EVALUATION OF STORMWATER QUALITY ASSOCIATED WITH MILLING OF HMA SURFACES

February 2010

Allison A. MacKay and James Mahoney

JHR 10-322 Project JH 06-9

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16. Abstract

Stormwater quality was examined for roadway runoff collected from milled and unaltered sections of hot milled asphalt roadway. Time series of total suspended solids, and total and dissolved copper, zinc and lead concentrations were examined for two co-located pairs of milled and unaltered roadway sections, one co-located pair of freshly paved and unaltered roadway sections, two milled roadway sections and four replicate observations for an unaltered roadway section. Comparison of event mean concentrations between milled and unaltered roadway sections showed runoff from milled sections to have more suspended solids and higher lead concentrations, but no difference in copper and zinc concentrations from unaltered roadway runoff. Generally, the flushing of materials from the road surface at all locations was flow-driven with incomplete wash-off of road way constituents during the short-duration convective storm events. Storm precipitation intensity was not an indicator of stormwater quality. Milled and unaltered road surface runoff water quality parameter concentrations in this study were within the ranges reported previously for unaltered rural and urban roadways. The presence of lead in runoff from milled roadway sections in this study indicated a roadside soil source of the solids resulting from overland flow from adjacent land surfaces onto the roadway. Future milling operations should proceed with consideration not to create new hydraulic connections with adjacent roadside areas that do not drain onto roadway surfaces.

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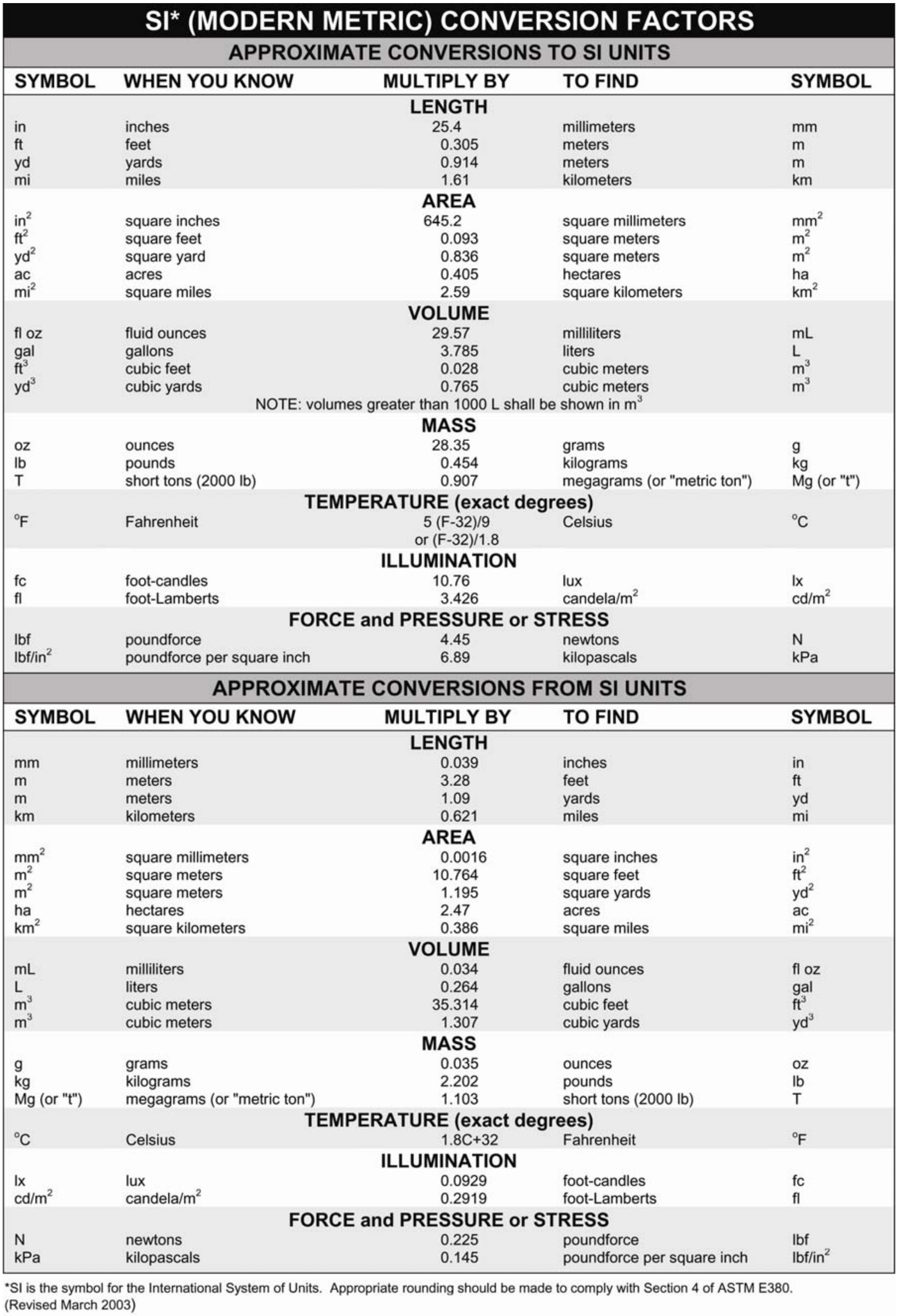

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Glossary of Terms

Dissolved metal concentration: Metal concentration (mass/volume) measured in water sample that has passed through a 0.45 µm pore size filter.

Event mean concentration (EMC): Flow-weighted average concentration (mass/volume) for a given water quality parameter.

First flux: Duration of time during a storm event that the relative cumulative mass of constituent removed from surface in runoff is greater than the relative cumulative volume of runoff generated from the surface.

Flux: Mass of material passing a unit area per unit time (mass/area/time).

Particle-associated metal concentration: Metal concentration (mass/volume) measured in a water sample that can be attributed to particles in the water sample. Particle-associated metal concentration is calculated by difference between the total metal concentration and the dissolved metal concentration.

Runoff: Volume of rain water that flows from the land surface.

Runoff coefficient: Ratio of volume (or intensity (length/time)) of runoff from a certain land area to the volume (or intensity) of precipitation that fell on the same land area.

Total metal concentration: Metal concentration (mass/volume) measured in water sample.

Total suspended solids: Mass of solids retained on a glass fiber filter (pore size ~ 1µm) per unit volume filtered (mass/volume).

Symbols
A (m^2) – road surface area
EMC (mass/volume) – event mean concentration
C (mass/volume) – stormwater constituent concentration
Cu_{diss} (µg/L) – dissolved copper concentration
Cu_{TOT} (µg/L) – total copper concentration
J (mass/m^2/min) – constituent mass flux from roadway surface
M(t) (mass) – cumulative mass of contaminant in stormwater from start of storm event
M_{TOT} (mass) – total mass of contaminant in stormwater at the end of the storm event
P_{avg} (mm/h) – time-averaged precipitation intensity
Pb_{diss} (µg/L) – dissolved lead concentration
Pb_{TOT} (µg/L) – total lead concentration
Q (m^3/h) – runoff volumetric flow rate
R_{avg} (mm/h) – time-averaged runoff velocity
TSS (mg/L) – total suspended solids
t (min) – time
t_{min} (min) – minimum time (to achieve first flush)
V (L) – runoff volume
V(t) (L) – cumulative mass of contaminant in stormwater from start of storm event
V_{TOT} (L) – total mass of contaminant in stormwater at the end of the storm event
v (mm/h) – runoff velocity
v_{avg} (mm/h) – time-averaged runoff velocity
Zn_{diss} (µg/L) – dissolved zinc concentration
Zn_{TOT}(µg/L) – total zinc concentration

Evaluation of Stormwater Quality Associated with Milling of HMA Surfaces

1. Introduction

1.1. Problem Statement

The common practice of milling old pavement from roadways prior to placing a new wearing surface has the potential to increase contaminant loads released from roadway surfaces during rain events. It is commonly recognized that runoff from undisturbed roadway surfaces constitute an important non-point source of contaminants to surface waters in the US (US EPA 1995). Materials on the roadway surface that are deposited from the atmosphere, vehicle emissions and vehicle component (e.g. brakes) and tire wear are washed from the surface by precipitation and suspended or dissolved in the stormwater (FHWA 1999). Typical stormwater constituents of concern include suspended solids that may clog receiving water bodies and heavy metals that may be toxic to aquatic organisms (US EPA 1995). Other contaminants may include nutrients and oil and grease (FHWA 1999). The extent to which these roadway contaminants may contribute to stormwater quality from milled roadway surfaces is unknown. Possible milled surface stormwater quality impacts could include an increased suspended solids load resulting from fine particles generated during milling. Anecdotal reports suggest oily sheens on waterways around milled surfaces that may result from fine asphalt particles from the road surface. Obviously, any generation of runoff from the milled surface requires that a rainfall event occur prior to placement of the new pavement surface, but this occurrence may be high given that a several-day to week interval can pass between pavement removal and placement of a new wearing surface. Thus, to assess whether stormwater best management practices (BMPs) should be integrated into pavement milling activities, and to provide insight to develop such BMPs, if required, there is an urgent need to characterize the release of roadway-derived contaminants from milled pavement surfaces.

1.2. Goals and Objectives

The objective of the proposed research was to characterize differences in water quality parameters between stormwater runoff from milled roadway surfaces and unaltered roadway surfaces.

The objective was achieved by completing the following tasks:

1. Collecting stormwater samples from milled and unaltered sections of roadway, including three co-located pairs of disturbed and unaltered sections of the same roadway.
2. Analyzing time course sample sets from each location for standard stormwater quality parameters, including total suspended solids, and total and dissolved copper, zinc and lead.
3. Determining whether significant differences in stormwater quality parameter measures were observed between milled and unaltered roadway surfaces and to identify, if possible, contaminant mobilization process from the roadway surface.

1.3. Scope

The objective of this research was to collect stormwater samples for comparison of water quality differences between milled and unaltered roadway surface runoff. The scope of the sample collection was limited to stormwater diverted from roadway surfaces through asphalt gutters. Such a stormwater flow conveyance design enabled the use of a mobile and temporary sample collection apparatus in this study. It is common, in routine stormwater quality monitoring, to collect stormwater samples by deploying sample collection apparatus in catch basins. In the case of milled road surfaces, the interim road grade will be depressed by up to ten centimeters below the top of catch basin grates. Roadway sections with such catch basin stormwater conveyance systems would require an extreme precipitation event to generate sufficient water volume to overtop the catch basin while the milled surface is exposed. Thus, while the results of this study provide representative measures of stormwater quality parameters for runoff from milled roadway surfaces, this study does not address the relative occurrence, or volume, of stormwater flow that is generated from milled surfaces.

Water quality parameters were limited to total suspended solids and heavy metals (copper, zinc, lead) to obtain high temporal resolution data for each storm event within the allocated budget. Thus, in-depth comparisons of suspended solids and heavy metals could be undertaken within and between road treatment types. Heavy metals were examined because of their ubiquitous presence in roadway runoff and their potential toxicity in aquatic systems. Early observations of roadway runoff water quality indicated that nickel and cadmium concentrations were not significant contributors to total metal loads (observations below detection limits). Oil and grease analyses were not undertaken since the budget would not enable sufficient observations to distinguish between milled and untreated surface runoff.

The significance of this research from this project is that the results may be used to:

- identify key water quality differences between stormwater runoff from milled and undisturbed roadway surfaces, and
- enable the evaluation of best stormwater management practices to be targeted to reduce elevated contaminant loads from milled roadway surfaces.

1.4 Report Organization

This final report on JHRAC project 06-9 is organized into five sections:

- **Section 2. State of Current Knowledge.** Typical characteristics of roadway-derived contaminants are reviewed including factors that contribute to the presence of contaminants on roadway surfaces and mobilization during precipitation events. Regulations that apply to the possible adoption of best management practices to minimize stormwater impacts on receiving waters for milling activities are reviewed.
- **Section 3. Methods.** The methodology for collection of stormwater samples from milled and undisturbed roadway sections is described in detail, including analytical methods for quantifying stormwater quality parameters.
- **Section 4. Results.** Time series plots of storm water quality parameter measures are presented for all sampling locations and events. Explanation of derived water quality parameters is provided.

- **Section 5. Stormwater Quality of HMA Surfaces.** Evaluation of differences in water quality parameters between milled and unaltered roadway surfaces is presented. Processes that may mobilize contaminants from roadway surfaces are discussed.
- **Section 6. Conclusions and Recommendations.** General considerations for implementation of best management practices during roadway milling are presented with consideration of the findings from Section 5.

2. State of Current Knowledge

2.1. Characterization of Roadway-Derived Contaminants

Observations of rainwater and snowmelt water from unaltered roadways indicate that heavy metals, suspended solids, bacteria, organic compounds and nutrients can be present (Barrett et al. 1998; Drapper et al. 2000). These runoff constituents originate from exhaust byproducts, tire and pavement wear, fluid leakage, wet and dry deposition and roadway maintenance activities (FHWA 1999). Factors that influence the magnitude of contaminant loads deposited on the roadway surface include vehicle traffic density, vehicle fleet composition, duration of the dry period preceding a particular runoff event and land use of the area surrounding the roadway (Sansalone and Buchberger 1997a; Choe et al. 2002). Typically, the contaminant concentrations and total loads in stormwater vary throughout a runoff event. The so-called "first flush" volume, about 20% of the total runoff volume (Deletic 1998), has contaminant concentrations that are at least an order of magnitude greater than the mean concentration of the event (Shinya et al. 2000; Choe et al. 2002). Consequently, spatial and temporal variations give rise to a wide range in roadway runoff water quality parameter values that cannot be predicted using standard transportation metrics or roadway classifications, even for unaltered roadway surfaces.

Despite the variable magnitude of contaminant loads during runoff events, the distribution of potentially harmful contaminants among dissolved and particulate phases in roadway runoff exhibit some consistencies among studies. Copper, zinc and lead tend to be particle-associated with greater concentrations associated with smaller particle sizes (Colandini et al. 1995; Sansalone and Buchberger 1997b). Cadmium and nickel tend to be dissolved in runoff water, or may be associated with fine particles that pass through the filters used to separate the particulate fraction (Sansalone and Buchberger 1997b; Shinya et al. 2000). Although these trends have been observed in multiple studies, it has not been possible to develop predictive correlations between dissolved or particulate contaminant concentrations and bulk water quality parameters (*e.g.*, total suspended solids) because of the variable nature of contaminant deposition patterns on roadways.

2.2. Pavement Milling Operations

The milling of old hot-mixed asphalt (HMA) pavement surfaces prior to the placement of new HMA pavements has become a common practice throughout Connecticut. Milling is implemented to remove many of the surface distresses of the old pavement that would affect the service life of the new pavement overlay, were they not removed. Milling also helps to maintain clearances under structures and to maintain the curb reveal in areas where raising the pavement height would be problematic. In many instances, the milling of roadways is performed well in advance of the paving operation. Such timing may result in milled pavement surfaces being exposed for periods of time ranging from a few days to a few weeks, during which interval a precipitation event may occur.

Pavement milling operations could be anticipated to contribute in several ways to differences in contaminant loads flushed from the road surface during runoff events, as compared to undisturbed roadway surfaces. First, the milling operation itself may produce fine solids that remain on the roadway surface, even after surface-sweeping has been completed. The concentration of suspended solids in stormwater from the milled surface may show an increase compared to the undisturbed roadway surface; however, the concentrations of associated toxic contaminants could be lower since the source of particles from milling operations is the grinding of asphalt aggregates, rather than vehicle brake and engine wear, the primary sources of heavy metal-containing particles on roadway surfaces (FHWA 1999). Anecdotal accounts of oil slicks on milled roadway surfaces suggest that decomposition of the asphalt binder in the pavement may occur, perhaps as a result of thermal degradation during the grinding process, giving rise to increased oil and grease and PAH concentrations in milled roadway runoff. Alternatively, increased tire wear resulting from the rough texture of milled pavement may increase the contribution of contaminants from vehicle tire sources on milled surfaces, relative to other vehicle sources of roadway contaminants. The actual scenario for roadway runoff from milled surfaces will also depend upon the combined effects of precipitation intensity and duration and alterations to the stormwater conveyance pathways resulting from milling activities.

2.3. Regulation of Roadway-Derived Contaminants

In response to the recognized importance of roadway surfaces as non-point sources of contaminants to surface waters in the US, the National Pollution Discharge Elimination System (NPDES) was expanded to include stormwater discharges (US EPA 2000) . The adoption of the so-called “Phase II” NPDES requirements in 2004 under the Connecticut General Permit for the Discharge of Stormwater sets requirements that apply to small Municipal Separate Storm Sewer Systems (MS4) (CT DEP 2004). An MS4 is defined under the federal Clean Water Act as a “conveyance or system of conveyance (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, man-made channels, or storm drains) ... designed or used for collecting or conveying storm water” (US EPA 2000) . The CT General Permit applies to MS4s owned or operated by state and municipal agencies and includes stormwater collection systems for state roadways located in, or on the periphery, of 130 Connecticut towns and cities (CT DEP 2004). The General Permit requirements set out an annual schedule of stormwater monitoring for a specified list of water quality parameters, including pH, oil and grease, measures of suspended solids and several nutrients. In addition to regular monitoring from outfalls in the MS4, the MS4 operator is required to develop a stormwater management plan that defines appropriate best management practices (BMPs) for improving stormwater quality and reducing stormwater quantity conveyed by the system (CT DEP 2004).

2.4. HMA Best Management Practices

The Phase II NPDES requirements have the greatest potential to impact roadway resurfacing activities through implementation of best management practices (BMPs) to control roadway- derived contaminants from pavement milling operations. The option of removing milling from the “toolbox” of pavement treatment options is not feasible because of the benefits provided in extending the service life of the new pavement, as well as maintaining roadway clearances with overhead structures. Thus, incorporation of additional BMPs (e.g. roadway surface sweeping is already conducted to minimize pavement particle residuals) into milling practices will be less costly and will result in more effective achievement of the environmental management goals. Detailed characterization of the water quality issues associated with pavement milling is required to provide the foundation to develop robust BMPs for these operations, if needed. In the case of roadway runoff from unaltered pavement surfaces, detailed water quality parameter characterization identified the need to decrease concentrations of fine particulate and dissolved metal contaminants and has spurred the development of passive treatment technologies such as sorptive infiltration trenches (Sansalone and Buchberger 1995) and filters (Center for Stormwater Technology Evaluation and Verification 2008) for application in locations where sensitive ecosystems may be heavily impacted by stormwater runoff.

3. Materials and Methods

3.1. Sample Collection

3.1.1. Sampling Apparatus

Roadway runoff was collected from the sample locations with an apparatus design that utilized asphalt curb cut-outs that divert flow from the road surface to ditches or other surface features (Figure 1). This design satisfied the requirement for a sampling collection system that could be deployed on short notice to address variableness in the seasonal schedule of milling operations that can arise from weather cancellations and equipment/material availability. Conventional catch basin sampling is not a viable option for milled roadway surfaces because milling lowers the roadway surface below grade for flow to overtop a storm drain.

Figure 1. Sample collection apparatus. Apparatus was deployed in an asphalt stormwater conveyance gutter (1) to await initiation after 60 mm/h precipitation intensity detected by a tipping bucket rain gauge (2). Stormwater flow was measured with an H-flume equipped with a bubble flow meter (3). Flow exiting the flume via a dump cup (4) was sampled using a 12-position automated sampler contained within a secure box (5).

The stormwater sample collection apparatus consisted of three principle components (Fig. 1). First, a tipping bucket rain gauge (ISCO 674, Teledyne ISCO, Lincoln, NE) was used to trigger the sampling system after recording a 60 mm/h threshold of precipitation. The rain gauge was used to record precipitation intensity through the duration of storm water sampling. Stormwater flow from the road surface was also recorded through the duration of the sampling event by directing flow from the asphalt cutout through an H-flume equipped with a bubble flow meter (ISCO 730, Teledyne ISCO). A piece of heavy gauge plastic polypropylene sheeting was secured to the asphalt channel using nails and supported with custom cut pieces of high density foam to form a smooth approach from the rounded asphalt channel to the flat-bottomed flume (not shown in Fig. 1). A dump cup was secured to the exit channel of the H-flume. Heavy gauge tubing was immersed to the base of the cup for withdrawal of water samples in to the automated 12-position sampler (ISCO 6700, Teledyne ISCO). The sampler was equipped with glass bottles that were soap-and-water washed, rinsed with high-purity water, acid-washed overnight with 10% nitric acid and rinsed repeatedly with high purity water.

The automated sampler was programmed with a timing schedule that balanced federal stormwater sampling regulations with the weather conditions anticipated in the milling season. NPDES requirements state that a representative storm water sample can be obtained as a grab sample within the first 6 hours of a precipitation event (CT DEP 2004). Ideally, samples would have been collected over the entire first 6 hours (1 per 30 min) of a storm event to provide a time course profile of the stormwater quality measures. Such a profile would enable assessment of the representativeness of a single grab sample collected at any point in the 6-hour period. The timing of the milling season from early summer until early fall was coincident with rainfall patterns in CT characterized by short-duration, high-intensity convective storms. Consequently, the autosampler was programmed to obtain evenly spaced samples over shorter durations, yielding 1 sample per 10 to 15 minutes.

3.1.2. Sample Locations

Roadway runoff was obtained from a total of 12 rainfall events and locations (Tab.1) on rural roads in Connecticut. The initially proposed sample design had included co-located sampling sites on the same roadway surface: One sample apparatus would collect runoff generated from a milled section of roadway and a second collection system would obtain runoff from a section of unaltered roadway that was closely located to, but not influenced by, the milled section of road. Such a matched pair approach would enable separation of milling effects on roadway runoff water quality from other effects such as traffic density, vehicle fleet composition, antecedent dry period, land use. Ultimately, as discussed below (Section 4.1. Sample Collection), replicate observations of an unaltered roadway surface (Rt. 195) were used to provide comparative storm water quality parameter measures for milled surfaces that lacked co-located controls.

Table 1. Sample locations.

Location	Date	Surface Type	Area (m^2)
Rt. 195 – Mansfield 41° 49’ 56”N. 72° 18’ 06”W	09-AUG-2007	Unaltered	1079
	14-APR-2008	Unaltered	1079
	28-APR-2008	Unaltered	1079
	02-MAY-2008	Unaltered	1079
I-84 offramp – Manchester	03-SEPT-2006	Milled	1898
	03-SEPT-2006	Unaltered	866
Rt. 87 – Franklin 41° 34’ 15.02”N. 72° 07’ 58.93”W	27-OCT-2006	Fresh Paved	1081
	27-OCT-2006	Unaltered	506
Rt. 82 – Montville 41° 30’ 7.38”N. 72° 12’ 15.57”W	29-AUG-2006	Milled	549
41° 30’ 7.80”N. 72° 12’ 30.78”W	29-AUG-2006	Unaltered	1161
Rt. 85 – Hebron	15-AUG-2008	Milled	1302
Rt. 149 – Colchester 41° 35’ 25.54”N. 72° 23’ 40.89”W	06-SEPT-2008	Milled	279

3.2. Analytical Methods

3.2.1. Total Suspended Solids

Total suspended solids (mg/L) were determined gravimetrically (Standard Methods 1995). Samples were filtered using pre-tared glass fiber filters (1.2 μm nominal pore size, Fisherbrand, Fisher, Pittsburgh, PA). Filters were placed in a 105°C drying oven for 24 hour, cooled in a dessicator and weighed. The mass of solids was calculated by difference in the filter mass after and before filtering and was divided by the volume of water filtered.

3.2.2. Heavy Metals

Total concentrations of copper, zinc and lead were determined using inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer 3300XL with nitric acid digestion, EPA Method 200.7). All analyses were conducted at the University of Connecticut Center for Environmental Sciences and Engineering following accepted Quality Assurance/Quality Control practices. A 5-point curve was used for instrument calibration. Each set of 12 sample analyses contained a blank sample, a sample of known concentration (standard) and a sample with a known added mass of metal (standard addition). Limits of quantification were 5 μg/L for copper and lead, and 10 μg/L for zinc.

Dissolved metal concentrations were determined by filtering sample aliquots through a 0.45 μm pore size filter (PTFE (polytertrafluoroethylene), Fisherbrand, Fisher) prior to sample preservation. Sample digestion and ICP-OES analyses proceeded as described for total metal concentrations.

4. Results

4.1. Sample Collection

Roadway runoff samples were collected from a total of 12 rainfall events and locations after deploying the sampling system 16 times. Several initial deployments of the sample collection apparatus indicated that convective storms did not always reliably generate precipitation at both the milled and unaltered sections of the same roadway, despite their less than 400 m separation distance. To ensure adequate sample collection from unaltered roadway surfaces, repeat observations were made for storm events at the Rt. 195 sample location (Tab. 1). These replicate Rt. 195 observations also provided a dataset for examination of the range in water quality parameter measures among storm events. The final sample set consisted of 4 replicate storm observations of unaltered roadway surface (Rt. 195), 2 sets of paired milled and unaltered surface samples from the same roadway (I-84, Rt. 82), 1 paired set of paved and unaltered roadway samples from the first storm event following new pavement placement (Rt. 87), and 2 milled roadway sample sets (Rt. 85, Rt. 149) (Tab. 1). For the Rt. 87 pair, only a composite water quality sample was available from the unaltered surface because the sampling hose mis-aligned within the autosampler carousel.

4.2. Data Analysis

Trends in water quality parameters in time and correlations between water quality parameters and/or flow parameters were examined using both raw data and derived parameters (Fig. 2 – 13). For each sample location, 4 to 12 time delimited observations were obtained of precipitation intensity, runoff flowrate, and total suspended solids concentrations. Total and dissolved copper, lead and zinc concentrations were obtained for 10 of the 12 sample sets. Instantaneous runoff flowrates were converted to effective velocities to be consistent with precipitation intensities by normalizing to the roadway area drained:

$$v = \frac{Q}{A} \tag{1}$$

where v (mm/h) is the runoff velocity; Q (m^3/h) is the runoff flowrate measured in the flume, and A (m^2) is the measured drainage area of the roadway surface. Additional time series data were obtained by calculating the instantaneous constituent mass fluxes from the roadway surface:

$$J = \frac{CQ}{A} \tag{2}$$

where J (mass/m^2/min) is the constituent flux, and C (mass/volume) is the concentration of the constituent in the runoff.

Several bulk stormwater parameters were used to compare observations between locations (Tab. 2). Time-averaged precipitation intensity and runoff velocities were calculated for each event and location:

$$v_{avg} = \frac{\sum v\Delta t}{\sum \Delta t} \tag{3}$$

where, for runoff velocity, v_{avg} (mm/h) is the time-averaged value; v (mm/h) is the instantaneous runoff velocity at time, t_n, Δt (h) is time increment between observations t_{n-1} and t_n, and the sums are across all time points. Event mean concentrations were also calculated for each event and location:

$$EMC = \frac{\sum C\Delta V}{\sum \Delta V} \tag{4}$$

where EMC (mass/L) is the event mean concentration, V (L) is the total volume of runoff between t_{n-1} and t_n, and the sums are across all time points.

Table 2. Stormwater quality parameter measures.

Location	**P_{avg}[a] (mm/h)**	**R_{avg}[b] (mm/h)**	**R/P**	**Event Mean Concentration (EMC)**					
				TSS[c] (mg/L)	**Cu_{TOT}[d] (µg/L)**	**Cu_{diss}[e] (µg/L)**	**Zn_{TOT} (µg/L)**	**Zn_{diss} (µg/L)**	**Pb_{TOT}[f] (µg/L)**
Rt. 195 – AUG 2007	6.22	1.48	0.24	21	17	21	31	25	0.2
Rt. 195 – 14-APR-2008	0.51	0.28	0.55	42	-[g]	-	-	-	-
Rt. 195 – 28-APR-2008	1.68	0.6	0.27	7	10	-	19	-	< 5[h]
Rt. 195 – 2-MAY-2008	0.56	0.43	0.22	90	38	-	115	-	6
I-84 Milled	**8.31**[i]	**0.06**	**0.01**	**1479**	**175**	**23**	**386**	**19**	**136**
I-84 Unaltered	3.49	0.73	0.21	13	29	14	38	19	< 5[h]
Rt. 87 Fresh Paved	*1.27*[j]	*3.89*	*2.95*	*62*	-	-	-	-	-
Rt. 87 Unaltered	2.34	2.04	0.87	8	-	-	-	-	-
Rt. 82 Milled	**0.46**	**1.71**	**3.71**	**112**	**27**	**20**	**55**	**23**	**27**
Rt. 82 Unaltered	0.46	0.53	1.16	15	84	56	337	314	< 5[h]
Rt. 85 Milled	**4.57**	**7.32**	**1.60**	**691**	**48**	**11**	**108**	**15**	**123**
Rt. 149 Milled	**8.55**	**9.19**	**1.08**	**703**	**58**	**11**	**132**	**18**	**118**
Flint & Davis 2007 – lowest EMC n = 32 repeat observ.				32	14		80		6
Flint & Davis 2007 – high EMC n = 32 repeat observ.				10,000	740		30,000		2,300

[a] Average instantaneous precipitation; [b] Average instantaneous runoff; [c] Total suspended solids; [d] Subscript 'TOT' indicates total metal concentration; [e] Subscript 'diss' indicates dissolved metal concentration; [f] Dissolved lead concentrations for all samples were below the 5 µg/L detection limit; [g] Dashes (-) indicate measurements were not obtained; [h] Values below detection limit; [i] Bold denotes milled surface locations; [j] Italics denotes fresh paved surface locations.

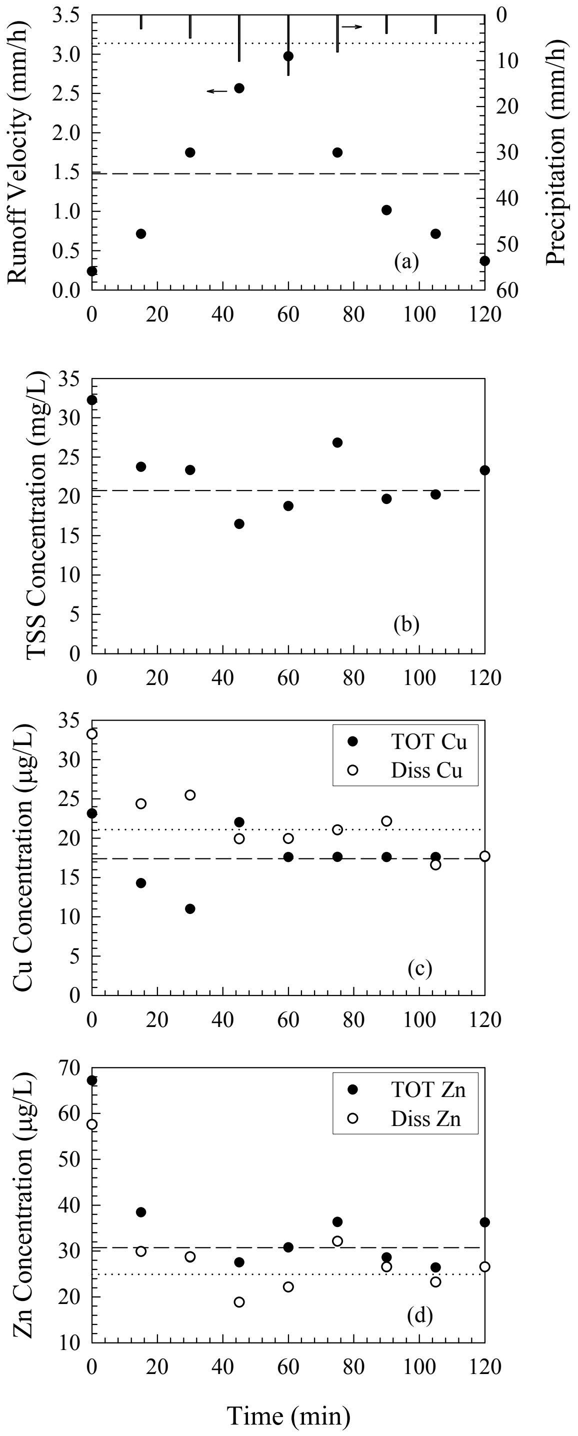

Figure 2. Rt. 195 09-AUG-2007 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total and dissolved copper concentration, and (d) Total and dissolved zinc concentration. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean (---) total or (...) dissolved concentrations.

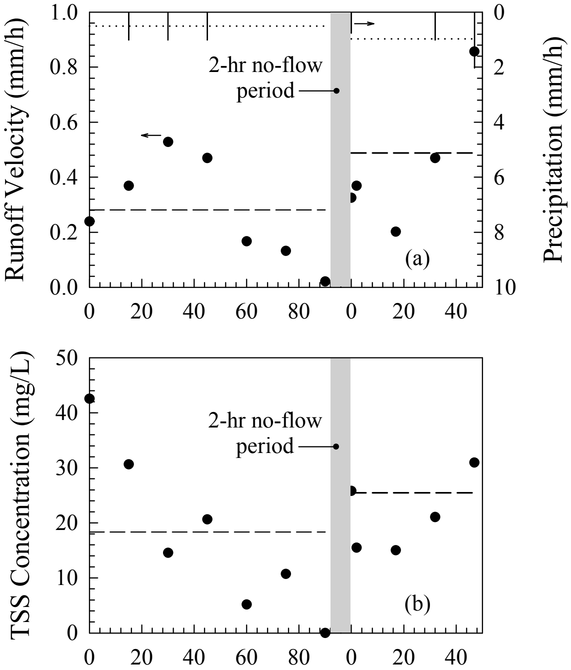

Figure 3. Rt. 195 14-APR-2008 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; and (b) TSS concentration. Metals analyses were not obtained for these samples. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Line in plot (b) indicates the event mean total concentration (---).

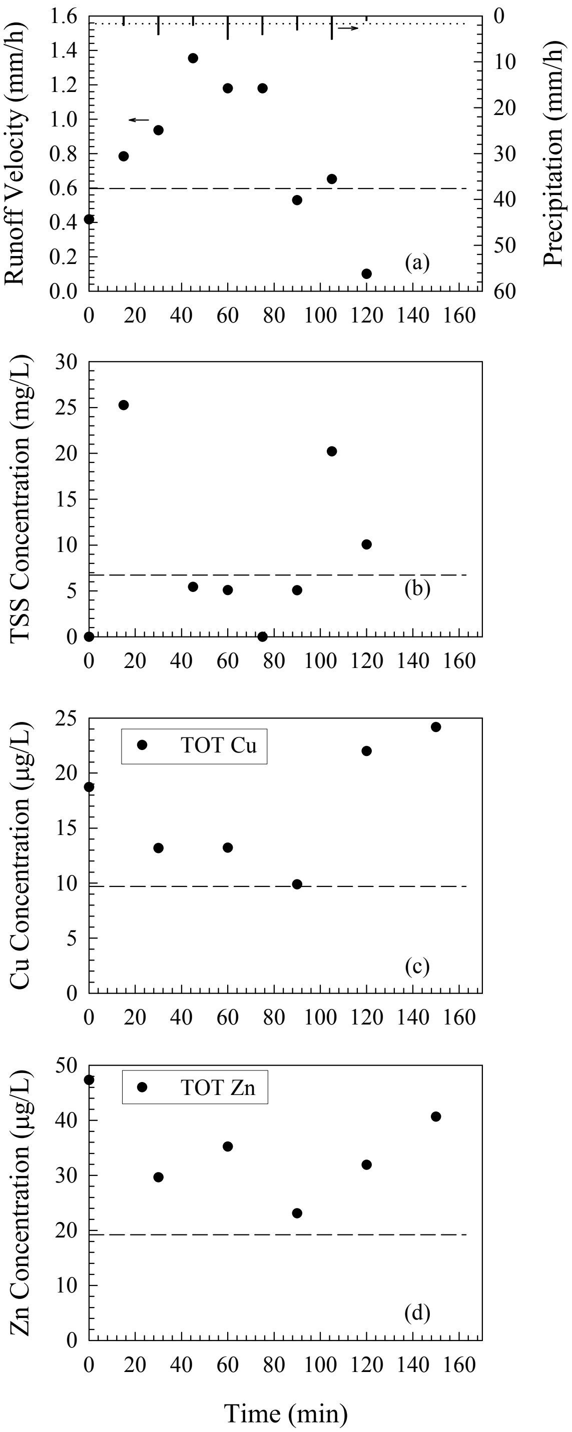

Figure 4. Rt. 195 28-APR-2008 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total copper concentration, and (d) Total zinc concentration. Dissolved metals analyses were not obtained for these samples and total lead concentrations were below the detection limit. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentrations.

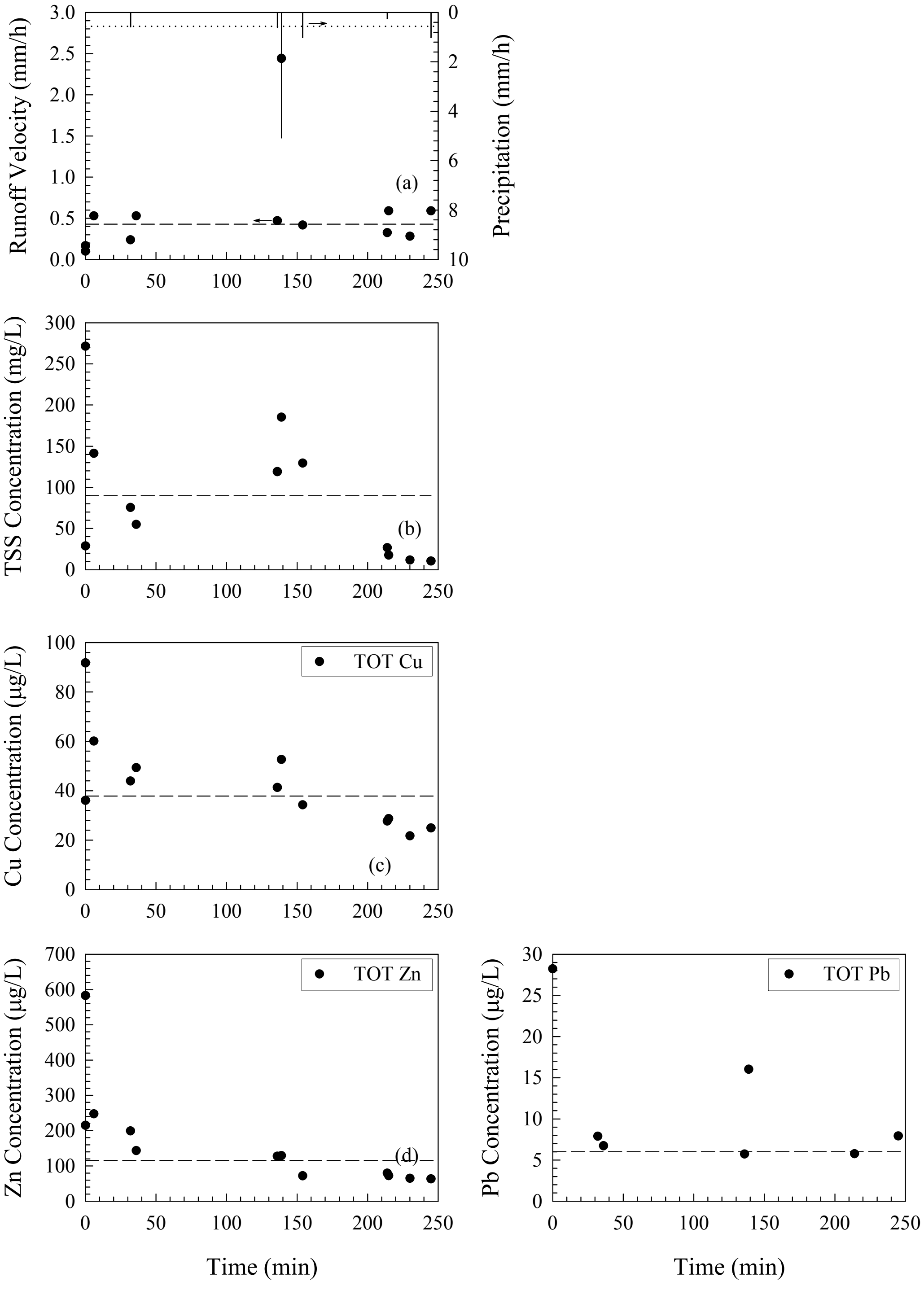

Figure 5. Rt. 195 02-MAY-2008 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total copper concentration; (d) Total zinc concentration, and (e) Total lead concentration. Dissolved metals analyses were not conducted on these samples. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentration.

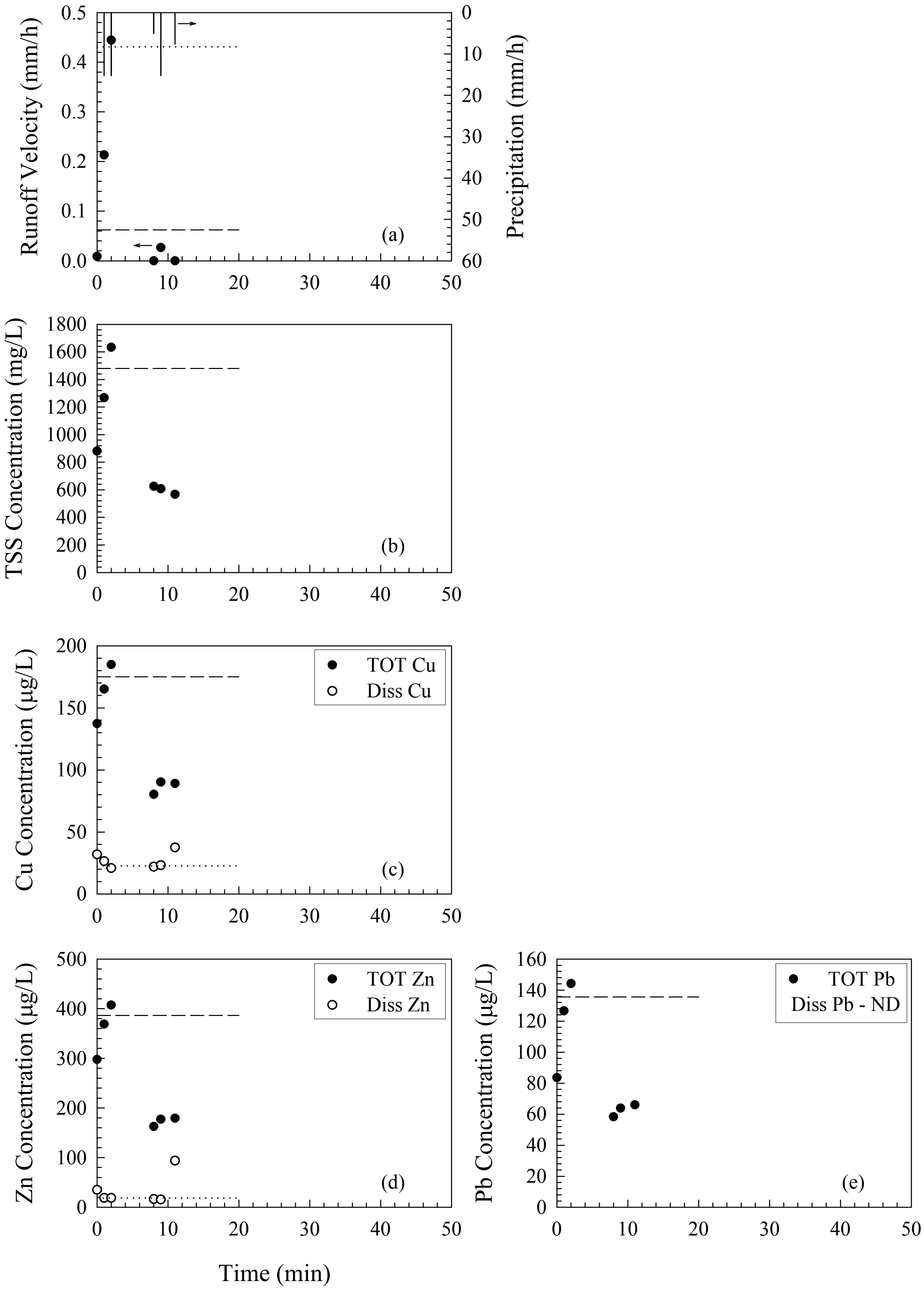

Figure 6. I-84 off ramp 03-SEPT-2006 Milled Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total and dissolved copper concentration; (d) Total and dissolved zinc concentration, and (e) Total lead concentration (dissolved lead concentrations were below the limit of detection). Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentration.

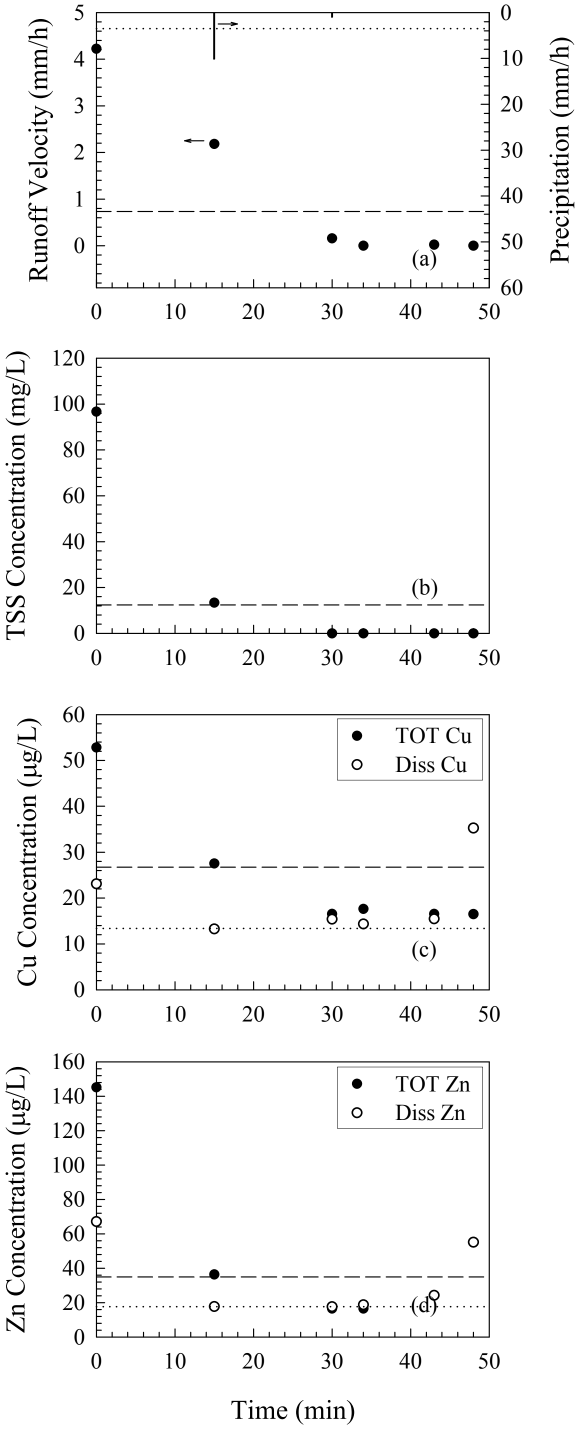

Figure 7. I-84 off ramp 03-SEPT-2006 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total and dissolved copper concentration, and (d) Total and dissolved zinc concentration. Total and dissolved lead concentrations were below the detection limit. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentrations

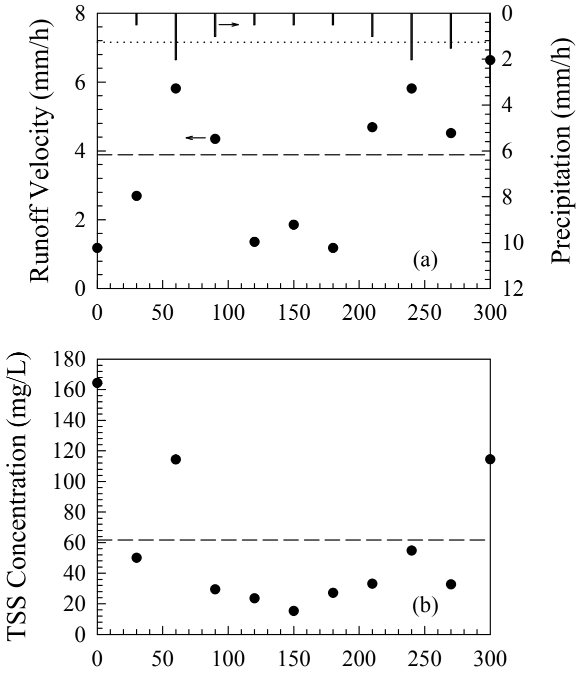

Figure 8. Rt. 87 27-OCT-2006 Freshly Paved Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity, and (b) TSS concentration. Metals analyses were not obtained for these samples. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Line in plot (b) indicates the event mean total (---) concentration.

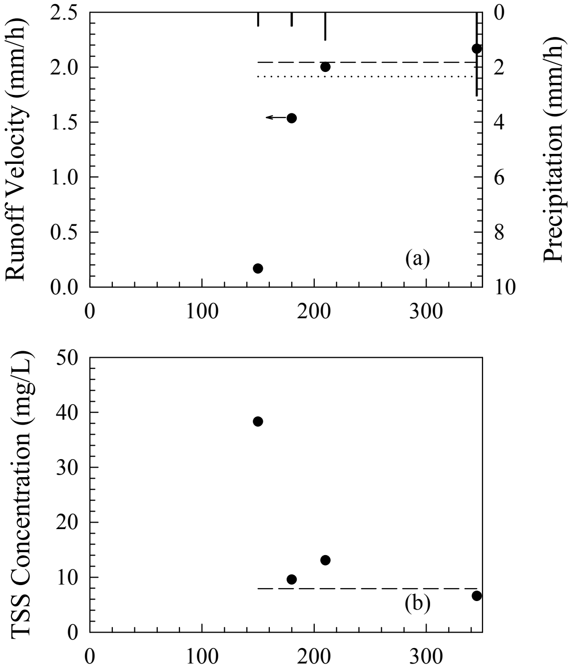

Figure 9. Rt. 87 27-OCT-2006 Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity, and (b) TSS concentration. Metals analyses were not obtained for these samples. Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plot (b) indicate the event mean concentration.

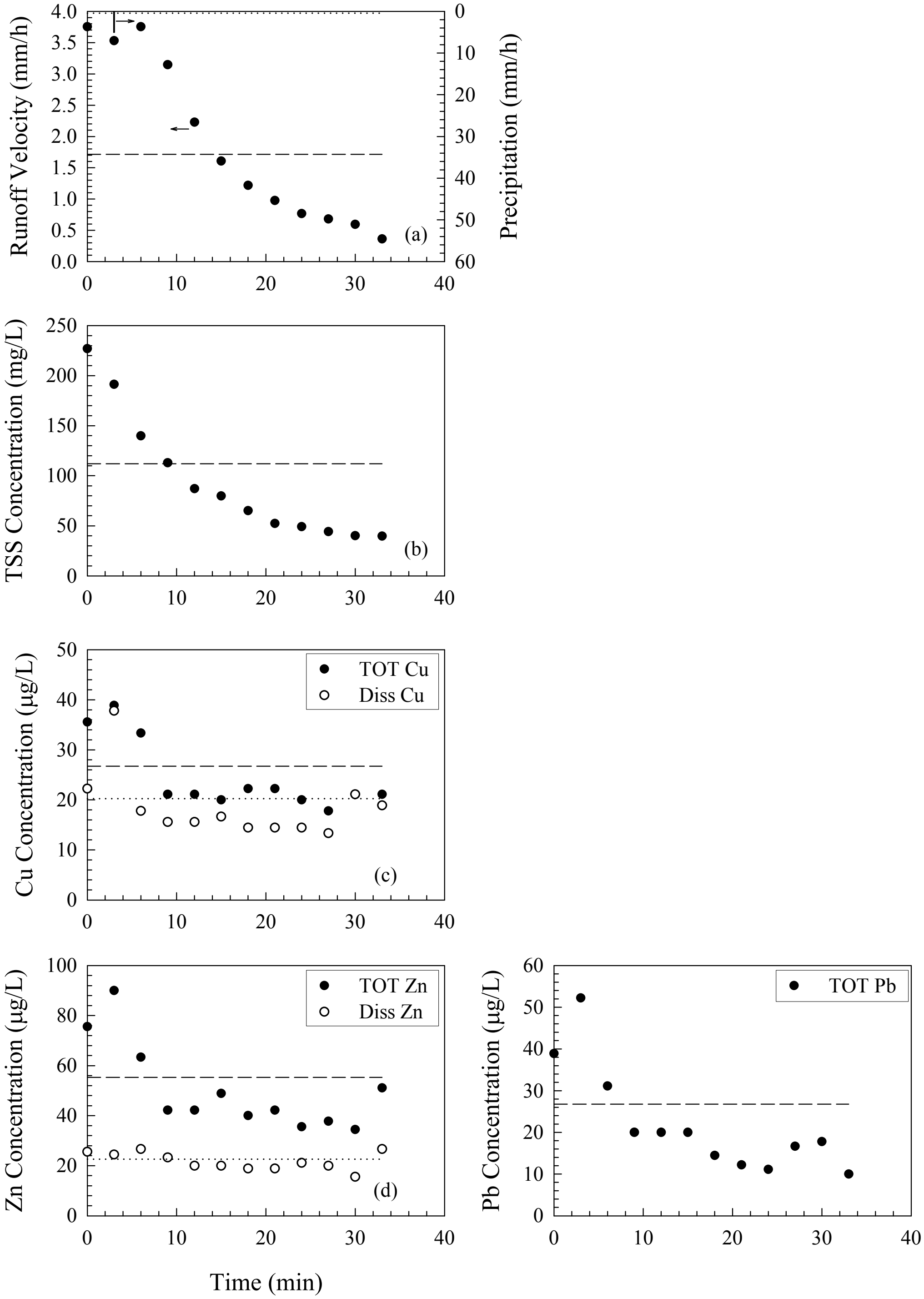

Figure 10. Rt . 82 29-AUG-2006, Milled Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total and dissolved copper concentration; (d) Total and dissolved zinc concentration, and (e) Total lead concentration (dissolved lead concentrations were below the detection limit). Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentrations.

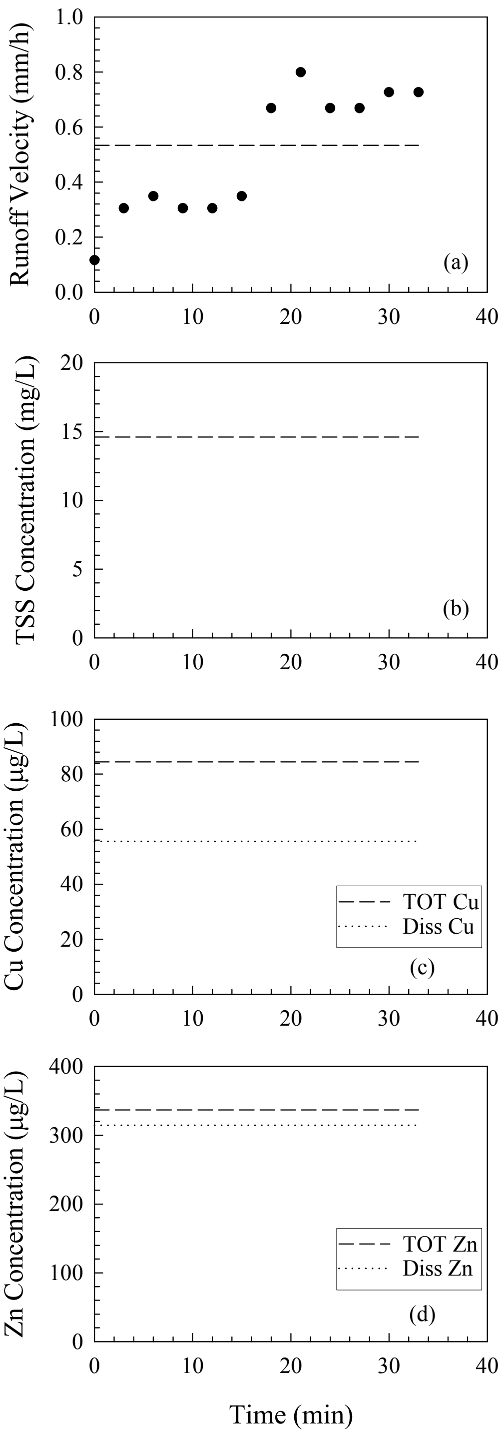

Figure 11. **Rt. 82 29-AUG-2006, Unaltered Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; Results of composite sample: Event mean concentration of: (b) TSS; (c) Total and dissolved copper , and (d) Total and dissolved zinc. Line in plot (a) indicates the average runoff velocity.**

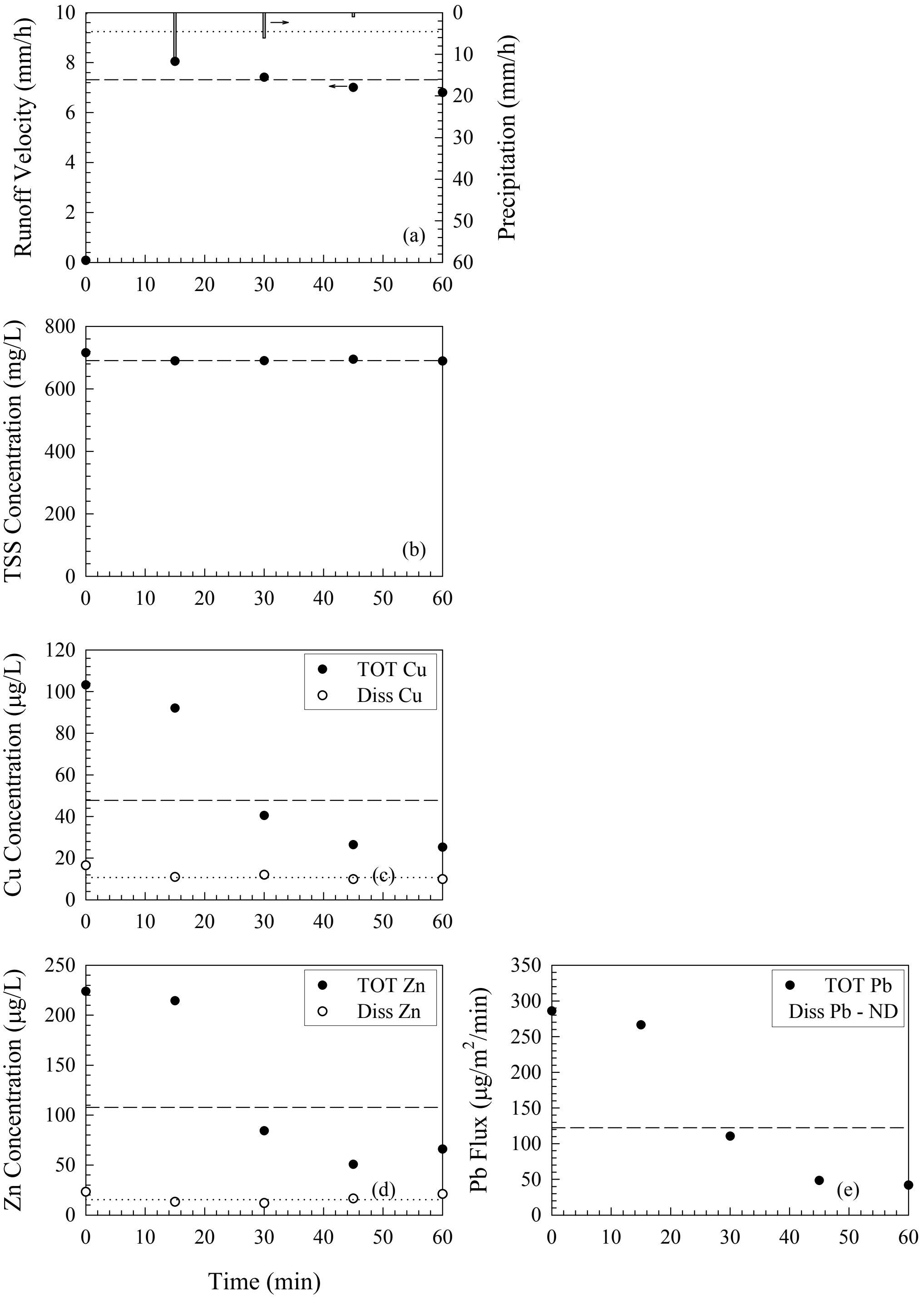

Figure 12. Rt. 85 15-AUG-2008, Milled Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity;(b) TSS concentration; (c) Total and dissolved copper concentration; (d) Total and dissolved zinc concentration, and (e) Total lead concentration (dissolved lead concentrations were below the detection limit). Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean total (---) or dissolved (...) concentrations.

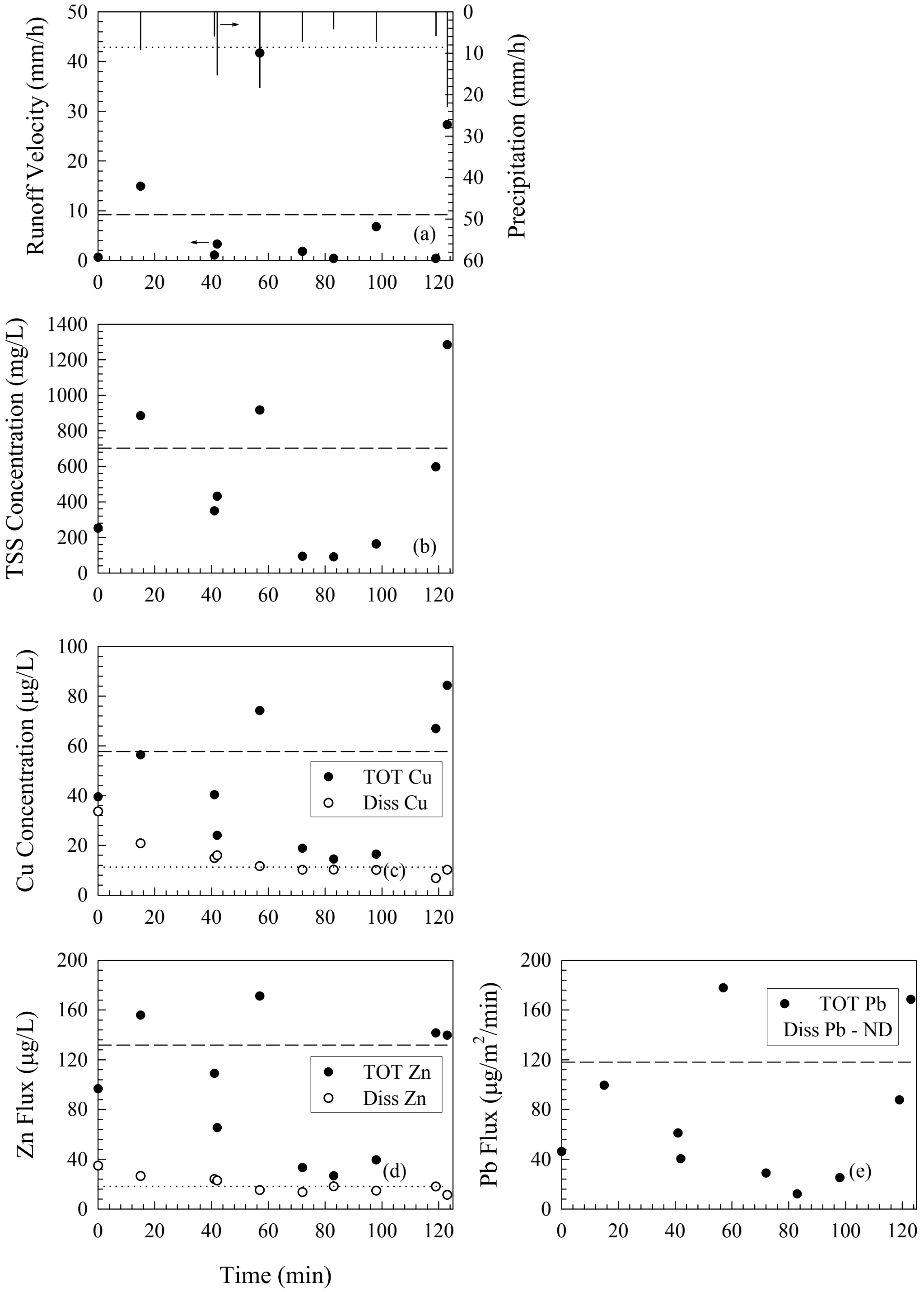

Figure 13. Rt.149 6-SEPT-2008, Milled Surface. Time series of instantaneous: (a) runoff velocity and precipitation intensity; (b) TSS concentration; (c) Total and dissolved copper concentration; (d) Total and dissolved zinc flux, and (e) Total lead concentration (dissolved lead concentrations were below the detection limit). Lines in plot (a) indicate the average runoff (---) and precipitation (...). Lines in plots (b) to (d) indicate the event mean (---) or (...) dissolved concentrations.

5. Stormwater Quality of HMA Surfaces

5.1. Water Quality Characteristics

Similar trends in roadway water quality were observed for all of the sampling locations and events. First, the transport of materials and solutes from roadway surfaces was flow-limited throughout the event duration. Flow-limited stormwater events are characterized by correlated trends in stormwater runoff rates and roadway contaminant concentrations. For example, such a correlation was observed for the sampling location on Rt 149 during a storm event with variable precipitation intensity (Fig. 13): Pulse increases in runoff velocity (Fig. 13(a)) at 15, 57, 98, and 123 minutes after the start of the storm event were reflected in increases in total suspended solids (TSS) (Fig. 13(b)), total copper (Cu_{TOT}) (Fig. 13(c)) and total zinc (Zn_{TOT}) (Fig. 13(d)) and lead (Pb_{TOT}) (Fig. 13(e)) concentrations. The importance of runoff rate contributions to stormwater quality is even more pronounced in comparisons of constituent fluxes from the roadway surface. Even for locations such as Rt. 195 on 09-AUG-2007 that exhibited little variability in water quality parameter concentrations throughout the storm event (Fig. 2), the total suspended solids, copper, and zinc, flux time series (Fig. 14) mirrored the runoff hydrograph (Fig. 2(a)): Constituent fluxes increased monotonically to maximum values at 60 min, followed by monotonic decreases in fluxes to the end of the storm event. Other locations also exhibited similar trends in water quality parameter fluxes, relative to runoff velocities, indicating runoff flow control of the mass of constituents washed from the roadway surface.

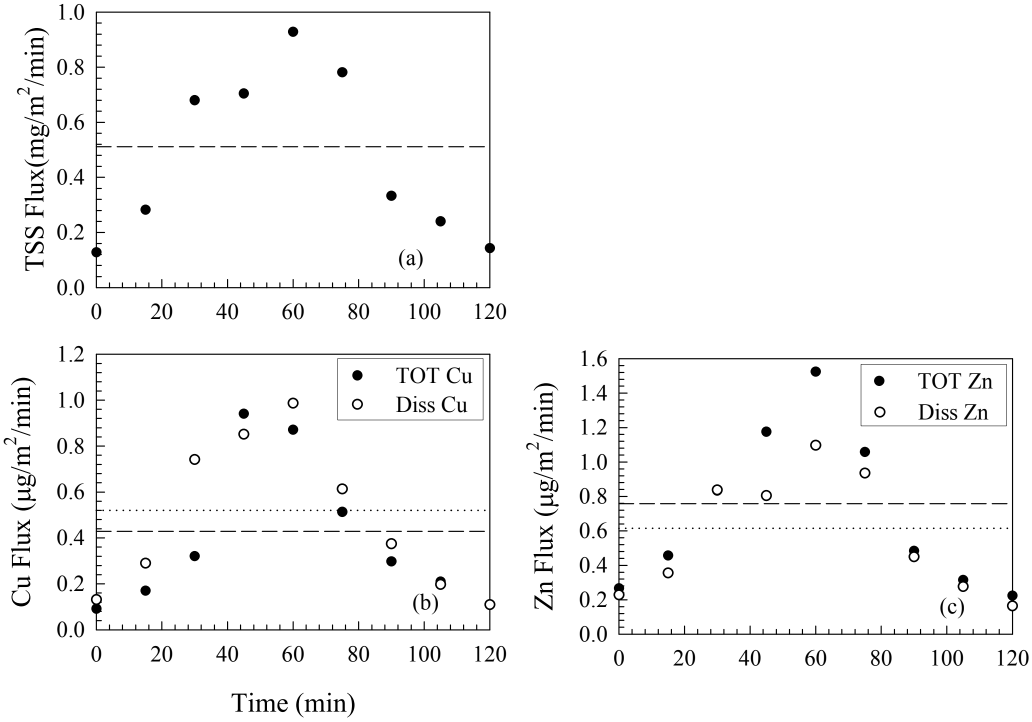

Figure 14. Rt. 195 09-AUG-2007 Unaltered Surface. Time Series of instantaneous fluxes of: (a) total suspended solids; (b) total and dissolved copper, and (c) total and dissolved zinc.

The entire duration of stormwater runoff for all sample locations and events would be characterized as the "first flush". The first flush concept has been introduced to aid in planning stormwater remedial measures with the aim of treating only the most contaminated roadway runoff water (Sansalone and Buchberger 1997a). The first flush has been defined as the duration of time for which a disproportionate fraction of roadway constituent load, relative to runoff volume, is removed from the roadway surface following the initiation of a storm event:

$$t_{\min} \ for \ 1 \geq \frac{M(t)/M_{TOT}}{V(t)/V_{TOT}} \tag{5}$$

where M(t) is the cumulative mass of contaminant at time 't', M_{TOT} is the cumulative total mass of contaminant; V(t) is the cumulative volume of runoff at time 't', and V_{TOT} is the total volume of runoff. Generally, the first flush occurs after approximately 20 percent of the runoff volume has been flushed from the roadway surface (Deletic 1998). However, in our study, the time at which the ratio, Eq. 5, for suspended solids was equal to 1 was coincident with the duration of the sampling event (Fig. 15). The only exception was the storm event on the Rt. 87 freshly paved surface for which a greater proportion of total suspended solids mass was washed off the roadway surface with the first 40% of stormwater volume (Fig. 15, dashed line). The Rt. 87 first flush may have resulted from the storm event occurring less than a week from initiation of the milling project, thereby limiting the reservoir of materials accumulated on the roadway surface by deposition and vehicle wear. In general, no evidence of particle wash off was observed over the short duration of the storm events sampled here.

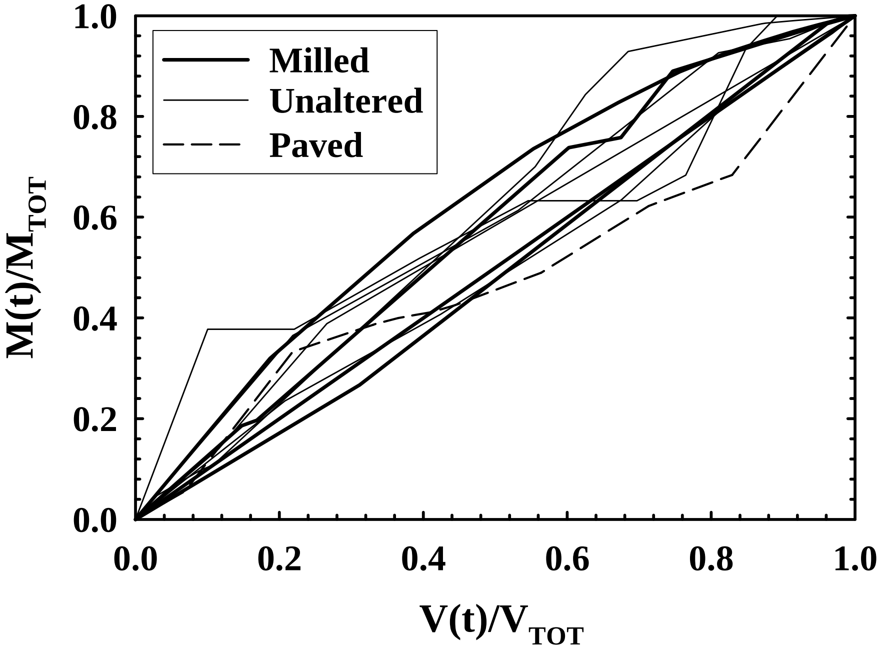

Figure 15. First flush evaluation for total suspended solids from all sample locations. The 1:1 line is omitted for clarity.

Heavy metal concentrations in stormwater were influenced by flow-related pulse inputs of particle-associated species. Dissolved copper and zinc concentrations in stormwater remained approximately constant throughout the duration of the sampling events (Fig. 6(c),(d); Fig. 7(c),(d): Fig. 10(c)(d); Fig. 12(c)(d); Fig. 13(c)(d); open circles). The dissolved concentrations of copper and zinc accounted for the total load of these metals (open circles ≈ closed circles) during periods of time in which total suspended solids concentrations were less than about 50 mg/L (*e.g.*, Fig. 2(c)(d), 0-20 min; Fig. 7(c)(d), 30-50 min). During other times, when total suspended solids values were greater than 50 mg/L at the sampling sites, total copper and zinc concentrations were much greater than the dissolved values, indicating a particle-associated contribution. The contribution of particle-associated metals was proportional to the total suspended solids with larger amounts of particle-associated metals (difference between open and closed circles) observed for times with higher total suspended solids, times also coincident with high runoff velocities (*e.g.*, Fig. 6, 0-10 min; Fig. 10, 0-30 min; Fig. 13, 15, 57, 120 min).

Roadway stormwater quality parameter concentrations observed in this study were within the range of values reported for other roadways (Flint and Davis 2007). Flint and Davis (2007) reviewed highway stormwater quality reports from 14 prior studies. Examination of their findings showed no differences between event mean concentrations of total suspended solids and heavy metals between urban and rural locations. Flint and Davis, themselves, monitored urban stormwater quality during 32 storm events over the course of a year at the same location in Mount Ranier, MD with high frequency sampling during the first hour of the storm event, similar to the sample durations in our study. Event mean concentrations of runoff constituents observed by Flint and Davis bracketed ranges in our study (Tab. 2); however median values from their study were greater than most of our observations. Thus, event mean concentrations of stormwater constituents from milled and unaltered roadway surfaces in Connecticut are typical of those observed elsewhere.

As has been observed at other sites (*e.g.*, Sansalone and Buchberger 1997a), the event mean concentration of water quality parameters from our study events exceeded local surface water protection criteria. For example, event mean concentrations of total copper, zinc and lead (Tab.2) were greater than the chronic freshwater aquatic life criteria of 4.8, 65, and 1.2 μg/L, respectively, for those metals (CT DEP 2002). The CT surface water quality standards do not explicitly indicate limits on total suspended solids; however, solids originating from road maintenance activities that follow best management practices are allowable. The preferred water clarity criteria of turbidity < 5 NTU (~ 5 mg/L suspended solids) would be exceeded with the samples collected in this study; however, solids were coarse and heavy according to visual observations during sample handling. Such coarse, heavy solids would be removed quickly by settling from storm water once more quiescent flow conditions were established, thereby yielding higher water quality.

5.2. Roadway Treatment Effects.

Event mean concentration comparisons indicated no clearly evident trend in water quality in stormwater from the milled surface as compared to unaltered roadway surfaces. In the case of total suspended solids, event mean concentrations in runoff from altered surfaces – I-84, Rt. 82, Rt. 87 – were always greater than co-located control observations (Fig. 16(a)). Of these milled locations, only the I-84 milled surface showed event mean suspended solids concentrations that were also much greater (1479 mg/L) than the range of values obtained for replicate observations at the same location (Rt. 195) (Tab. 2). The event mean concentrations of total suspended solids at the unpaired Rt. 85 and Rt. 149 locations were significantly greater than those observed for the 7 unaltered roadway surfaces (Fig. 16(a)). Although no unaltered roadway sections were co-sampled for Rt. 85 and 149 to confirm whether the total suspended solids event mean concentrations were within a typical range for those highways, the observations summarized in Fig. 16 (a) are suggestive of high total suspended solids associated with exposed milled pavement surfaces during short-duration rain events.

In contrast to total suspended solids, event mean concentrations of total copper and zinc for milled roadway surfaces were generally within the range of values obtained for unaltered surfaces. Given the importance of solid-associated metals to total concentrations (see Section 5.1. Water Quality), sample locations with high suspended solids might be anticipated to have total metal concentrations that were greater than the unaltered roadway samples. Such a relationship was true only for total copper concentrations for the I-84 milled roadway (Fig. 16(b)); however, the I-84 milled surface event mean concentration for total copper (175 μg/L) was only twice the upper range of values (84 μg/L) for unaltered roadway sections. All of the other milled roadway sections (solid bars, Fig 16(b)(c)) had total copper and total zinc event mean concentrations that were within the range observed for the unaltered roadway samples (open bars, Fig. 16(b)(c)). Together, the water quality observations for copper and zinc suggest that roadway milling yields no significant differences in water quality from unaltered roadway surfaces.

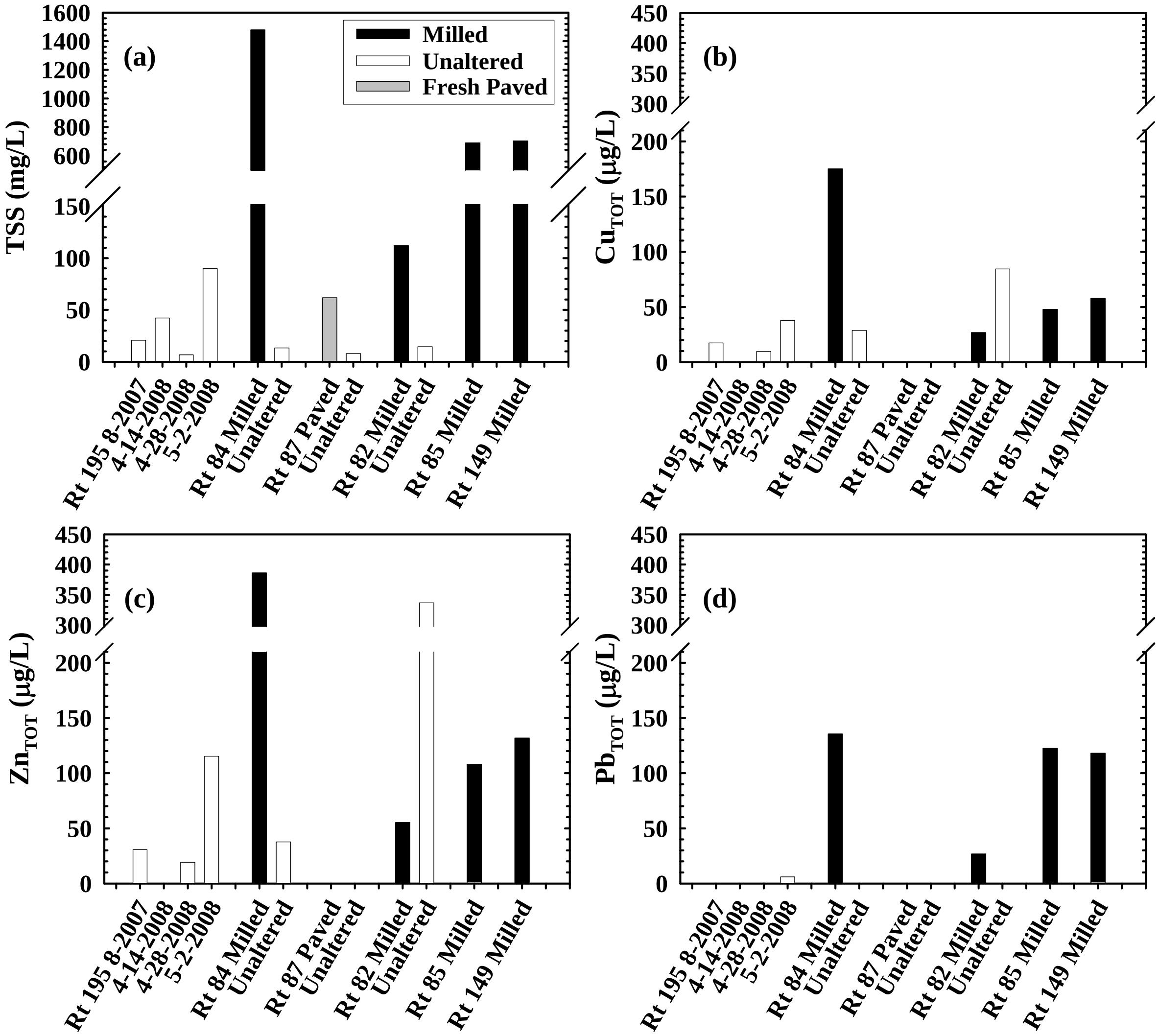

Figure 16. Event mean concentrations of water quality parameters for all locations and events: (a) total suspended solids; (b) total copper; (c) total zinc, and (d) total lead.

Trends in event mean total lead concentrations did not reflect those of the other heavy metals, but rather paralleled those for total suspended solids. Total lead concentrations in the unaltered roadway runoff samples were above the 5 µg/L detection limit only for 7 of 12 samples from Rt. 195 2-MAY-2008 (event mean concentration: 6 µg/L); whereas, total lead was above quantifiable levels for all of the milled roadway runoff samples (Fig. 16(d)). The occurrence of event mean total lead concentrations on the order of 100 mg/L at the I-84, Rt. 85 and Rt. 149 locations is suggestive that milling the surface leads to decreased water quality for the lead concentration parameter over unaltered roadway surfaces.

5.3. Mobilization Processes.

The presence of lead in stormwater samples from the milled roadway locations provides insights into the processes mobilizing contaminants from roadway surfaces. A major source of lead in environmental systems was vehicle emissions of lead additives in gasoline (FHWA 1999). Phase-out of leaded gasoline usage began in the U.S. in the mid-1980s and was completed by 1996 (Federal Register 1996). As a result, the presence of lead in a subset of our stormwater samples likely indicates a legacy source, such as soil from embankments at the side of the roadway that had accumulated lead from pre-1996 vehicle emissions.

Several lines of evidence support roadside soil erosion as the source of lead in the roadway runoff. First, the runoff coefficients for the locations Rt. 82, Rt. 85 and Rt. 149 were all greater than 1 (Tab. 2). Runoff coefficients were calculated as the ratio of time-averaged runoff velocity to time-averaged precipitation intensity. Runoff coefficient values greater than 1 would suggest that the roadway surface area used to convert runoff flow rates to effective velocities (Eq. 1) underestimated the actual drainage area. In such cases, the roadside land area also contributed flow to the surface of the roadway draining to the sample collection system. Collected stormwater samples thus contained an unknown contribution of materials from both the milled surface and the adjacent land area. Visual inspection of solids in the sample jars collected from Rt. 85 and Rt. 149 were consistent with a greater load of particles from the adjacent land area. Solids collected on the filters for total suspended solids quantification were fine, brown-colored solids, as typical of a dispersed soil, whereas visual observation of the road surface following sweeping of a freshly milled road section showed coarser black particles.

Examination of the relative concentrations of copper, zinc and lead in the stormwater samples also was consistent with a soil particle source of lead. The strongest correlation between event mean total suspended solids and total metal concentrations was for lead, although total copper and zinc concentrations were also co-correlated with suspended solids (Fig. 17). Closer inspection of the time series plots of metal concentrations indicated that high total lead concentrations were coincident with separation between total and dissolved copper and zinc concentrations. For example, the highest total lead concentrations in the I-84 milled surface storm event occurred for the second and third observations (Fig. 6(e)). These samples also contained the highest total suspended solids concentrations of the event (Fig. 6(b)) and virtually all of the copper and zinc was particle associated, represented by the difference between the total (filled circles) and dissolved (open circles) amounts (Fig. 6(c)(d)). Similar trends are evident for Rt. 85 where decreasing lead concentrations were coincident with decreasing contributions of particle-associated copper and zinc to the respective totals (Fig. 12), and for Rt. 149 at the 15, 57, and 123 min observation times (Fig. 13). Furthermore, the ratio of copper-to-zinc-to-lead in the particle phase (0.2-0.5:1:1) was similar to values reported for U.S. surface soils samples from within 1 m of the roadway surface, as were the effective solid phase metal concentrations from our study (*e.g.*, EMC Pb_{TOT}/EMC TSS = 92 – 240 mg/kg) (Sansalone and Glenn 2007; Woodard et al 2007; Zehetner et al 2009).

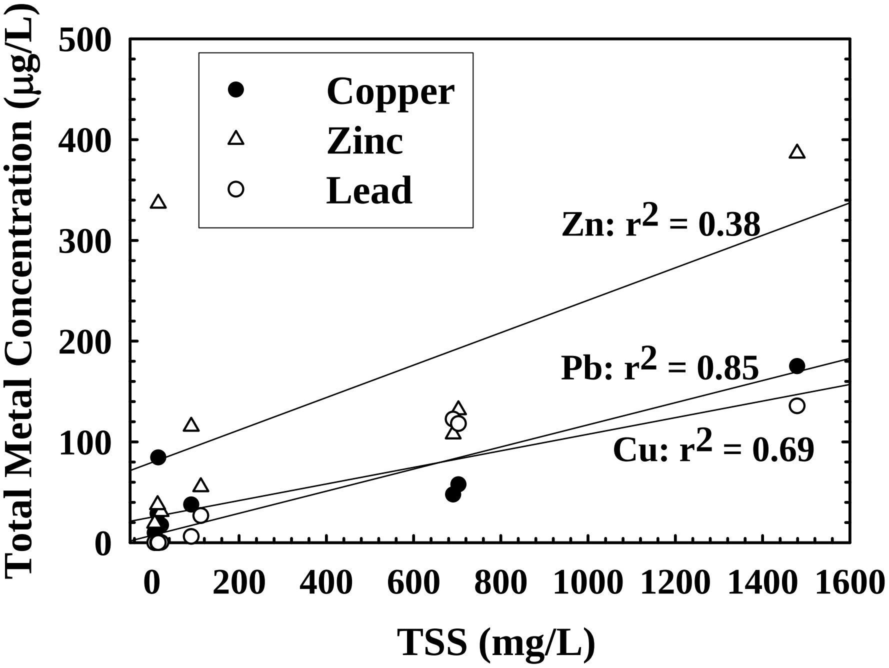

Figure 17. Correlation between metal concentrations and total suspended solids for all sample locations and events. Event mean concentrations are reported. Coefficients of variation are reported for linear regressions.

Although the importance of particle phases was identified for both solids and heavy metals, no correlations with stormwater flow parameters was observed for the sample set. Two of the sample sets, Rt. 85 and Rt. 149, were known to be collected during unusually intense storms, including Hurricane Hannah (Rt. 149). High precipitation intensities may be anticipated to scour more solids from the road surface and/or to induce more soil erosion from roadside regions. Comparisons between event mean total suspended solids concentrations and precipitation intensity (Fig. 18) or runoff velocity (not shown) showed no clear trend. Increased constituent loads with increasing flow can be characterized by a threshold intensity above which suspended solids concentration measures are significantly greater than those associated with lower precipitation intensities. Examination of individual storm events through time point-by-time point comparison of runoff velocity and total suspended solids concentration failed to indicate any relationship between water quality constituents and threshold flows.

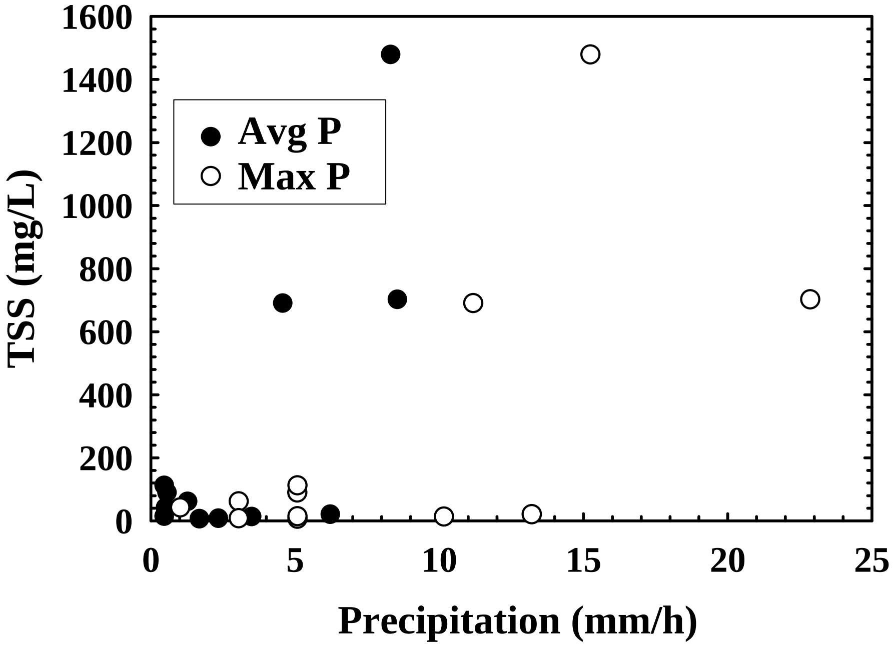

Figure 18. Effect of precipitation intensity on event mean total suspended solids concentration. Solid circles represent average precipitation intensities and open circles indicate maximum precipitation intensity during the storm event.

Antecedent dry period also was not a factor in the magnitude of the suspended solids concentrations observed in the stormwater runoff. Precipitation records from Bradley International Airport (NOAA 2003), located 54 to 93 km from the stormwater sampling locations, indicated 1 to 3 dry days prior to all sampling events. Airport observations may not represent accurately local rainfall during the summer season, characterized by convective storms.

6. Conclusions and Recommendations

Milling of HMA surfaces had no direct impact on water quality of roadway runoff obtained from these surfaces. Stormwater quality of runoff obtained from milled roadway surfaces differed little from runoff from unaltered roadway surfaces. Comparisons of road surface flushing mechanisms and event mean concentrations of water quality parameters yielded similar values for both milled and unaltered roadway surfaces. The one exception was event mean total suspended solids that were greater for milled surfaces; however, correlation of high total suspended solids with the occurrence of particle-associated lead in the milled surface runoff suggested a roadside source of solids, not residual HMA particles generated during milling.

The coincident observations of suspended solids and lead at milled locations may suggest alterations of stormwater conveyance systems and structures. For example, removal of asphalt curbing may allow overland flow from disturbed soil embankments onto the road surface, contributing to roadway runoff. Therefore, milling activities should proceed with consideration not to create new hydraulic connections with adjacent roadside areas that do not drain onto the road surface.

Scheduling of roadway resurfacing projects in Connecticut need not be modified for weather conditions to minimize impacts on water quality of stormwater generated during the project duration. The lack of trends in total suspended solids or heavy metal event mean concentrations with precipitation suggest that rain storm intensity was not a factor in storm water quality. The somewhat higher event mean total suspended solids concentrations for milled surfaces were within ranges reported for other, unaltered road surfaces. The timing of the milling season with summer in Connecticut results in localized convective rainfall events characterized by sporadic generation of rainfall runoff that is short in duration. Milled roadway surfaces that employ catch basin and storm drain runoff conveyance systems may not yield any stormwater during summer convective storm events because water accumulation on the road surface must be great enough to overtop drainage structures.

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