Analysis of Street Sweeping Efficiencies for Road Runoff Pollution Reduction

Frances J. Charters

Department of Civil and Natural Resources Engineering
Hydrological and Ecological Engineering Research Group

Contents

Executive Summary

Road runoff is a key contributor of sediment and heavy metal pollution to urban waterways. Street sweeping is considered as a potential pollutant reduction measure as it removes built-up pollutants directly from the road surface. There are two levels of benefit recognized for street sweeping: the removal of gross pollutants and litter is termed 'aesthetic sweeping', while removal of finer particles and associated pollutants such as heavy metals can be termed 'effects mitigation', as it reduces the amount of pollutants entering the receiving environment. However, studies to date have been inconclusive on street sweeping's effectiveness for ecological protection. Several factors influence the effectiveness of street sweeping, including climate factors such as rainfall intensity, duration and length of antecedent dry period; surface factors such as traffic intensity and roughness; pollutant factors such as available accumulated load and particle size distribution; and sweeper factors such as sweeper type, speed, frequency, and prioritization of roads. Matching the location and frequency of sweeping to load generation is key for achieving overall effectiveness in street sweeping for effects mitigation.

This study developed new data on the unswept and swept runoff quality from five road sites around Christchurch city. The selected sites represented a range of traffic intensities and surrounding land-use activities (both of which can correlate to pollutant load build up on the surface). The sites were also selected in proximity to other Christchurch City Council surface water monitoring sites. The new data contrasts with previous studies, which have mostly focused on road sediment characterization rather than unswept and swept road runoff comparisons. Quantification of the swept road runoff quality is valuable for understanding what is entering roadside sumps and what is potentially being passed onto the receiving environment. This informs expected adverse impacts that needs to be managed.

A rainfall simulator was used at each site to generate unswept road runoff (at 11 mm/hr intensity), vacuum-swept road runoff and regenerative-swept road runoff (both at 11, 22 and 33 mm/hr intensities). Runoff samples (whole of flow) were collected three times during each plot to quantify first flush effects. Samples were analysed for total suspended solids, particle size distribution, total and dissolved copper and total and dissolved zinc.

Lunns Road, a medium-trafficked industrial road, was found to have the highest pollutant concentrations for sediment and heavy metals, with first flush concentrations of 360-1,200 mg/L TSS, 1,630-3,057 µg/L total copper and 1,550-6,148 µg/L total zinc. This also had the finest PSD. Overall, the two industrial/commercial sites (Lunns Road and Princess Street) and one residential street with a very coarse chipseal surface, Montana Ave, were found to

have substantially higher pollutant concentrations in both unswept and swept runoff. The sites with the lowest pollutant concentrations were a highly trafficked but smooth inner city road (Durham Street) and a low trafficked, moderately smooth residential road (Sabys Road).

The regenerative sweeper was observed to be 18-77% (average of 49%) effective at removing TSS for the situations where TSS >150 mg/L. Similarly, vacuum sweeping was seen to achieve 0-69% removal rates (average of 50%) for TSS where TSS >300 mg/L. This corroborates a theory in literature of different sweeper technologies requiring a minimum threshold amount of sediment on a surface before they become effective. At TSS concentrations less than these thresholds, no consistent removal was observed (assuming that the swept plots had similar unswept pollutant build up to the unswept plot). There was also visual evidence of slurry deposits on the road surface caused by the regenerative sweeper, indicating need for refined operating procedures. For Lunns Road, the site of the highest TSS concentrations, particle size analysis indicates that the regenerative sweeper was able to remove fine sediment down to around the 10 µm size range. The successful removal of this fine sediment bodes well for reducing the adverse ecological effects on the receiving waterway as it is these finer size fractions that have proportionally more ecotoxic heavy metals adsorbed to their surface and are less likely to get captured in any catchpits or catchpit inserts.

For effects mitigation, this study’s data indicates that the greatest benefit from future sweeping operations would be to prioritise sweeping of industrial/commercial roads (i.e. higher frequency) and coarse asphalt roads for residential areas. Standard Operating Procedures are needed to ensure sweepers are cleaned and maintained such that deposition of pollutants cannot occur, and operators are trained to inspect for sweeping and catchpit maintenance needs when they are out on site. Further assessment is recommended on the optimization of street sweeping scheduling with consideration given to scheduling of catchpit insert cleaning and identification of priority streets.

1 Introduction and project scope

Runoff from urban surfaces such as roads contributes sediment and heavy metal pollution into our waterways, causing both immediate and long-term adverse impacts on aquatic ecosystems. Street sweeping is one measure that has the potential to minimise the amount of pollutants that can reach the waterways from road runoff (Depree, 2011).

The practice of street sweeping aims to lift and retain sediment from road surfaces, reducing the sediment and associated particulate metals concentrations in road runoff when it next rains. By proxy, the process of sediment removal will also remove particulate metals (metals adsorbed to the surface of the sediment). The typical objective for street sweeping is to remove gross pollutants (including litter and organic matter), from blocking drains and roadside catchpits or sumps. However, street sweeping is an important component of the road runoff treatment train, in tandem with catchpits. Street sweeping provides a function of maintaining higher catchpit removal efficiencies by taking out some of the pollutant loads that would otherwise fill the catchpits.

Christchurch City Council (CCC) engaged the University of Canterbury (UC) to undertake field trials of unswept and swept road runoff quality to assess the effectiveness of street sweeping for pollutant reduction. This report documents Phase 2 of a wider project "Comprehensive Stormwater Network Discharge Consent (CSNDC); Schedule 4(c) - a trial for increased targeted/selective street sweeping", which seeks to optimise the effectiveness of its street sweeping practices for pollutant removal from road runoff and also ensure that Council meets its obligations under the CSNDC conditions. Phase 1 was a literature review that identified the most influential factors for street sweeping, and it informed the design of the street sweeping field trials of Phase 2. Phase 2 aimed to create a dataset of road runoff quality to compare the relative difference between unswept and swept conditions, rainfall intensity and road surface characteristics (traffic intensity, surface condition) on runoff quality. This report extends the literature review from Phase 1 and outlines the methodology and results from the Phase 2 field trials.

2 Literature Review

2.1 Factors influencing the build up and wash off of pollutants from road surfaces

Previous studies have identified a range of factors that affect the build-up and physico-chemical characteristics of the pollutants, and therefore how they can be captured by street sweepers (Amato et al., 2010; Calabrò, 2010; Depree, 2011; Hixon & Dymond, 2018; Kang et al., 2009; Kim et al., 2014; Pitt, 1979; Selbig & Bannerman, 2007; Sutherland & Jelen, 1997; Walker et al., 1999). Other factors influence the wash off of the remaining (post-sweeping) particles and therefore the resultant post-sweeping runoff quality (Egodawatta et al., 2007). These factors can be broadly categorised into: surface factors, pollutant characteristics, climate characteristics (how it rains) and technology factors (street sweeper type and operation) (Figure 1).

2.2 Factors influencing the ability of street sweeping to remove particles from the road surface

2.2.1 Initial pollutant loading, length of antecedent dry period and season

The length of antecedent dry period has been demonstrated to drive the rate of pollutant build up on a surface in dry weather (Wicke et al., 2012). Importantly, pollutant build up reaches a saturation maximum over time; as the number of antecedent dry days increases, the rate of pollutant accumulation decreases until saturation is reached. Typical saturation periods of 6-7 days have been reported for road and carpark sediment (Egodawatta & Goonetilleke, 2006; Sartor et al., 1974; Wicke et al., 2012).

In turn, the length of the antecedent dry period is related to the season. For example, analysis of Christchurch rainfall data from 2010 to 2021 shows rain events in winter have the shortest ADDs (average of 3.1 days, range of 0.3-19.3 days), while summer events have the longest ADDs (average of 4.2 days, range of 0.3-29 days) (unpublished; data sourced from NIWA's Kyle St weather station, analysed by Frances Charters, University of Canterbury). This suggests the pollutant build up may vary seasonally. However, a count of the number of events that exceed 6 days (the indicated saturation period) shows there as just as many winter events with ADD >6 days, as summer and spring events (with autumn recording 14% more than winter). Therefore, for the Christchurch climate, it is unlikely that seasonally-responsive scheduling of street sweeping will provide much additional benefit.

Several studies have found that street sweepers are unable to remove particles unless the surface loading is greater than a particular threshold amount, which, in turn, varies based on particle size distribution (Law et al., 2008; Walker et al., 1999). Mechanical sweepers have a loading threshold three times higher than regenerative-air sweepers (see Section 2.3.1).

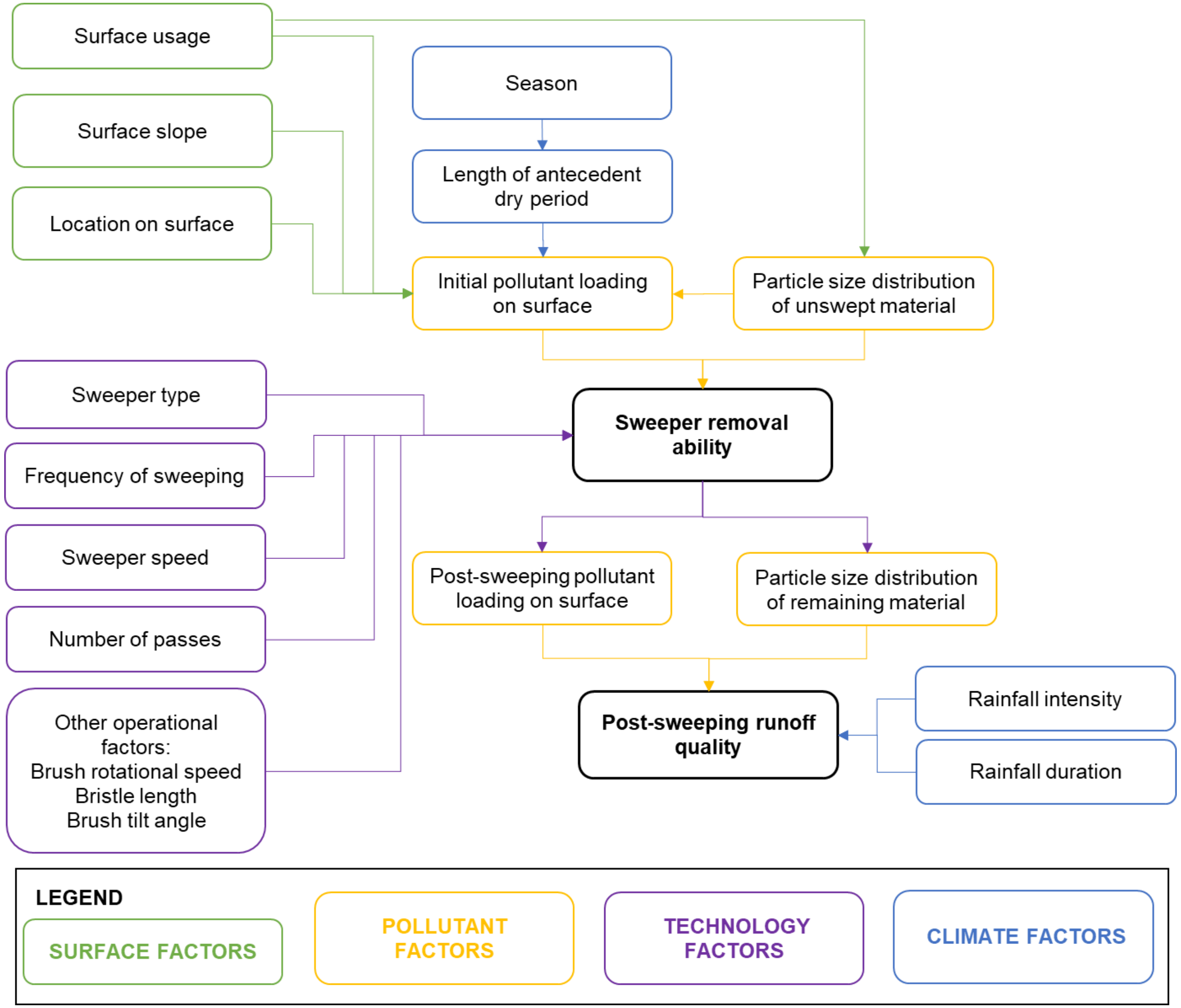


Figure 2-1: Factors that influence street sweeping performance

2.2.2 Surface usage and surrounding catchment activities

Traffic intensity influences both the amount (load) and nature of the pollutants on a road surface. Local untreated road runoff quality data from Christchurch has shown corresponding increases in suspended solids and metals concentrations with increasing traffic intensity (Charters et al., 2021). It is therefore important to assess a range of road surfaces to capture variation in sweeping performance associated with the variability of pollutant loading and particle size distribution.

Nearby activities have also been recognised as a contributing factor to road pollutant build-up (Depree, 2008; Jeong et al., 2020). Industrial and construction activities can contribute as additional source of sediment and/or heavy metals to the direct deposition sources from vehicles on roads. Two recent New Zealand studies have found that industrial/commercial activities are a stronger influence on pollutant loads in catchpit sediments that traffic intensity (SCO Consulting, 2022, 2024)

2.2.3 Surface slope and location on surface

One study reported that higher concentrations of fine sediment were found in areas of greater slope (e.g. the sloped side of channels by the kerb edge) (Wang et al., 2020). Furthermore, other studies have shown ~90% of sediments are found within 2 m from the kerb (Duncan et al., 1985; Grottker, 1987; Pitt, 1979). One study concluded that street sweeping should be performed solely in the edge lanes of the roadway (Amato et al., 2010).

2.3 Factors influencing runoff quality post-sweeping

2.3.1 Sweeper type and influence of particle size distribution

Street sweepers can generally be categorised into three categories (Amato et al., 2010):

1. Mechanical broom – uses a rotating brush head along the gutter line, followed by a pick-up broom to sweep the dislodged particulate matter onto a conveyor belt into a hopper.
2. Vacuum-assisted broom – uses an impeller/fan to create suction to draw up particulates dislodged by a rotating brush head.
3. Regenerative air – uses blown air to dislodge particulates which are then vacuumed into a hopper; also uses a rotating brush along the gutter line.

Vacuum-assisted and regenerative-air sweepers are better at removing fine particles (<100 um), while mechanical sweepers are more effective for larger particles (>100-125 um) (Amato et al., 2010; Calabrò, 2010). For broom sweepers, operational factors such as brush rotational speed, bristle length and brush tilt angle have all been shown to affect removal efficiency (Kim et al., 2014). Overall, vacuum-assisted broom and regenerative air sweepers are more effective than mechanical broom sweepers (Wang et al., 2020), due to the expected particle size distribution of road-deposited solids (RDS) (Charters et al., 2015). However, both mechanical and regenerative sweepers require a minimum threshold amount of sediment on the street surface before they become effective (Walker et al., 1999). For example, the removal efficiency of regenerative sweepers for particles 250-2,000 µm has been observed to drop to zero due to this threshold effect (Sutherland & Jelen, 1997).

Fine particles are more difficult to remove due to their stronger attachment to the road surface (Kim et al., 2014). Managing fine particles is of concern as they have been found to be readily mobilised by even small rain events (Calabrò, 2010) (Walker et al., 1999), and they carry a higher concentration of associated particulate metals (Maniquiz-Redillas & Kim, 2014; Sansalone et al., 1996). One study suggested use of a tandem operation, where a mechanical street sweeper is used to first remove coarser particles, followed by a regenerative-air sweeper to remove finer particles, in order to maximise solids removal (Amato et al., 2010). However, an earlier study by Sutherland and Jelen (1997) had found the tandem operation to be the least efficient despite some high individual removal efficiencies, with substantial performance variation. Instead, Sutherland and Jelen (1997) recommended a small-micron sweeper for more effective removal of smaller size fractions, as testing demonstrated its effectiveness without the threshold effect seen for mechanical and regenerative sweepers.

Another recognised issue with water-based dust suppression methods used on sweepers such as regenerative sweepers is that they can resuspend the finer particles and mix with the water to form a slurry that adheres to the road surface (Walker et al., 1999).The finer particles can also escape sweeper capture as they are readily mobilized into the air by the high pressure air that is used to dislodge the coarser particles. The small-micron surface sweeper that was identified by Sutherland and Jelen (1997) as the most efficient sweeper type sweeps dry, with no water being used, and this is considered a key contributor to its improved performance. Overall, however, Walker et al. (1999) concluded that the role of sweeper type on pollutant removal efficiencies is outweighed by other factors such as surrounding land use activities, antecedent dry period, sweeping frequency and timing and sweeper operation.

2.3.2 Sweeper speed and number of passes

Multiple passes have not been found to increase the overall removal rate of particles (Kim et al., 2014). This is considered to be due to the fineness of the remaining particles and their stronger attachment to the road surface. However, sweeping speed has been found to substantially influence the removal rates, with one study reporting 60% RDS removal at 4-8 km/hr compared to <5% removal at 20 km/hr (Kim et al., 2014).

2.3.3 Frequency of sweeping

As expected, more frequent sweeping has been found to correlate to improved pollutant removal rates. One study suggested a sweeping frequency based on three times the mean inter-event dry period (in this case, 8 days, for Melbourne, Australia), as approximately 35% of rain events in that climate were considered to be gross pollutant transporting events (Walker et al., 1999). However, how much influence sweeping frequency has on the resultant runoff quality is related to the local build-up dynamics that drive how quickly maximum saturation is reached on the road surface (see Section 2.2.1).

This study also considered whether local rainfall conditions create source-limited or transport-limited wash off conditions. Supply-limited conditions occur where there are no longer any solids able to be washed off a surface even when there is still rainfall occurring. Transport-limited conditions occur where larger particles are not able to be mobilised due to lower-energy rainfall dynamics. Given Christchurch's low intensity rainfall climate (Charters et al., 2016), transport-limited conditions are likely for the majority of rain events. In transport-limited conditions, street sweeping techniques may be best tailored to fines removal and there may be only incremental benefits from increasing street sweeping (Walker et al., 1999).

2.3.4 Rainfall intensity and duration

Rainfall intensity is an indication of the kinetic energy present that allows the entrainment and transport of particles in runoff from a surface (Egodawatta et al., 2007). Therefore, it can be expected that runoff quality for a given event depends on the size of particles remaining on a swept street surface and the corresponding rainfall intensity. Larger particles will require greater intensity in order to be mobilised.

Differences have been noted in literature between the sediment sizes that natural rainfall can readily entrain compared to the sizes that sweepers can entrain. Calabrò (2010) concluded that natural rain picks up proportionally more finer particles of the available sediment on a road surface, due to the smaller sizes being easier to entrain as they require less energy to do so. However, a mechanical sweeper was found to be able to pick up a higher proportion of the available coarser particles (>425 um), as these were less caught up in interstitial spaces that may prevent the sweeper brush and vacuum from entraining them. Similarly, Pitt and Sutherland (1982) concluded that a significant proportion of the larger dirt particle sizes picked up by street sweepers are not easily transported by natural rain. Furthermore, they considered that removal of these coarser particles during sweeping exposes the smaller sheltered particles and makes them available for wash off during the next rain event, increasing the amount of fine TSS washed off in road runoff.

Street sweeping effectiveness studies have used both natural rainfall and simulated rainfall events. For the simulated rainfall studies, various approaches have been taken to select a meaningful intensities and durations. For example, Kim et al. (2014) selected a rainfall intensity based on 60-min maximum precipitation from historic rain data. Herngren et al. (2005) used 4 different intensities, applied for 12 different durations to matched to Annual Exceedance Probability (AEP) events.

2.3.5 First flush effect

A 'first flush' effect where the initial runoff is more polluted than later runoff could be expected from road runoff, based on what has been observed previously in literature (Deletic, 1998; Kayhanian et al., 2012) . This first flush effect is driven by the initial availability of pollutants on the road surface that can be readily washed off by the applied rain. Later in the same rain event, the remaining pollutants on the surface are typically coarser (i.e. heavier) or more embedded within the interstitial spaces around the road chip, and therefore require more energy to be entrained and washed off from the surface.

2.4 Reported unswept road runoff quality

Reported road runoff quality from New Zealand and overseas shows substantial variation in sediment and heavy metal concentrations (Figure 2-2 to Figure 2-4; see Appendix F for a summary of the data sources). Higher trafficked roads have been found to typically produce higher pollutant concentration but not always. The range for TSS is greater for collector and local roads than what has been reported for highways and arterial roads. However, a first flush effect has been consistently observed regardless of traffic intensity for TSS, copper and zinc. It should be noted that copper concentrations in road runoff may change from this historic data where changes such a move to copper-free brakes pads have been made. However, there is insufficient data reported in literature to identify any effect to date from such copper reduction strategies.

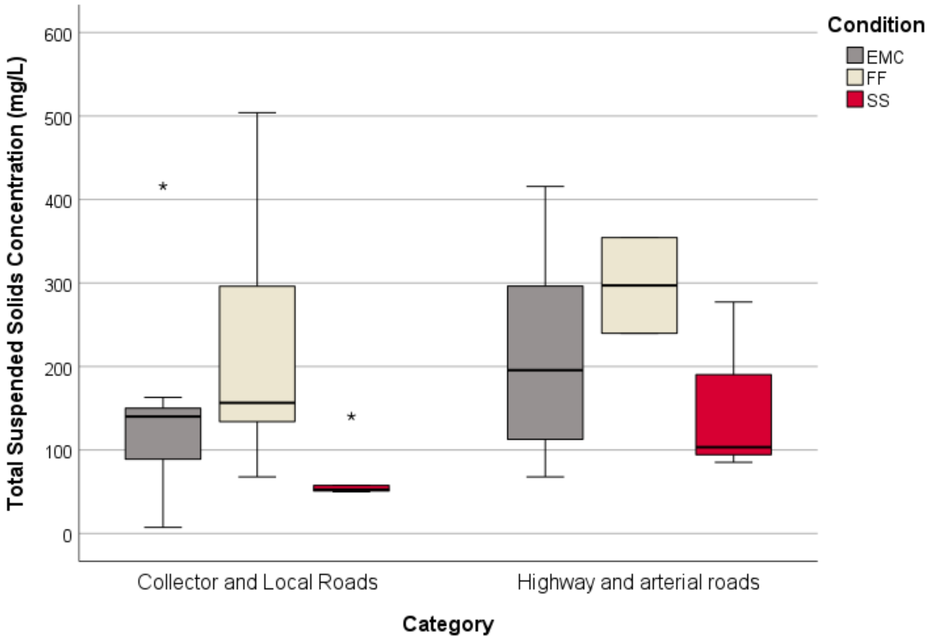


Figure 2-2: Reported TSS concentrations in road runoff from higher and lower trafficked roads, for Event Mean Concentration (EMC), first flush (FF) and second stage (SS) data.

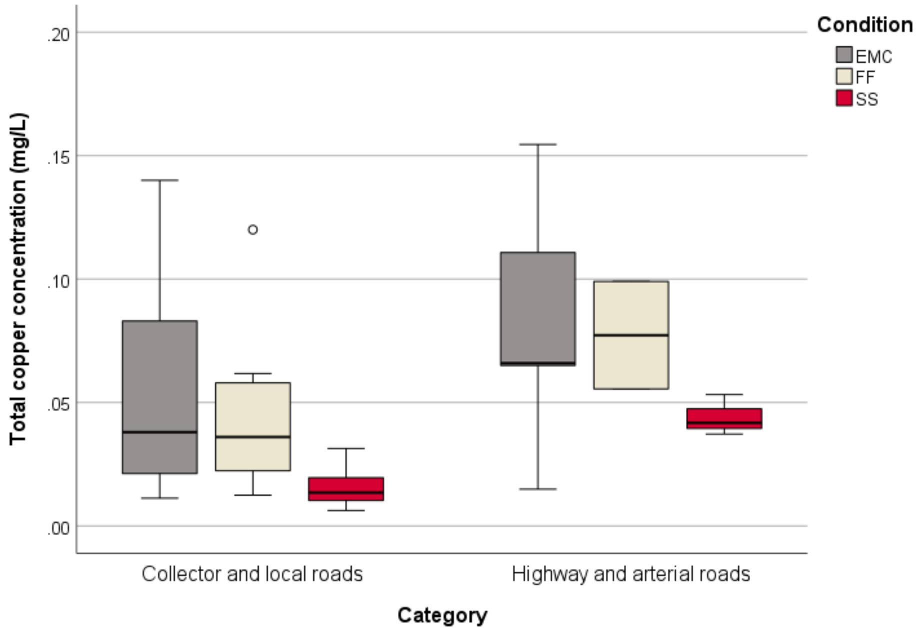


Figure 2-3: Reported total copper concentrations in road runoff from higher and lower trafficked roads, for Event Mean Concentration (EMC), first flush (FF) and second stage (SS) data.

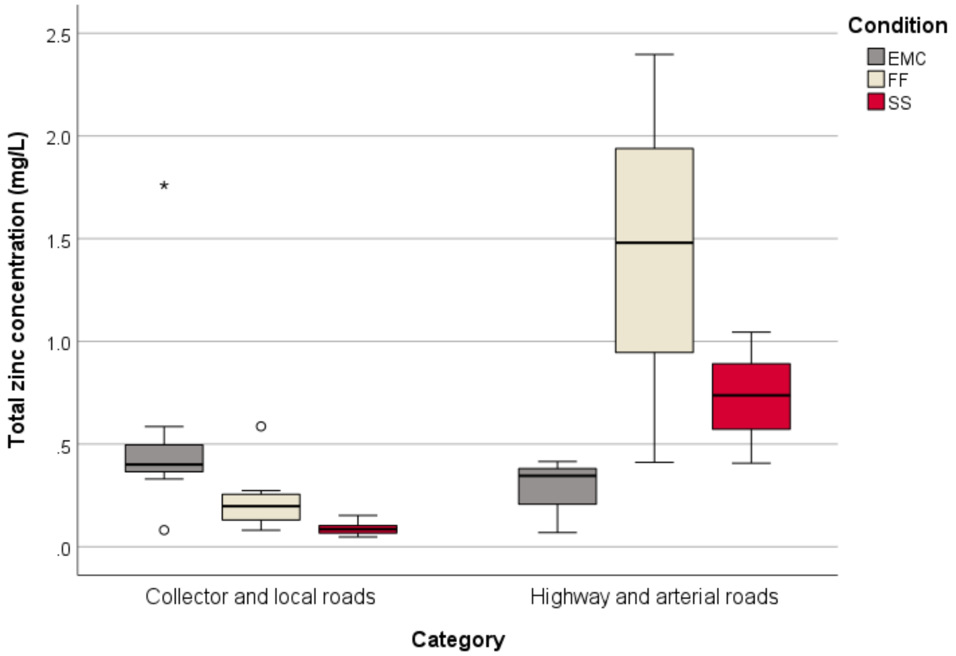


Figure 2-4: Reported international and national total zinc concentrations in road runoff from higher and lower trafficked roads, for Event Mean Concentration (EMC), first flush (FF) and second stage (SS) data.

2.5 Reported efficiencies of street sweeping for road pollutant reduction

There is limited data on the quantified reduction in runoff pollution that can be achieved with street sweeping at both a New Zealand and international level (Table 2-1). Furthermore, the findings are inconsistent, with a range of TSS removal rates ranging from 0% to 96% for different sweeping technology and particle size fractions, although the same sweeping technology also reports a wide performance variation. For example, two different studies reported 30 and 78% TSS removal for a standard vacuum-assisted sweeper, and 5 to 48% in two phases of a single study.

Of the limited data, most is for TSS and only one study provided quantified removal rates for copper and zinc. Overall, these studies are inconclusive about the benefits of street sweeping for direct removal of pollutants. However, the benefit of street sweeping in reducing pollution from roads in urban waterways should be considered in context of the role it has as part of a treatment train for road runoff.

Table 2-1: Reported efficiencies of street sweeping for pollutant reduction

Study	Location	Sweeper Type	Reported percent removals (%)
Kim et al. (2014)	Korea	Vacuum assisted	TSS: 78% Cu: 31% Zn: 5%
Selbig and Bannerman (2007)	Wisconsin, US	Air sweeper	TSS: 24-46%
		High-frequency broom	TSS: 24-48%
	Treatment phase (mean yield reduction)	Regenerative air	TSS: 25%
		Vacuum assisted	TSS: 30%
		High-frequency broom	TSS: 5%
Sutherland and Jelen (1997)	US	Small micron surface sweeper (a type of vacuum-assisted dry sweeper)	TSS: 70% for <63 µm; up to 96% for >6,300 µm.
		Regenerative air	TSS: 32% for <63 µm; Down to 0% for 250-2,000 µm, but up to 100% for 600-2,000 µm.
Pitt and Bissonette (1984)[1]	Washington, US	Mechanical broom	TSS: 0% for <125 µm
Sartor and Boyd (1972)[1]	US	Mechanical broom	TSS: 20% for <150 µm, 60% for <800 µm, 63% for <2,000 µm.

[1] Study used older sweeping technology, so removal efficiency may be less than what can be achieved by more modern sweeping technology

2.6 Particle size dynamics in road runoff and street sweeping

The relative sizes of particles in road runoff is important to characterise for two key reasons. Firstly, finer particles have a higher ratio of surface area to volume and therefore have proportionally more binding sites for heavy metals adsorption. This means smaller particle size fractions have a higher concentration of ecotoxic heavy metals and are of priority for sediment removal to protect downstream receiving environment health (Walker et al., 1999). Depree (2008) found particles <63 µm held at least twice as much zinc and copper as particle size fractions >63 µm. Finer size particle fractions are also more readily mobilised during rainfall due to requiring less energy to wash off and entrain in runoff from the road surface.

Secondly, treatability of sediment via processes such as filtering or settling is connected to the individual sizes of particles. Coarser particles settle faster than finer sediment due to a higher settling velocity, with some fine sediment unlikely to settle out at all. However, where catchpit filters are in place, smaller size fractions may be captured more readily. A study of 200 µm mesh filters found 20% of the captured particles were <63 µm (SCO Consulting, 2024), demonstrating the value of functioning catchpit filters. However, studies have shown that the sediment capture efficiency of catchpit insert reduces rapidly once the insert unit is over 50% full (SCO Consulting, 2024). Therefore, street sweeping at appropriate frequencies for the road pollutant conditions could offer a significant benefit in maintaining the effectiveness of catchpit inserts further down the treatment train.

Particle size analysis of road sediment in literature (from both unswept and swept roads) shows a wide range of distribution across particle size fractions (Figure 2-5), reflecting the diversity of sediment build up and wash off conditions. Direct comparisons within individual studies of unswept and swept PSDs show finer PSDs for the swept runoff, indicating that the coarser particles have been successfully removed by the street sweeper. However, there is no difference shown between the range of swept PSDs and unswept PSDs when viewed across all studies.

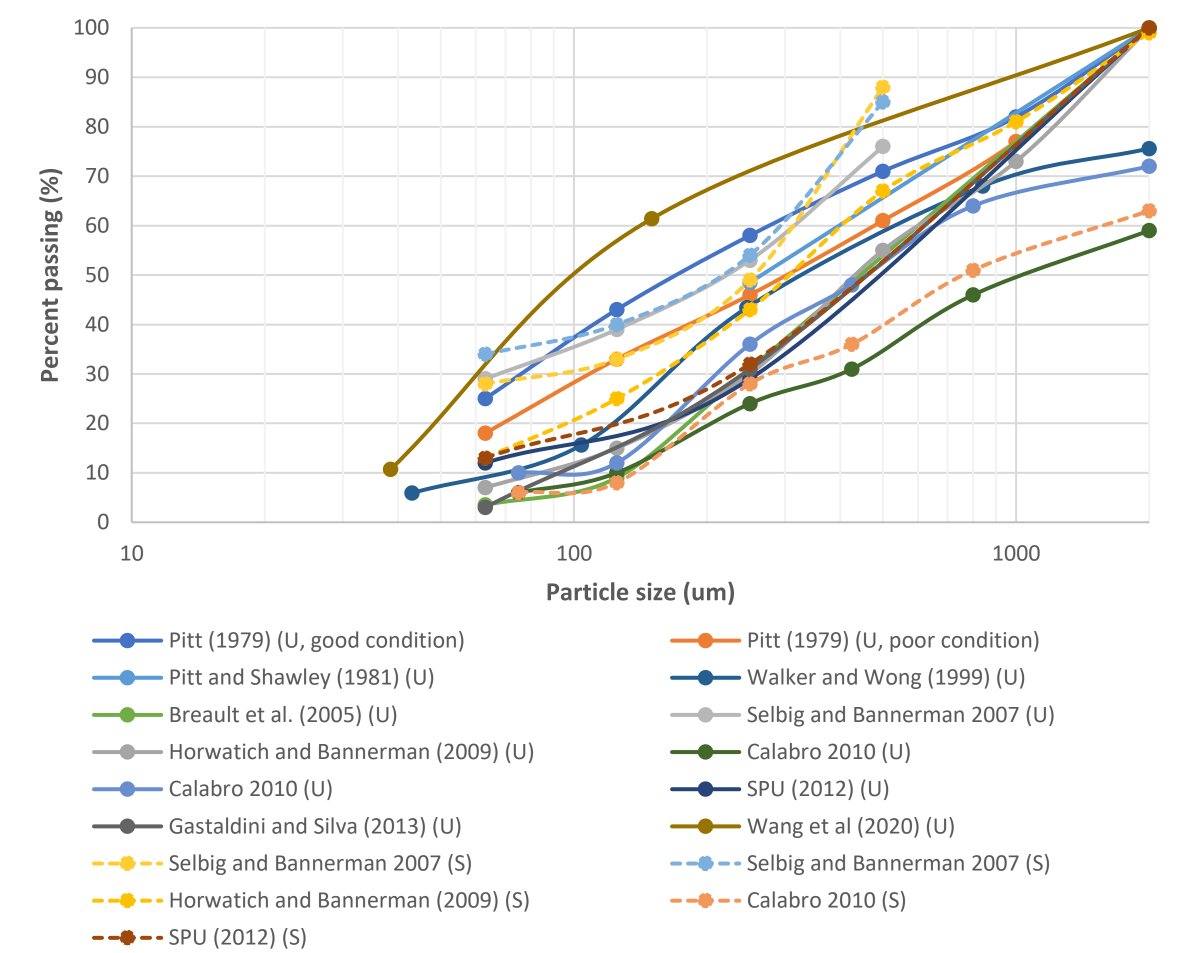


Figure 2-5: Cumulative particle size distribution of road sediment from unswept (U) and swept (S) roads reported in literature

Table 2-2: Reported particle size capture efficiency (percentage) in unswept and street sweeping captured sediment

Study	Location	Sweeper type	Fine (um)			Medium (um)		Coarse (um)
			0-63	63-125	125-250	250-500	500-1,000	>1,000
UNSWEPT								
Pitt (1979)[1]	California, US	Unswept, good condition	25	18	15	13	11	18
		Unswept, poor condition	18	15	13	15	16	23
Pitt and Shawley (1981)[1]	California, US	Unswept		48.5 (0-250 µm)		51.5 (250-1,00 µm)		nd
Breault et al. (2005)[1]	Massachusetts, US	Unswept	3.5	5.5	22		69 (250-2,000 µm)	
Horwatich and Bannerman (2009)[1]		Unswept, multiple streets	7	8	15	25	18	27 (1,000-2,000 µm)
SPU (Seattle Public Utilities) (2012)[1]	Washington, US	Unswept	12	17 (63-250 µm)		68 (250-1,000 µm)		nd
Gastaldini and Silva (2013)[1]	Santa Maria, Brazil	Unswept	3	28 (63-250 µm)		69 (250-1,000 µm)		nd
SWEPT								
Chang et al. (2005)[2]	Taipei, Taiwan	Tandem with washer	10-98					
Selbig and Bannerman (2007)[2]	Wisconsin, US	Vacuum assisted	10	18	28	30	38	50
		Regenerative air	-50	-8	10	20	34	35
Ang et al. (2008)[2]		Mechanical broom	57	20	50	60	nd	nd
Horwatich and Bannerman (2009)[1]	Wisconsin, US	Swept, multiple streets	13	12	18	24	14	18 (1,000-2,000 µm)
SPU (Seattle Public Utilities) (2012)[1]	Washington, US	Swept	13	19 (63-250 µm)		71 (250-1,000 µm)		nd
Kim et al. (2014)	Kyunggi, Korea	Vacuum assisted	18 (<75 um)	50 (>75 um)	nd	nd	nd	nd

[1] Data sourced from (Hixon & Dymond, 2018)

[2] Data sourced from (Amato et al., 2010)

[3] nd – no data available for the particular size fraction

3 Methodology

3.1 Selection of trial sites

Five sites were selected to develop a road runoff quality dataset representative of a range of traffic intensities and catchments (Table 3-1). The sites also represent locations that are in close proximity to CCC's monthly surface water quality monitoring programme sites, wet weather monitoring programme sites or other water quality-related projects.

Table 3-1: Summary of sampling sites

Site	Description
1. Durham Street N, southeast side from Kilmore Street intersection	Central City multi-lane road, in Ōtakaro/Avon River catchment. 11,863 AADT[1] (2020). Runoff from this road section is routed through The Commons raingardens for treatment prior to discharge into the Ōtakaro/Avon River.
2. Princess Street, off Matipo Street	Commercial/light industrial area, in Addington Brook catchment (a priority catchment of concern given its poor water quality). 3,547 AADT[1] (2018).
3. Lunns Road, off Annex Road	Industrial area, heavy vehicle traffic, in Curletts Stream catchment (a priority catchment of concern given its poor water quality; site adjacent to CCC long-term surface water monitoring site). 5,670 AADT[1] (2021).
4. Montana Ave, off Ilam Road	Residential area, in Okeover Stream catchment (focus of much UC research). 2,300 AADT[1] (2013).
5. Sabys Road, off Halswell Junction Road	Residential area, in Halswell River catchment (Water quality issues, with little available data and opportunity to inform a site-specific integrated management plan). 3,629 AADT[1] (2017).

[1] Annual average daily traffic count (AADT) based on data from indicated years (Christchurch City Council, 2023)

3.2 Rainfall simulator set up

3.2.1 Overview of rainfall simulator

A Norton rainfall simulator (2 head unit) was used for all field trials. The simulator was run at 6 psi operating pressure. The simulator was calibrated in the laboratory prior to deployment to confirm the applied intensities that the road surface would receive during field trials (Table 3-2). In the field, the simulator was supplied with water pumped from a feeder tank on site, filled from Christchurch Council public water supply hydrant via tanker truck.

Table 3-2: Calibrated rainfall intensities used in the field trials

Applied Rainfall Intensity (mm/hr)	Simulator settings (at 6 psi pressure, 1.9 m above road surface)	Representative rainfall conditions (as at Addington, Christchurch) [1]
11	Single sweep, Speed 1	1 hour duration 0.5% AEP event
22	Single sweep, Speed 2	30 minute duration 0.2% AEP event
33	Single sweep, Speed 3	30 minute duration 0.05% AEP event

[1] Sourced from NIWA (2017) for historical data conditions, at Kyle Street Weather Station, Addington, Christchurch

3.2.2 Trial conditions

Trial conditions were selected to enable assessment of how key factors influence the quality of the road runoff, with a view to informing the optimum use and scheduling of street sweepers for various road types in Christchurch city (Table 3-3, Figure 3-1).

A minimum antecedent dry period of three days was used, as local Christchurch data indicates a maximum build up on road surfaces occurs after 4-6 dry days (Wicke et al., 2012). Four days antecedent dry period was initially selected but did not provide sufficient opportunity for trialling. In fact, between February and July 2023, no trials were able to be conducted due to not being able to meet the four days antecedent dry period during the working week, and therefore the minimum antecedent dry period was reduced to three days upon agreement with CCC and Environment Canterbury. Three days provided a balance of ensuring there was reasonable build up on the surface whilst providing sufficient opportunity to trial between natural rain events.

Table 3-3: Trial conditions for each site

Trial No.	Sweeper conditions [1]	Antecedent dry period (days)	Rainfall intensity (mm/hr)	Indicative sampling times since start of runoff (mins)
1 (Baseline)	Unswept	≥ 3	11	0, 7, 15
2	Vacuum	≥ 3	11	0, 7, 15
3	Vacuum	≥ 3	22	0, 7, 15
4	Vacuum	≥ 3	33	0, 7, 15
5	Regenerative	≥ 3	11	0, 7, 15
6	Regenerative	≥ 3	22	0, 7, 15
7	Regenerative	≥ 3	33	0, 7, 15

[1] Single pass of sweeper at 5 km/hr

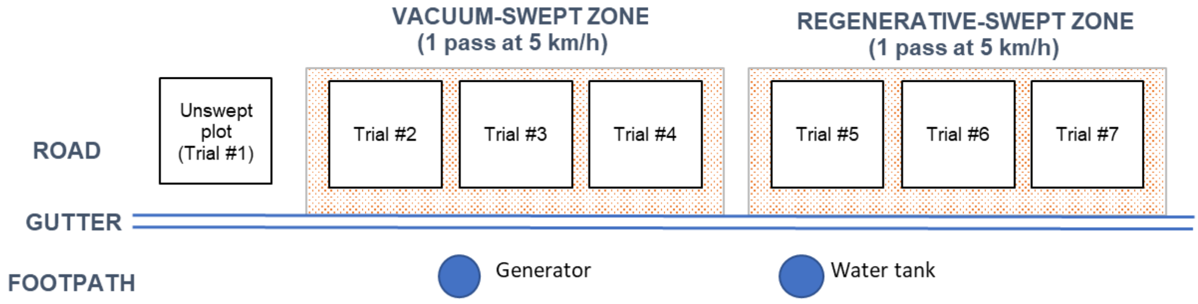


Figure 3-1: Site layout of trial plots

3.3 Sample collection, preservation and analysis

3.3.1 Sample capture system

For each trial, a 1 m^2 sampling plot with an outlet point was set up under the rainfall simulator (Figure 3-2). The plot design was based on a proven approach from international literature, following Herngren et al. (2005). Using a sampling plot provided the key advantage of enabling the rainfall simulator to be set up and samples collected on any road space, independent of the condition of the kerb and channel or presence of sumps. Samples were taken using whole-of-flow capture into HPDE containers. Samples were taken at the start of runoff (t=0), then after typically 7 minutes and 15 minutes of runoff, in order to capture any temporal differences in runoff quality (Table 3-3).

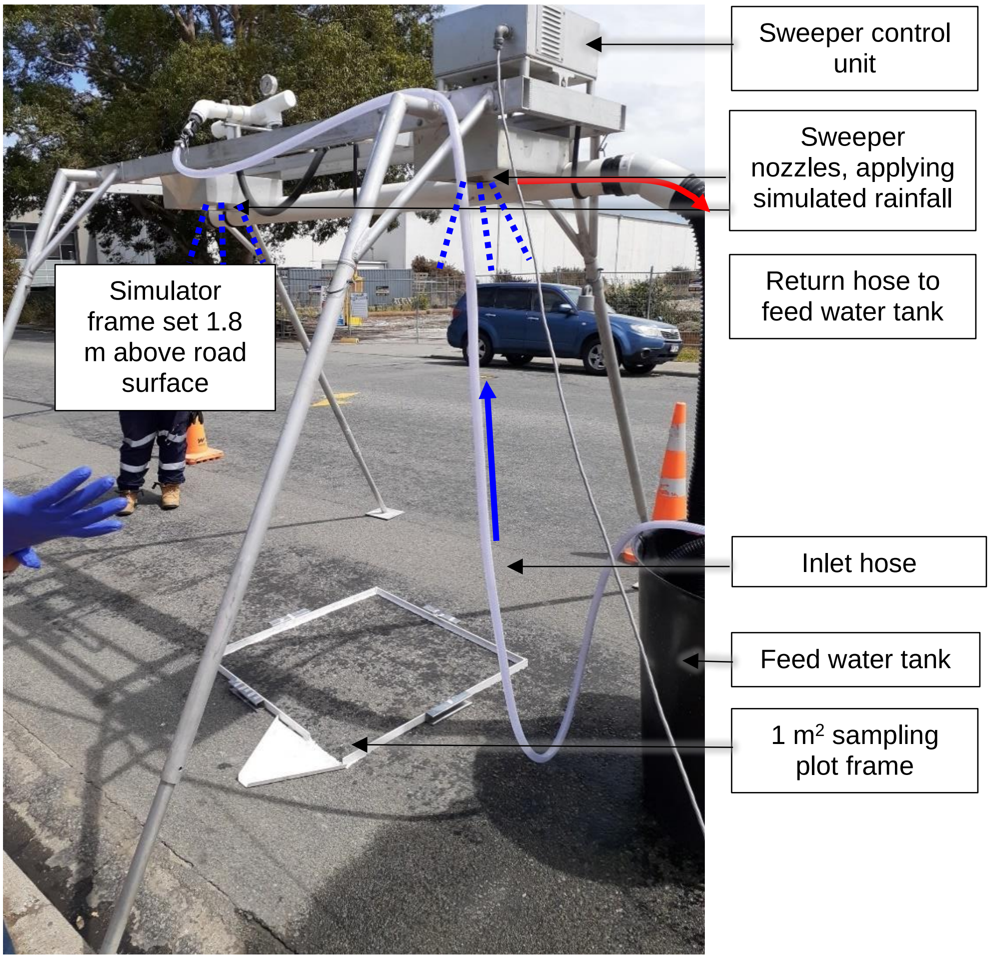


Figure 3-2: Rainfall simulator and sample capture plot set up

3.3.2 Sample preservation and analysis

All samples were analysed for sediment and selected heavy metal concentrations (Table 3-4). 1 L of raw sample was collected in 1 L HDPE bottles for each sampling timepoint. Raw samples were then split, with a 200 mL subsample taken off for particle size analysis.

For most trials, raw samples were taken immediately after each trial session to the relevant labs for analysis (transported on ice at ≤4°C). For the Durham Street N site, where the trials were undertaken as night works, one of the Montana Ave trial days and the Sabys Road site, all samples were instead taken to the Environmental Laboratory at the University of Canterbury for storage until the CCC Lab reopened. Prior to storage at UC, subsamples were taken for total metals and dissolved metals (filtered with 0.45 um filter) and preserved with nitric acid to pH <2. Chain of custody forms were used to record all handling of samples that were sent to the CCC Lab.

Table 3-4: Analytical methods

Analyte	Analyser	Sample preparation and analytical method used	Limit of detection
Total suspended solids	CCC Laboratory, Bromley	Filtration with 1.2 um glass fibre filter, mass retained on filter (Method 2540D, (American Public Health Association, 2005))	3 g/m^3
Particle size distribution	Environmental Laboratory, Department of Civil and Natural Resources Engineering, University of Canterbury	Mastersizer 3000 laser diffraction unit, range 0.002-5,000 µm	0.002 µm
Total zinc and copper	CCC Laboratory, Bromley (preservation with acid undertaken at UC Environmental Laboratory when overnight storage was necessary)	Preservation with nitric acid to pH <2, followed by acid digestion and filtration with 0.45 um (Methods 3030E, 3030B, 3125B (American Public Health Association, 2005)) ICP-MS analysis (trace level)	Cu: 0.53 mg/m^3 Zn: 1.1 mg/m^3
Dissolved zinc and copper	CCC Laboratory, Bromley (filtration and preservation with acid undertaken at UC Environmental Laboratory when overnight storage was necessary)	Filtered with 0.45 um filter, preserved with nitric acid to pH <2 (Methods 3030B, 3125 B (American Public Health Association, 2005)) ICP-MS analysis (trace level)	Cu: 0.53 mg/m^3 Zn: 1.1 mg/m^3

Particle size analysis (PSA) was undertaken using a Malvern Instruments Mastersizer 3000 laser diffraction unit (0.01-3,500 µm range). A refractive index of 1.457 and absorption index of 0.01 was used, assuming non-spherical, inorganic silica-based particulates. PSA was undertaken only for samples that could achieve adequate obscuration (i.e. the raw samples had sufficient density of particles for accurate particle size analysis). This meant that first flush samples were able to be analysed from all trials, but later stage samples were only able to be analysed from trials run under higher intensities or where the accumulated sediment concentrations were sufficiently elevated.

3.4 Quality assurance/quality control

Key quality assurance and control activities were taken in the field and lab as follows:

- In the field, feeder tank water samples were taken each trial day to quantify the background water quality being applied from the rainfall simulator. The hydrant was flushed prior to filling the tanker tank.
- Where multiple trial days were required at a site, a second unswept trial plot was run when the second trial day was run under different conditions than the first day. This resulted in two unswept trials plots being undertaken at Montana Ave and Lunns Road. This provided the benefit of also quantifying the variation in unswept road runoff quality.
- For TSS and heavy metals analysis, duplicates were taken and analysed by CCC Laboratory for every 10th sample received.
- For PSA analysis, triplicate particle size distribution readings are taken for each sample and an average of the three readings is used. A target sample obscuration of 8-12% was used.

4 Results and Discussion

4.1 Trial day conditions

Antecedent dry periods varied between 3.0 and 8.5 days, with a median of 4.8 days (Table 4-1; further details in Appendix A). All sites had been swept within 4 weeks of the day of trial. The trials took place between 16 January to 2 February 2023, and 8 August to 13 November 2023. The gap in the sampling period was due to a prolonged period of wet weather in autumn and winter that meant the >3 days dry period criteria could not be achieved.

Table 4-1: Trial days' characteristics

Trial Date	Trial Site	Session	Length of antecedent dry period (days)	Date when last swept
16 January 2023	Montana Ave	1 of 2	4.0	19-24 December 2022 (4 weeks prior)
1 February 2023	Montana Ave	2 of 2	4.3	16-22 January 2023 (2 weeks)
2 February 2023	Lunns Road	1 of 2	5.3	1-8 January 2023 (4 weeks)
8 August 2023	Durham Street	1 of 2	5.3	Unconfirmed
15 August 2023	Durham Street	2 of 2	3.4	Unconfirmed
25 August 2023	Sabys Road	1 of 1	8.5	7-13 August (3 weeks)
6 October 2023	Lunns Road	2 of 2	3.0	11-17 September 2023 (4 weeks)
13 November 2023	Princess Street	1 of 1	7.2	6-12 November (1 week)

4.2 Unswept and swept road runoff quality

4.2.1 Sediment

The highest TSS concentrations were observed at Lunns Road, an area with surrounding industrial/commercial activities (Figure 4-1), with first flush (i.e. first 1 L of runoff) concentrations of 695 and 1,195 mg/L TSS for the two unswept plots. However, there was an unusually high TSS concentrations recorded for one of the unswept plots at Montana Ave (636 mg/L TSS), a site in a low trafficked residential street. This indicates that traffic intensity cannot be used as a sole indicator of likely unswept runoff quality. In contrast, surface roughness was visually observed to be correlated to unswept TSS concentration, with the two sites with coarsest surface type (coarse chipseal at Lunns Road and Montana Ave) having the highest unswept TSS, and the site with the smoothest surface (smooth asphalt at Durham Street) found to have the lowest unswept TSS concentration.

The swept plots from each site did not show any trend of reduced TSS concentrations compared to the unswept plot(s) (Figure 4-1). For the vacuum-swept plots, TSS concentrations were found to exceed the unswept concentrations for four of the five sites (all except Montana Ave for vacuum swept), while for the regenerative swept plots, swept TSS concentrations exceeded the unswept concentration for three of the five sites (exceptions were Princess Street and Lunns Road) (Figure 4-2). The difference between plots may not be a direct measure, however, of altered load due solely to sweeping, as there will be some variations in the amount of available pollutants on each adjacent plot.

Comparison of TSS concentration with increasing applied rainfall intensity showed that there was not a consistent increase in TSS for the vacuum-swept trials (exception was Montana Ave) (Figure 4-2). Three of the five sites did show an increased TSS concentration under increased intensity for the regenerative-swept trials (Durham Street, Sabys Road and Princess Street). Graphical analysis of TSS concentration over time for all trials at each site is provided in Appendix B-1.

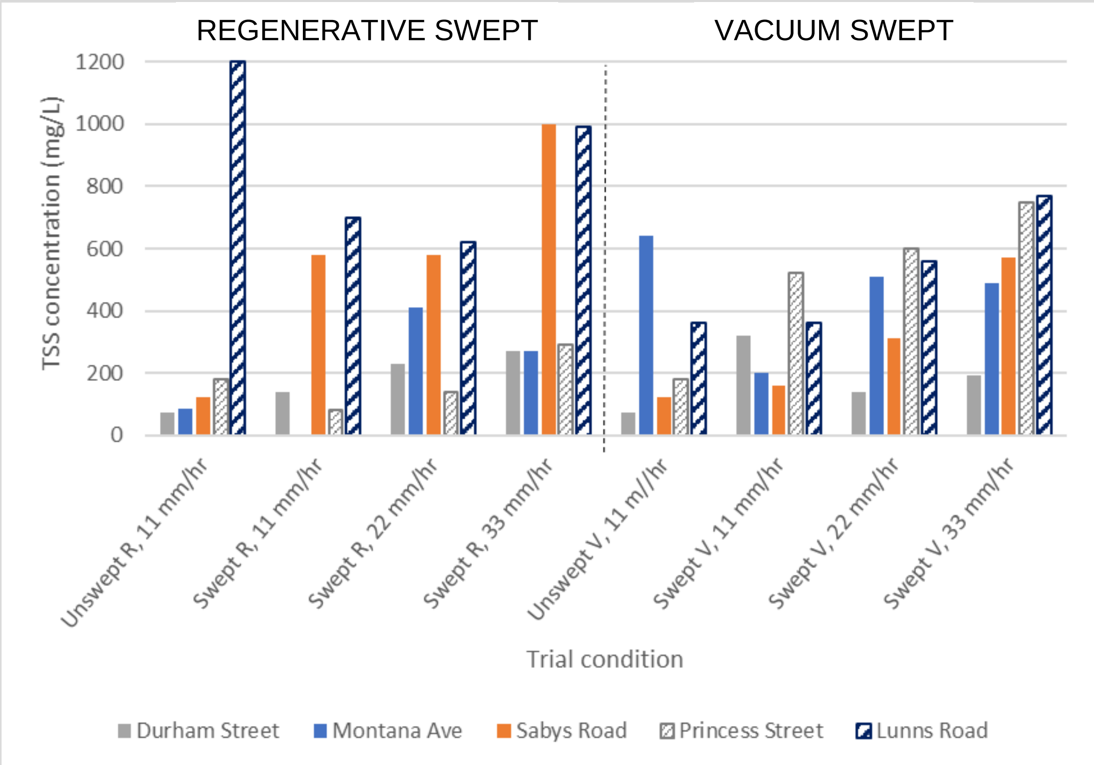


Figure 4-1: Comparative first flush TSS concentrations for all trials, across the five sites

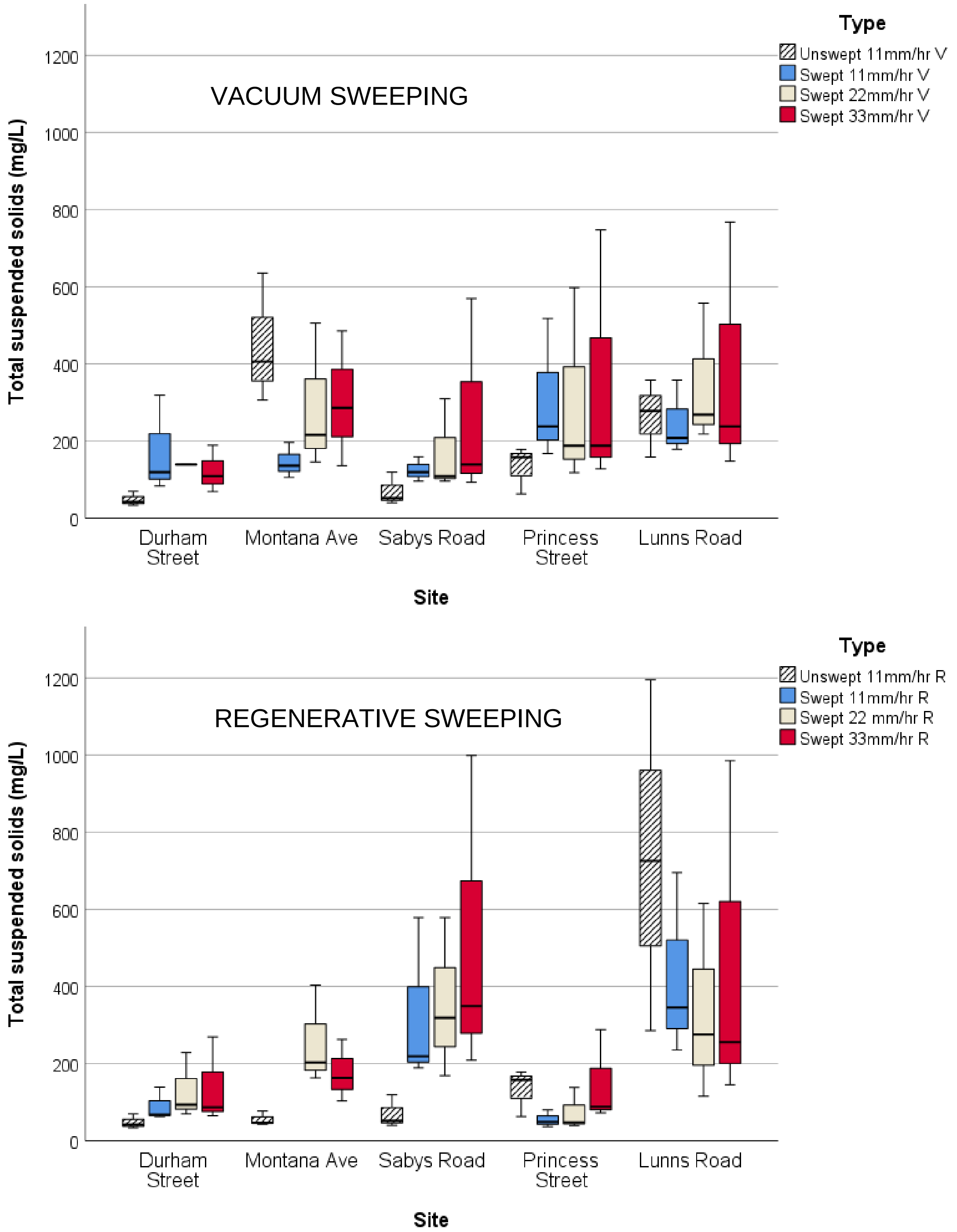


Figure 4-2: Total suspended solids concentration ranges in road runoff from each of the five sites for vacuum sweeping (top) and regenerative sweeping (bottom)

Particle size was found to vary substantially between the different sites (Figure 4-3). The coarsest unswept PSDs were observed at the low trafficked residential roads: Sabys Road and Montana Ave. The finest unswept PSDs were observed at Lunns Road, a moderately trafficked industrial road. There was also substantial variation in PSD for the same site across different trial days.

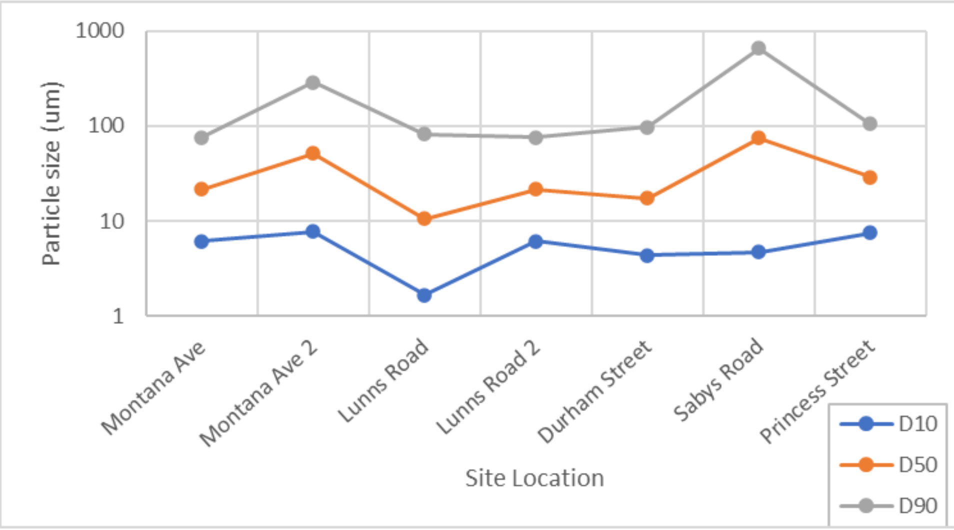


Figure 4-3: Comparison of unswept plots' D_{10}, D_{50} and D_{90} PSD metrics for all sites (First flush, t=0) (D_{10}, D_{50} and D_{90}: the size of particle at which 10%, 50% and 90% of particles exceed this diameter, respectively)

PSD comparisons between unswept and swept plots for each site showed Montana Ave, Lunns Road and Princess Street all had swept plots with coarser PSDs than the unswept plot trialled at the same 11 mm/hr intensity (for both vacuum and regenerative swept plots). This generally corresponds with the sites that produced lower TSS concentrations for the swept plot than the unswept plot, suggesting that a range of sizes including fines were being removed. For each size fraction, only a proportion of the particles were being removed (i.e. the sweepers were not seen to remove all particles down to a certain size threshold).

As applied rainfall intensity increased, the coarseness of the PSD was expected to increase due to the increase in energy available to mobilise and entrain the larger particles. However, this was only observed in a consistent manner at Lunns Road. This site had the high TSS concentration and the D_{10}, D_{50} and D_{90} sizes (the size of particle at which 10%, 50% and 90% of particles exceed this diameter, respectively) were observed to increase with both increasing intensity and from unswept to swept (at the same intensity) (Figure 4-4). However, the increase in PSD coarseness is not to an extent that is likely to cause substantial differences in the environmental effects imposed by the sediment or associated metals.

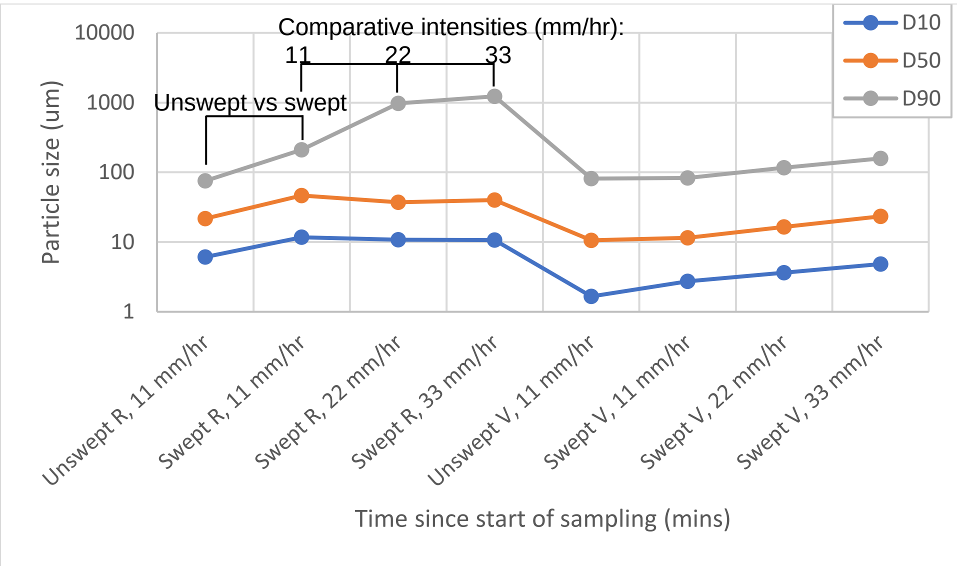


Figure 4-4: Lunns Road D10, D50 and D90 sizes for the first flush sample from each trial

Limited data was able to be collected to characterise the temporal change in PSD as many of the later stage samples (i.e. t=7 or 15 mins) had insufficient particle density for PSD to be accurately analysed. The exception was the high TSS concentrations at Lunns Road (Figure 4-5). A clear trend of increasing D_{10}, D_{50} and D_{90} over time provides of evidence of the finer particles being preferentially washed off (as could be expected, as more readily mobilised), resulting in increasing coarseness of particle size metrics as only larger particles remain available for later wash off.

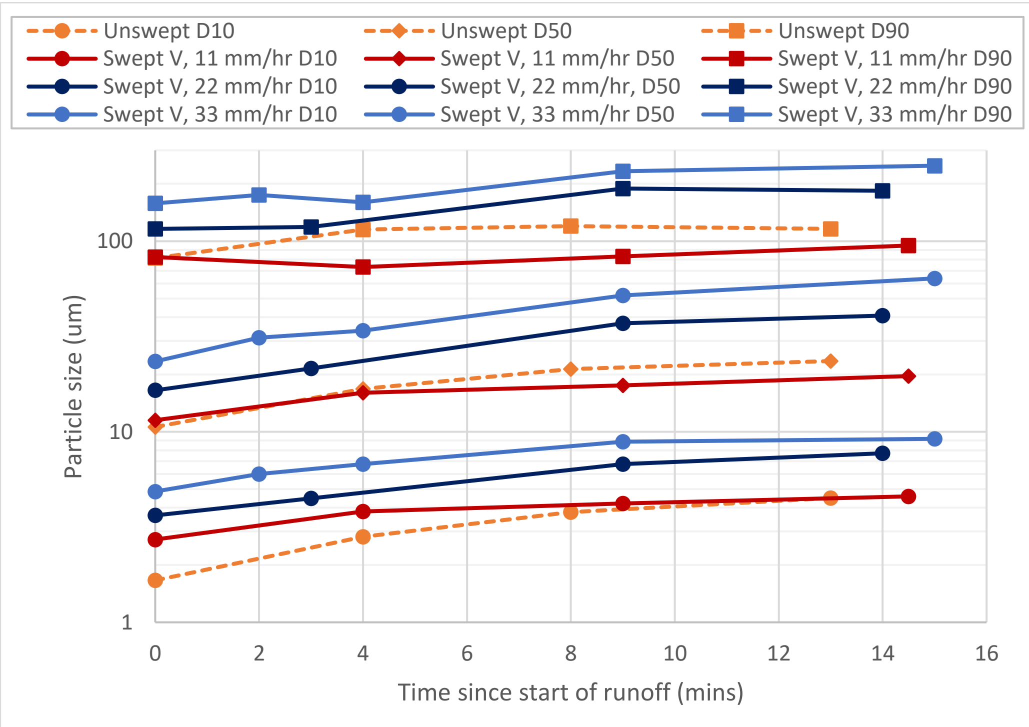


Figure 4-5: Lunns Road D10, D50 and D90 sizes over time for the unswept and vacuum-swept plots

At a more nuanced level, the PSDs for the Lunns Road trials were observed to be centred around 10 µm for the vacuum-swept trials (similar to the corresponding unswept trial) and 50 µm for the regenerative-swept trials (where the unswept trial centred around 20 µm) (Figure 4-6; figures for all sites provided in Appendix B-2). Comparison of the variation in PSDs for each site found that Durham Street had the smallest variation and Sabys Road had the largest variation (Figure 4-7). Both these sites had the lowest TSS concentrations of the five sites and suggests that PSD variation is not correlated to the TSS concentration.

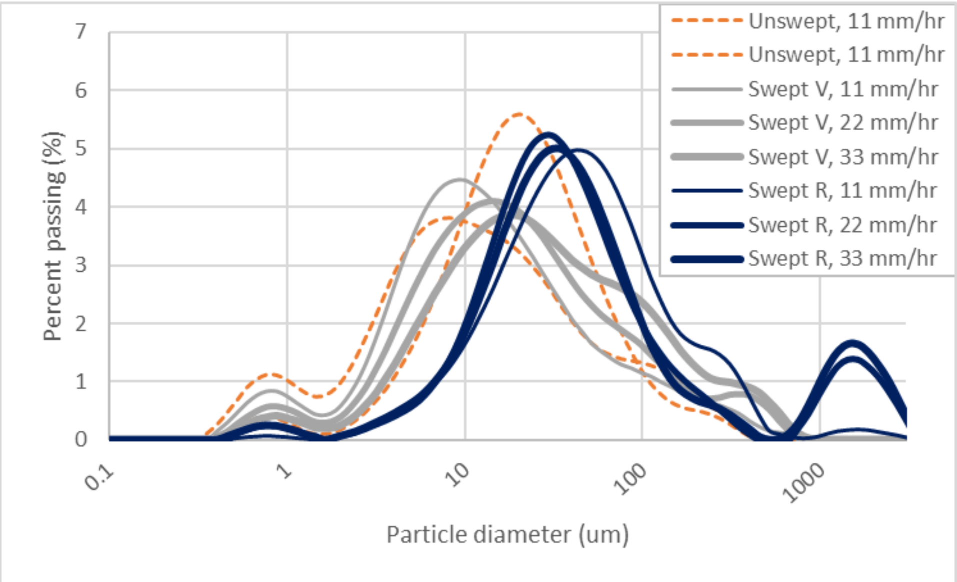


Figure 4-6: Variation in particle size distribution in road runoff pre- and post-sweeping for Lunns Road site

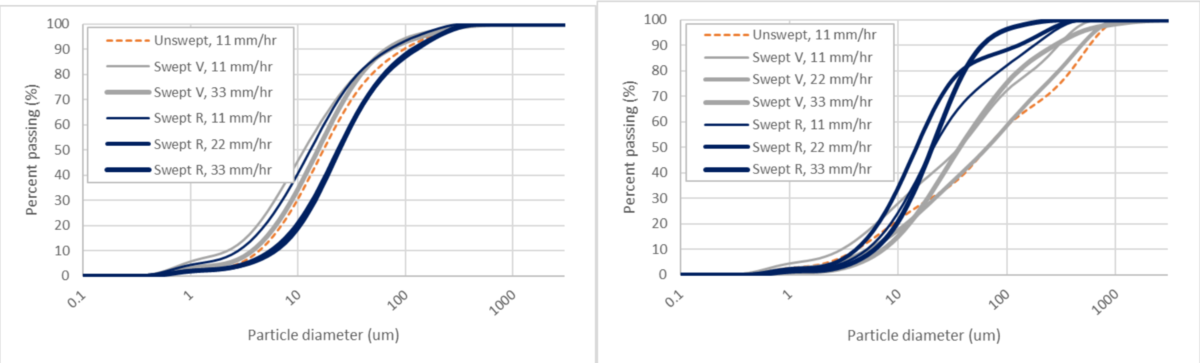


Figure 4-7: Cumulative particle size distribution for all trials for Durham Street (left) and Sabys Road (right)

4.2.2 Zinc and copper

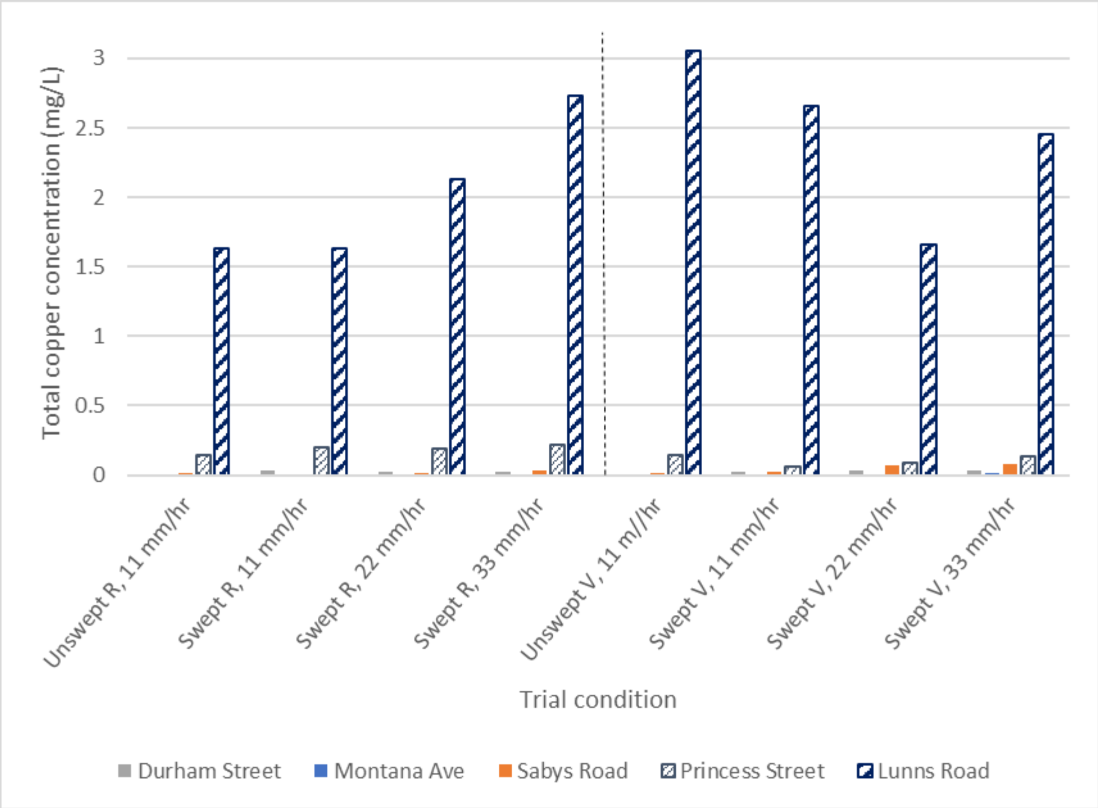
As there were some metals found in the tank water (feeding the rainfall simulator), all raw pollutant concentration data was adjusted by discounting the background tank water concentration to produce adjusted runoff concentration data. While sediment in the tank water was negligible, zinc and copper was sometimes found in the tank water to exceed the runoff sample value. Where this occurred these data points were not included in further analysis. Figures showing the raw and adjusted zinc and copper values are provided in Appendix B-3 and B-4. Hereafter, all data presented in this section is adjusted concentrations.

Lunns Road had the highest first flush copper concentrations (1,630-3,057 µg/L), with a factor of 8-700 greater than that of the other trialled sites (Table 4-2, Figure 4-8). The next highest site was Princess Street (58-220 µg/L), with the remaining sites all recording runoff copper concentrations of <85 mg/L. Similarly, Lunns Road also had the highest first flush zinc concentrations (1,550-6,148 µg/L), with a factor of 2-78 times that of other sites (Table 4-2, Figure 4-9).

Table 4-2: Copper and zinc concentration ranges (µg/L) for first flush samples across all plots at each site

Pollutant	**Trial Site**				
	Montana Ave	**Sabys Road**	**Durham Street**	**Lunns Road**	**Princess Street**
Total copper	15	9-83	4-37	1,630-3,057	58-220
Dissolved copper	37-88[1]	3-12	0.7-17	203-843	24-50
Total zinc	463-779	78-588	86-316	1,550-6,148	11-1,190
Dissolved zinc	56-2,283[1]	4	9-69	270-5,183	50

[1] Where the metal is ~100% in dissolved form, the dissolved concentrations provided by ICPMS analysis can be higher than the corresponding total concentrations due to the acid digestion method used to prepare the total metals sample for analysis



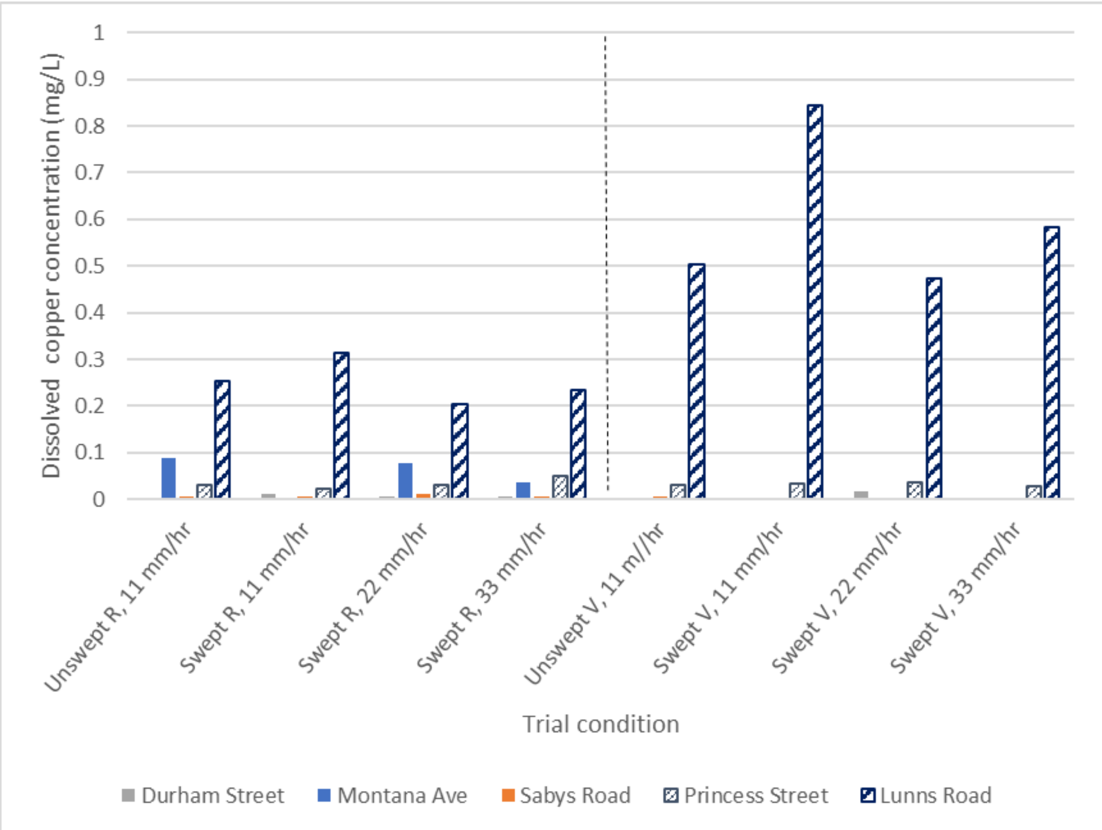


Figure 4-8: Total (top) and dissolved (bottom) first flush copper concentration ranges in road runoff from each of the five sites

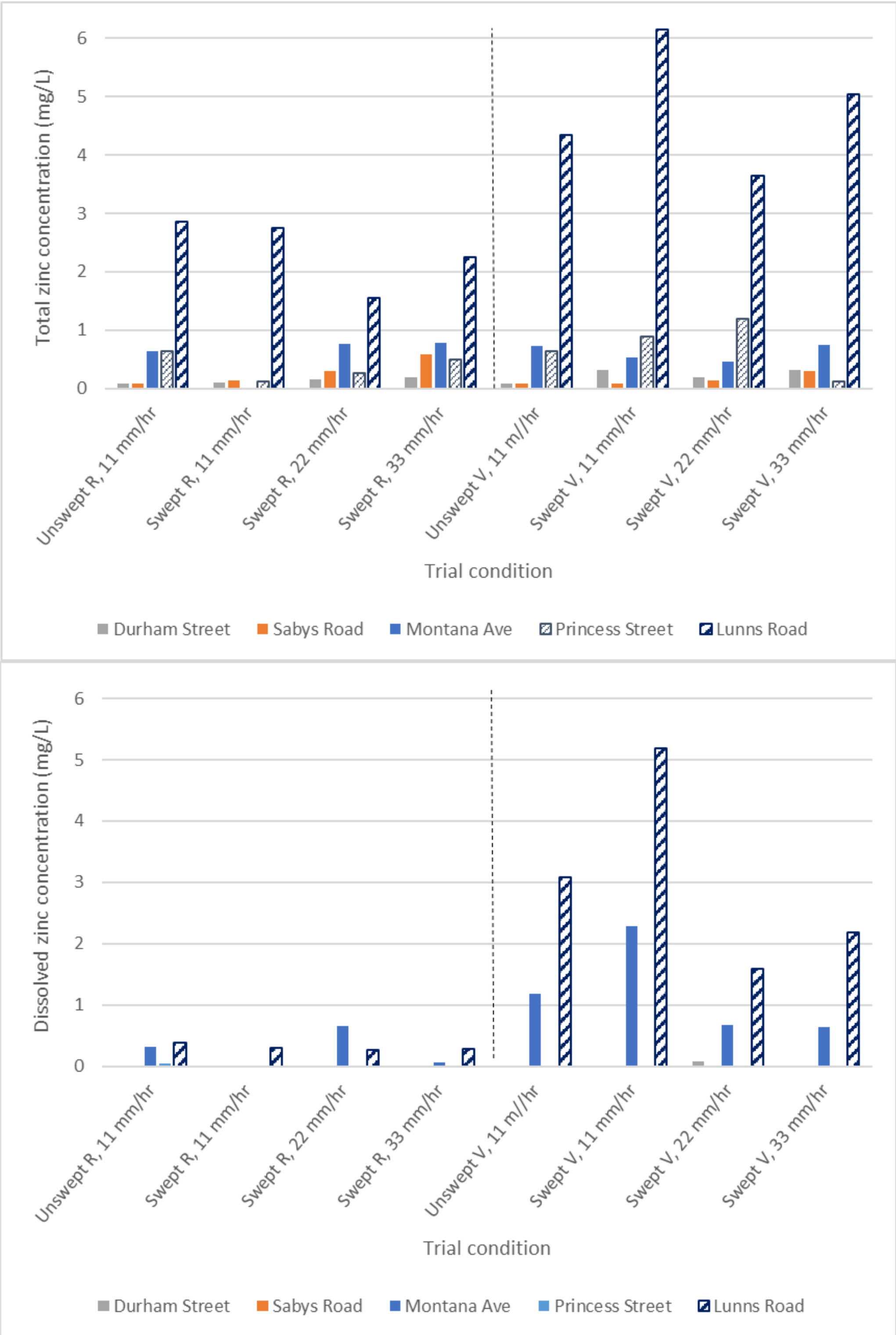


Figure 4-9: Total (top) and dissolved (bottom) first flush zinc concentration ranges in road runoff from each of the five sites

Metals partitioning analysis shows that Lunns Road, Durham Street and Princess Street had average unswept dissolved copper percentages between 14-20%, while Sabys Road was much higher at 63%. There was more variation for zinc partitioning, ranging from 99% dissolved at Montana Ave, to 67% at Lunns Road (site with the highest zinc concentrations), to only 2-3% dissolved at Sabys Road and Princess Street. There is a consistent increase in the proportion of particulate metals post-sweeping, which corroborates with the observation of sediment deposition from the sweeper operation (see Section 4.5 for further details). The sole exception was the vacuum-swept samples at Lunns Road where the average percent dissolved increased from 67% to 87%. Figures of all partitioning data for copper and zinc for unswept, vacuum- and regenerative-swept plots are provided in Appendix B-3 and B-4.

Mixed, instream water quality limits for (dissolved) copper and zinc are 1.8 µg/L and 15 µg/L, respectively (Environment Canterbury, 2023) for the lowland, spring-fed urban waterways that are the receiving environments for these sites' runoff. Given that the dissolved metals concentrations at Lunns Road have been observed at 300-400 times these limits, this indicates that this road runoff is likely contributing to adverse ecological impacts in the receiving Curletts Stream.

4.2.3 Comparison to international and national literature-reported runoff quality and particle size distribution

This study's FF TSS concentrations were often higher than any reported previously in literature, particularly those recorded at Lunns Road, Princess Street and Sabys Road (Figure 4-10**Error! Reference source not found.**). One FF sample (unswept) at Lunns Road (1,195 mg/L) was 1.8 x higher than the highest reported concentration from literature. However, it should be noted that the majority of the international data is Event Mean Concentration (EMC) and so represents an average concentration over a whole rain event.

Similarly, the FF copper and zinc concentrations observed in this study were generally higher than what has been reported previously in both FF and EMC data. For copper, even the SS data (samples taken 15 minutes after the start of each trial) was generally higher than the FF and EMC data reported elsewhere. Even with the change to copper free brake pads in private vehicles, the copper concentrations in the runoff at Lunns Road are very high compared to what has been reported previously both in New Zealand and internationally. This suggests heavy vehicles' contribution remains an important focus for effective source reduction of copper.

The unswept PSDs observed in this study were all finer than what has been reported to date, with the exception of the two most recent published studies - Charters et al. (2015), which had PSD data from Ilam Road in Christchurch, and Wang (2020), which had PSD data from Yixing City in Eastern China (Figure 4-11). The two sites with high TSS concentrations – Lunns Road and Princess Street – were finer than any reported PSD profiles.

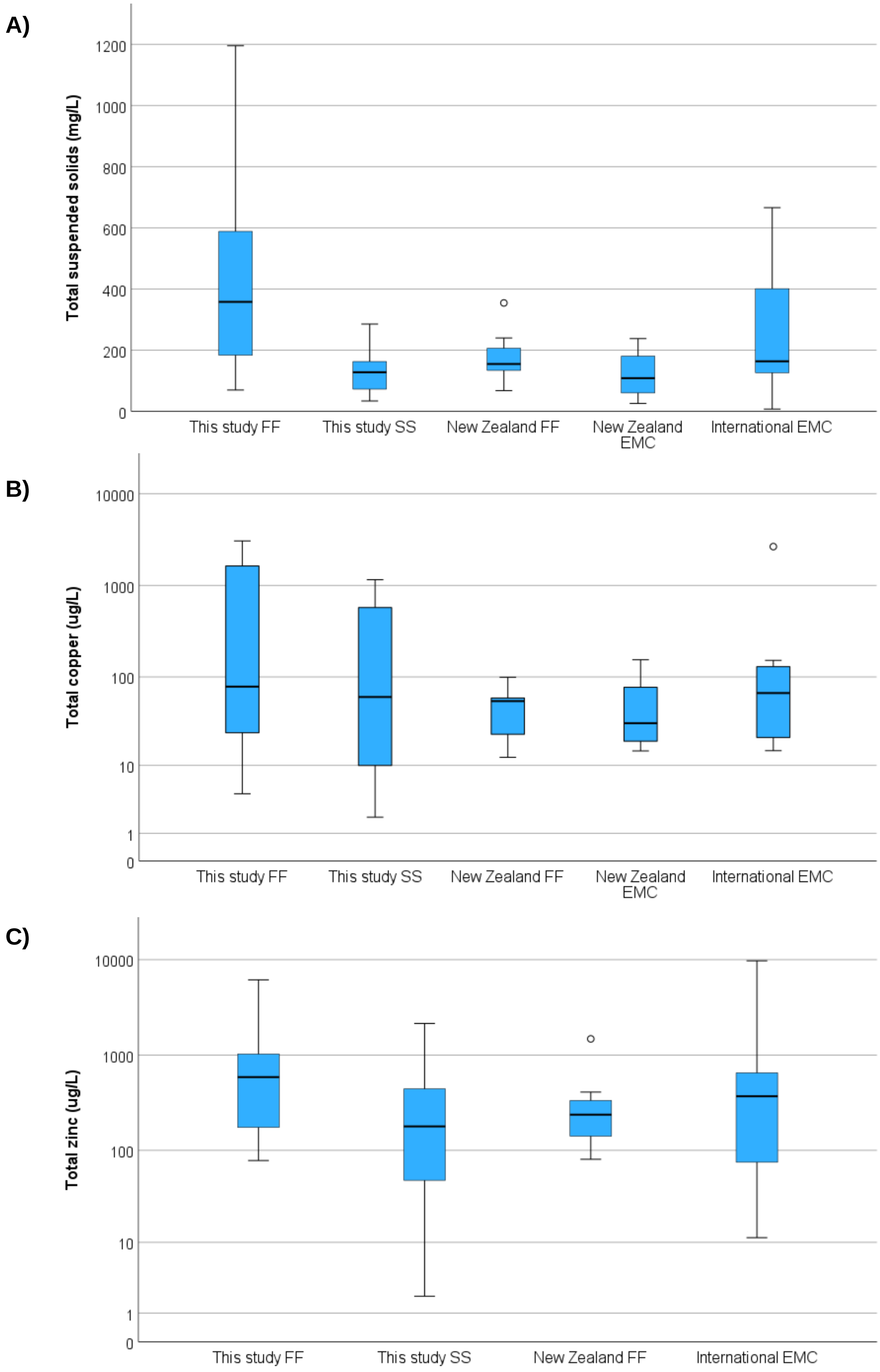


Figure 4-10: Comparison of A) total suspended solids, B) total copper and C) total zinc concentrations from this study to previous New Zealand and international studies (note log scale used for copper and zinc data)

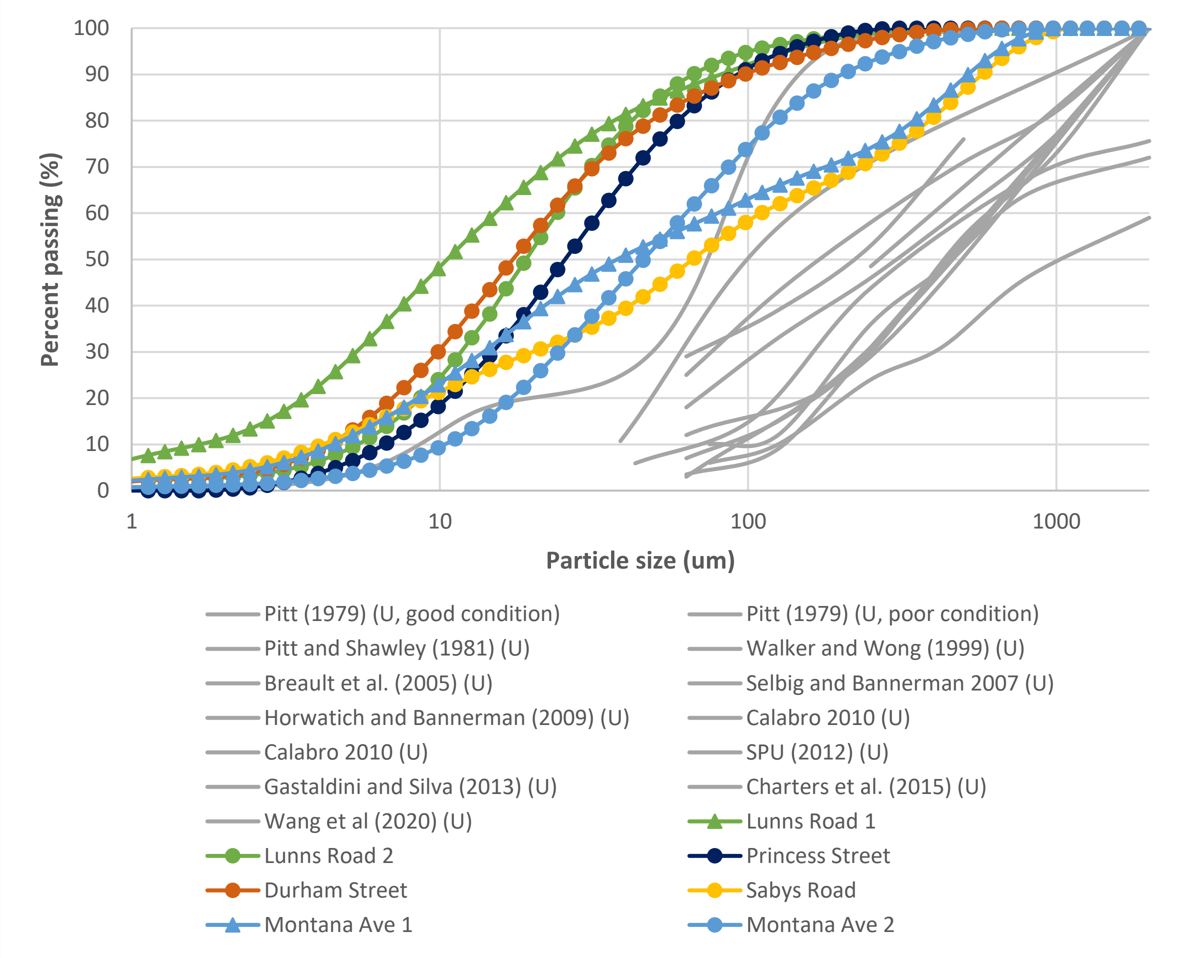


Figure 4-11: Comparison of particle size distribution from this study to previous New Zealand and international studies

4.3 Percent removal of pollutants

4.3.1 Sediment

Increases in TSS concentration between unswept to swept plots, as outlined in Section 4.2.1) were generally observed for TSS, with the exception of Lunns Road for both vacuum and regenerative swept, Montana Ave for vacuum swept and Princess Street for regenerative swept (Figure 4-12). It was visually observed that the regenerative sweeper deposited a slurry on parts of the road surface (see Section 4.5 for more details), which may contribute to the higher TSS seen in the swept plots, as well as variation in available pollutant loads between adjacent plots. Of those sites where positive percent removals were found, the highest removal rate was seen at Princess Street with 22-77% removal by the regenerative sweeper, followed by Montana Ave with 65-67% removal by the vacuum sweeper and Lunns Road with 18-52% with the regenerative sweeper. These three sites had the highest unswept TSS concentrations and corroborate the observation in literature that sweeper efficiency is related to a threshold amount of sediment available on the surface, before any effective removal is observed. Based on the data from this study, results indicate that this threshold may be >300 mg/L for vacuum sweeping and >150 mg/L for regenerative sweeping. See Appendices C and D for further figures and summary data on percent removal analysis.

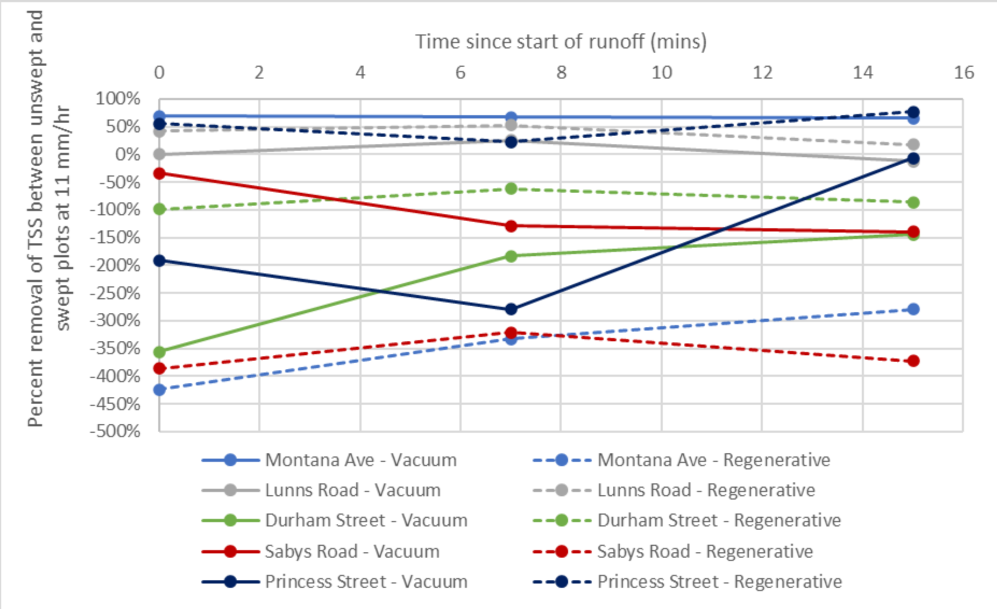


Figure 4-12: Percent removal of TSS (unswept vs swept at 11 mm/hr) over time for all sites

4.3.2 Zinc and copper

Zinc and copper removal rates between unswept and swept plots showed largely negative removal rates and the same inconsistency in removal rates as was seen for TSS (Figure 4-13). The regenerative sweeper achieved total copper removal rates of 13-41% at Lunns Road and -145-66% at Princess Street, the sites with the highest total copper concentrations. However, the vacuum only achieved positive removal rates in two instances (and only at 10%) across all five sites. The sweepers were similarly successful at reducing total zinc, with the regenerative sweeper achieving 4-43% removal at Lunns Road. The vacuum sweeper had inconsistent performance across the sites for total zinc.

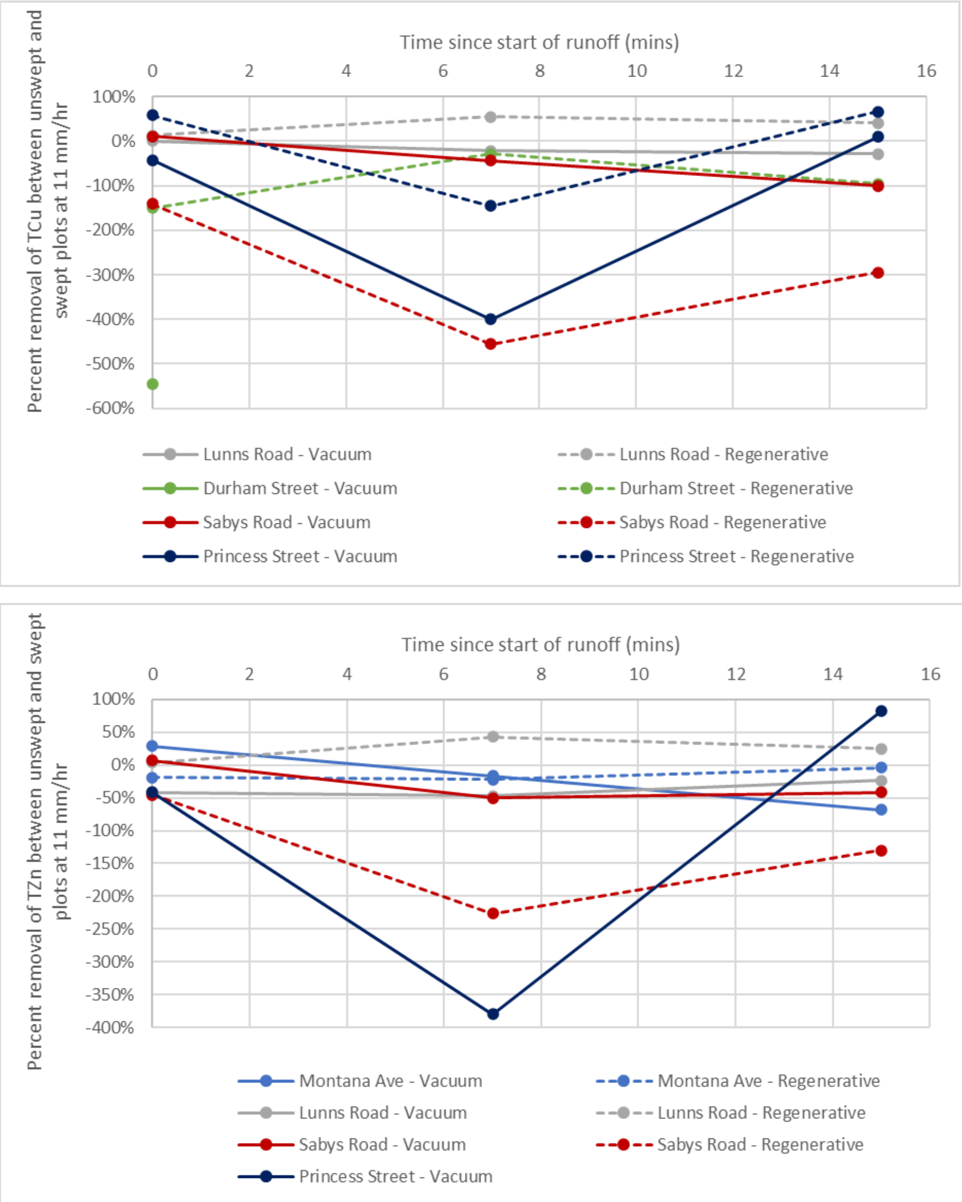


Figure 4-13: Percent removal of total copper (top) and total zinc (bottom) (unswept vs swept at 11 mm/hr) over time for all sites

4.4 Correlations between variables

4.4.1 Influence of surface factors: Effect of traffic intensity, land use activities and surface condition on road runoff quality

Pollutant concentrations were not found to be correlated with traffic intensity as the site with the highest pollutant concentrations had only moderate traffic (5,670 AADT), while the highest trafficked road, Durham Street at with 11,863 AADT, consistently returned some of the lowest pollutant concentrations. However, the two sites with industrial and/or commercial land use, Lunns Road and Princess Street, were found to have the highest pollutant concentrations. This suggest that for the trialled sites, the traffic type – in the case of the industrial areas, there are more heavy vehicles that deposit proportionally more sediment and heavy metals on the road surface – and sediment-generating activities – construction activities that contributes sediment; air emissions – have a greater influence on the resultant pollutant load than just traffic count. Furthermore, Montana Ave, a low trafficked residential street had high sediment load in one of its unswept plots, indicating that surface roughness and the increased ability to hold sediment in the interstitial spaces when the surface is very coarse may have a greater influence on pollutant load than just traffic count. It should be noted, however, that the two unswept plots completed at Montana Ave showed substantial variation in sediment load and it may therefore be difficult to achieve consistent pollutant reduction benefits on this sort of coarse but low trafficked street as the loading may not always reach a threshold where sweeping is effective. Therefore, future sweeping operation should focus on industrial/commercial areas of the city as a priority, and an increased frequency of sweeping on road sections of coarse chipseal should also be considered.

The higher TSS concentrations in the runoff post-sweeping suggest that the sweepers may be loosening the sediment that has collected on the road surface but the vacuum component of the sweeper is unable to remove all this loosened sediment. Then when rainfall occurs, more sediment is able to be mobilised than would have been possible on the unswept surface. This indicates carry over of pollutants between rain events is an important process to be considered in Christchurch's relatively low intensity rainfall climate. Options to address this via sweeping could be to do repeat sweeping within dry periods to give more opportunity to loosen and remove sediment, particularly for coarse road surfaces. However, further field data of whether multiple sweeps can provide this benefit is recommended, as some studies have concluded that multiple passes did not provide a significant increase in removal rate.

4.4.2 Influence of climate factors: Effect of simulated rainfall intensity on road runoff quality

Contrary to indications from literature, an increased applied rainfall intensity did not always correlate with an increased TSS concentration (Figure 4-2) for the same site. However, it was more likely to be observed at the regenerative-swept plots than the vacuum-swept plots. Where it was observed for the regenerative-swept plots (at Durham Street, Princess Street and Sabys Road), there was no consistency as to whether the site produced high or low post-swept TSS concentrations overall, i.e. this phenomenon was not seen to relate to a site's overall TSS concentrations.

4.4.3 Observation of first flush phenomenon in road runoff

A clear first flush phenomenon was observed for all trial plots, at all sites. Intra-event samples show a consistent pattern of highest concentration at the start of each trial, with subsequent samples at t=7 minutes 34-69% of t=0 TSS concentrations and samples at 15 minutes 33-50% of t=0 concentrations. A summary table of first flush ratios is provided in Appendix E.

A stronger first flush effect (as evidenced by later stage concentrations being a lower percentage of the first flush concentration) was found to be correlated with higher rainfall intensity for most sites, for both vacuum-swept and regenerative-swept plots. The sole exceptions were the regenerative-swept plots at Montana Ave and the vacuum-swept plots at Durham Street. However, comparison of the first flush ratios between corresponding unswept and swept plots at 11 mm/hr at each site did not show any consistent reduction or amplification of the first flush effect due to sweeping. Therefore, there is no evidence that street sweeping can reduce first flush effects from road surfaces. However, it should be noted that first flush effects are attenuated with increasing runoff surface area, as the time of concentration varied more widely. Consideration could be given to giving some priority to sweeping operations along road areas nearer the discharge points into the receiving waterway.

4.5 Field observations of street sweeping

Visual observations of street sweeping during each trial day confirmed that the street sweepers were effective at removing gross pollutants and litter from the road surface, kerb and channel. However, the combination of pressured air and water used by the regenerative sweepers sometimes resulted in deposition of a sediment-laden water slurry along the swept area (Figure 4-14). Billowing dust was also observed out the back of these sweepers, which could result in additional sediment being deposited on the swept zone prior to trialling. This limitation with regenerative sweepers (slurry deposition and billowing dust) has also been observed previously (Depree, 2011).

Optimisation of street sweeping could therefore include development of Standard Operating Practices (SOPs) to ensure low sweeper speeds are used (this trial was conducted at 5 km/hr), hoppers are regularly cleaned out to reduce carryover between sites or runs and water use is minimised in regenerative sweepers if not needed for picking up gross pollutants or litter.

Figure 4-14: Dirt streaks on road created by regenerative sweeper

4.6 Limitations and assumptions

As with any data-rich study, there are always limitations stemming from the inability to repeat all experiments. In trialling a diversity of sites, applied intensity and two sweeper types, the dataset for each condition was therefore limited. However, a key objective of these field trials was to provide initial data to guide and prioritise further investigations.

The variation observed for Lunns Road and Montana Ave, where two unswept plots were able to be trialled under different antecedent conditions, demonstrate the large variability in unswept conditions at a single site over time. There will also be spatial variation in available pollutant load that this study was not able to characterise, which may have influenced the lack of pollutant reductions found between unswept and swept plots at many sites. Further replication of unswept conditions would provide a clearer indication of: 1) the extent of spatial variation in a small road area, and 2) the likelihood of unswept TSS concentrations reaching the threshold needed for regenerative or vacuum sweepers to be effective.

For low intensity trials, it took several minutes to accumulate sufficient sample volume for analysis. This means those results are an average for the sample collection period and will dampen the magnitude of true first flush concentrations. This implies that the initial first flush concentrations feeding into the stormwater pipe network off the road could be substantially higher than concentrations recorded in this study. If the sampling site is close to where the stormwater is discharged into the receiving environment (such as at Lunns Road), this indicates that there could be high contaminant concentrations being passed into the waterway during the initial stages of each rain event with greater adverse impacts than expected (depending on dilution and mixing properties of the discharge relative to the stream). This emphasises the importance of catchpit filters to attenuate any first flush and the need for targeted wet weather receiving environment monitoring.

The tank water from the Christchurch public water supply was found to be elevated in copper or zinc on different occasions: elevated total copper at Montana Ave Day 1 and 2; elevated dissolved copper at Montana Ave and Princess Street; elevated total zinc at Durham Street and Princess Street, and elevated dissolved zinc at Durham Street, Princess Street and Sabys Road. This meant that some copper and zinc road runoff results could not be analysed as the background (applied) concentration exceeded the runoff concentration. As yet, the source of these elevated copper and zinc concentrations has not been identified.

Factors that have been identified as a contributor to street sweeping performance and/or road runoff quality but have not been assessed or isolated via this study's methodology include:

- Spatial variation of available pollutant load across the road area. Previous studies have found that the vast majority of load accumulates in the gutters or within 0.5 m of the road edge (Deletic & Orr, 2005), however, there is little information on the distribution of pollutants along the roadway (i.e. parallel to the kerb), but potential influences would include traffic entering driveways or use of onsite parking.
- Build up rates on different surface types (i.e. how rapidly the steady state between deposition and emission is reached (Amato et al 2010)). Previous studies, such as Kim et al. (2014), have measured daily build up to help determine optimal sweeping frequency. It is likely that scheduling sweeping for at least 72 hours days post-rain will increase the opportunity for the sweeping to pick up higher amounts of accumulated pollutants (Section 2.2.1), however, more knowledge is needed on the build up dynamics and when threshold concentrations for effective sweeping are likely to be reached.
- The effect of road shape on wash off, as reported by Walker et al. (1999)
- Operational methods for each sweeper, including cleaning procedures and running the regenerative sweeper without water

5 Conclusions and recommendations

This study did not find clear evidence of reduced pollutant concentrations between unswept and swept road areas. There was some evidence that regenerative and vacuum sweeping may become effective at built-up sediment concentrations of >150 mg/L and 300 mg/L, respectively. However, the small dataset creates limitations on this conclusion and further study of high build up roads in industrial/commercial areas is recommended to strengthen this conclusion.

Key findings from the data are:

- The highest unswept TSS, zinc and copper concentrations were found at Lunns Road, an industrial road with medium traffic intensity.
- In general, the influencing factors for the highest pollutant loads were considered to industrial/commercial areas (of particular concern in terms of heavy metal concentrations) and road surface roughness (coarse asphalt accumulated more particulates). No correlation was found between unswept traffic intensity and TSS concentration.
- Regenerative sweeping provided consistent benefit (i.e. positive removal rates) where TSS >150 mg/L (two of the five sites), while vacuum swept provided positive removal rates where TSS > 300 mg/L (only one out of the five sites), suggesting there may be a threshold effect where sweeping effectiveness responds to a minimum accumulated amount of particulates.
- Street sweeping should be considered as part of a treatment train for road runoff that includes targeted use of catchpit inserts. If street sweeping can reduce any amount of particulates entering the inserts, it will prolong the efficiency of the inserts as their efficiency significantly reduces once over half full.
- Increased applied rainfall intensity was not found to correlate with increasing TSS concentration for the vacuum-swept trials but was seen for three of the five regenerative-swept sites. There was no correlation to site TSS concentrations (i.e. the three sites observed to have this trend for regenerative-swept plots included two low post-sweeping TSS sites (Durham Street and Princess Street) and one high post-sweeping TSS site (Sabys Road)).
- The coarseness of the PSD was only seen to increase with increasing rainfall intensity at the Lunns Road site.
- The finest unswept PSD was observed at Lunns Road – yet this site had the greatest removal – confirming that once there is enough sediment available, sweeping was effective, even if sediment is fine.

- Fine sediment suggests vehicle contributions such as brake dust as a key source, as this has been found to be particularly fine.
- The swept plots were found to be coarser than unswept plots at 3 of the 5 sites. This generally corresponded with sites where swept TSS was lower than unswept, suggesting a range of sizes including fines were being removed by the sweepers.
- Copper was found to be highest at Lunns Road with first flush total copper concentrations of 1,630-3,057 ug/L (8-700 times greater than the other sites). Even with the introduction of copper-free brake pads, the high copper concentrations at Lunns Road indicate management of heavy vehicles' contribution of copper is needed to achieve substantial source reductions of copper.
- Lunns Road also had the highest zinc concentrations, with first flush total zinc concentrations of 1,550-6,148 u/L (2-78 times that of the other sites).
- The dissolved metals proportion is over 300-400 times greater than the relevant receiving environment guideline values, indicating that the road runoff is likely to be causing adverse impacts in the receiving waterways such as Curletts Stream (Lunns Road's receiving waterway).
- The sweepers may be loosening the accumulated sediment but unable to remove it via vacuum, resulting in increased sediment concentrations in the next rain event. Further investigation is recommended into the benefits of multiple sweeper passes within a dry period (not necessarily completed together but across multiple days to ensure adequate build up is reached before each sweep). The results of this study have been unable to provide evidence to direct a certain frequency of sweeping.
- If any preference was to be given to sweeper type, the data indicates regenerative sweepers are more effective at lower TSS concentrations and therefore would provide more pollutant reduction across a greater range of roads.

Recommended Future Work

Further field investigations are recommended into the role of catchpit inserts in removing pollutants. The optimization of street sweeping scheduling should be assessed with consideration given to scheduling of catchpit insert cleaning and identification of priority streets (i.e. industrial/commercial and coarse chipseal residential streets).

Standard Operating Procedures are also a priority for development, to provide consistent guidance to operators on the cleaning of sweeper units, operating speed, use of water, number of passes and sweeping goals for different types of roads. These guidelines can build upon what have been developed elsewhere, including several SOPs developed in the US and local guidance such as Depree (2011). SOPs will also serve as a communication tool of the science behind effective sweeping procedures, as ultimately the operators are the ones spending the most time out on the roads and can be effective eyes-on-the ground for sweeping and catchpit maintenance needs.

Any future runoff trials should prioritise confirming and characterizing the range of pollutant concentrations and particle size characteristics on industrial roads where there is heavy vehicle traffic. This study's data indicates that these are the roads that contribute the highest sediment and heavy metal concentrations. These field trials should also seek to quantify the variation in unswept and swept runoff quality, in order to confirm the range of unswept runoff that can be found at a single site, indicate how often the sediment concentration thresholds occur where the regenerative and vacuum sweepers were seen to be effective, as well as provide replication of this study's initial swept plots for quality assurance purposes.

Lab-based experimental studies could be undertaken to further evaluate whether sweeper action is loosening sediment without removing it from the surface, leading to higher runoff concentrations from the swept surface. This would guide whether multiple passes should be undertaken as standard procedure.

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Appendix A Summary of field trial conditions

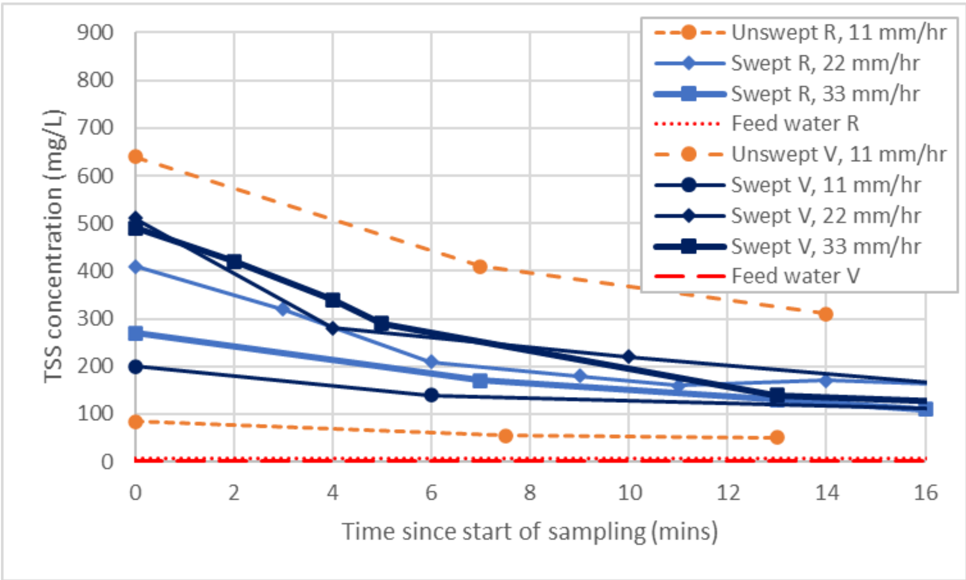
Site	Dates of Trials	Preceding rain event details				Trials Run	Applied intensity (mm/hr)	Samples	Comments
		Dry days since preceding rain (days)	Total depth (mm)	Max. hourly intensity (mm/hr)	Average event intensity (mm/hr)				
Montana Ave	16 January 2023	4.0	0.6	0.4	0.20	Unswept Regenerative	11 22,33	Multiple samples within 20 min period to characterize FF effect	Unable to complete 11 mm/hr vacuum-swept plot due to feeder hose break
	1 February 2023	4.3	7.3	4.5	1.83	Unswept Vacuum	11 11, 22, 33	Multiple samples within 20 min period to characterize FF effect	
Lunns Road	2 February 2023	5.3	7.3	4.5	1.83	Unswept Vacuum	11 11, 22, 33	Multiple samples within 20 min period to characterize FF effect	
	6 October 2023	3.0	2.2	0.9	0.31	Unswept Regenerative	11 11, 22, 33	0, 7, 15 mins	
Durham Street	8 August 2023	5.3	4.8	0.6	0.28	Unswept Vacuum	11 11, 22, 33	0, 7, 15 mins	
	15 August 2023	3.4	1.2	1.2	1.20	Regenerative	11, 22, 33	0, 7, 15 mins	Only one sample successfully obtained from the 22 mm/hr regenerative swept plot as sampling frame leaked
Sabys Road	25 August 2023	8.5	3.4	1.4	0.49	Unswept Vacuum Regenerative	11 11, 22, 33 11, 22, 33	0, 7, 15 mins	
Princess Street	6 November 2023	7.2	9.2	1.6	0.42	Unswept Vacuum Regenerative	11 11, 22, 33 11, 22, 33	0, 7, 15 mins	

Appendix B Summary runoff quality data

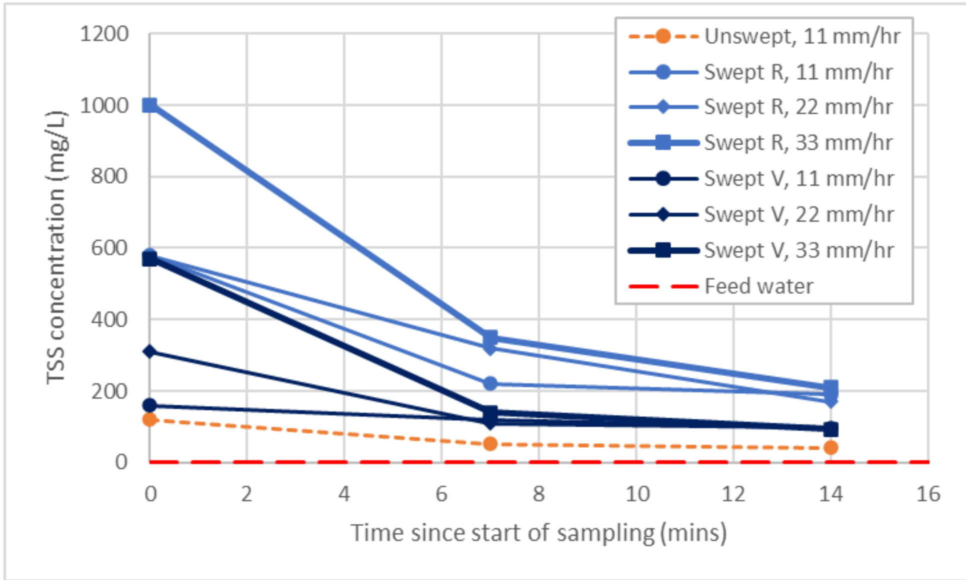
1. *Total Suspended Solids Data*

a. TSS concentration over time for each trials, at each site

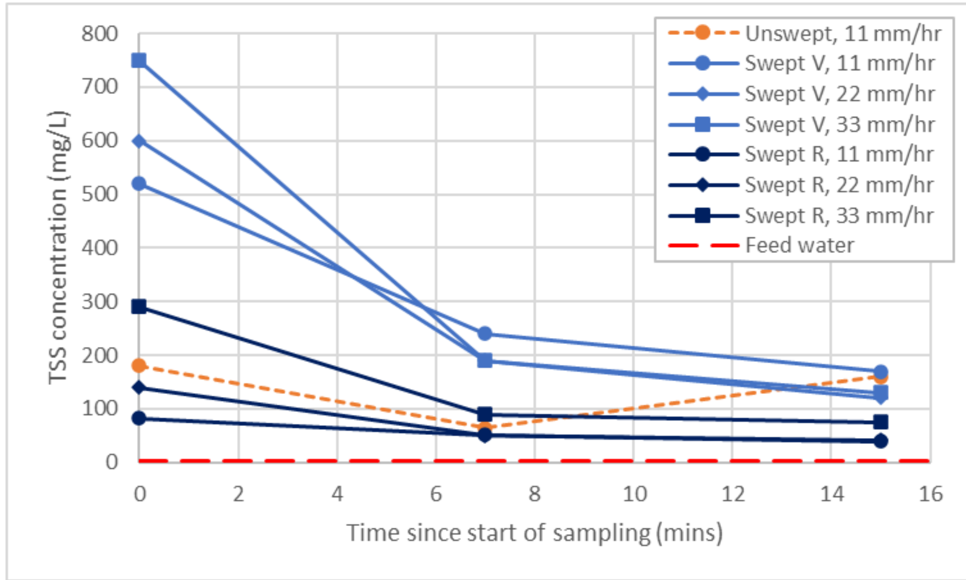
Montana Ave



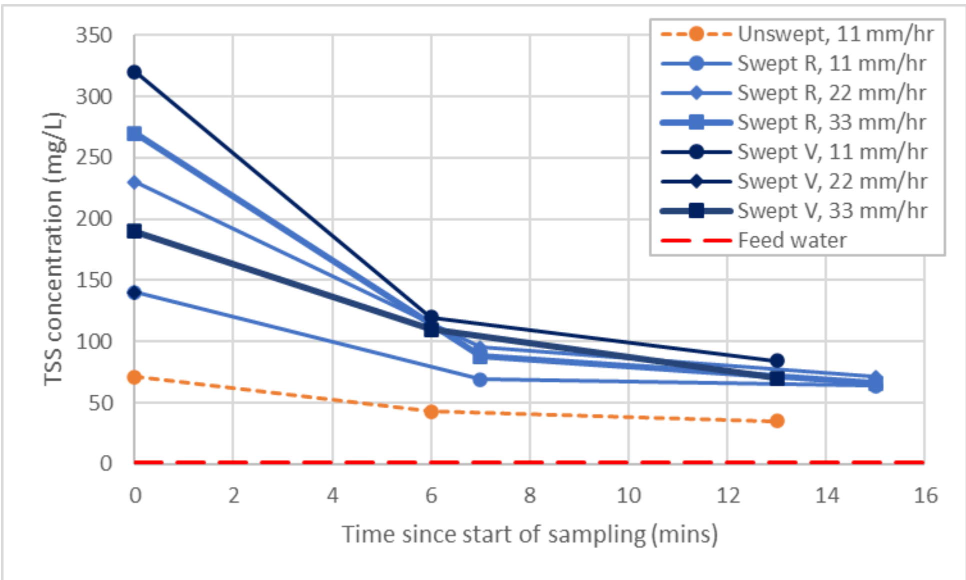
Sabys Road



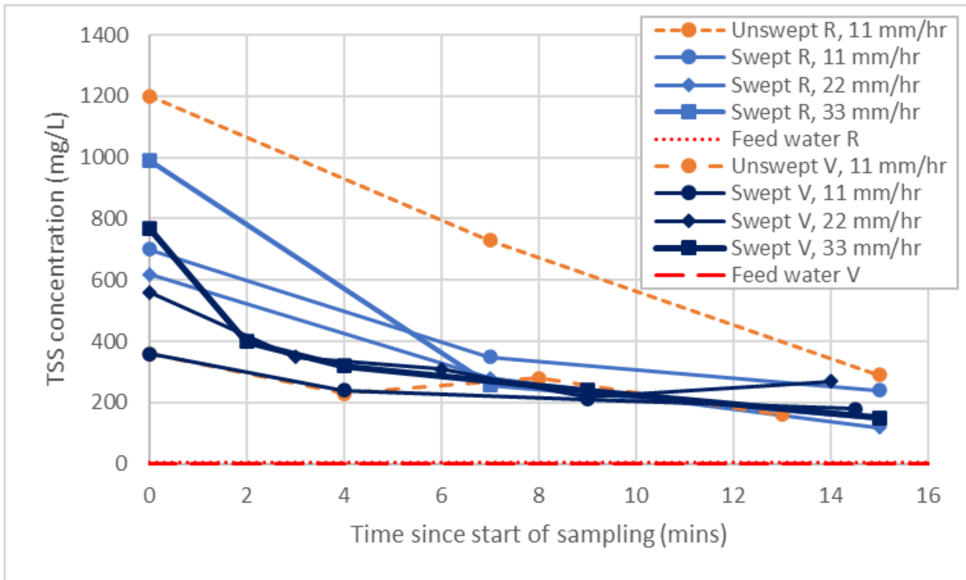
Princess Street



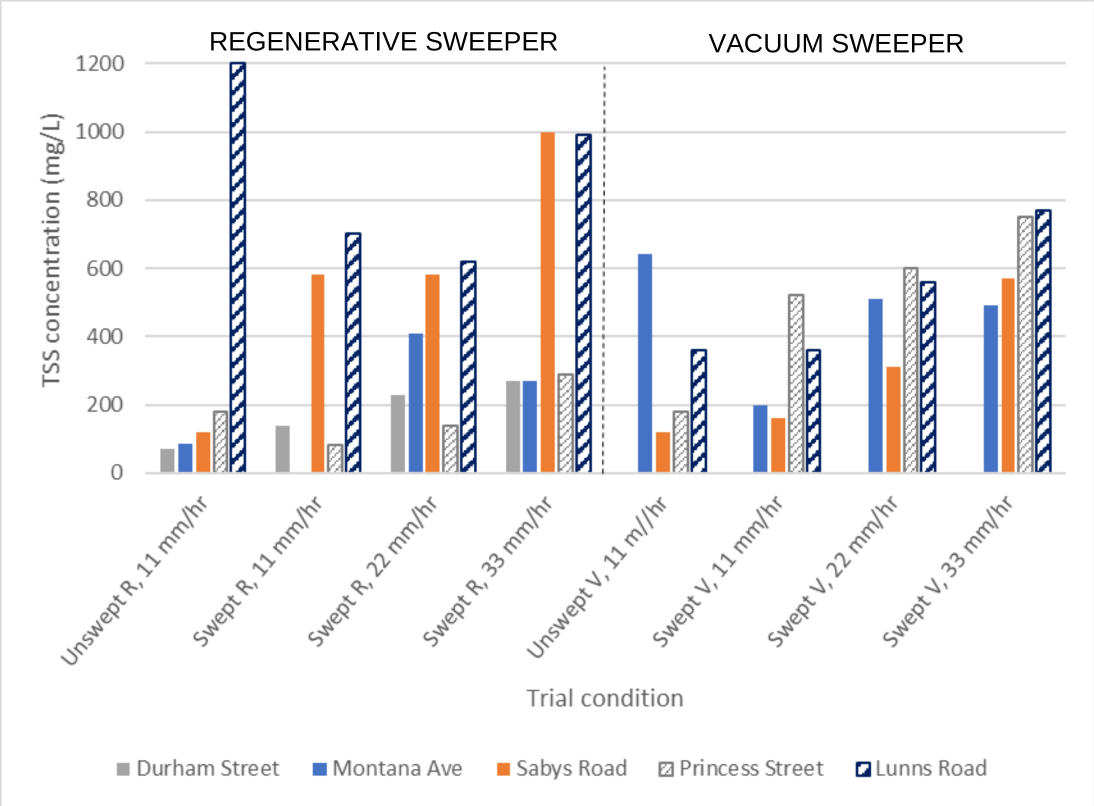
Durham Street



Lunns Road



b. Comparative first flush TSS concentrations for all trials, across the five sites



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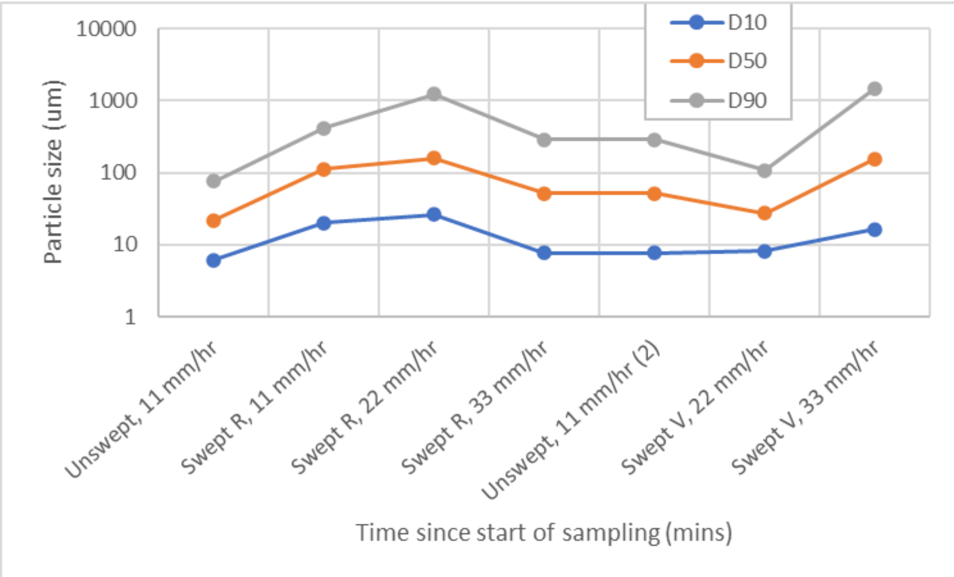
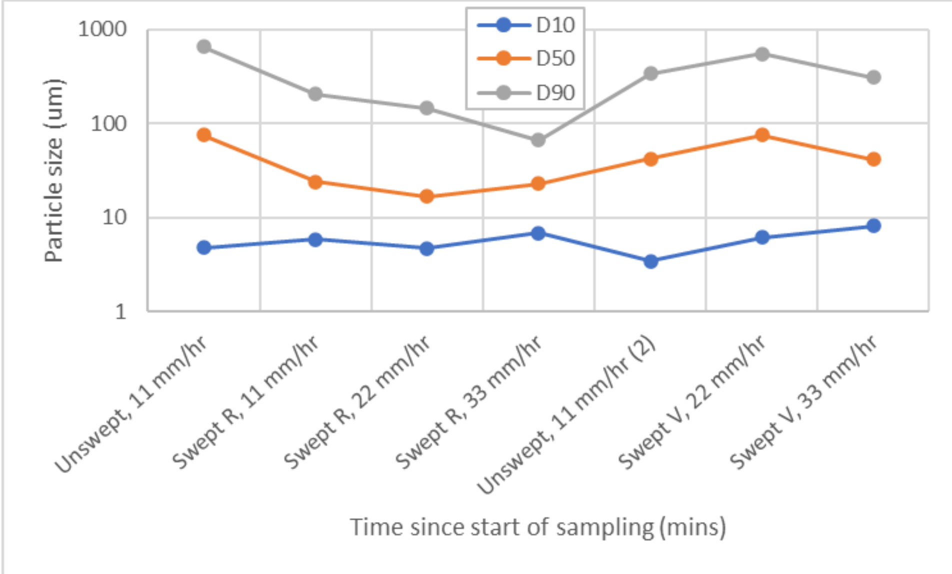
2. Particle Size Distribution Data

a) Summary of D_{10}, D_{50} and D_{90} for each trial, at each site (First flush, t=0)

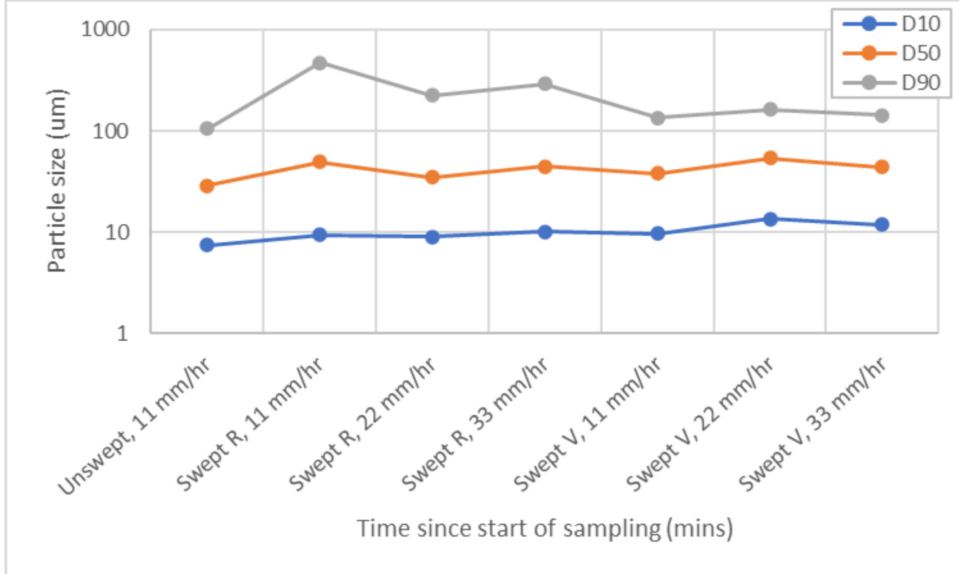
Montana Ave



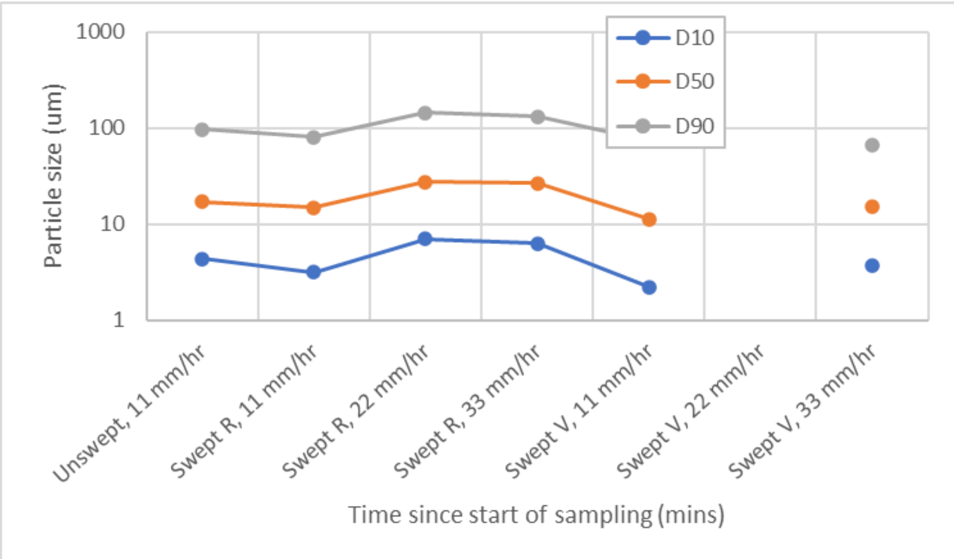
Sabys Road



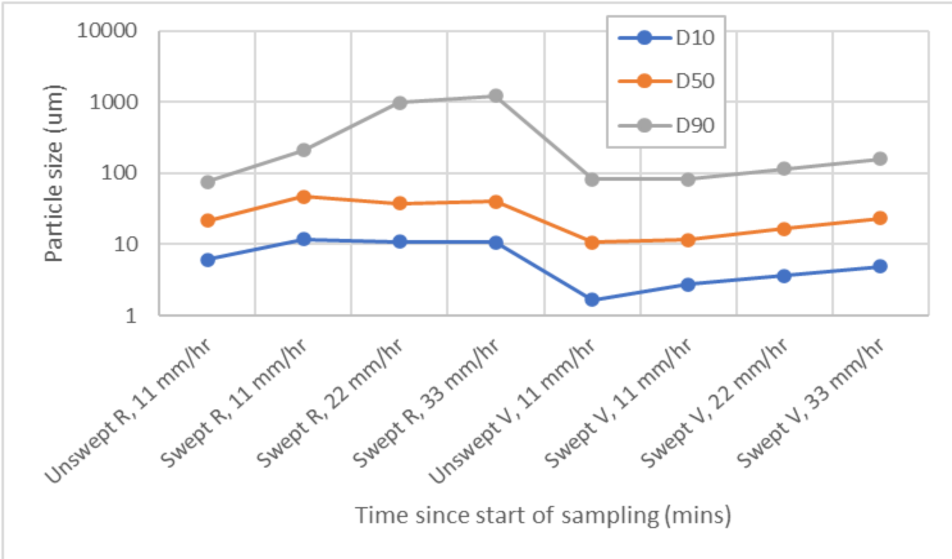
Princess Street



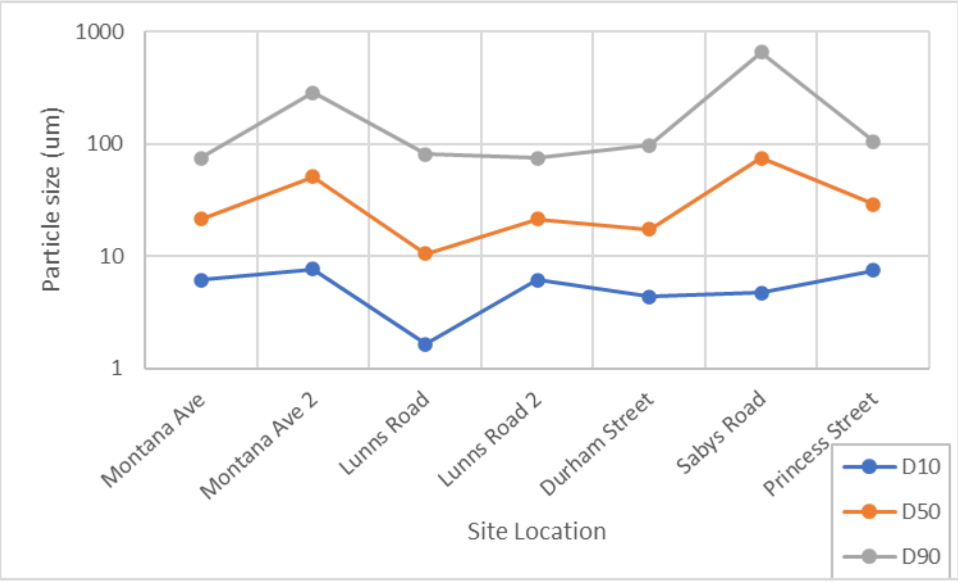
Durham Street



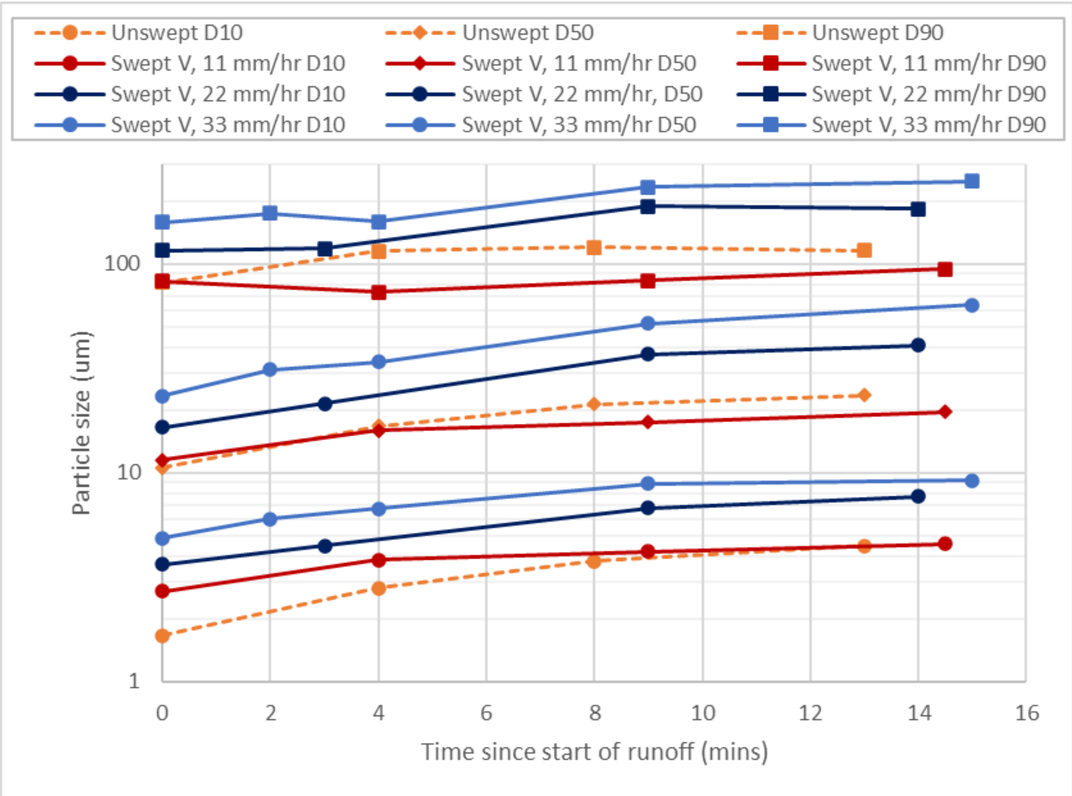
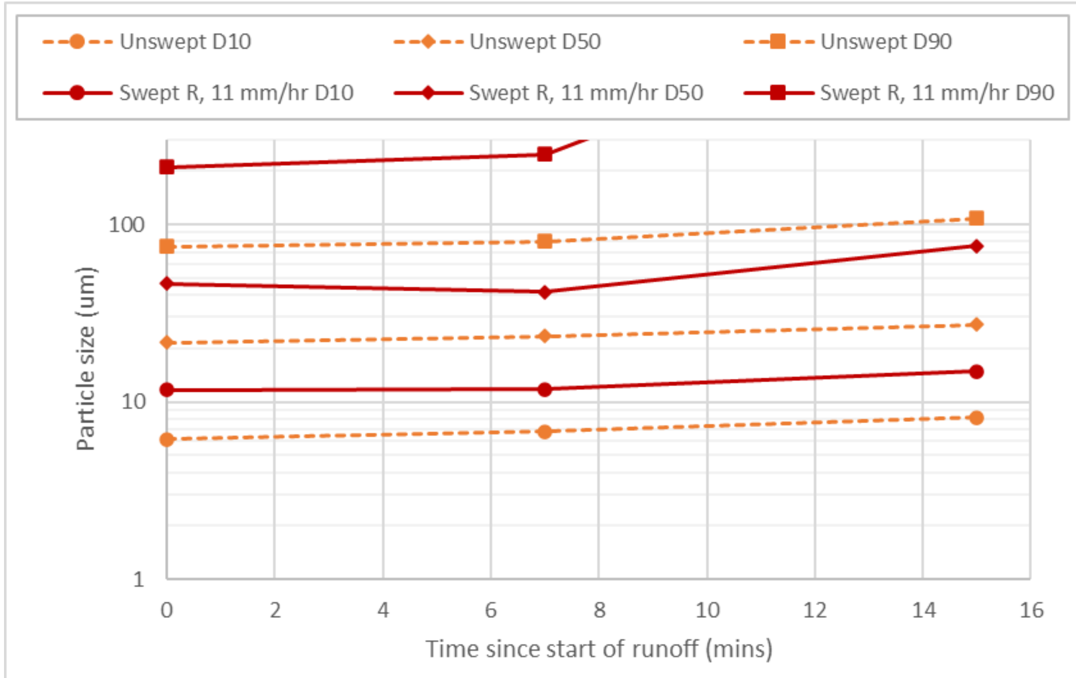
Lunns Road



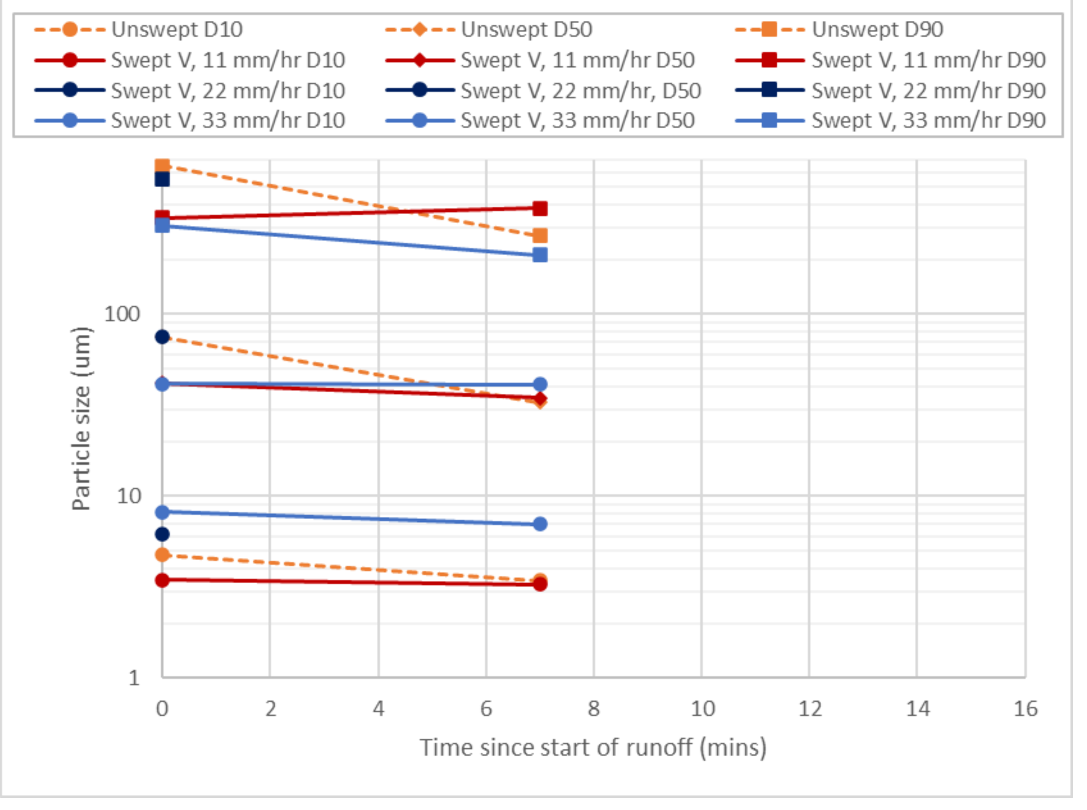
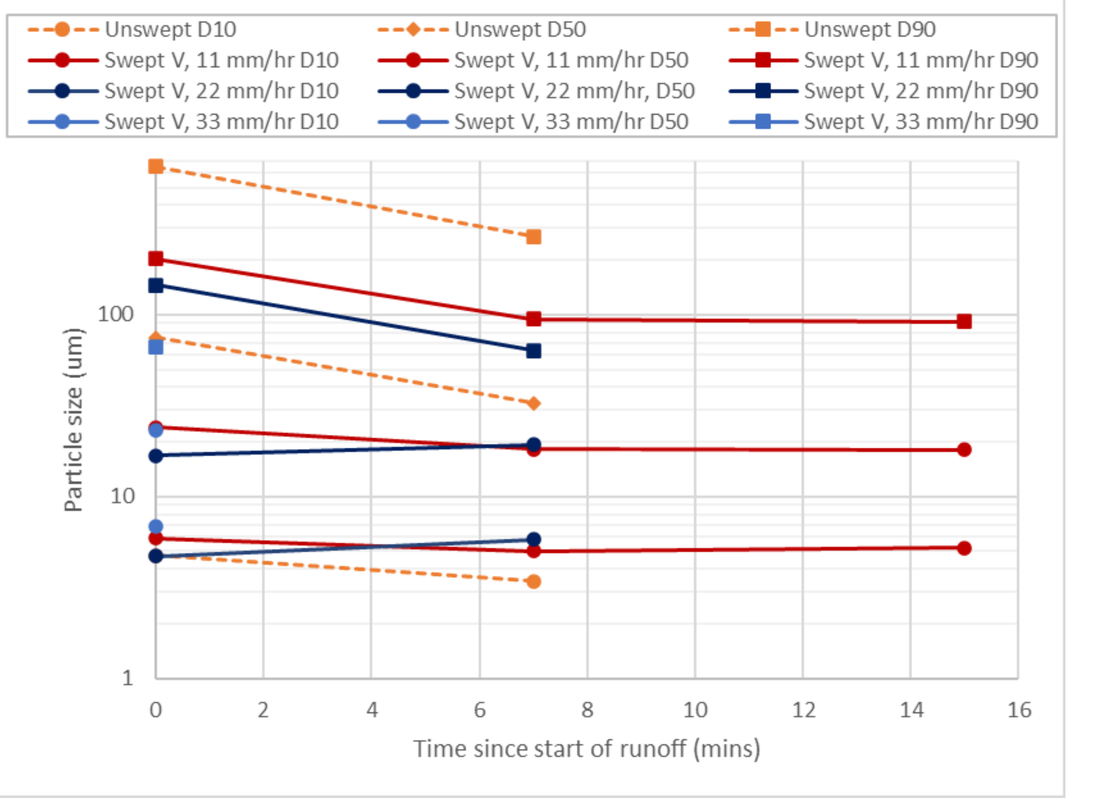
b) Comparison of unswept plots' PSD across all sites (First flush, t=0)



c) Intra-event variation in D_{10}, D_{50} and D_{90} at <u>Lunns Road</u>, for trials where intra-event PSD data could be obtained

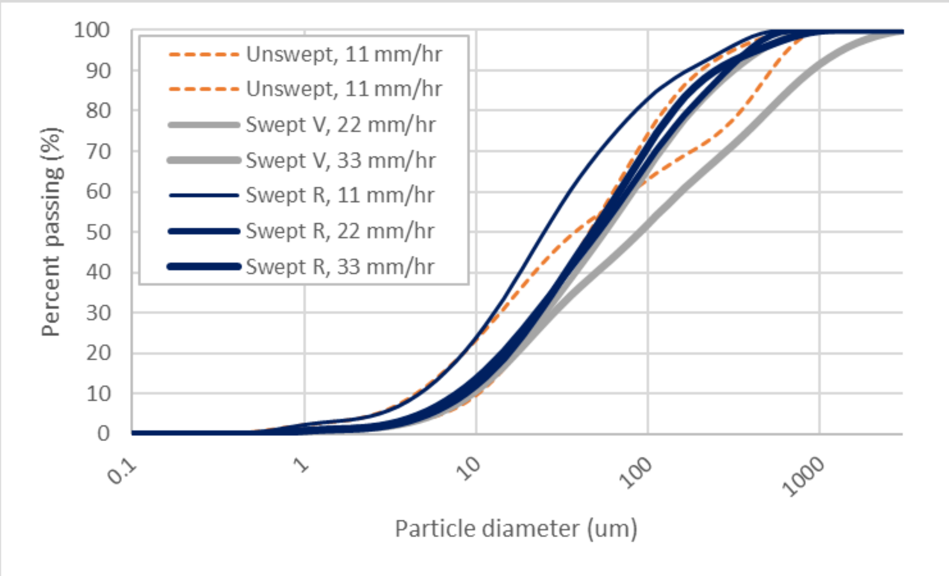
Unswept and vacuum-swept trials	Unswept and regenerative-swept trials
	

d) Intra-event variation in D10, D50 and D90 at Sabys Road, for trials where intra-event PSD data could be obtained

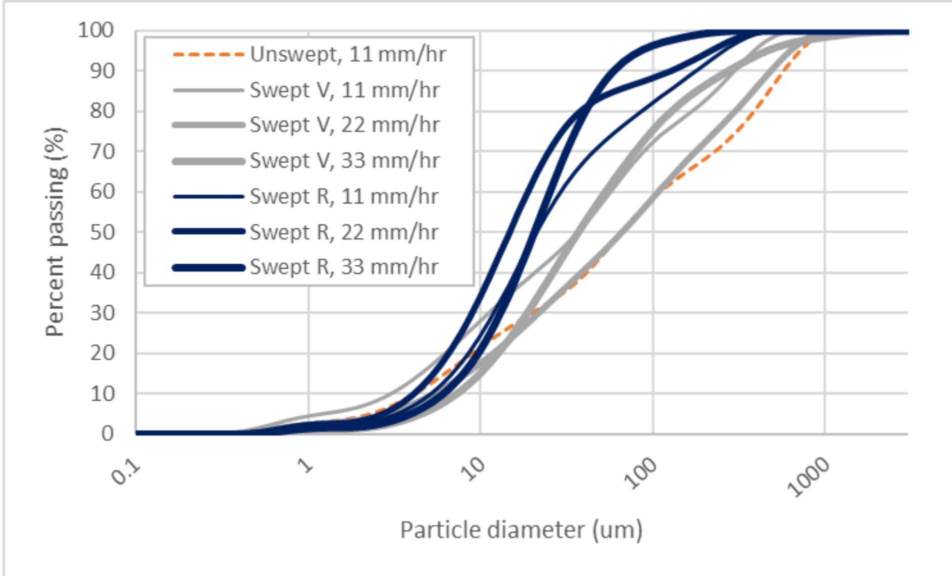
Unswept and vacuum-swept trials	Unswept and regenerative-swept trials
	

e) Cumulative PSDs for each trial, at each site (First flush, t=0)

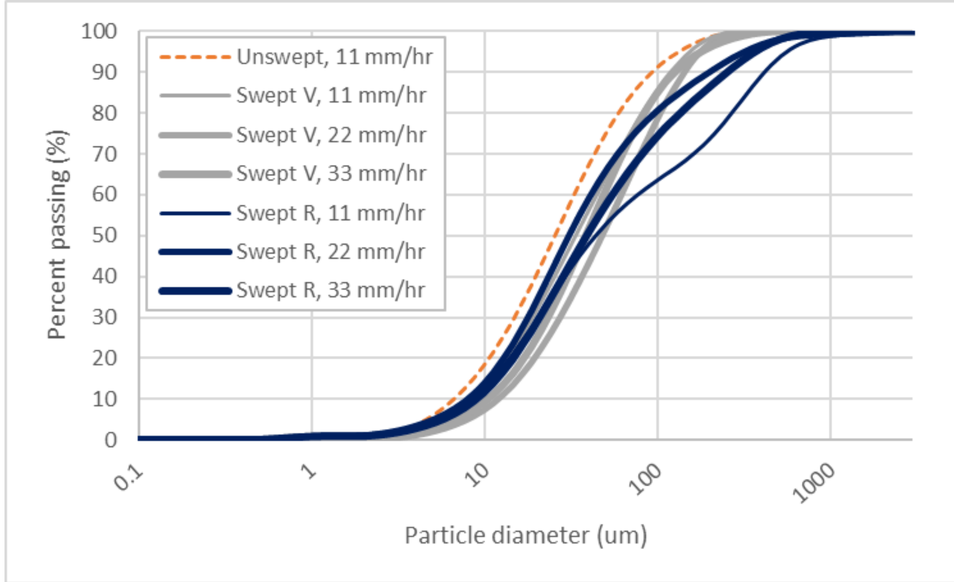
Montana Ave



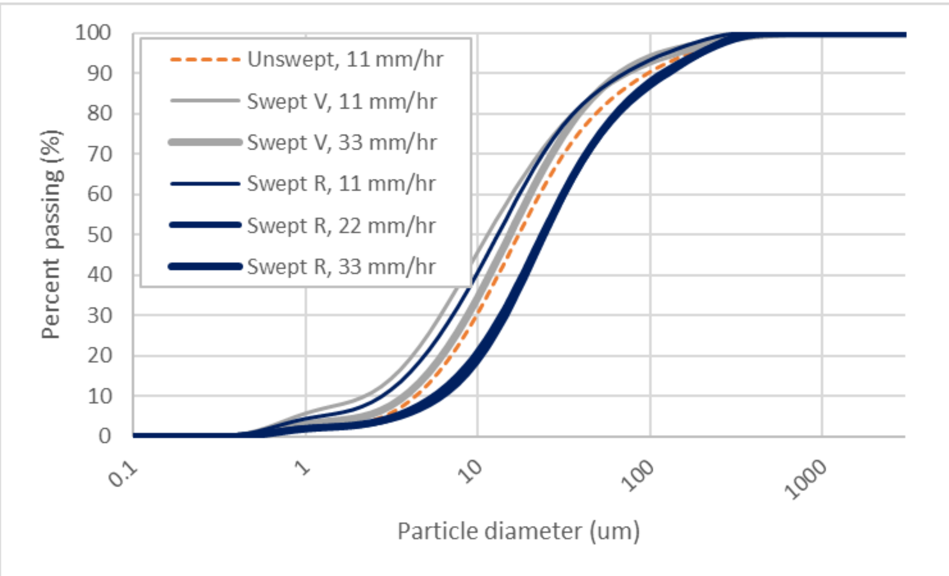
Sabys Road



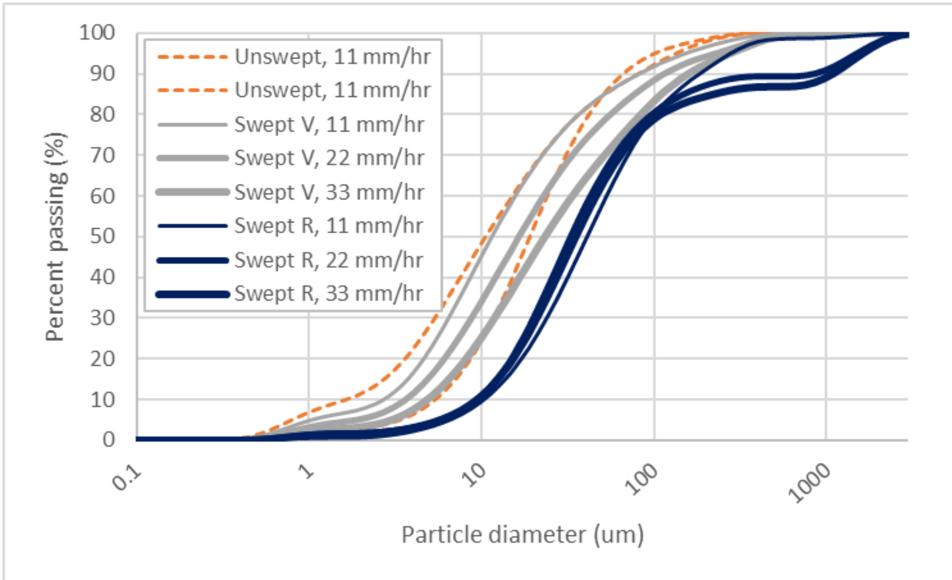
Princess Street



Durham Street

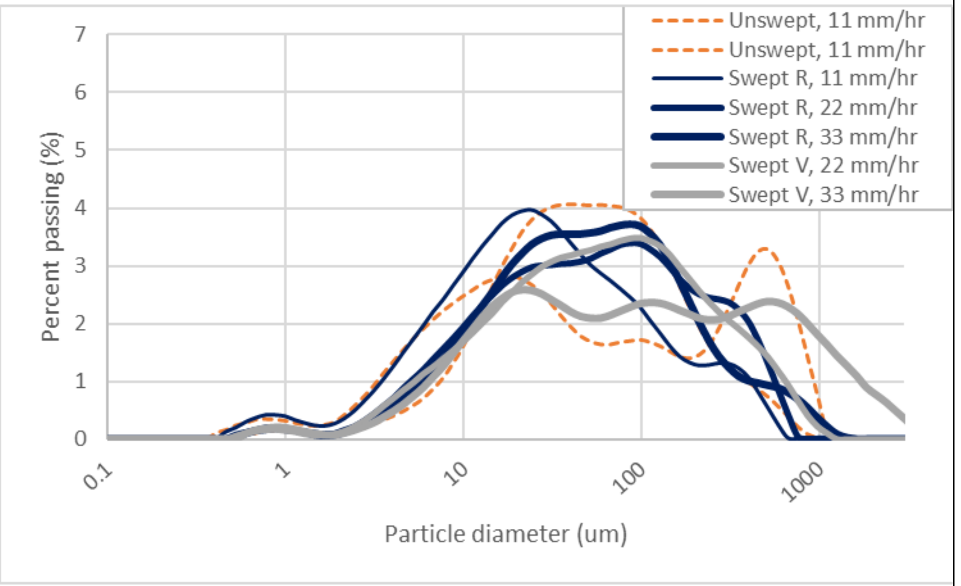


Lunns Road

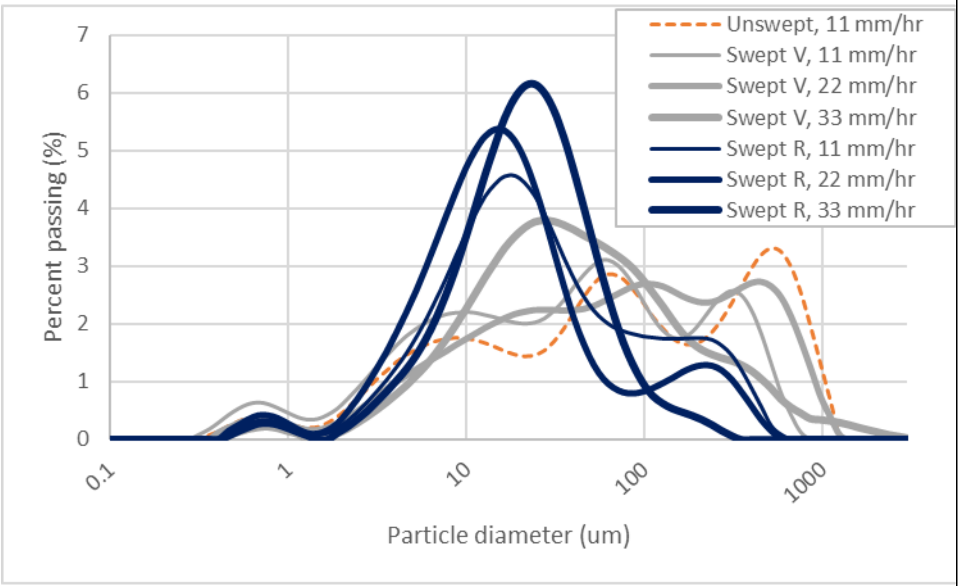


f) Frequency PSDs for each trial, at each site (First flush, t=0)

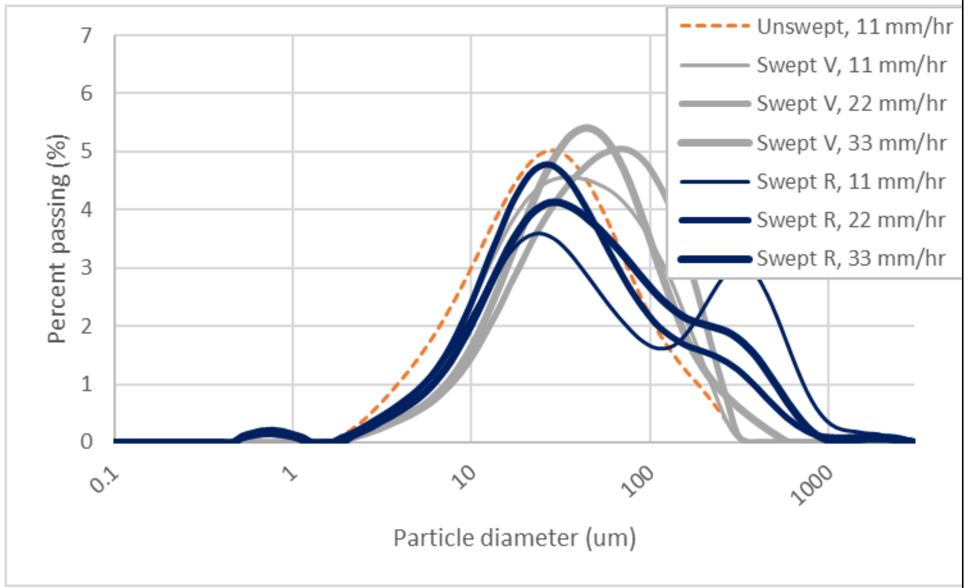
Montana Ave



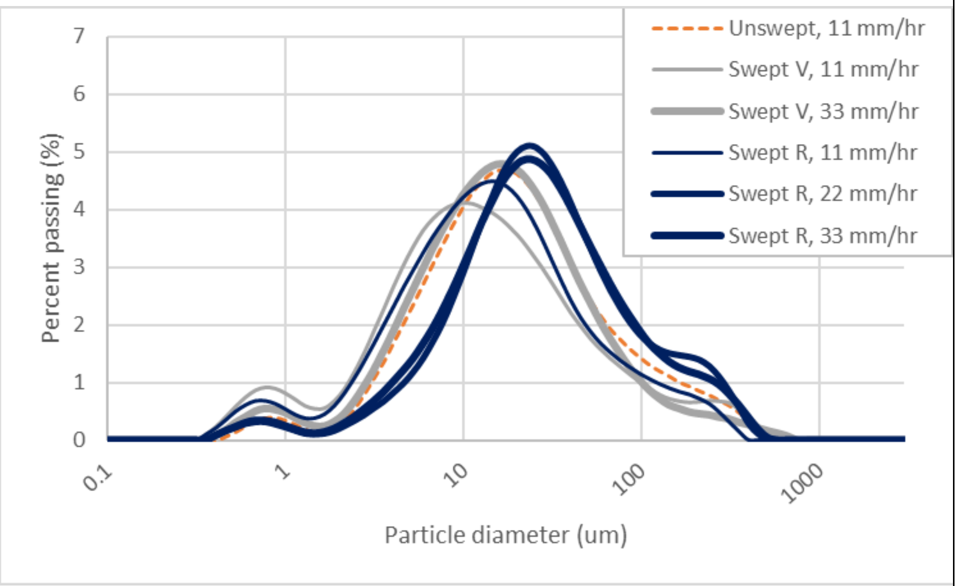
Sabys Road



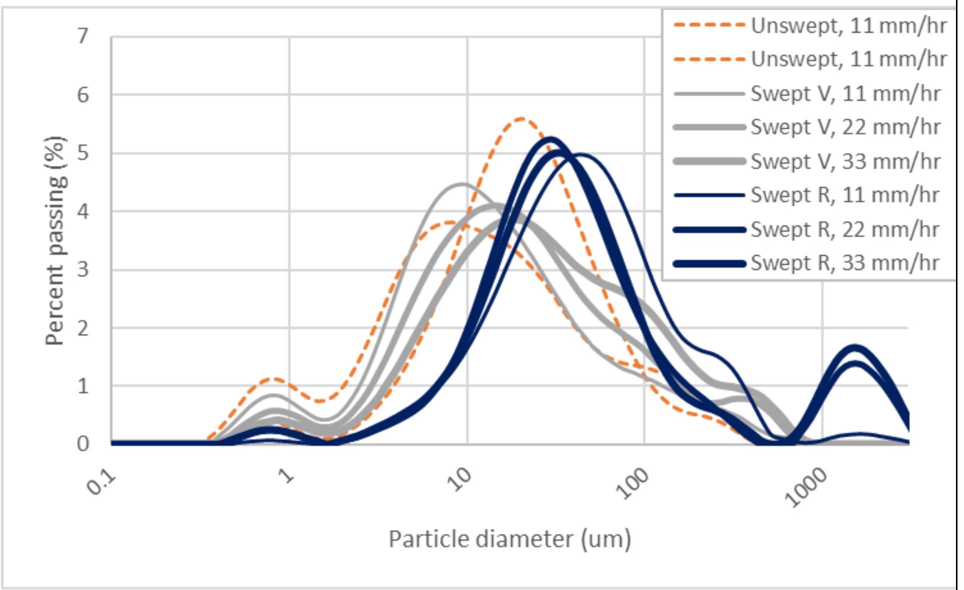
Princess Street



Durham Street



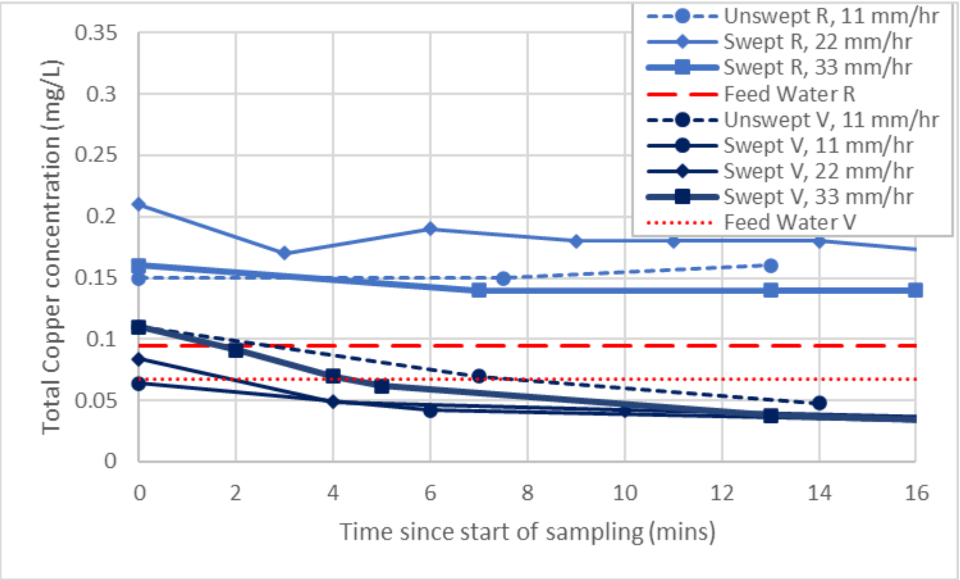
Lunns Road



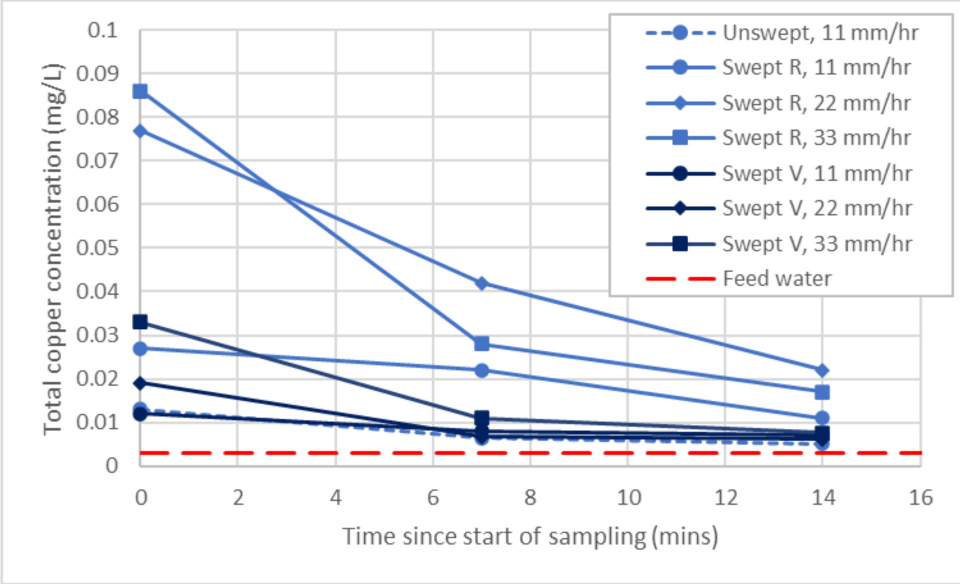
3. *Copper Data*

a. Raw total copper concentration over time for each trials, at each site

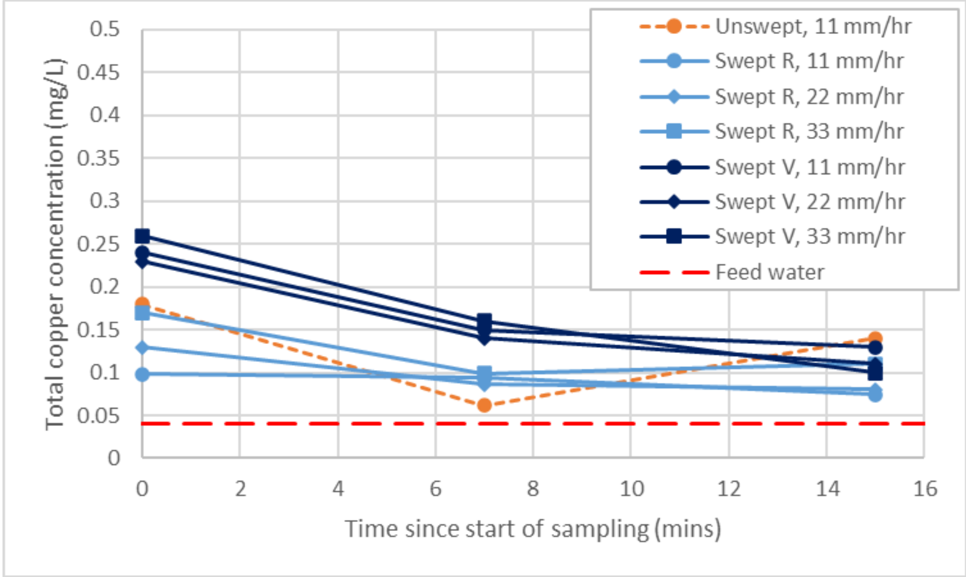
Montana Ave



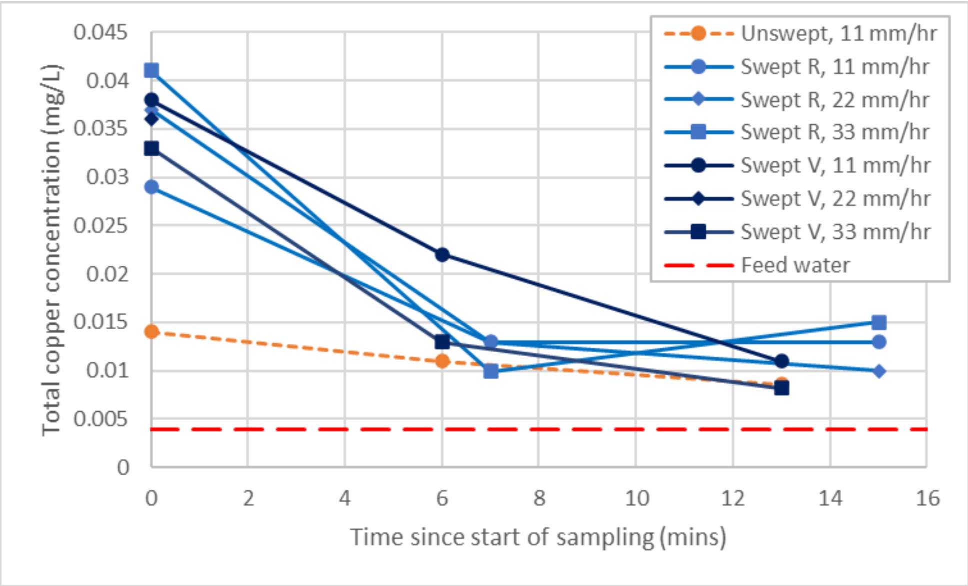
Sabys Road



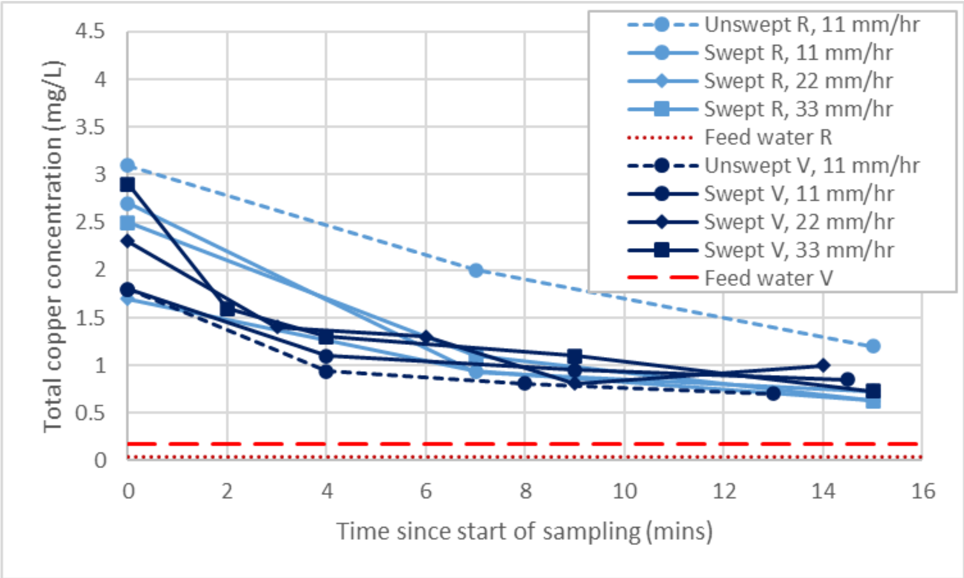
Princess Street



Durham Street

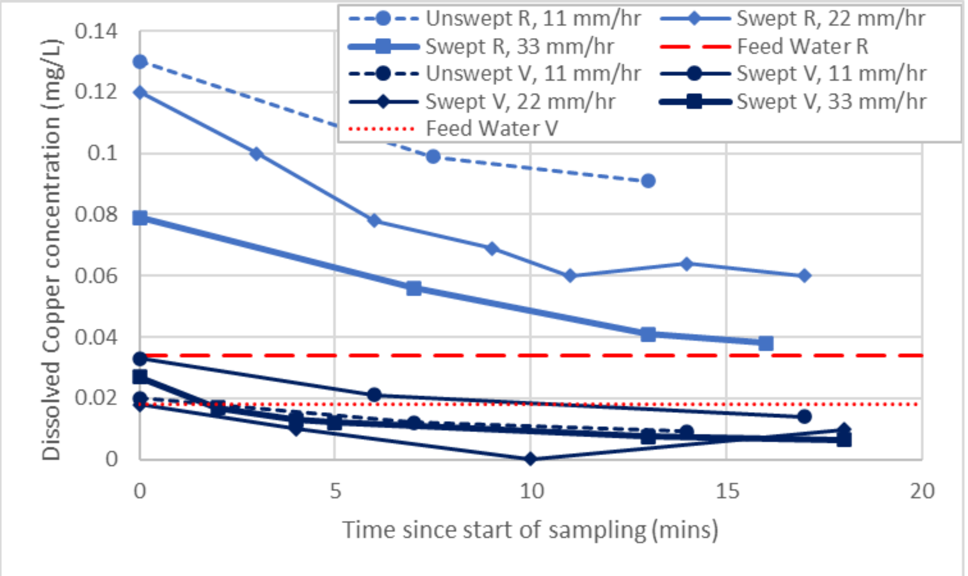


Lunns Road

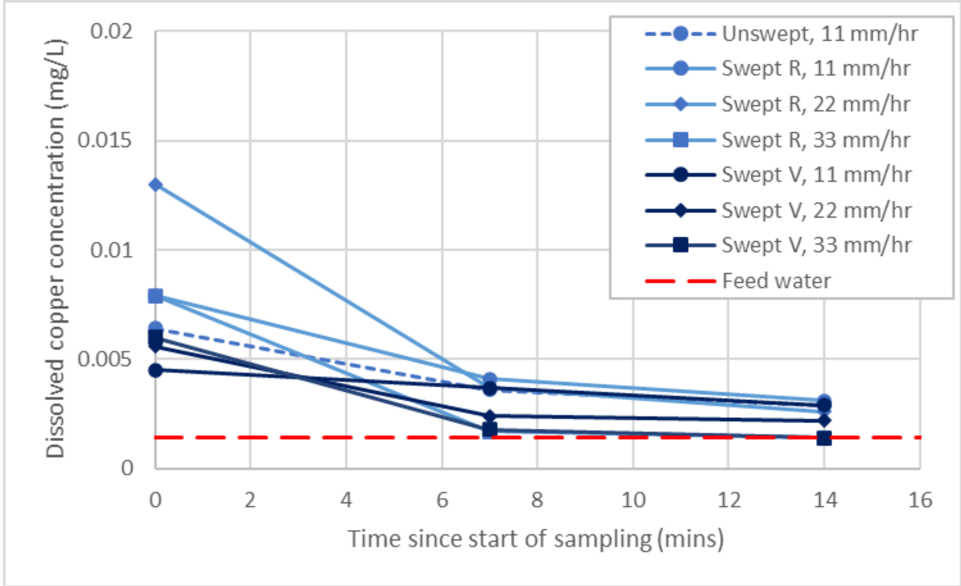


b. Raw dissolved copper concentration over time for each trials, at each site

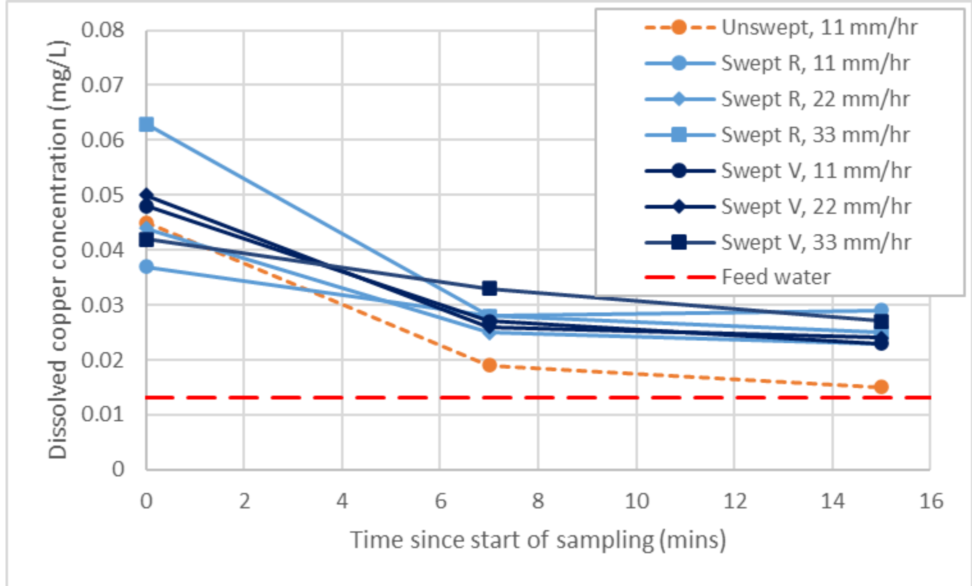
Montana Ave



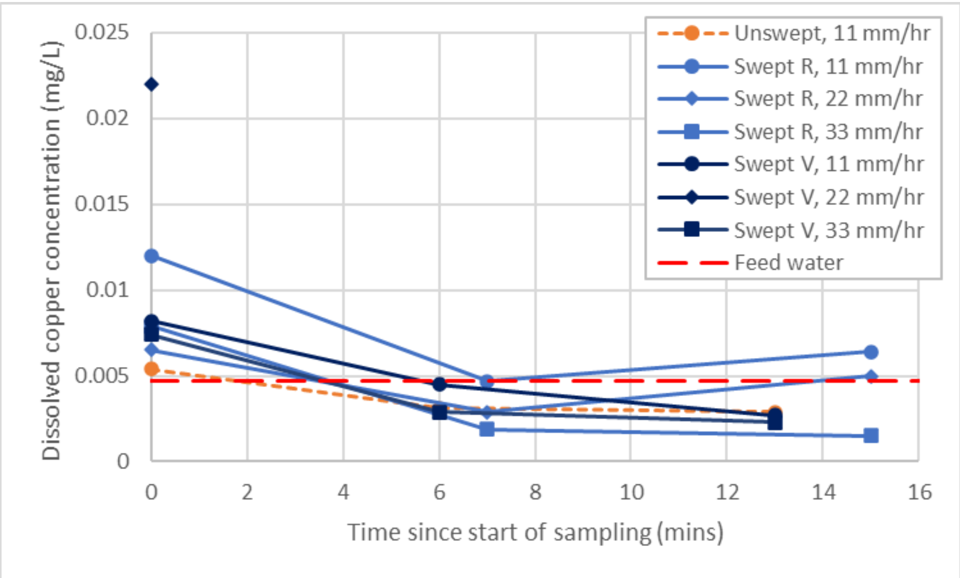
Sabys Road



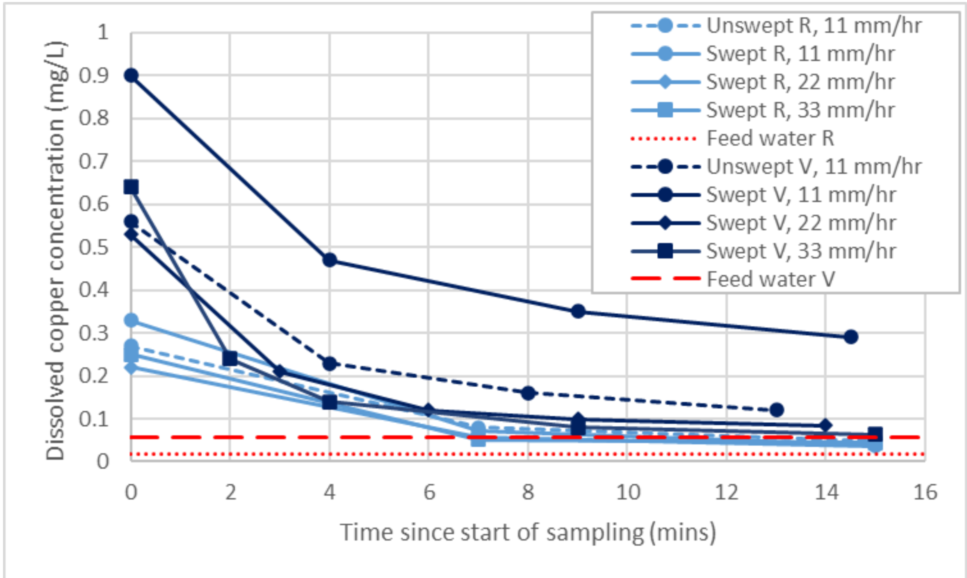
Princess Street



Durham Street



Lunns Road

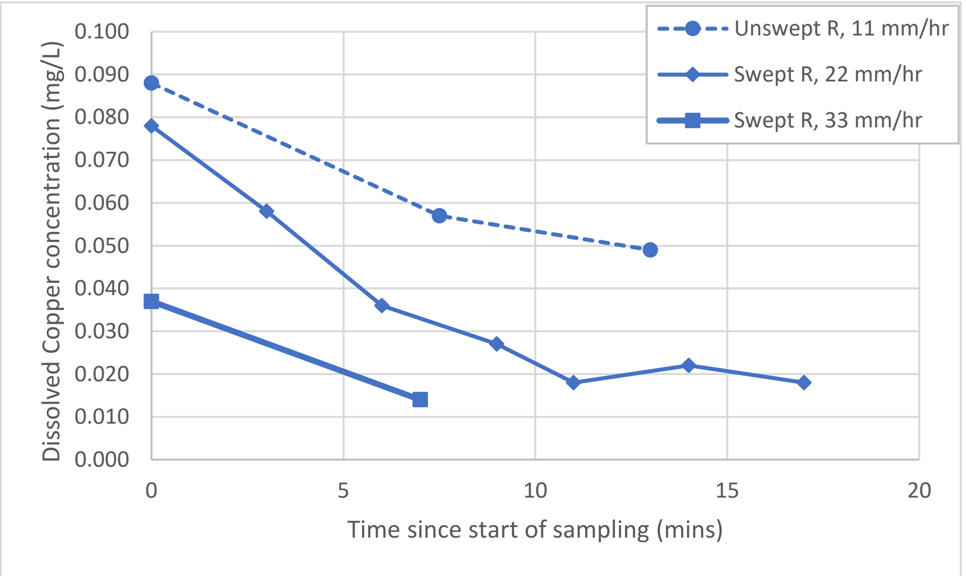


c. <u>Adjusted</u> total and dissolved copper concentration over time for each site where runoff > feed water concentrations (where adjusted concentration = raw – background concentration)

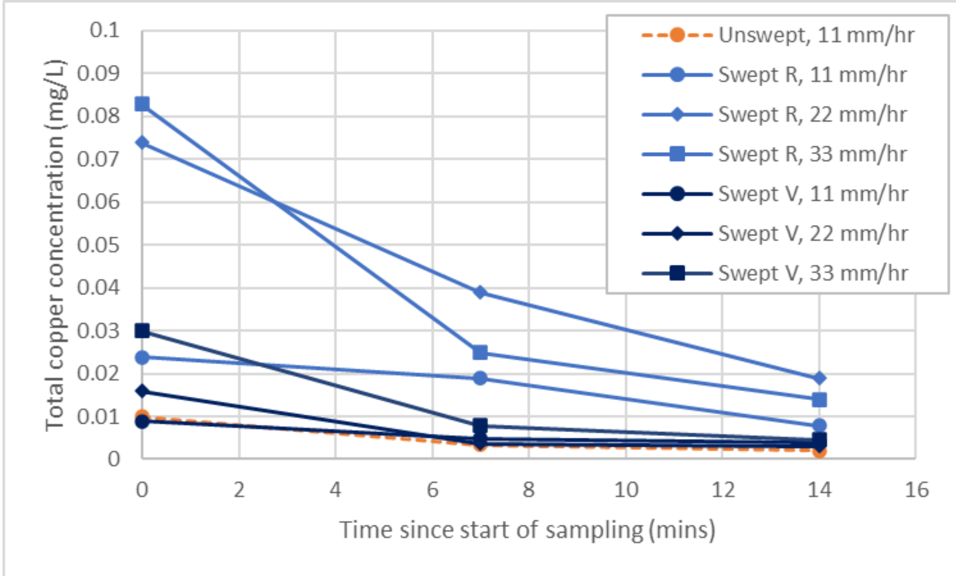
Montana Ave

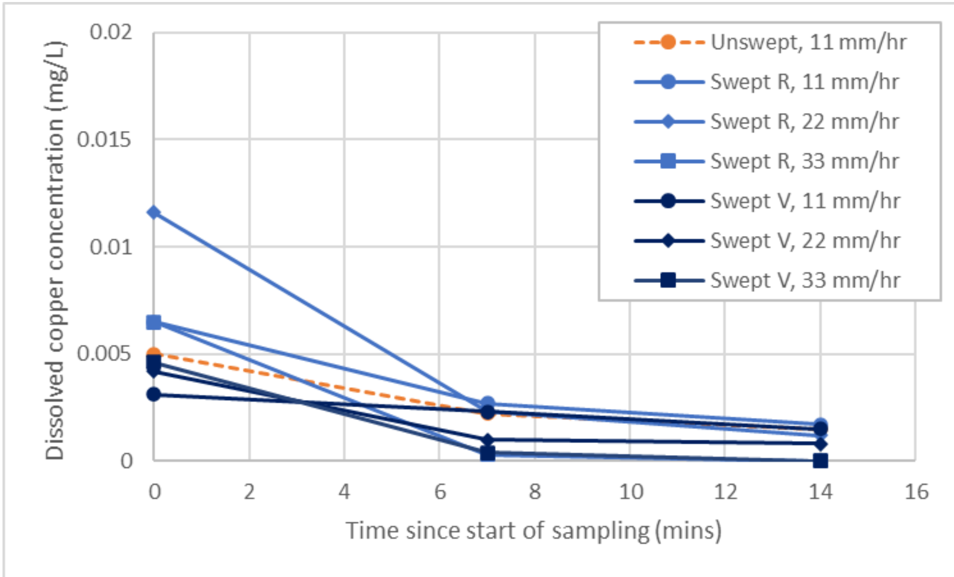
Total: Only the first flush sample for the unswept plot was above total copper background values.

Dissolved:

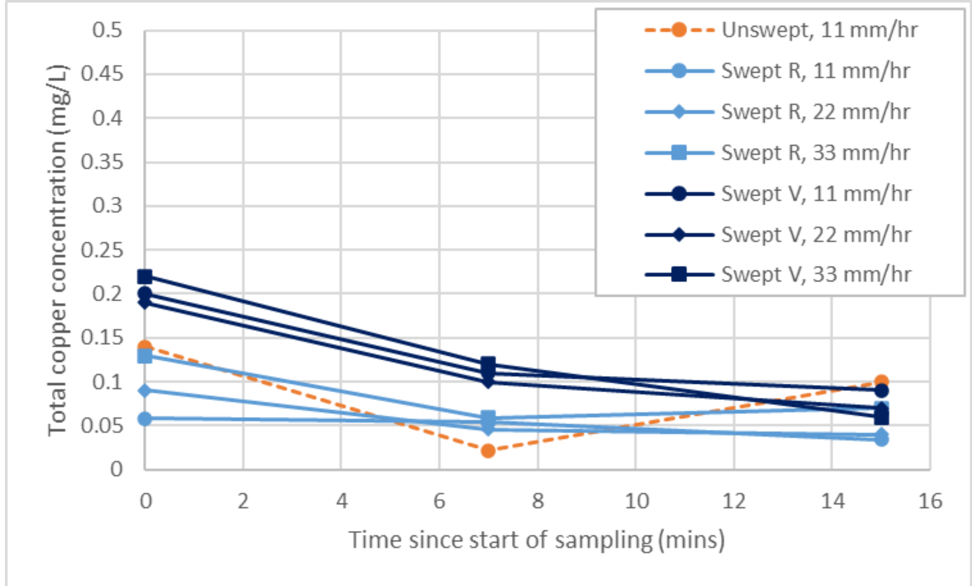


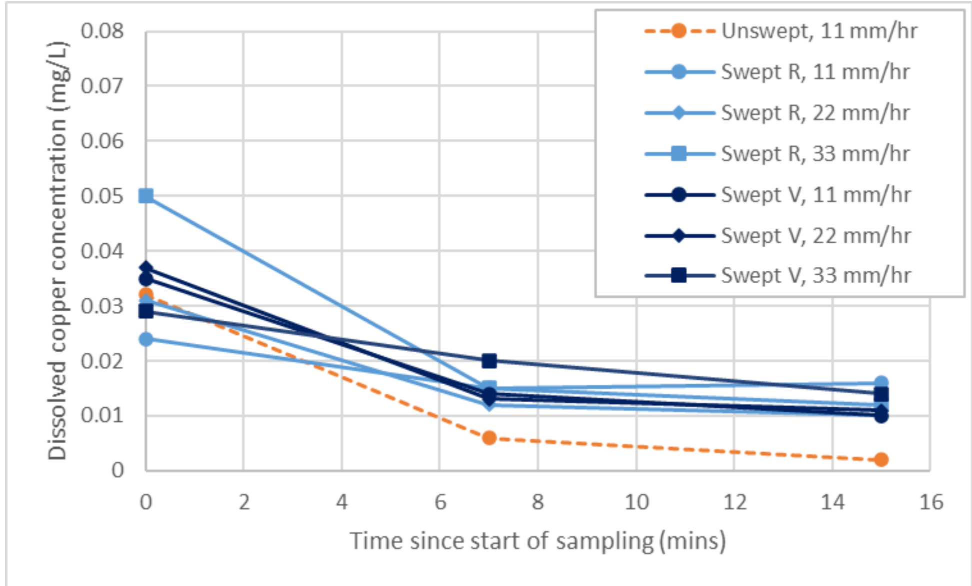
Sabys Road





Princess Street





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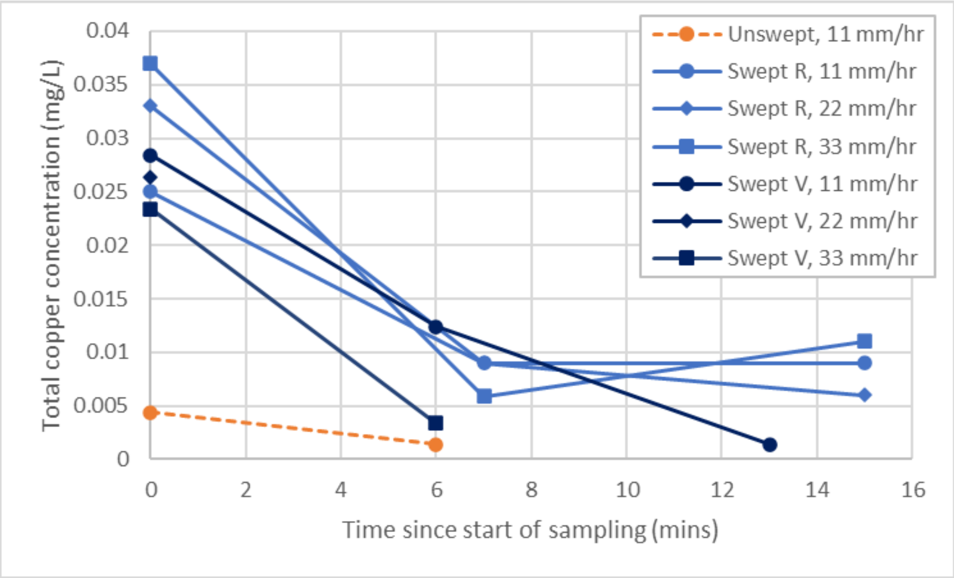
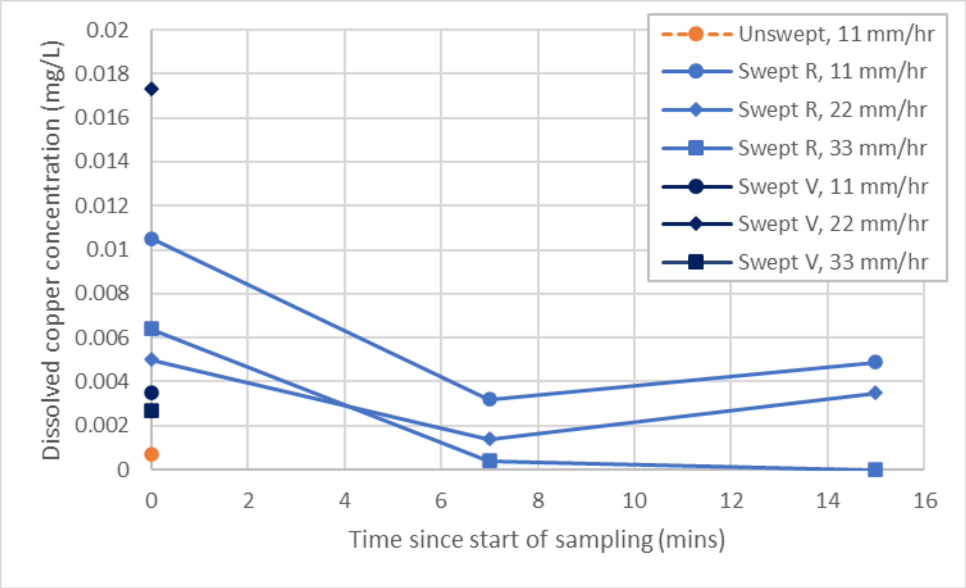
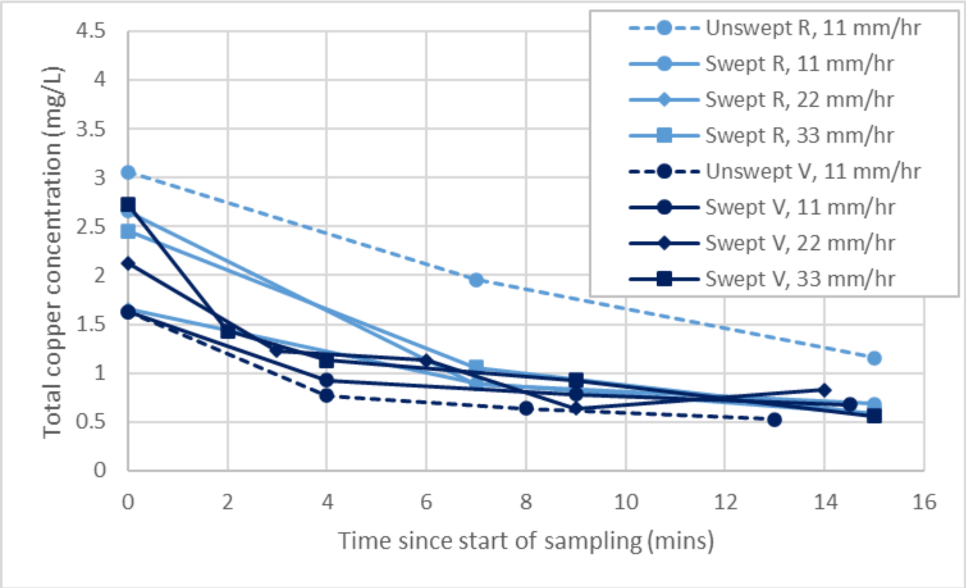
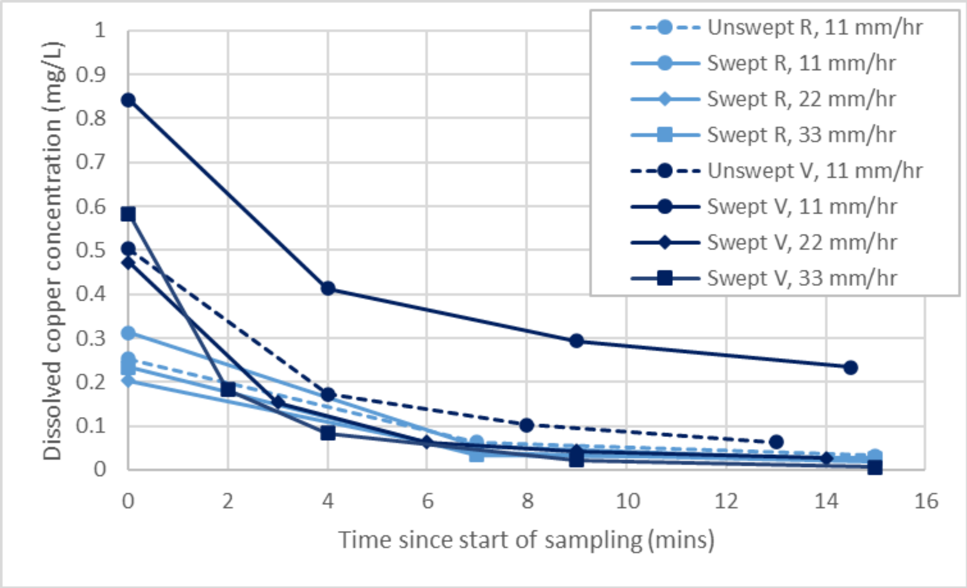
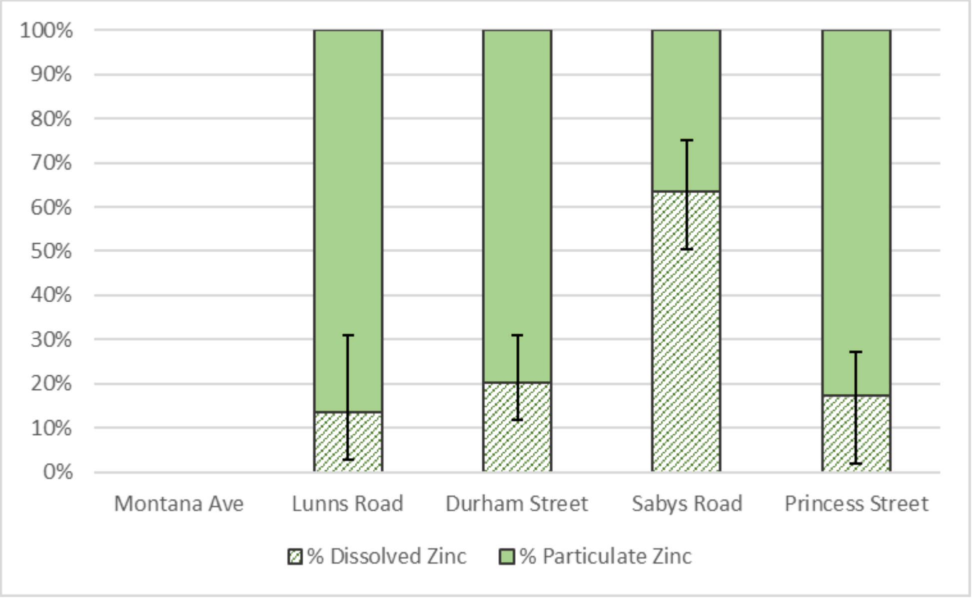
Durham Street	*Lunns Road*	
 	 	

d. Copper partitioning across all trials for each site (average for site, with bars showing minimum and maximum)

Unswept



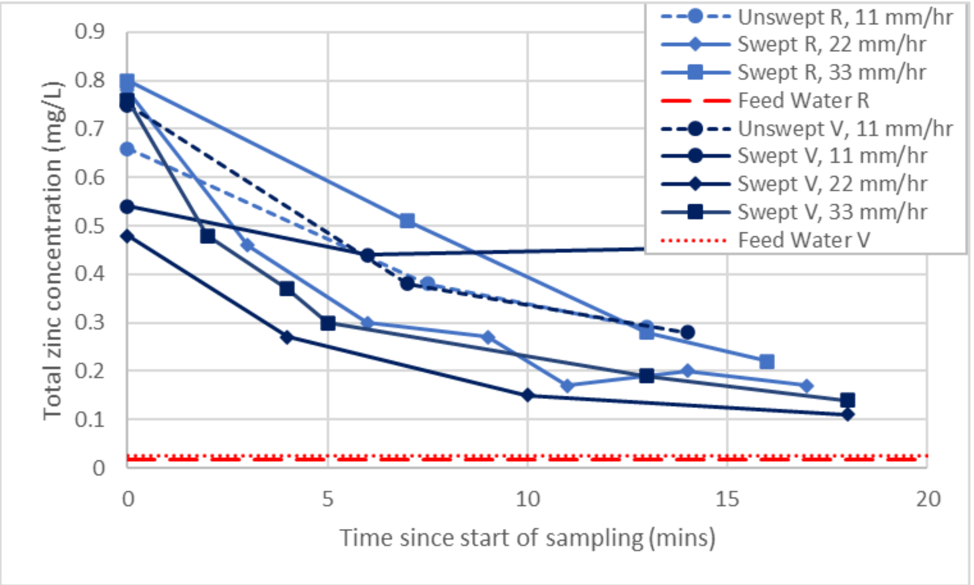
Vacuum Swept

Regenerative Swept

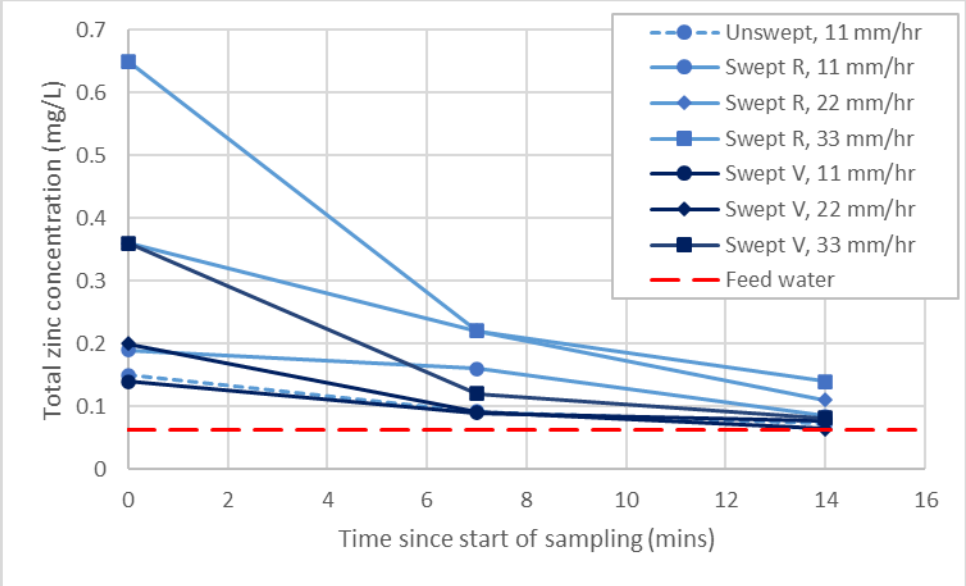
4. Zinc Data

a. Raw total zinc concentration over time for each trials, at each site

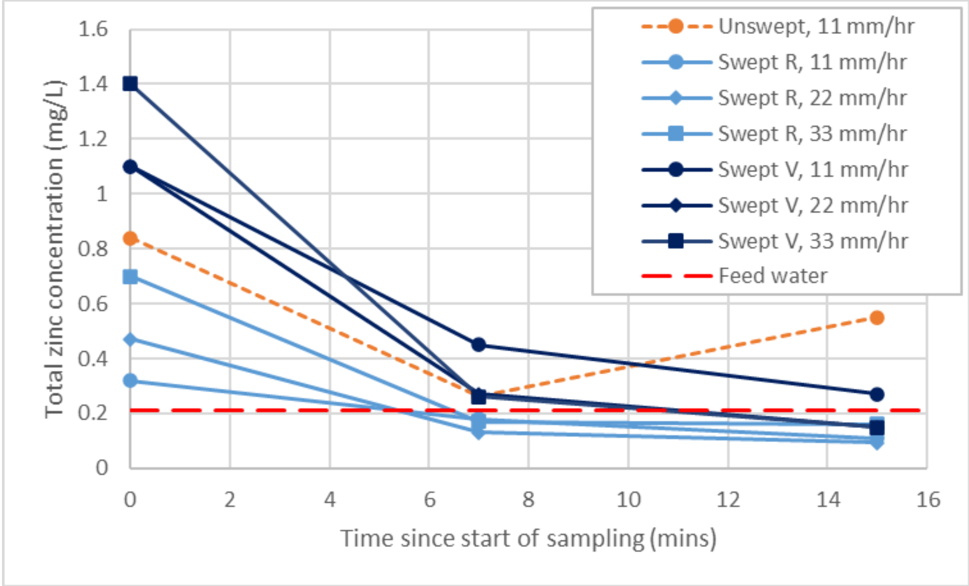
Montana Ave



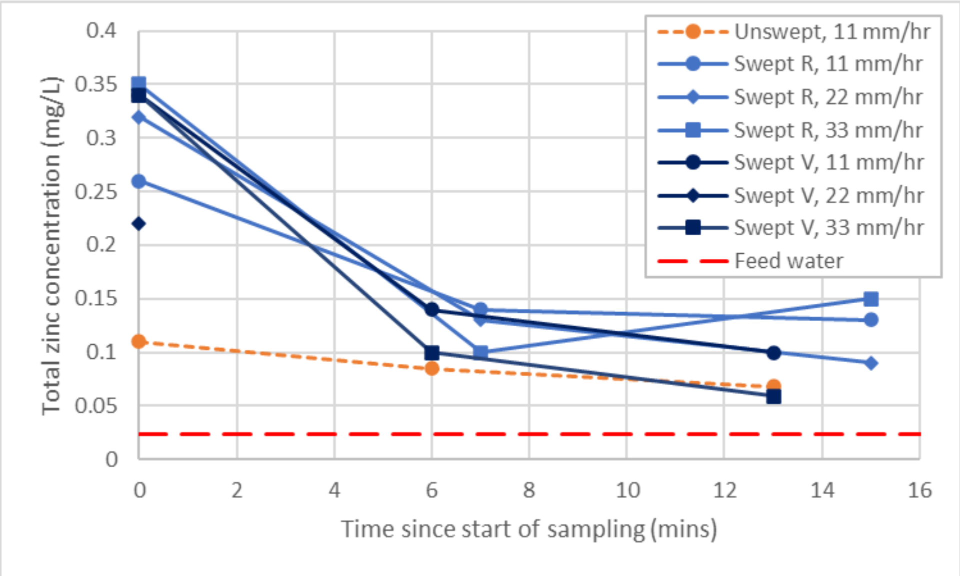
Sabys Road



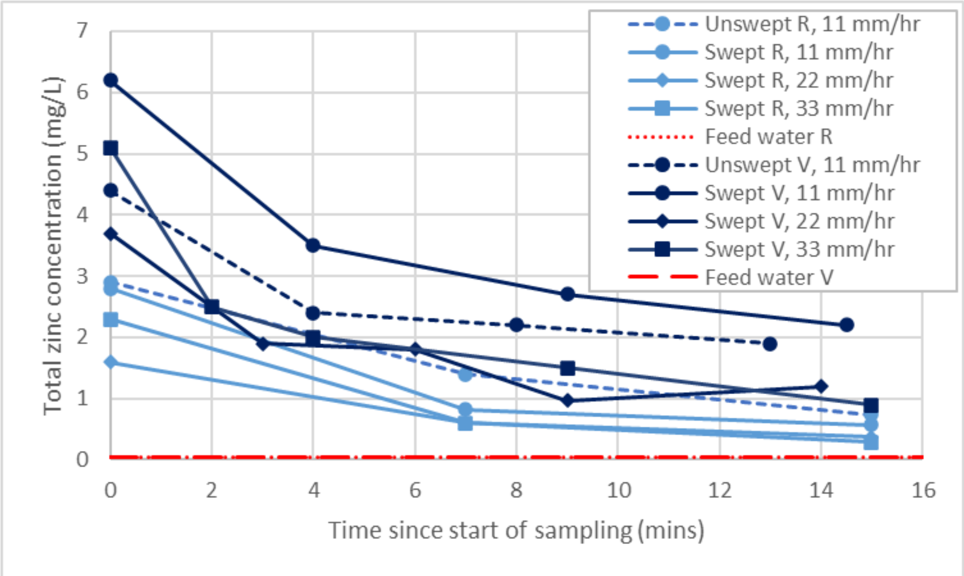
Princess Street



Durham Street

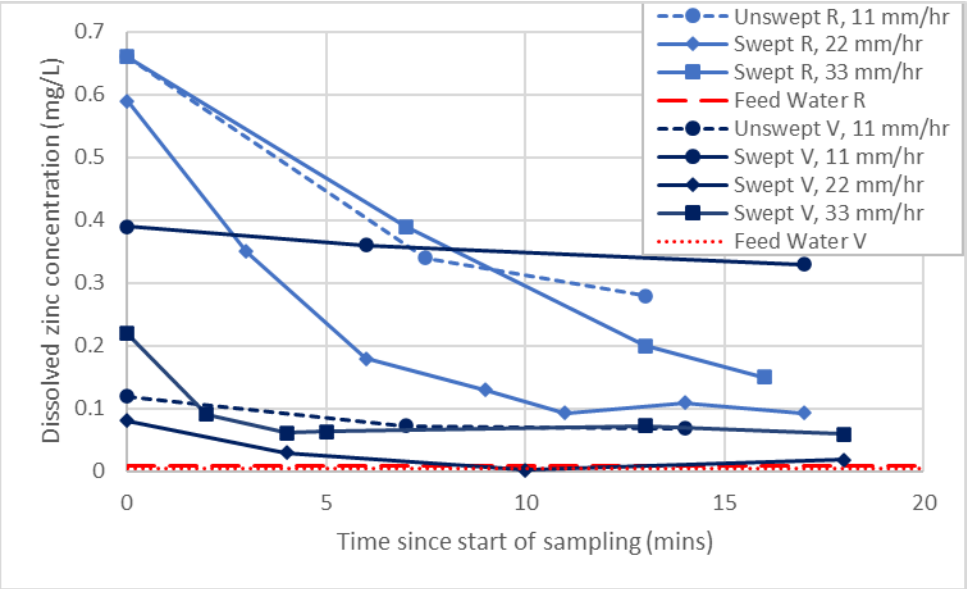


Lunns Road

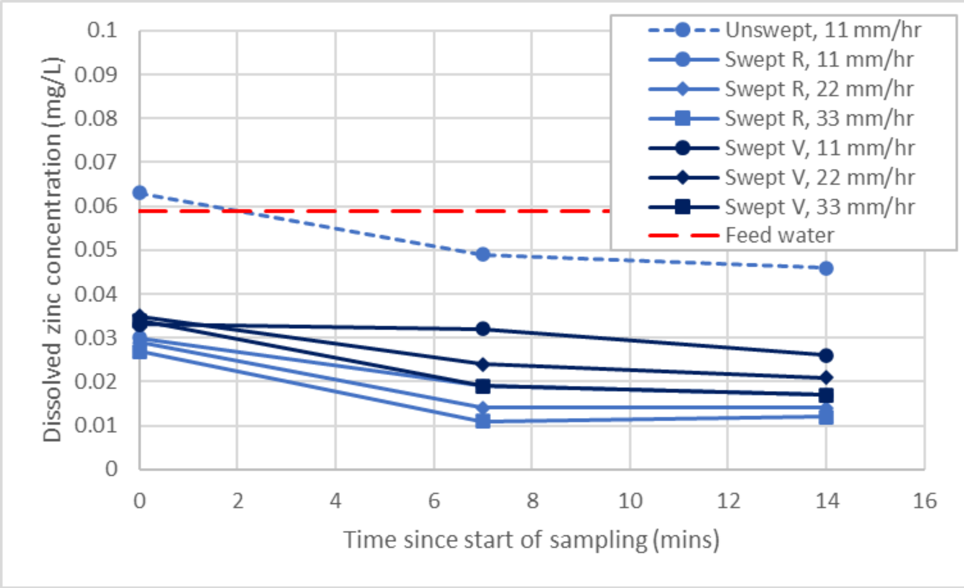


b. Raw dissolved zinc concentration over time for each trials, at each site

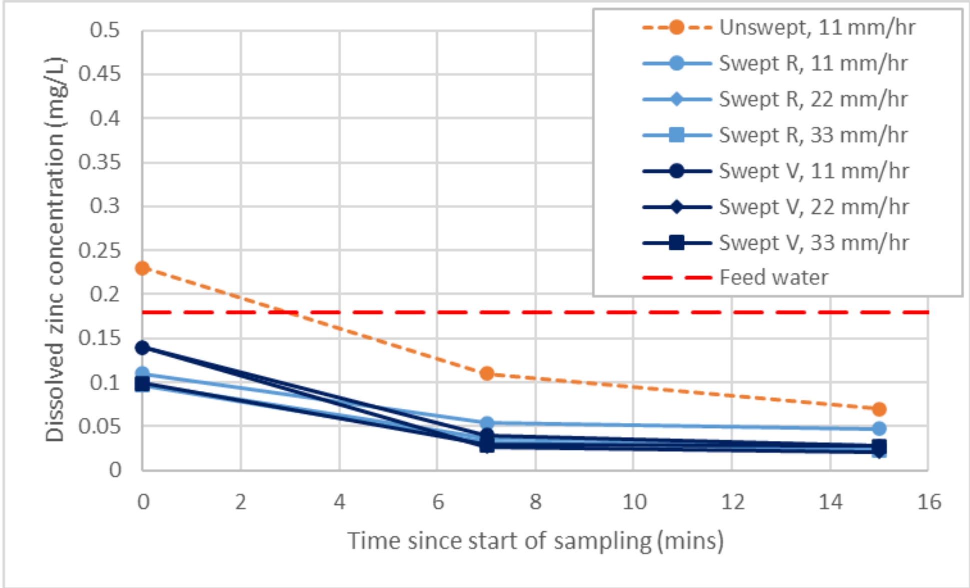
Montana Ave



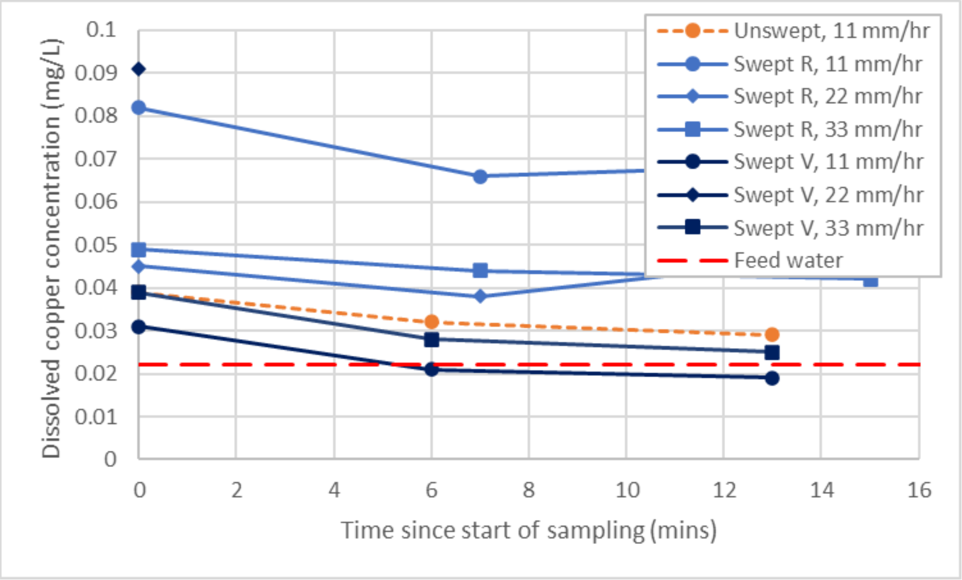
Sabys Road



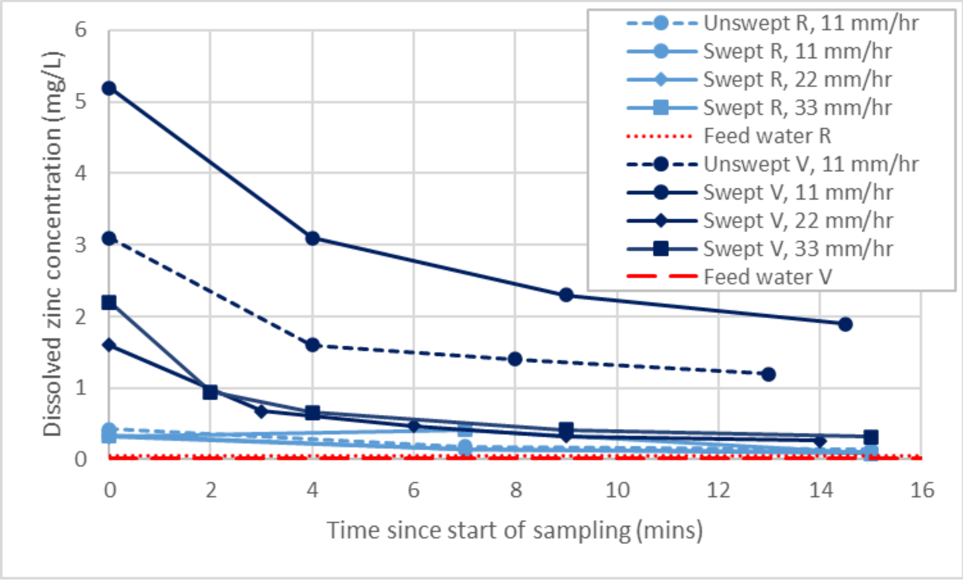
Princess Street



Durham Street

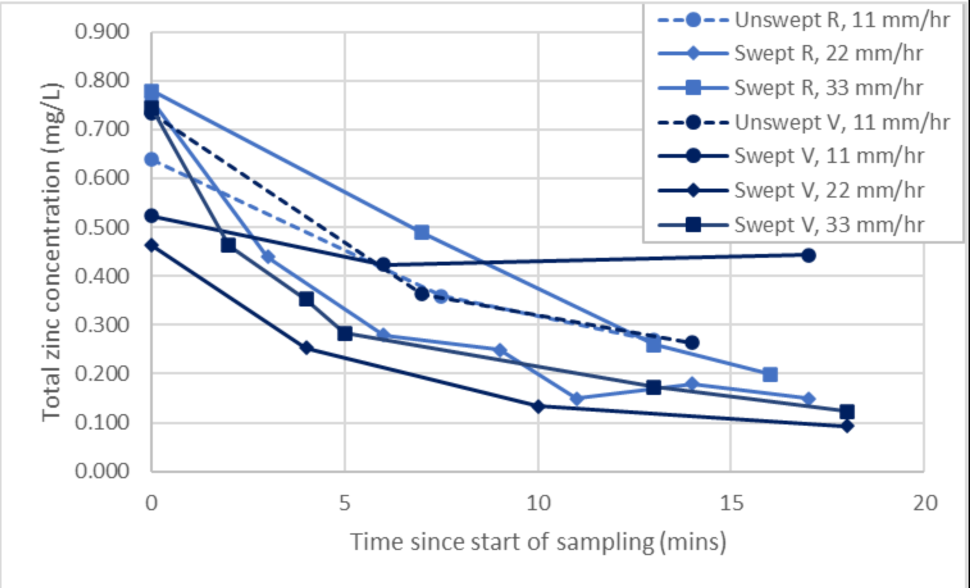


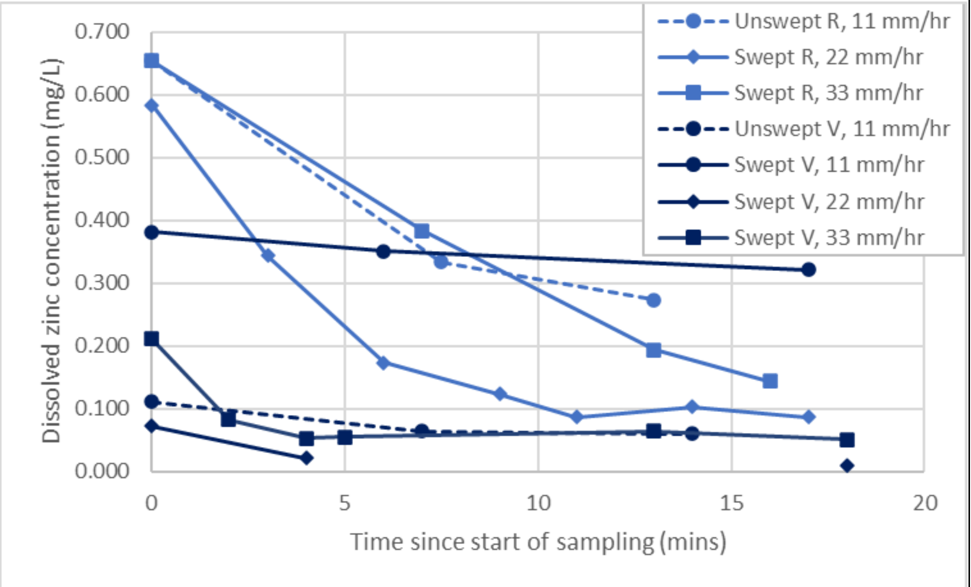
Lunns Road



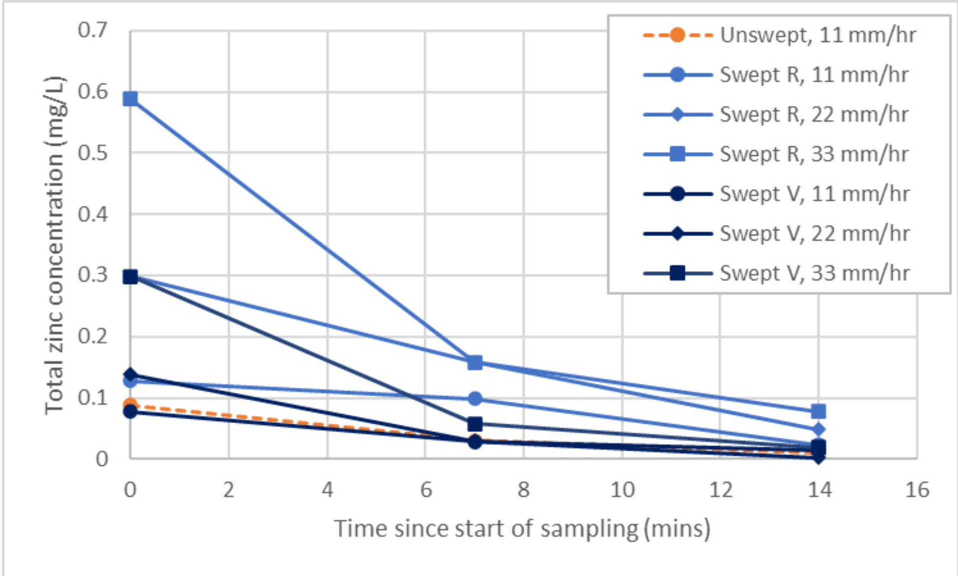
c. Adjusted total and dissolved zinc concentration over time for each site where runoff > feed water concentrations (where adjusted concentration = raw – background concentration)

Montana Ave



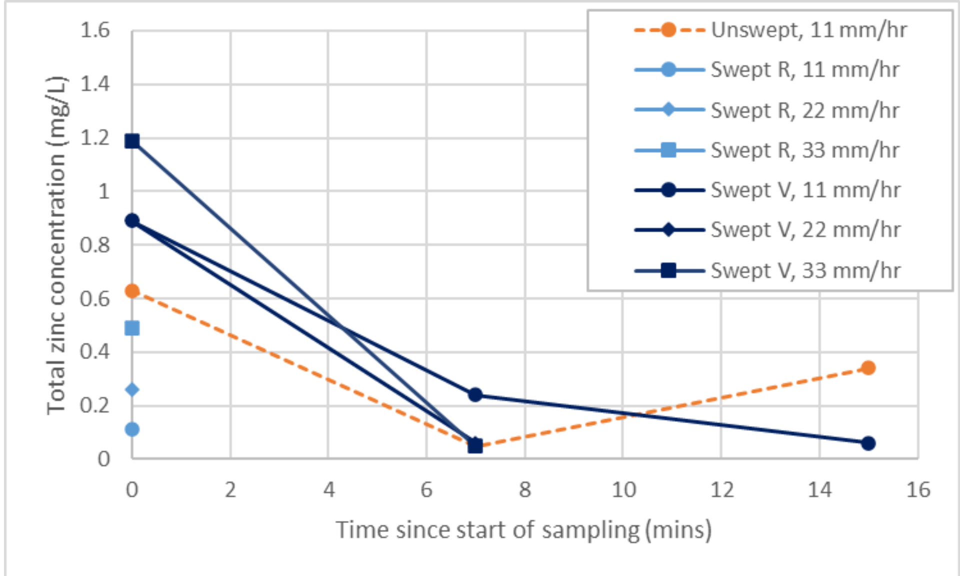


Sabys Road



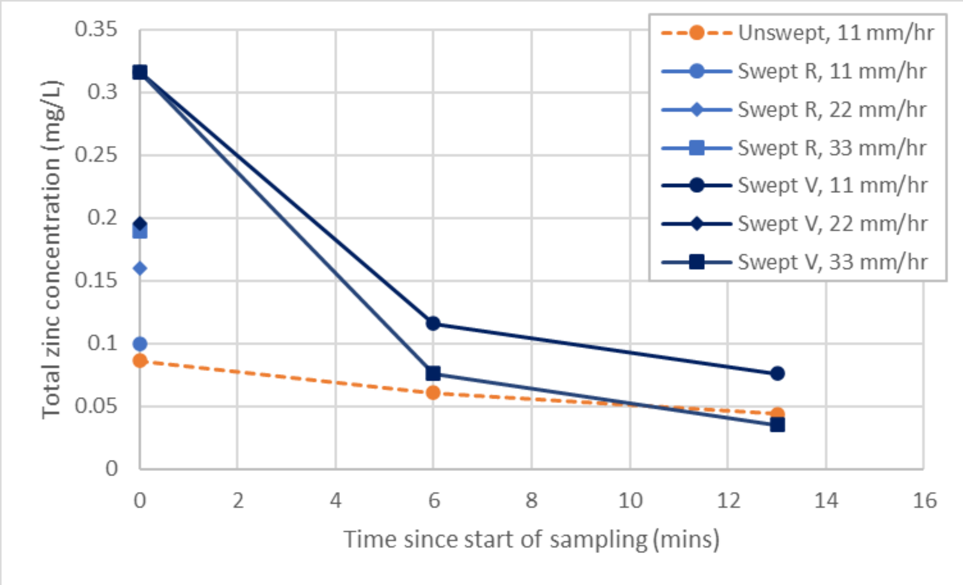
Only the first flush sample for the unswept plot was above dissolved zinc background values.

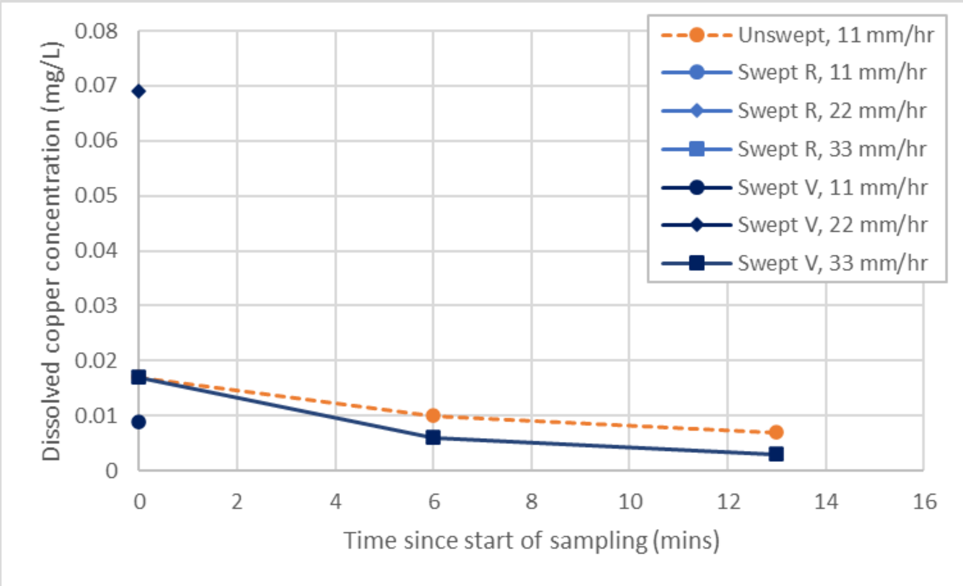
Princess Street



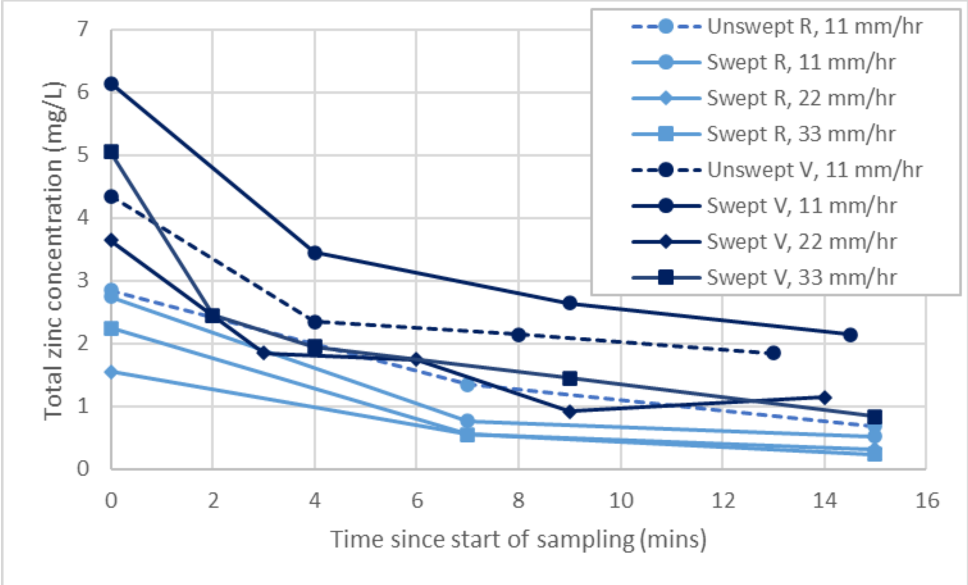
Only the first flush sample for the unswept plot was above dissolved zinc background values.

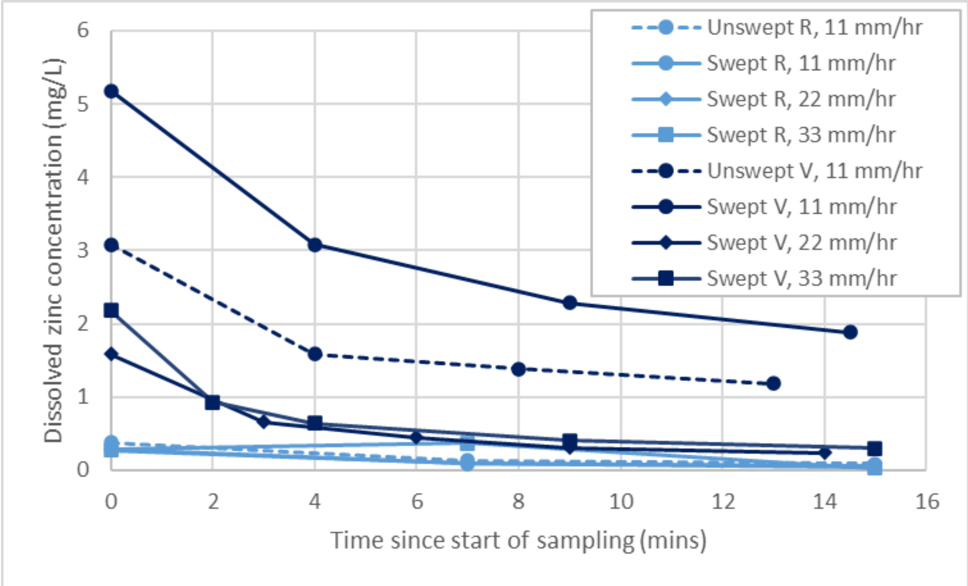
Durham Street



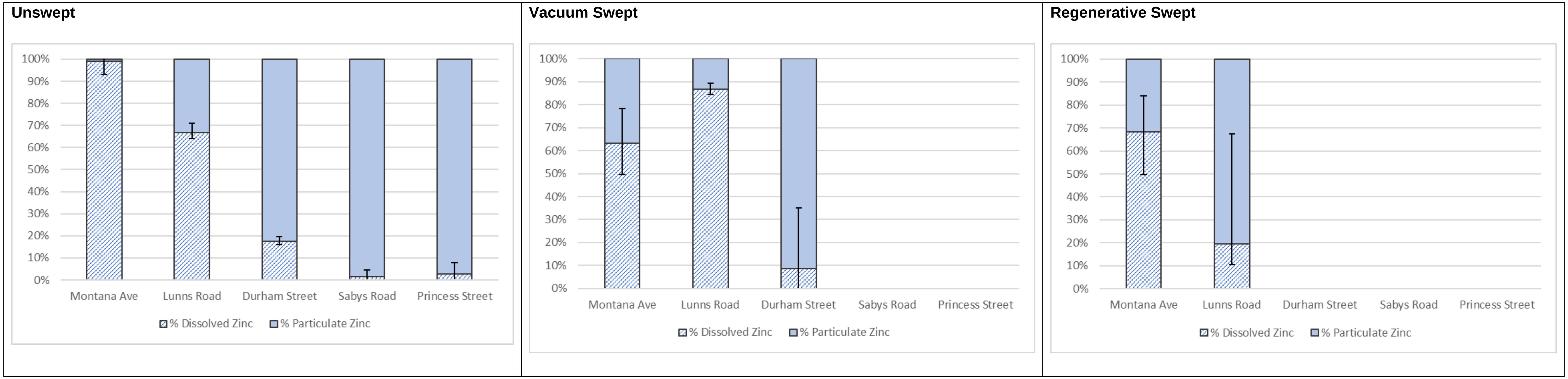


Lunns Road





d. Zinc partitioning across all trials for each site (average for site, with bars showing minimum and maximum)



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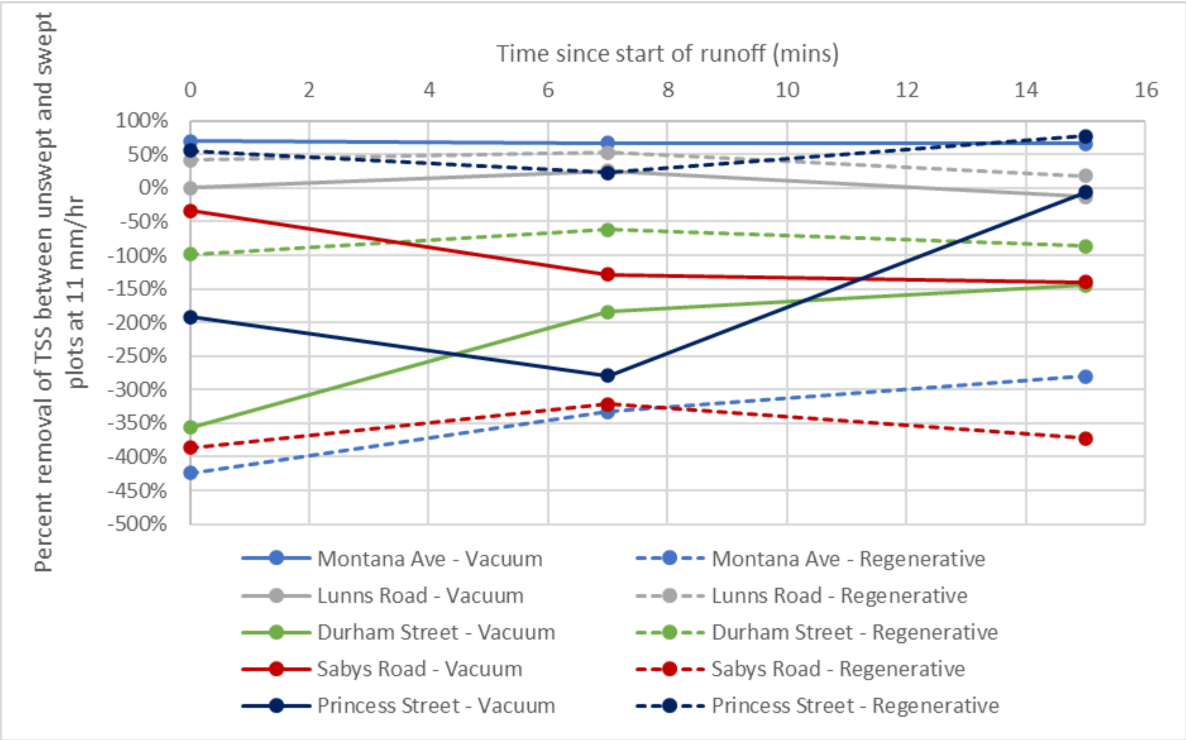
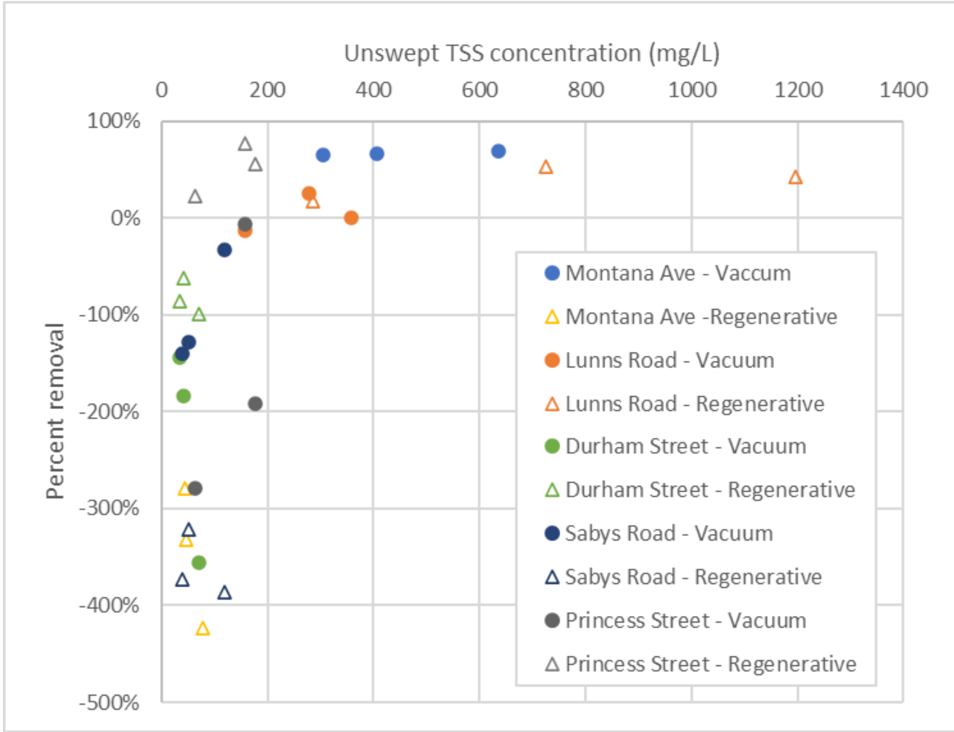
Appendix C Percent removal of pollutants between unswept and swept plots (at 11 mm/hr applied rainfall intensity)

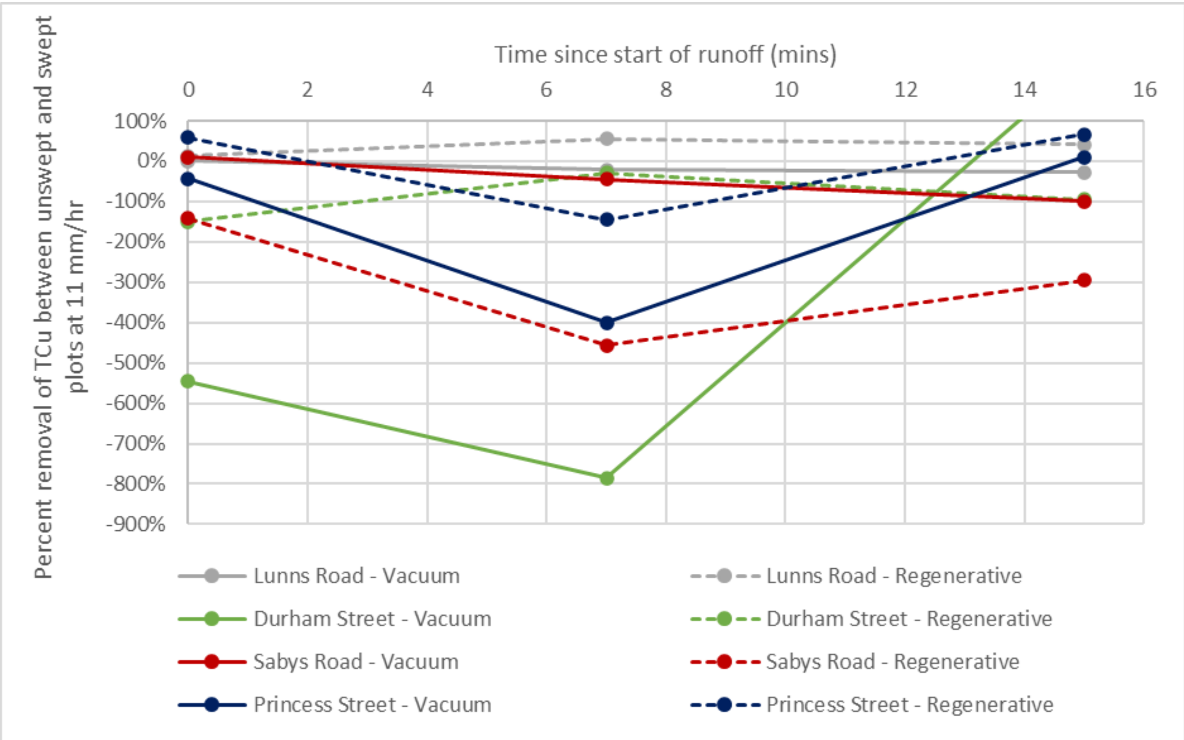
Total suspended solids



Percent removal against unswept TSS concentration

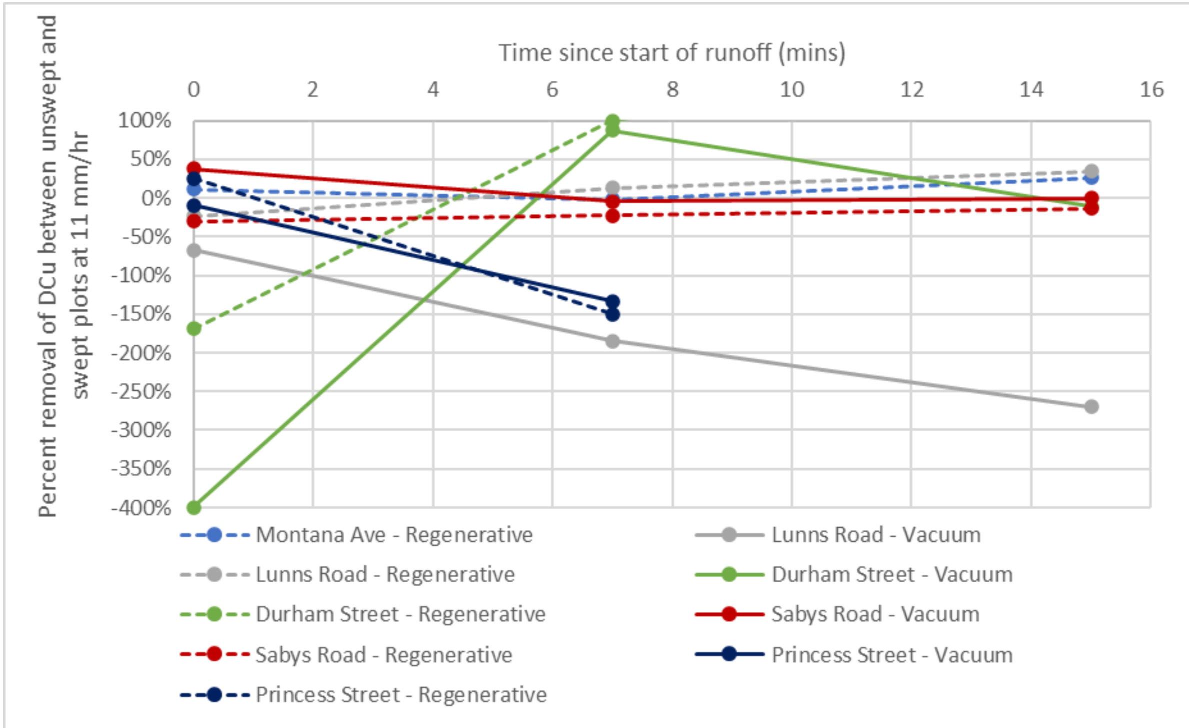


Total Copper



Note: Montana Ave vacuum and regenerative performance not shown as baseline total copper concentration > unswept and swept runoff concentrations

Dissolved Copper



Note: Montana Ave vacuum performance and Princess Street 15 mins samples' not shown as baseline dissolved copper concentration > unswept and/or swept runoff concentrations

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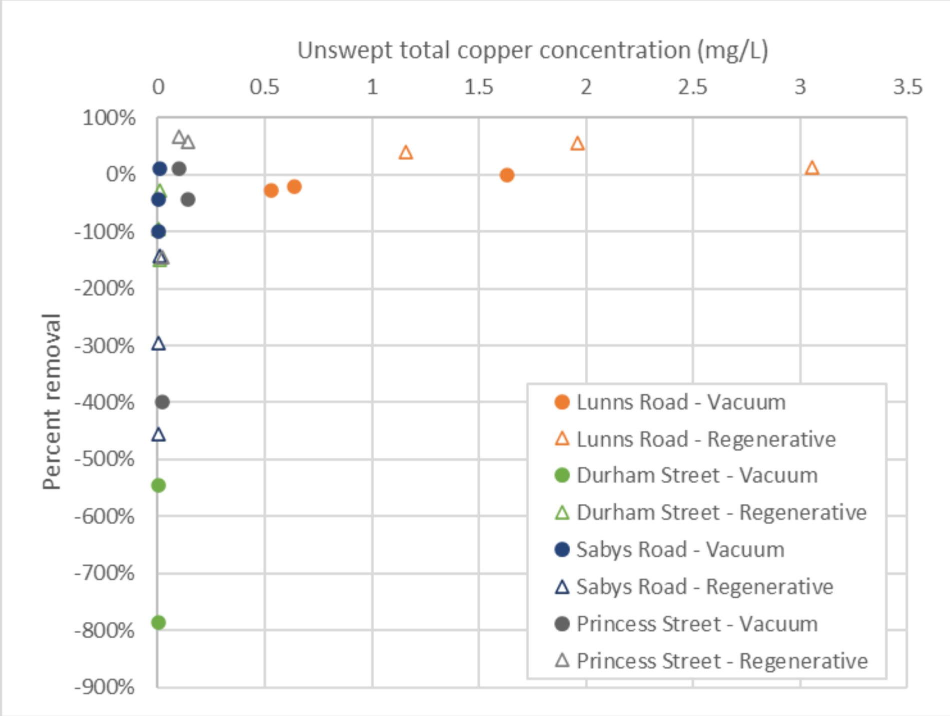
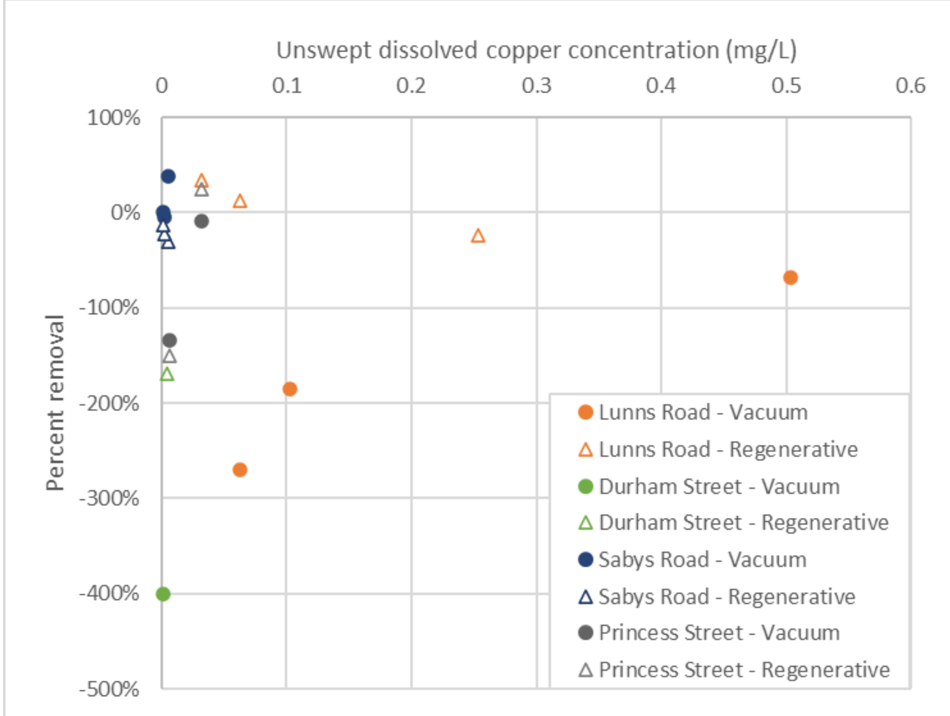
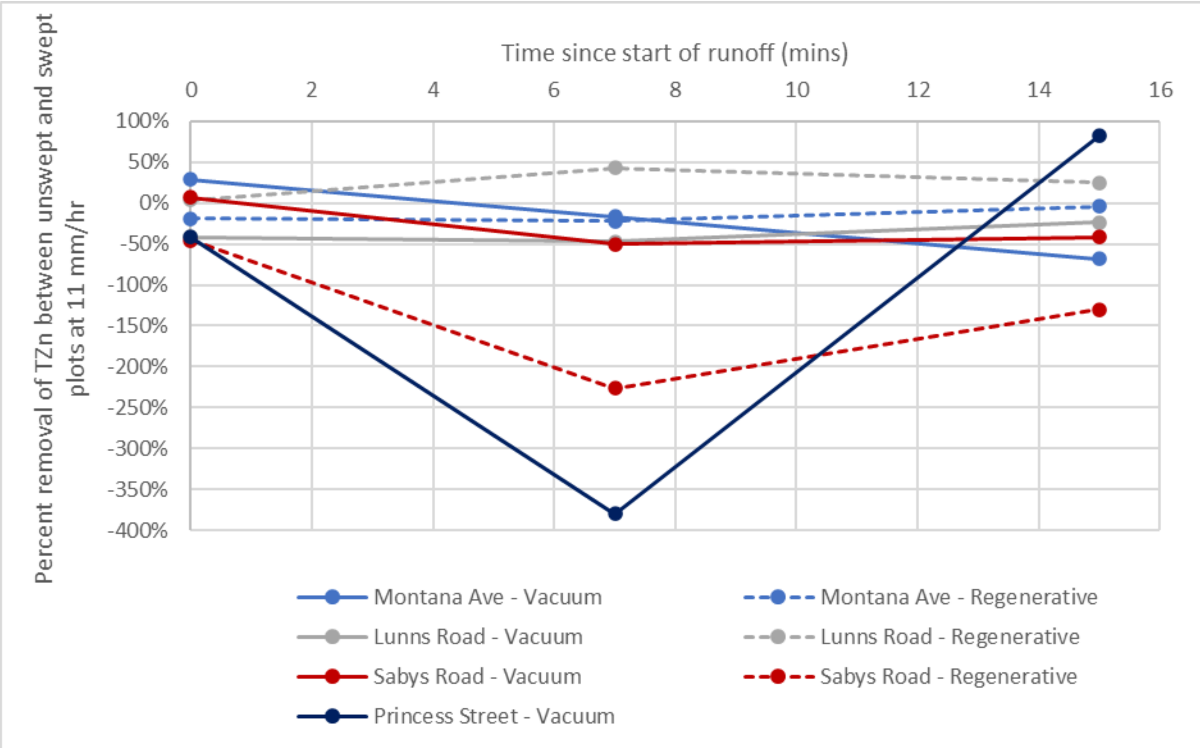
Percent removal against unswept total and dissolved copper concentrations



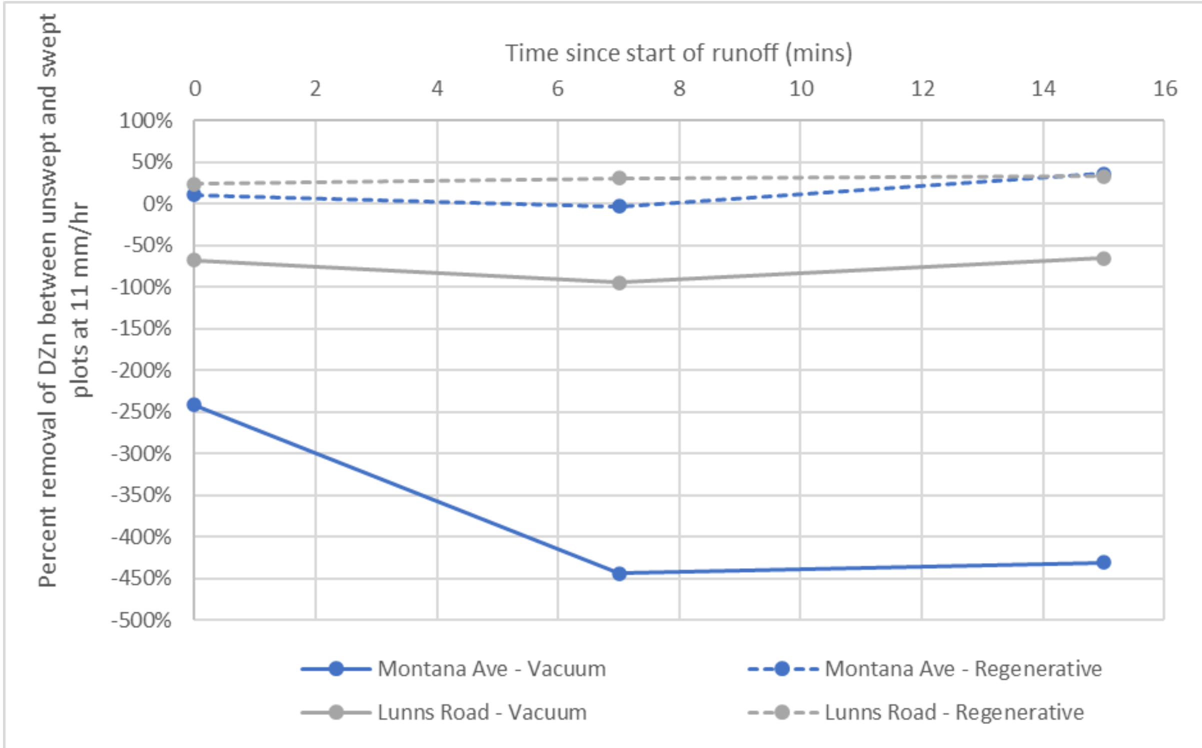


Total Zinc



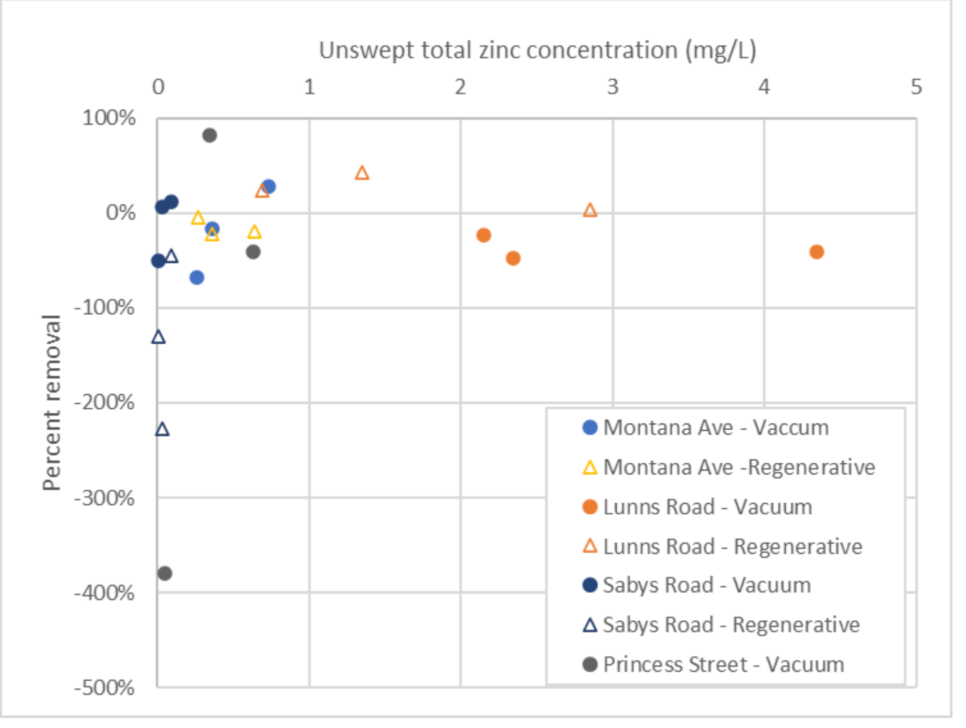
Note: Durham Street vacuum and regenerative and Princess Street regenerative performance not shown as baseline total zinc concentration > unswept and swept runoff concentrations

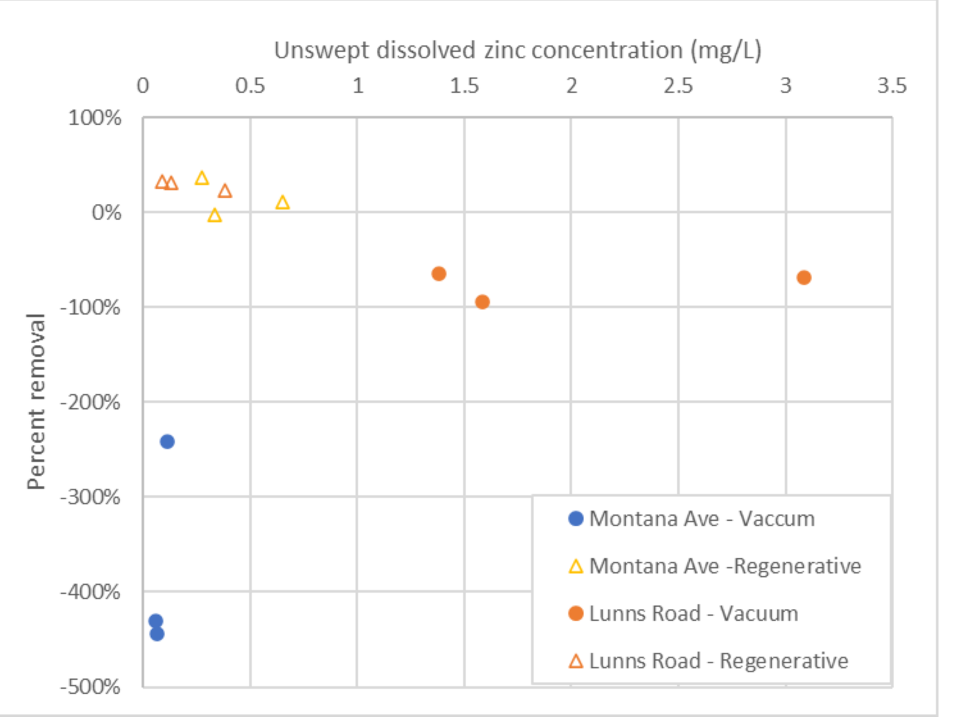
Dissolved Zinc



Note: Durham Street, Sabys Road and Princess Street vacuum and regenerative performance not shown as baseline dissolved zinc concentration > unswept and swept runoff concentrations

Percent removal against unswept total and dissolved zinc concentrations





Appendix D Street sweeping performance data from field trials

Table D1: TSS data

Site	Time since start of runoff (mins)[1]	Adjusted TSS concentrations at 11 mm/hr				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Montana Ave	0	635.8	195.8	76.9	402.9	**69%**	-424%
	7	405.8	135.8	46.9	202.9	**67%**	-333%
	15	305.8	105.8	42.9	162.9	**65%**	-280%
Lunns Road	0	358.0	358.0	1195.4	695.4	0%	**42%**
	7	278.0	208.0	725.4	345.4	**25%**	**52%**
	15	158.0	178.0	285.4	235.4	-13%	**18%**
Durham Street	0	69.9	318.9	69.7	138.7	-356%	-99%
	7	41.9	118.9	41.7	67.7	-184%	-62%
	15	33.9	82.9	33.7	62.7	-145%	-86%
Sabys Road	0	119.0	159.0	119.0	579.0	-34%	-387%
	7	52.0	119.0	52.0	219.0	-129%	-321%
	15	40.0	96.0	40.0	189.0	-140%	-373%
Princess Street	0	177.7	517.7	177.7	79.7	-191%	**55%**
	7	62.7	237.7	62.7	48.7	-279%	**22%**
	15	157.7	167.7	157.7	36.7	-6%	**77%**

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

Table D2: Total copper data

Site	Time since start of runoff (mins)[1]	Adjusted total copper concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Montana Ave	0	0.043	nd	nd	nd	nd	nd
	7	0.003	nd	nd	nd	nd	nd
	15	nd	nd	nd	nd	nd	nd

Site	Time since start of runoff (mins)[1]	Adjusted total copper concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Lunns Road	0	1.63	1.63	3.057	2.657	0%	**13%**
	7	0.64	0.78	1.957	0.887	-22%	**55%**
	15	0.53	0.68	1.157	0.687	-28%	**41%**
Durham Street	0	0.0044	0.0284	0.01	0.025	-545%	-150%
	7	0.0014	0.0124	0.007	0.009	-786%	-29%
	15	nd	0.0014	0.0046	0.009	nd	-96%
Sabys Road	0	0.0099	0.0089	0.0099	0.0239	**10%**	-141%
	7	0.0034	0.0049	0.0034	0.0189	-44%	-456%
	15	0.002	0.004	0.002	0.0079	-100%	-295%
Princess Street	0	0.14	0.2	0.14	0.058	-43%	**59%**
	7	0.022	0.11	0.022	0.054	-400%	-145%
	15	0.1	0.09	0.1	0.034	**10%**	**66%**

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

[2] nd – indicates no data available as feed water concentrations exceeded the sample concentrations

Table D3: Dissolved copper data

Site	Time since start of runoff (mins)[1]	Adjusted dissolved copper concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Montana Ave	0	nd	nd	0.088	0.078	nd	**11%**
	7	nd	nd	0.057	0.058	nd	-2%
	15	nd	nd	0.049	0.036	nd	**27%**
Lunns Road	0	0.503	0.843	0.253	0.313	-68%	-24%
	7	0.103	0.293	0.063	0.055	-184%	**13%**
	15	0.063	0.233	0.032	0.021	-270%	**34%**
Durham Street	0	0.0007	0.0035	0.0039	0.0105	-400%	-169%
	7	nd	nd	nd	0	nd	nd
	15	nd	nd	nd	0.0017	nd	nd

Site	Time since start of runoff (mins)[1]	Adjusted dissolved copper concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Sabys Road	0	0.005	0.0031	0.005	0.0065	**38%**	-30%
	7	0.0022	0.0023	0.0022	0.0027	-5%	-23%
	15	0.0015	0.0015	0.0015	0.0017	0%	-13%
Princess Street	0	0.032	0.035	0.032	0.024	-9%	**25%**
	7	0.006	0.014	0.006	0.015	-133%	-150%
	15	0.002	0.01	0.002	0.016	-400%	-700%

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

[2] nd – indicates no data available as feed water concentrations exceeded the sample concentrations

Table D4: Total zinc data

Site	Time since start of runoff (mins)[1]	Adjusted total zinc concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Montana Ave	0	0.733	0.523	0.639	0.759	**29%**	-19%
	7	0.363	0.423	0.359	0.439	-17%	-22%
	15	0.263	0.443	0.269	0.279	-68%	-4%
Lunns Road	0	4.348	6.148	2.85	2.75	-41%	**4%**
	7	2.348	3.448	1.35	0.77	-47%	**43%**
	15	2.148	2.648	0.69	0.52	-23%	**25%**
Durham Street	0	0.086	0.316	nd	0.1	-267%	nd
	7	nd	nd	nd	nd	nd	nd
	15	nd	nd	nd	nd	nd	nd
Sabys Road	0	0.088	0.078	0.088	0.128	**11%**	-45%
	7	0.03	0.028	0.03	0.098	**7%**	-227%
	15	0.01	0.015	0.01	0.023	-50%	-130%
Princess Street	0	0.63	0.89	0.63	0.11	-41%	**83%**
	7	0.05	0.24	0.05	nd	-380%	nd
	15	0.34	0.06	0.34	nd	**82%**	nd

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

[2] nd – indicates no data available as feed water concentrations exceeded the sample concentrations

Table D5: Dissolved zinc data

Site	Time since start of runoff (mins)[1]	Adjusted dissolved zinc concentrations at 11 mm/hr [2]				Percent removal (%)	
		Unswept Vacuum	Swept Vacuum	Unswept Regen.	Swept Regen.	Vacuum	Regen.
Montana Ave	0	0.1116	0.3816	0.6538	0.5838	-242%	11%
	7	0.0646	0.3516	0.3338	0.3438	-444%	-3%
	15	0.0606	0.3216	0.2738	0.1738	-431%	37%
Lunns Road	0	3.083	5.183	0.38	0.29	-68%	24%
	7	1.583	3.083	0.13	0.09	-95%	31%
	15	1.383	2.283	0.09	0.06	-65%	33%
Durham Street	0	0.017	0.009	nd	nd	47%	nd
	7	0.01	nd	nd	nd	nd	nd
	15	0.007	nd	nd	nd	nd	nd
Sabys Road	0	0.004	nd	0.004	nd	nd	nd
	7	nd	nd	nd	nd	nd	nd
	15	nd	nd	nd	nd	nd	nd
Princess Street	0	0.05	nd	0.05	nd	nd	nd
	7	nd	nd	nd	nd	nd	nd
	15	nd	nd	nd	nd	nd	nd

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

[2] nd – indicates no data available as feed water concentrations exceeded the sample concentrations

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Appendix E Ratio of first flush to later stage concentrations for total suspended solids

Site	Time since start of runoff (mins)[1]	Adjusted TSS concentrations								Ratio of FF concentrations							
		Unswept Vacuum 11 mm/hr	Swept Vacuum 11 mm/hr	Swept Vacuum 22 mm/hr	Swept Vacuum 33 mm/hr	Unswept Regen. 11 mm/hr	Swept Regen. 11 mm/hr	Swept Regen. 22 mm/hr	Swept Regen. 33 mm/hr	Unswept Vacuum 11 mm/hr	Swept Vacuum 11 mm/hr	Swept Vacuum 22 mm/hr	Swept Vacuum 33 mm/hr	Unswept Regen. 11 mm/hr	Swept Regen. 11 mm/hr	Swept Regen. 22 mm/hr	Swept Regen. 33 mm/hr
Montana Ave	0	633.5	193.5	503.5	483.5	69.8	395.8	395.8	255.8	100%	100%	100%	100%	100%	100%	100%	100%
	7	403.5	133.5	213.5	283.5	39.8	195.8	195.8	155.8	64%	69%	42%	59%	57%	49%	49%	61%
	15	303.5	103.5	143.5	133.5	35.8	155.8	155.8	95.8	48%	53%	29%	28%	51%	39%	39%	37%
Lunns Road	0	356	356	556	766	1190.8	690.8	610.8	980.8	100%	100%	100%	100%	100%	100%	100%	100%
	7	276	206	216	236	720.8	340.8	270.8	250.8	78%	58%	39%	31%	61%	49%	44%	26%
	15	156	176	266	146	280.8	230.8	110.8	140.8	44%	49%	48%	19%	24%	33%	18%	14%
Durham Street	0	68.8	317.8	137.8	187.8	68.6	137.4	227.4	267.4	100%	100%	100%	100%	100%	100%	100%	100%
	7	40.8	117.8		107.8	40.6	66.4	92.4	85.4	59%	37%		57%	59%	48%	41%	32%
	15	32.8	81.8		67.8	32.6	61.4	68.4	63.4	48%	26%		36%	48%	45%	30%	24%
Sabys Road	0	118	158	308	568	118	578	578	998	100%	100%	100%	100%	100%	100%	100%	100%
	7	51	118	108	138	51	218	318	348	43%	75%	35%	24%	43%	38%	55%	35%
	15	39	95	95	92	39	188	168	208	33%	60%	31%	16%	33%	33%	29%	21%
Princess Street	0	175.4	515.4	595.4	745.4	175.4	77.4	135.4	285.4	100%	100%	100%	100%	100%	100%	100%	100%
	7	60.4	235.4	185.4	185.4	60.4	46.4	45.4	85.4	34%	46%	31%	25%	34%	60%	34%	30%
	15	155.4	165.4	115.4	125.4	155.4	34.4	37.4	70.4	89%	32%	19%	17%	89%	44%	28%	25%

[1] For earlier trials where more frequent sampling was undertaken the t=7 and t=15 values have been taken from the nearest timepoint.

Appendix F International and national road runoff quality data sources

Reference	Location	Road surface type	Source	Data Type	Pollutants
Driscoll et al. (1990)	International	Urban road	Combined sites	EMC	TSS, Cu, Zn
Drapper et al. (2000)	International	Urban road	Combined sites	EMC	TSS
Dean et al. (2005)	International	Highway	Single site	EMC	TSS, Cu
Gnecco et al. (2005)	International	Urban road	Single site	EMC	TSS, Cu, Zn
Han et al. (2006)	International	Highway	Single site	EMC	TSS, Cu, Zn
Göbel et al. (2007)	International	Urban road	Combined sites	EMC	TSS, Cu, Zn
Huang et al. (2007)	International	Highway	Single site	EMC	TSS
Kayhanian et al. (2007)	International	Highway	Combined sites	EMC	TSS, Cu, Zn
Selbig and Bannerman (2007)	International	Urban road	Combined sites	EMC	TSS, Cu, Zn
Gan et al. (2008)	International	Urban road	Single site	EMC	TSS, Cu, Zn
Yufen et al. (2008)	International	Urban road	Unspecified	EMC	TSS
Auckland Regional Council (2010)	NZ	Urban road, highway	Unspecified	EMC	TSS, Cu

Reference	Location	Road surface type	Source	Data Type	Pollutants
Saijun et al. (2010)	International	Urban road	Single site	EMC	TSS, Zn
Fassman and Blackbourn (2011)	NZ	Urban road	Single site	EMC	TSS, Cu
Trowsdale and Simcock (2011)	NZ	Urban road	Single site	EMC	TSS, Cu
Berndtsson (2014)	International	Urban road	Single sites	FF	TSS, Cu, Zn
Kim et al. (2014)	International	Highway	Single site	EMC	TSS, Cu, Zn
Wu et al. (2015)	International	Urban road	Combined sites	EMC	TSS
Hilliges et al. (2017)	International	Urban road	Single site	EMC	TSS, Cu, Zn
Ghosh and Maiti (2018)	International	Highway	Combined sites	EMC	Cu, Zn
Robertson et al. (2019)	International	Highway	Combined sites	EMC	TSS
Charters et al. (2020)	NZ	Urban road, highway	Single sites	FF, SS	TSS, Cu, Zn
Charters et al. (2021)	NZ	Urban road	Single sites	FF, SS	TSS, Cu, Zn

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