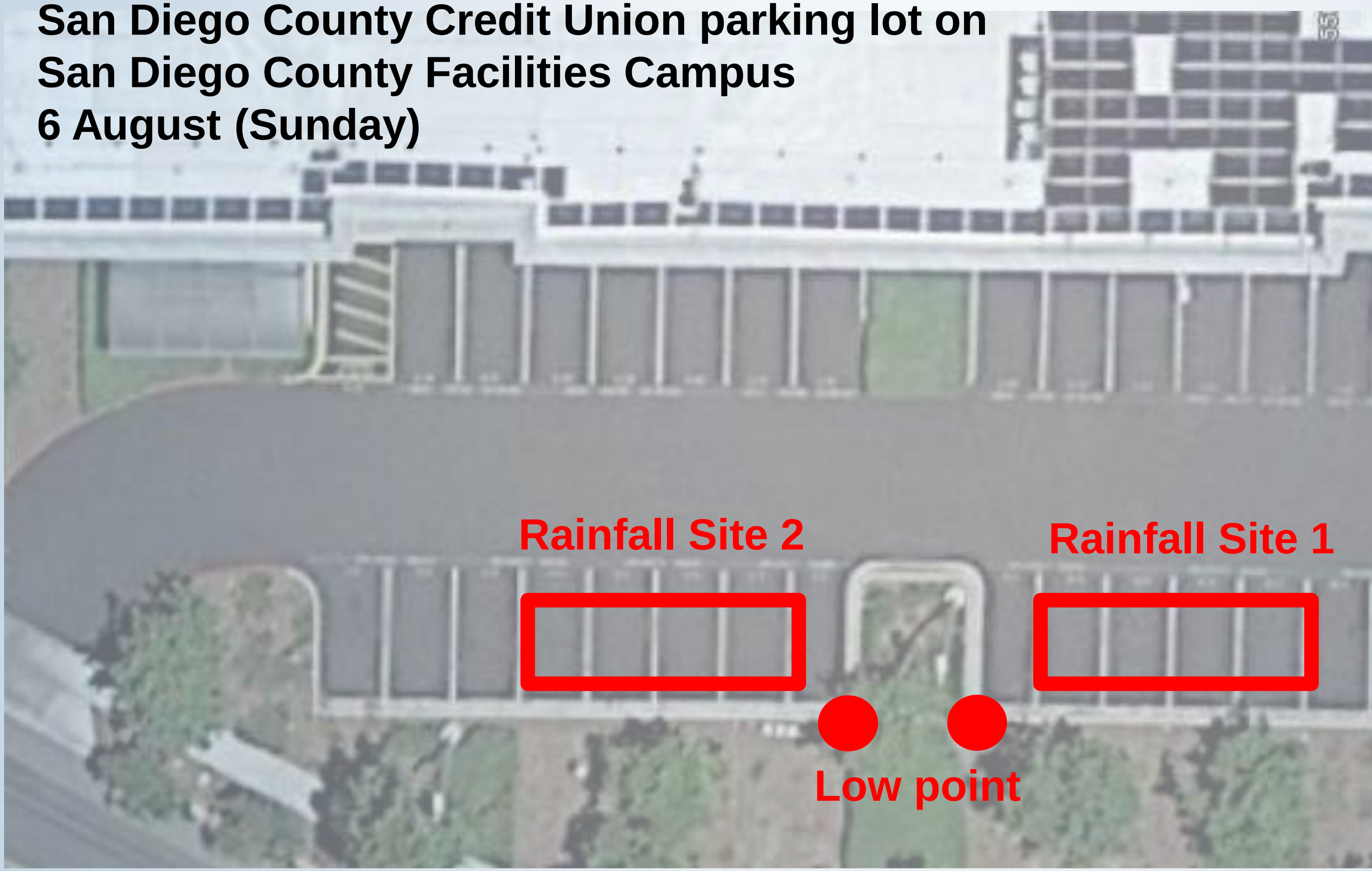
1. Did the rainfall and sample collections method work?

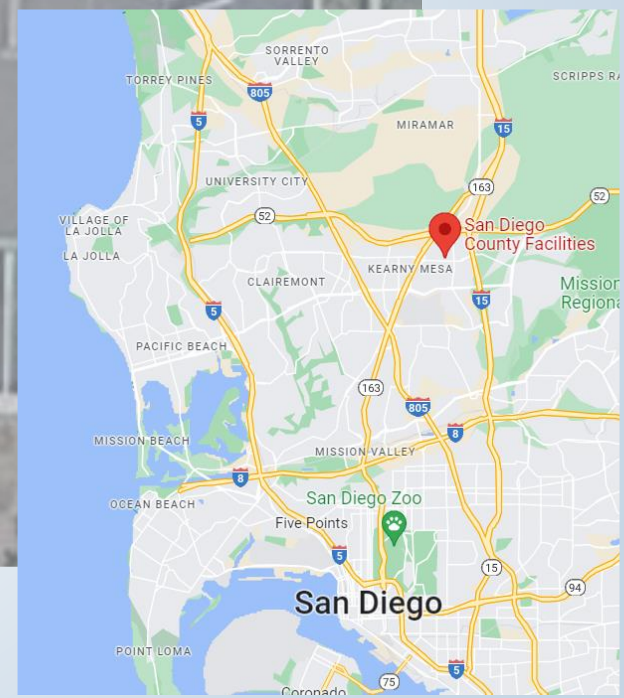
2. Is a 30-minute rainfall event sufficient for full testing?

3. Did the SDCCU location generate an adequate pollutant load?

Pilot test

San Diego County Credit Union parking lot on San Diego County Facilities Campus
6 August (Sunday)





Pilot test

1. Rain for 30-min on a street segment

2. Collect whole-of-event composite

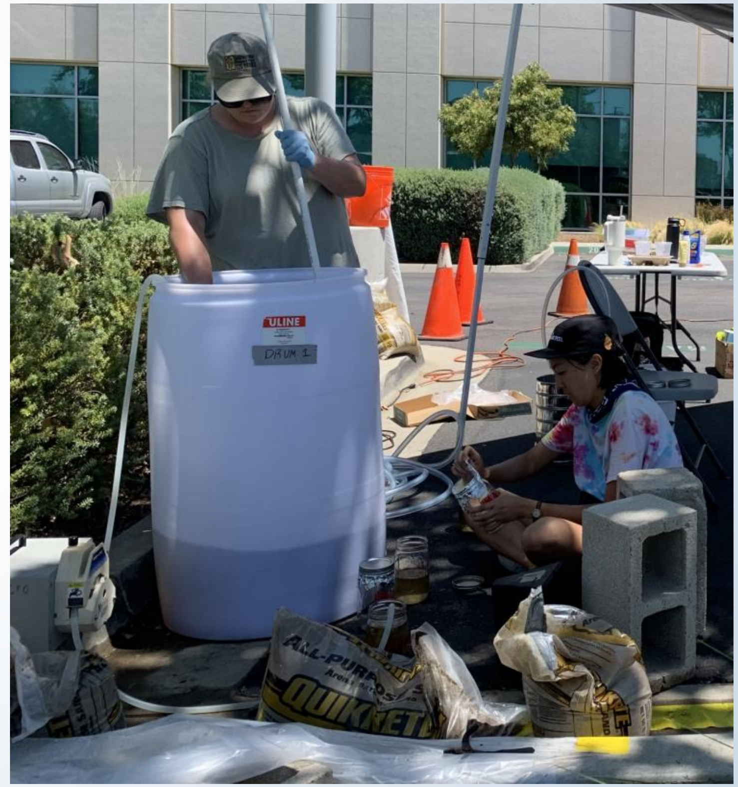
Pilot test

3. Split whole-of-event composite into depth-integrated aliquots

Aliquot 1

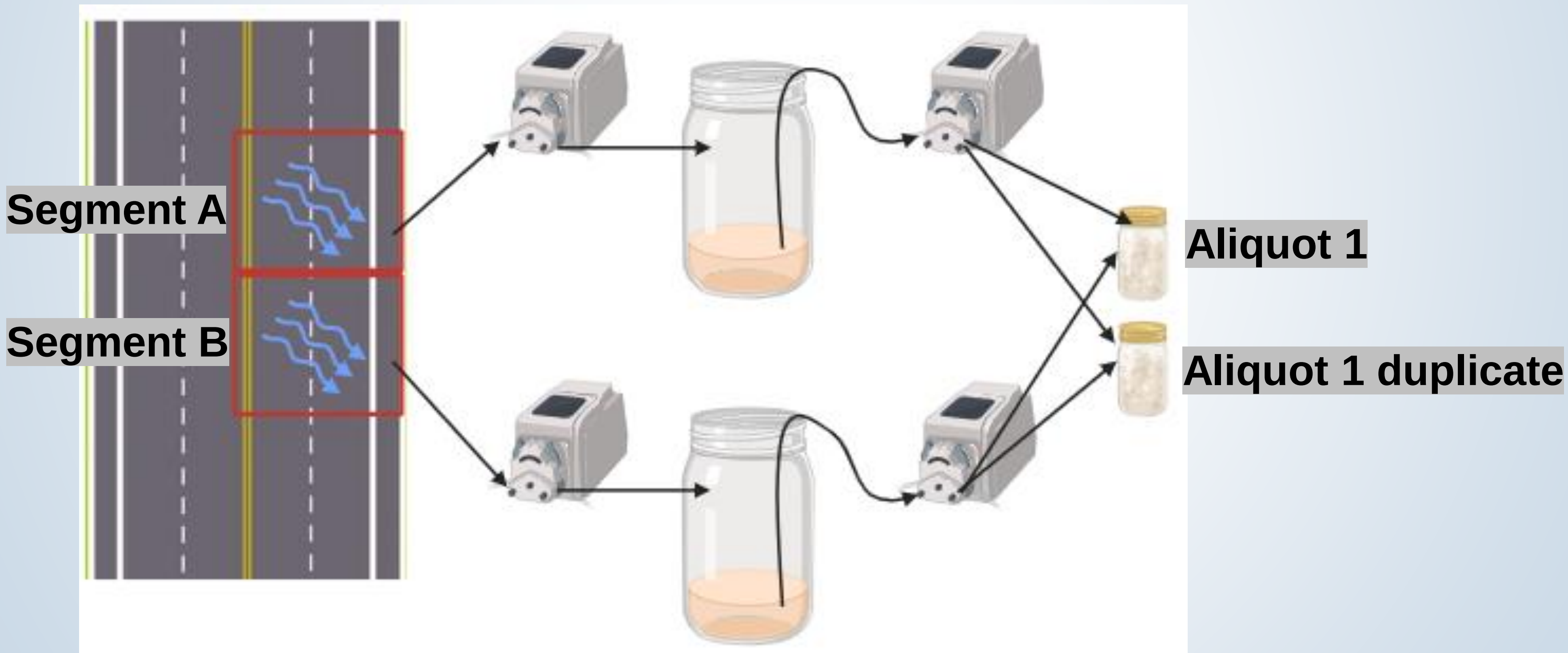
Aliquot 1 Duplicate

Whole-of-Event Composite



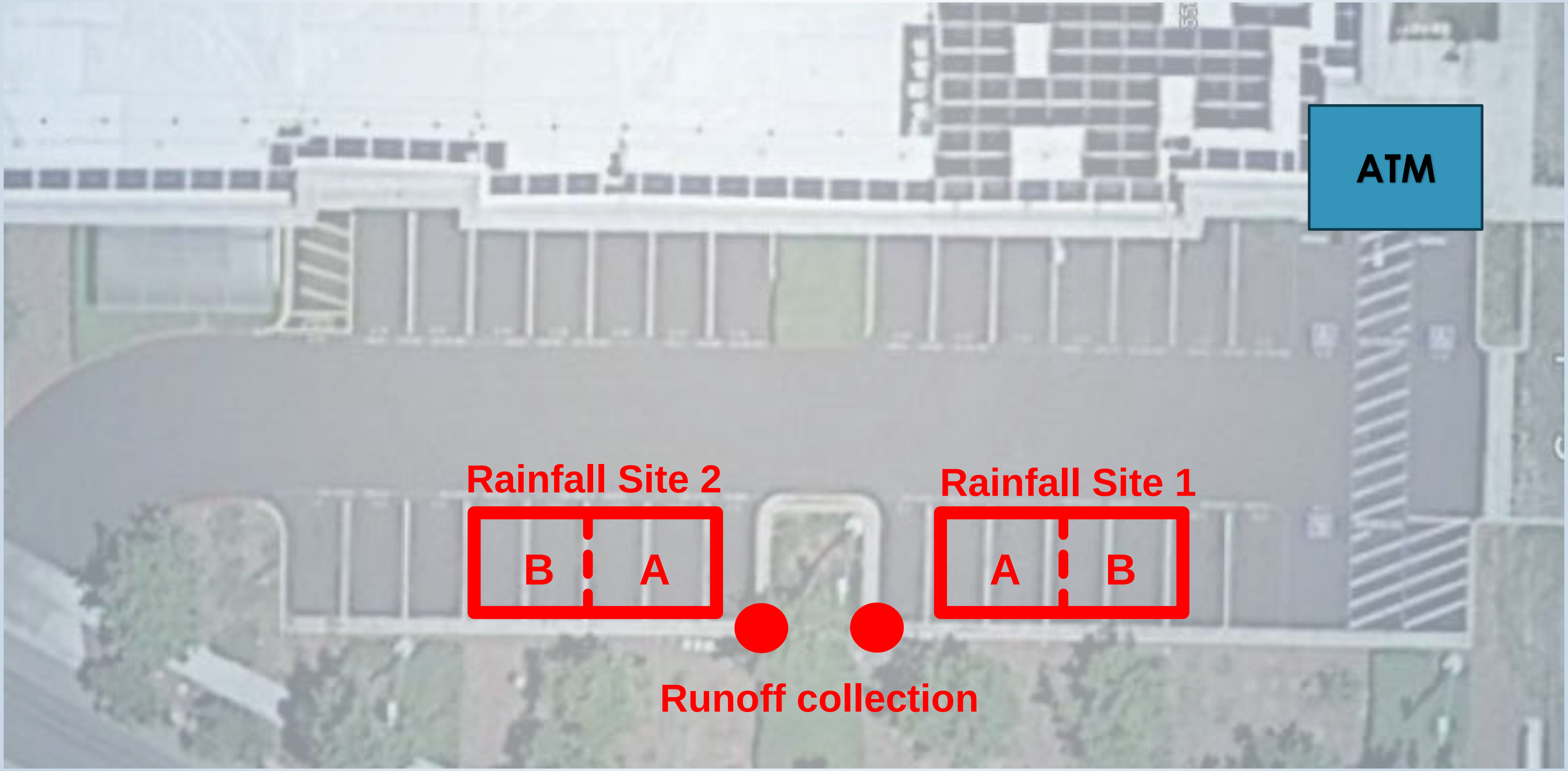
Pilot test

4. Repeat process in another segment - or for another 30 min in same segment (for 60 min total)



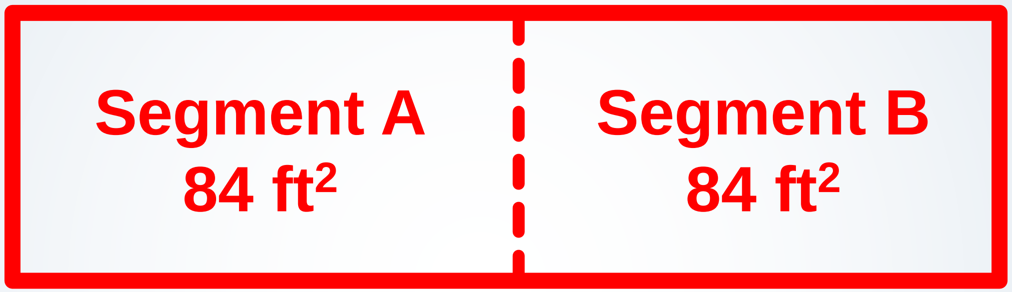
Whole-of-Event Composites

Pilot test



Pilot test

Rainfall Site



3 x 30-min Whole of Event Composites

A

B1

B2

Pilot test

Rainfall Site

Segment A	Segment B
84 ft^2	84 ft^2

3 x 30-min Whole of Event Composites

A — **B1**, **B2**

Test Samples

Sample 1 = A + B1 (30 min, 168 ft^2)
Sample 2 = B1 (30 min, 84 ft^2)
Sample 3 = B1 + B2 (60 min, 84 ft^2)

Analysis

Site heterogeneity: 1 vs 2
Test duration: 2 vs 3

Questions we hope to answer today

1. Did the rainfall and sample collections method work?

2. Is a 30-minute rainfall event sufficient for full testing?

3. Did the SDCCU location generate an adequate pollutant load?

1. Did the methods work?

☑ **Rainfall generation: Can we make it rain?**

- **~750 L of water used for 3 hours of rain**
- **Confirms 1.25 in/hr design intensity**

1. Did the methods work?

☑ **Rainfall generation: Can we make it rain?**
- ~750 L of water used for 3 hours of rain
- Confirms 1.25 in/hr design intensity

☑ **Rainfall runoff recovery: Can we collect representative runoff?**
- ~50% of water recovered from rainfall

1. Did the methods work?

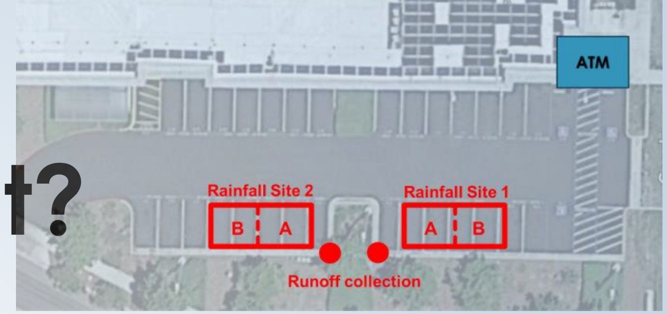
☑ **Rainfall generation: Can we make it rain?**
- ~750 L of water used for 3 hours of rain
- Confirms 1.25 in/hr design intensity

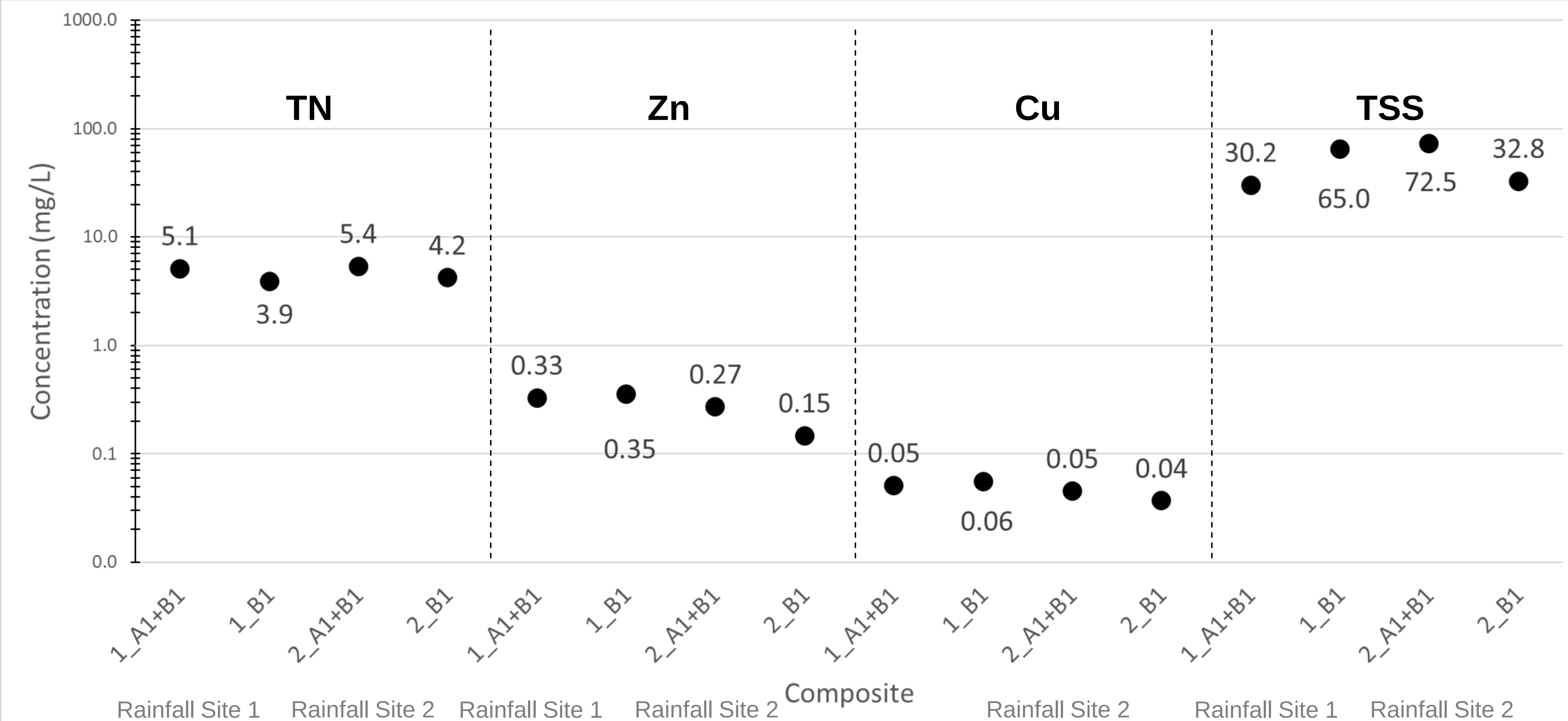
☑ **Rainfall runoff recovery: Can we collect representative runoff?**
- ~50% of water recovered from rainfall

☑ **Pollutant data: Are sample collection methods repeatable?**
- No outliers in field samples
- Field duplicates (<10% difference)
- Tap blank concentrations < field sample concentrations
- Site was heterogeneous for TSS

How many segments to test?

30-min duration tests

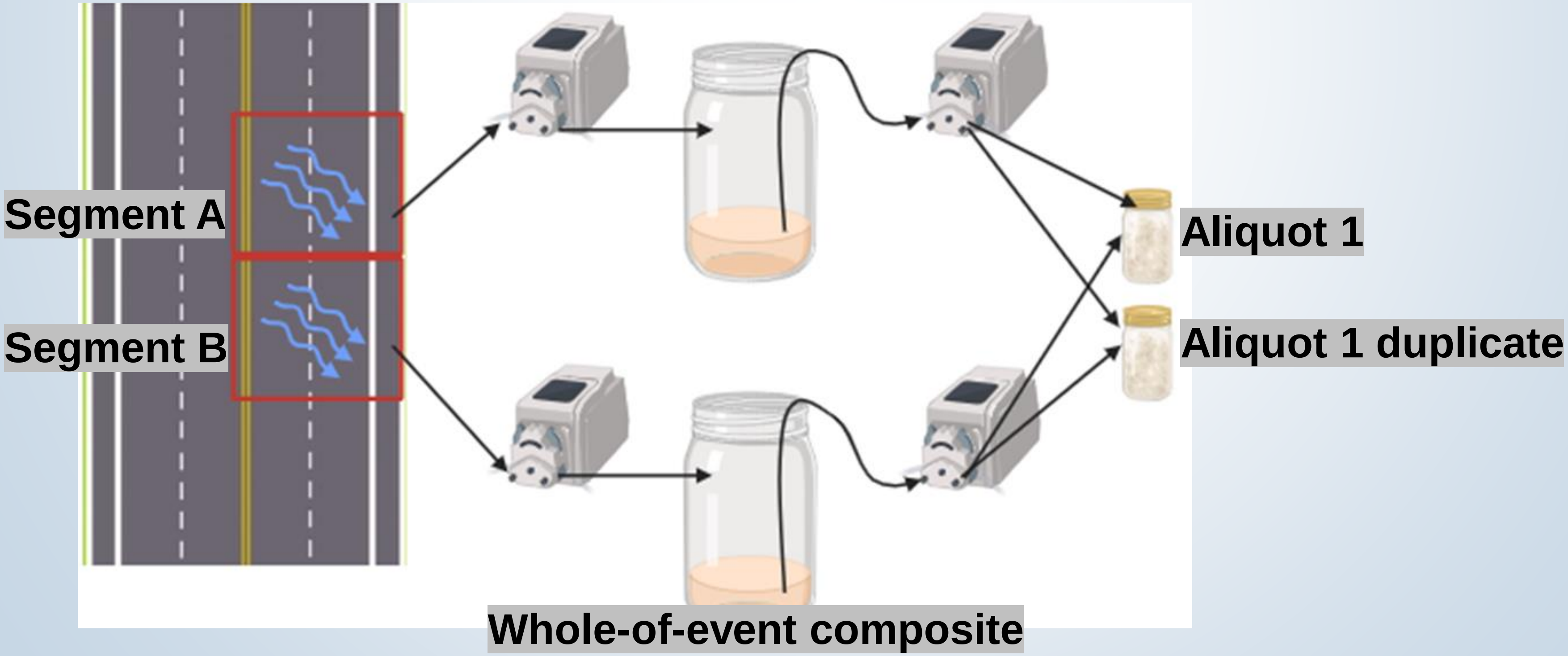




1. Did the methods work?

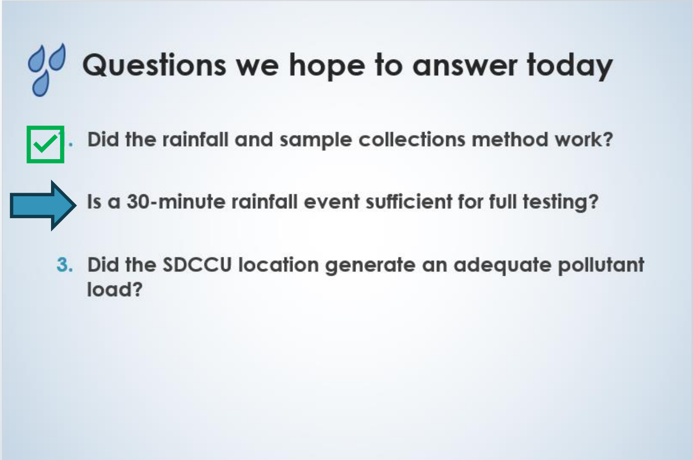
Pollutant data: Are sample collection methods repeatable?

- No outliers in field samples
- Tap blank concentrations < field sample concentrations
- Field duplicates (<10% difference)
- Confirmed site heterogeneity for TSS

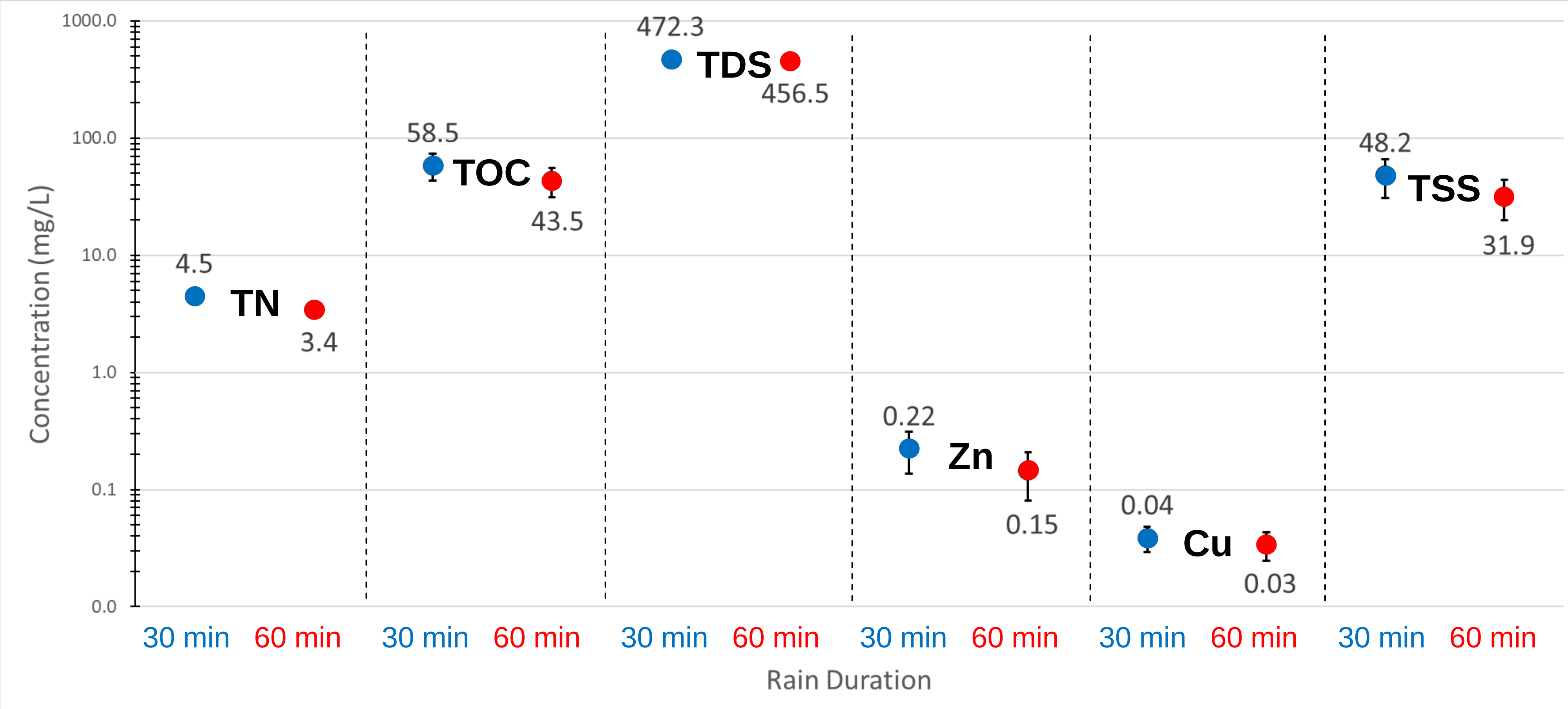


2. Is 30 minutes sufficient?

- Key rainfall parameter (arbitrary): 25-yr event
  - 1.25 in/hr for 60 minutes
- Logistics limitations with 1-hr rainfall
- Collected 30-min and 60-min events at pilot test



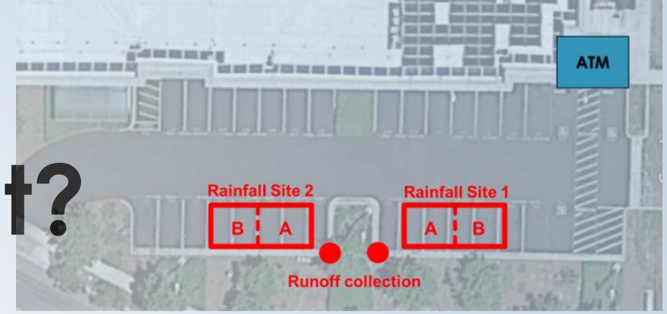
2. Is 30 minutes sufficient?

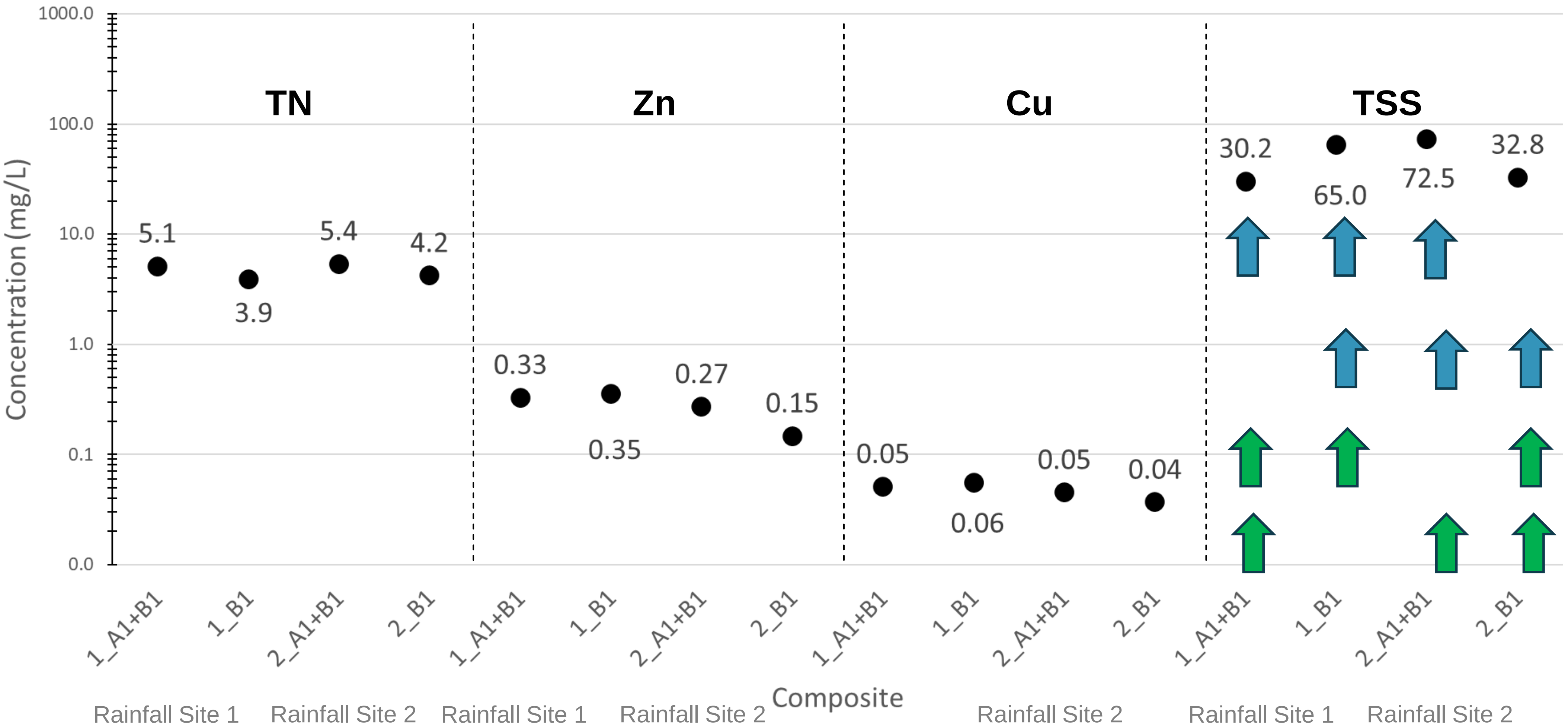


- **30 min conc > 60 min conc**
- **Longer rain duration dilutes concentration**
- **Want higher concentration to detect difference**

How many segments to test?

30-min duration tests





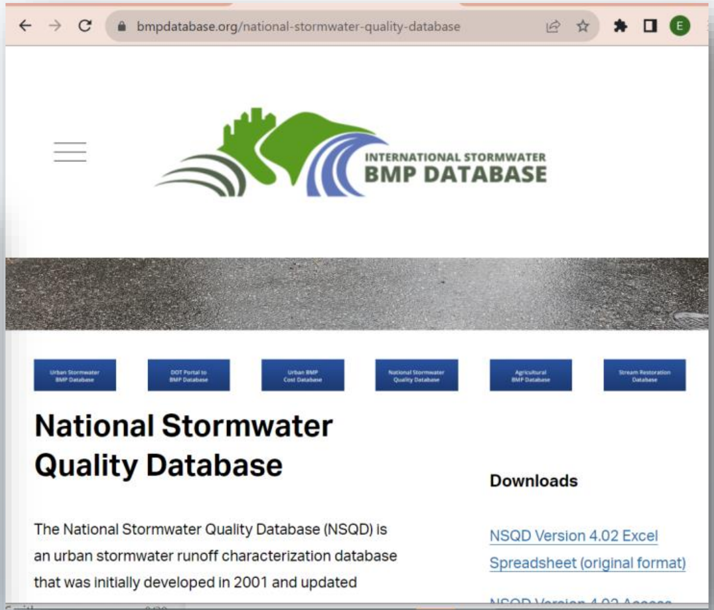
3. Adequate pollutant load?

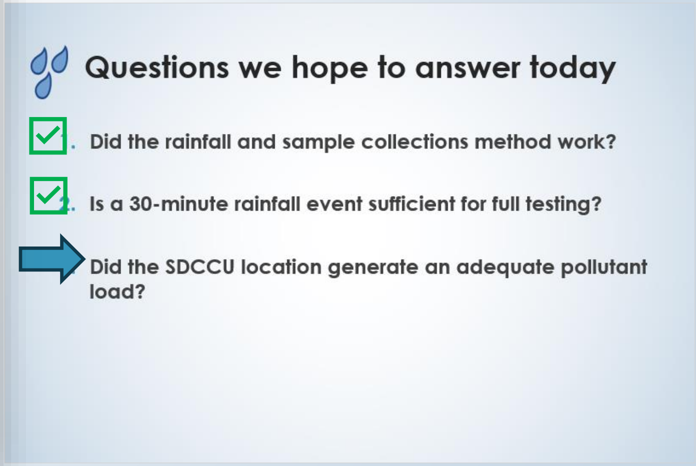
Question 1: Is it dirty compared to what is typical?

- **National Stormwater Quality Database (NSQD)**

Question 2: Is it dirty enough to measure a difference?

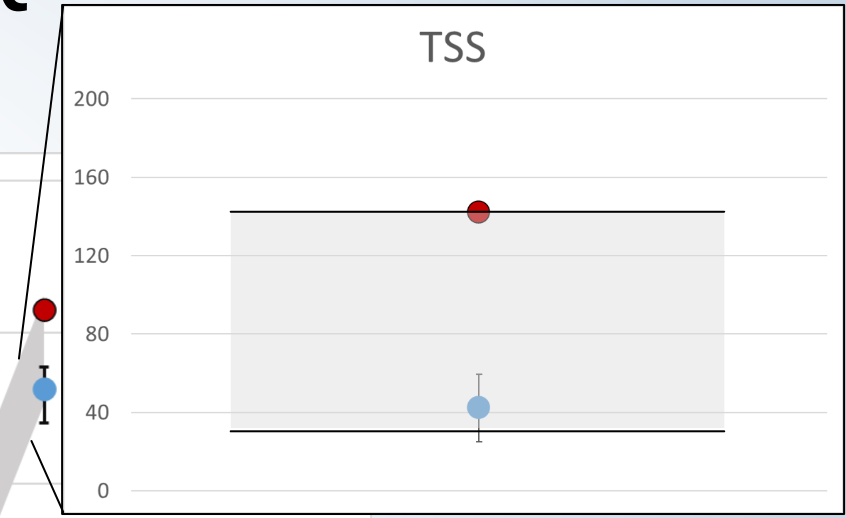
- **T-test for differences between swept and unswept**

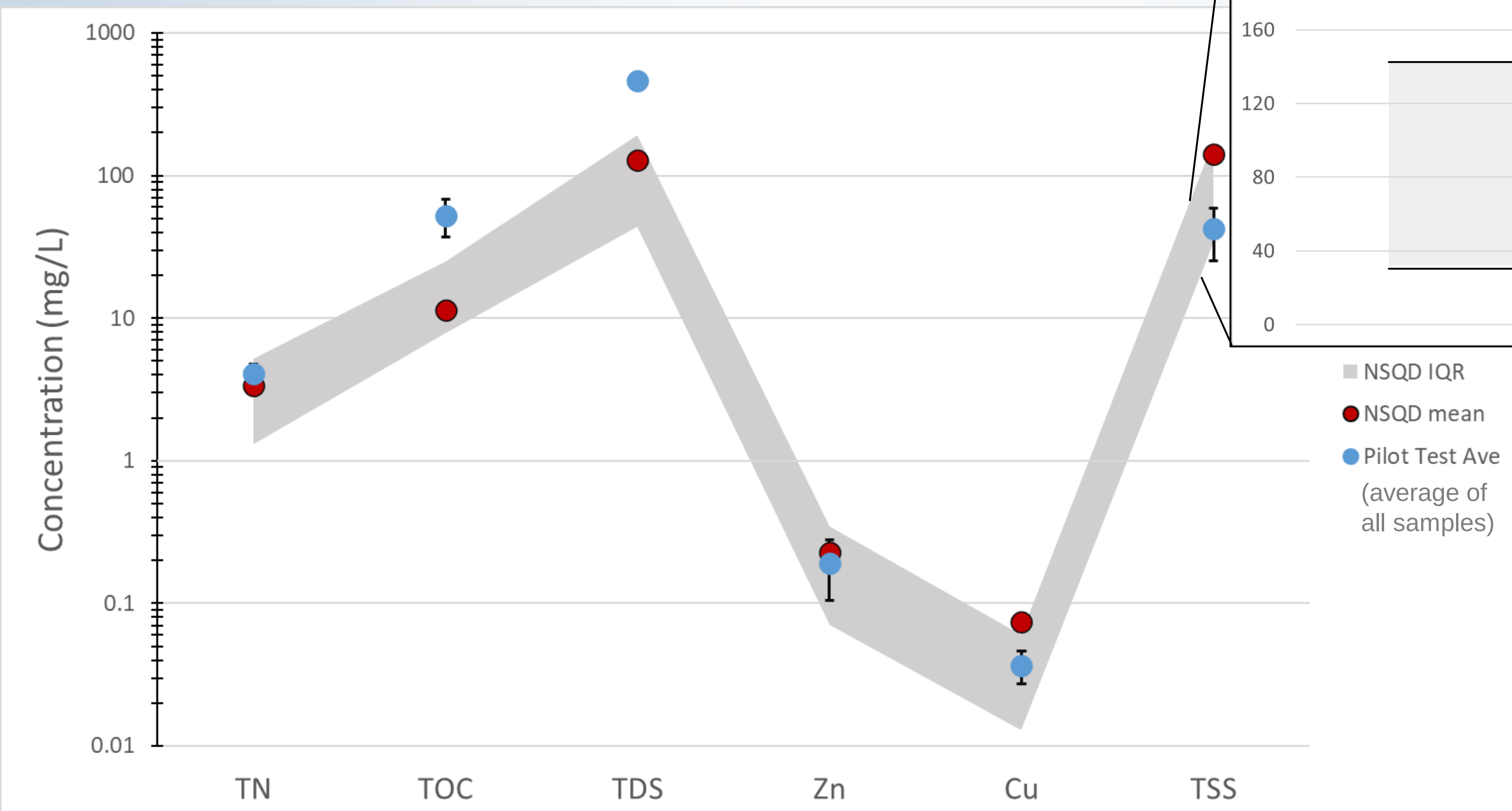




3. Adequate pollutant load?

Question 1: comparison to NSQD





- **All constituents comparable to national database**
- **However, TSS is a concern (low)**

Reference data: Freeway data from 2015 National Stormwater Quality Database

3. Adequate pollutant load?

Low TSS

Possible explanations:

- **TSS may have been left along flowpath (across parking lot and in gutter)**
- **rough pavement**

Improvements:

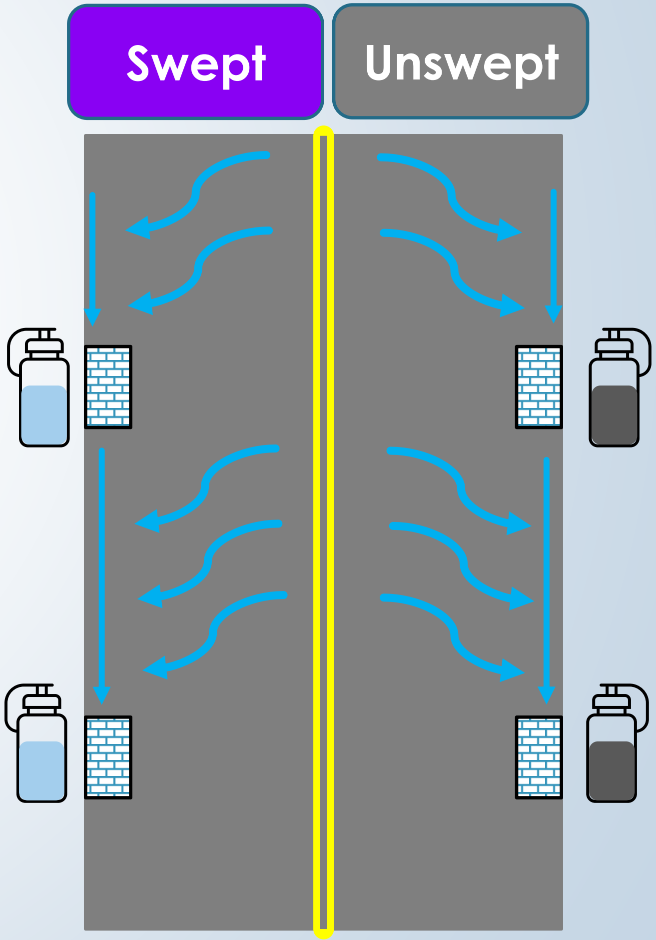
- **collect closer to generation**

3. Adequate pollutant load?

Question 2 – t-test for differences

Goal:
To determine if a measured difference is random or attributable to an intervention.

Street sweeping question:
If we see a 10% mean difference between swept and unswept conditions, what is our confidence that the difference is because of street sweeping?



3. Adequate pollutant load?

Question 2 – t-test of difference in means

Assumptions/independent variables

- Test family → t-test of means
- Total sample size (number of field days)→ N=5
- Detectable effect size → 10% reduction
- Standard deviation from pilot test → 16 mg/L

	Pilot unswept	Hypothetical swept (10% reduction)
Mean (mg/L)	40	36
Std dev (mg/L)	16	16

$p=0.42$

3. Adequate pollutant load?

Question 2 – t-test of difference in means

Assumptions/independent variables

- Test family → t-test of means
- Total sample size (number of field days)→ N=5
- Detectable effect size → 10% reduction
- Standard deviation from pilot test → 16 mg/L

	Pilot unswept	Hypothetical swept (10% reduction)	Hypothetical unswept	Hypothetical swept (10% reduction)
Mean (mg/L)	40	36	171	154
Std dev (mg/L)	16	16	16	16
		p=0.42		p=0.10

Questions answered today(?)

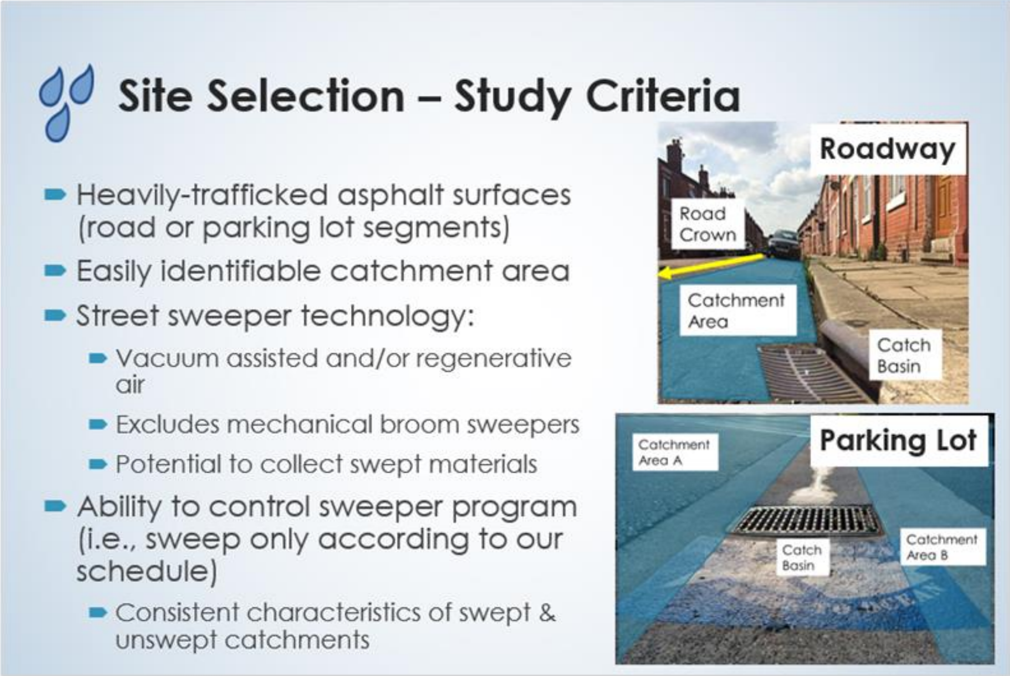
1. Did the rainfall and sample collections method work?

2. Is a 30-minute rainfall event sufficient for full testing?

3. Did the SDCCU location generate an adequate pollutant load?

Next Steps: Go / No-go on Pilot Site

- GO
  1. Secure sweeper
  2. Antecedent dry period?
  3. Schedule tests & sweeping
- NO-GO
  a. Other candidate sites??
  b. Pilot test = lose 1 "real" test day
- Recommendation: controlled testing only (no natural events)



Questions?

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SMC
Southern California
STORMWATER MONITORING
Coalition

SCCWRPer Soaker

SCCWRP
Established 1969

APPENDIX D. ADDITIONAL WATER QUALITY RESULTS – INDIVIDUAL PAHS

	Unswept (ng/L)	Swept (ng/L)			Unswept (ng/L)	Swept (ng/L)
1-Methylnaphthalene				**Benzo[k]fluoranthene**		
Event 1	5.7	6.905		Event 1	1	1
Event 2	6.34	5.06		Event 2	1	1
Event 3	5.52	4.35		Event 3	12.7	4.715
Average	5.85	5.44		Average	4.9	2.24
1-Methylphenanthrene				**Biphenyl**		
Event 1	6.37	6.25		Event 1	12.9	7.86
Event 2	3.65	3.6		Event 2	6.7	6.22
Event 3	6.56	4.065		Event 3	6	4.59
Average	5.53	4.64		Average	8.53	6.22
2,3,5-Trimethylnaphthalene				**Chrysene**		
Event 1	1	1		Event 1	12.5	6.3
Event 2	1	1		Event 2	15	5.61
Event 3	2.52	1.595		Event 3	123	52.25
Average	1.51	1.2		Average	50.17	21.39
2,6-Dimethylnaphthalene				**Dibenz[a,h]anthracene**		
Event 1	4.24	3.86		Event 1	1	1
Event 2	3.33	3.28		Event 2	1	1
Event 3	3.2	1.675		Event 3	10.4	5.76
Average	3.59	2.94		Average	4.13	2.59
2-Methylnaphthalene				**Dibenzothiophene**		
Event 1	9.43	11.94		Event 1	15	13.2
Event 2	6.56	8.84		Event 2	11.2	10.8
Event 3	8.36	5.895		Event 3	17	16.05
Average	8.12	8.89		Average	14.4	13.35
Acenaphthene				**Fluoranthene**		
Event 1	1	1		Event 1	39	25.35
Event 2	1	1		Event 2	31.9	26.3
Event 3	4.04	2.305		Event 3	41.1	21.3
Average	2.01	1.44		Average	37.33	24.32
Acenaphthylene				**Fluorene**		
Event 1	2.77	9.08		Event 1	6.22	10.045
Event 2	5.58	8.49		Event 2	5.81	5.84
Event 3	3.51	3.26		Event 3	4.62	3.03
Average	3.95	6.94		Average	5.55	6.31

	Unswept (ng/L)	Swept (ng/L)			Unswept (ng/L)	Swept (ng/L)
Anthracene				**Indeno[1,2,3-cd]pyrene**		
Event 1	1	1		Event 1	15.6	7.5
Event 2	1	1		Event 2	10.3	9.24
Event 3	2.86	2.34		Event 3	22.3	8.965
Average	1.62	1.45		Average	16.07	8.57
Benz[a]anthracene				**Naphthalene**		
Event 1	35.1	20.25		Event 1	24.3	37.7
Event 2	33.5	23		Event 2	14.3	20.3
Event 3	34.2	13.8		Event 3	19.4	15.15
Average	34.27	19.02		Average	19.33	24.38
Benzo[a]pyrene				**Perylene**		
Event 1	20.1	15.75		Event 1	1	1
Event 2	15.2	13.8		Event 2	1	1
Event 3	16.2	6.785		Event 3	2.72	1.495
Average	17.17	12.11		Average	1.57	1.17
Benzo[b]fluoranthene				**Phenanthrene**		
Event 1	16.1	9.925		Event 1	24.5	20.4
Event 2	8.68	9.47		Event 2	23.9	20.7
Event 3	23.1	10.735		Event 3	29	18.4
Average	15.96	10.04		Average	25.8	19.83
Benzo[e]pyrene				**Pyrene**		
Event 1	23.2	14.85		Event 1	58.5	34.25
Event 2	19.6	13.8		Event 2	45.8	39.8
Event 3	33.5	14.25		Event 3	59.1	31.85
Average	25.43	14.3		Average	54.47	35.3
Benzo[g,h,i]perylene						
Event 1	49	23.25				
Event 2	44.2	27.9				
Event 3	54.7	22.85				
Average	49.3	24.67				

	% Recovery	
	Unswept	**Swept**
d10-Acenaphthene		
Event 1	54	63.5
Event 2	48	59
Event 3	79	73
Average	60.33	65.17
d10-Phenanthrene		
Event 1	64	77
Event 2	61	76

Event 3	74	75.5
Average	66.33	76.17
d12-Chrysene		
Event 1	87	85
Event 2	80	93
Event 3	107	109
Average	91.33	95.67
d12-Perylene		
Event 1	86	89
Event 2	77	78
Event 3	74	80
Average	79	82.33
d8-Naphthalene		
Event 1	52	60
Event 2	46	51
Event 3	54	50.5
Average	50.67	53.83

APPENDIX E. MICROPLASTICS QA SAMPLE RESULTS

Table E1. Microplastic (MP) counts and minimum detectable amounts (MDAs) for all blanks associated with Event 3 microplastics samples.

Sample ID	Size Fraction (µm)	Microplastics Count*	Minimum detectable amount**
Method Blank	500	1	6
	355	1	8
Total MP	355 & 500	2	
Sieve Blank	500	3	14
	355	0	3
	125	15	36
	63	8	24
	20	11	29
Total MP	All size fractions	37	
Equipment Blank	500	0	3
	355	1	8
	125	12	31
	63	56	94
	20	159	229
Total MP	All size fractions	69	
Tap Blank	500	0	3
	355	0	3
	125	4	16
	63	13	33
	20	12	31
Total MP	All size fractions		

*Particles in blanks of Event 3 samples were analyzed by Fourier-transform infrared spectroscopy (FTIR). Particles identified as polymers with an HQI >60% are identified as microplastics in this table.
**The MDA is the minimum number of microplastic particles (Lao and Wong, 2023) that must be present in a sample to give a specified power, 1-β, where β is the probability of a Type II error (false negative). The MDA is calculated with β = α = 0.05, where α is the significance level (i.e., the probability of a Type I error or false positive) (MARLAP, 2004). The use of these standard values for α and β allows for meaningful comparison of analytical procedures. MDA values are matrix-specific and must be determined separately for each matrix.

Table E2. Microplastic concentration for equipment blanks associated with Event 3 microplastics sampling.

Sample ID	Size Fraction (µm)	Microplastics/Liter (MP/L)
Equipment blank*	500	0.00
	355	0.013
	125	0.151
	63	0.704
	All size fractions	0.868

*79.5 L of water collected and sieved