A LOW IMPACT DEVELOPMENT METHOD FOR MITIGATING HIGHWAY STORMWATER RUNOFF - USING NATURAL ROADSIDE ENVIRONMENTS FOR METALS RETENTION AND INFILTRATION

by

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Abstract

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Stormwater runoff from highways is laden with contaminants, particularly heavy metals that adversely impact receiving waters. Traditional BMPs such as stormwater retention and detention facilities, while capable of settling out particulate bound metals, have high installation costs and considerable right of way requirements, and are thus not ideally suited for certain locations. Under some circumstances the natural roadside environment may adequately infiltrate stormwater runoff while also concentrating traffic generated contaminants, much like vegetated filter strips and biofiltration swales, preventing the discharge of metals to receiving waters. This research investigates the utility of these roadside areas, or low impact development (LID) low impact areas (LIAs), for stormwater contaminant mitigation. Three LIA natural roadside environments were instrumented with slot drains, precipitation and flow measurement devices, and sample collection apparatus in order to quantify overland flow and

contaminant transport at three distances from the pavement edge. For all 36 precipitation events documented at the Pullman LIA site, stormwater runoff was completely infiltrating within 2 m of the roadway – runoff did not reach the 2 m or 4 m slot drains. Of the 18 precipitation events documented at the Spokane LIA site, only five events resulted in runoff at the 3.2 m distance, and only one of these events resulted in runoff at the 6.1 m distance. For this single event, all the measured runoff at the distant slot drains were less than 3% of the runoff that was measured at the 0 m distance (the edge of the pavement surface), indicating that greater than 97% was infiltrated. At the 0 m distance at the Pullman LIA site, metals concentrations of sediment collected in the slot drain for 9 events varied little between samples. Comparing total mass of metals of sediment collected in the 0 m slot drain with the total mass of metals of stormwater runoff collected in the composite sampler, Cu and Zn were predominantly associated with runoff (60-65%), Cd was almost exclusively associated with runoff (97%), and Pb was primarily associated with sediment (65%).

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Dedication

To my wife –

For her patience, love, support, and infectious laugh.

Avec des pêches, ma guenon.

1 INTRODUCTION

1.1 Background

Since the passing of the Clean Water Act in 1972, there have been increasing efforts by state and federal regulatory agencies to implement control strategies for preserving and improving receiving water quality. Extensive research has been performed to identify sources, transport mechanisms, and impacts of transportation generated water pollution in an attempt to develop effective mitigation strategies, or Best Management Practices (BMPs). While hydrologic controls have been implemented for decades in an attempt to reduce localized flooding by matching the peak design flow with the peak pre-disturbance flow, the natural flow regime can be significantly altered as these peak discharges are extended far beyond pre-disturbance durations, resulting in greater cumulative kinetic energy imposed upon a natural channel. This in turn results in increased sediment transport, stripping the channel bed of not only benthic substrate but also of essential autochthonous and allocthonous organic matter. This shift in the natural flow regime is potentially more than the native ecological systems can tolerate (Poff et al., 1997). Hence there has also been a movement to restore natural hydrology, and treatment mechanisms are thus increasingly designed to satisfy both flow control and runoff quality concerns by attempting to eliminate discharge to receiving waters entirely. With regard to runoff quantity and quality treatment, facility selection and design is highly dependant on expected pollutant load, contributing impervious surface area, storm event frequency and duration, adjacent soil infiltration rates, incidence of

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frozen soils, available highway right-of-away area, local land use, and proximity to receiving waters.

1.2 Purpose of study

In response to the growing cost of addressing stormwater runoff quality concerns and the tightening discharge limits to receiving waters, there has been much recent interest in exploring low cost/low impact mitigation strategies that concentrate and retain contaminants onsite while concurrently reducing stormwater volume through infiltration. This popular movement has been labeled Low Impact Development (LID), and it has seen much success in urban and suburban areas. Within the right-of-way of most highway corridors are areas down gradient and adjacent to paved surfaces, including meadows, scrubland, embankments and wooded areas, which may be considered low impact areas (LIAs). These LIAs may be ideal for natural dispersion of stormwater volume and retention of transportation generated contaminants. Utilizing the existing right-of-way LIAs as for contaminant concentration and stormwater volume reduction could potentially minimize quantity and quality impacts to receiving waters, while also reducing costs, as traditional curb and gutter systems, associated conveyance structures and detention/retention basins are expensive to install and maintain. However, using LIAs for such stormwater mitigation may only be appropriate for a limited range of applications. Utilization of LIAs, when appropriate, may add to the many design options available to the stormwater control engineer.

Other LID stormwater mitigation strategies that are gaining popularity and increased implementation are vegetated buffer strips and biofiltration swales. These engineered BMPs have proven to be reasonably effective under certain circumstances, and are desirable alternative for planners compared with detention ponds and infiltration galleries due to their low cost, ease of construction, and reduced right of way requirements. While the effectiveness of engineered vegetated buffer strips and biofiltration swales have been investigated, little information exists as to the ability of natural LIAs to retain contaminants in highway stormwater runoff. It is hypothesized that, since the science of contaminant transport mechanisms suggest that horizontal and vertical migration is minimal for suspended solids and associated toxic metals, contaminant retention within LIAs is probable. As a result, the Washington State Department of Transportation has commissioned Washington State University to perform a field and laboratory investigation of LIA stormwater treatment methods. While there are many other transportation generated contaminants, such as nutrients and petroleum hydrocarbons, this study will specifically address metals and particulates in stormwater and their retention in LIAs.

1.3 Contaminant Retention Potential

Non-point sources of pollution, including highway traffic, generate contaminants such as metals and particulates that are suspended in plumes surrounding transportation corridors. These contaminants settle on roadway surfaces, surrounding vegetation and soils. Typically, these contaminants are washed from the impervious surfaces and stripped out of the atmosphere during

precipitation events and depending upon site specific conditions, may ultimately be transported into receiving waters through drainage systems and/or indirect runoff. Where drainage systems do not exist and runoff is insufficient to reach receiving waters, terrestrial environments become the primary sink for the stormwater pollutant loads, adding to the contaminants that have accumulated on nearby vegetation and soils through atmospheric deposition. In this way the terrestrial environments adjacent to highways accumulate and concentrate contaminants. Of high concern are heavy metals due to their relative toxicity and tendency for bioaccumulation. Particulates are also of significant concern as metals tend to partition onto particulate matter.

As metals have a high affinity for soils and organics in particular, and particulates are easily trapped or settle out in overland flow processes, natural dispersion may ultimately succeed in filtering metals from infiltrating stormwater. If it can be demonstrated that runoff can be completely infiltrated through natural dispersion, then traditional engineered stormwater routing and retention/detention treatment devices may be unnecessary in certain situations. The objective of this research is to demonstrate that metals in stormwater are captured in LIAs as a result of stormwater infiltration. Following is a review of the published literature summarizing the influencing variables, transport mechanisms, and fate of particulates and metals in roadside environments.

2 LITERATURE REVIEW

2.1 Source of metals

Contaminants associated with transportation are generated from a variety of sources. Metal species, including Pb, Zn, Cd, and Cu, are generated from mechanical friction of engine and suspension systems, break pad and tire wear (Hewitt and Rashed, 1990; Muschack, 1990), and undercarriage and auto body rust and corrosion. Also, metal debris and lead tire weights (Root, 2000) fall off of vibrating automobiles. These particles and metal pieces are further ground mechanically between tires and the road surface to fine particulates (Sansalone and Buchberger, 1997b), and are subject to elemental desorption and corrosion (Matthes et al., 2002). Most particulates are generated from tire (20-30% of total) and pavement abrasions (40-50% of total) (Sansalone and Tribouillard, 1999). Zinc plated traffic railings are also susceptible to ion desorption and can contribute to zinc loadings (Legret and Pagotto, 1999).

2.2 Factors Influencing contaminant quantity and quality

The quantity and quality of traffic-generated contaminants are influenced by functional, physical, and regional factors. Functional influences include traffic volume and density (Daines and Motto, 1970; Ward et al., 1977; Wheeler and Rolfe, 1979; Fakayode and Olu-Owolabi, 2003), and traffic type (commuter, commercial, industrial, construction, and/or agricultural traffic). Physical influences include pavement type and condition (Pagotto et al., 2000; Dean et al., 2005), operation and maintenance practices (Ball et al., 1998), and the presence of rumble strips which may assist in dislodging metal laden debris from

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vehicles through increased vibration. Regional regulations, such as the composition of gasoline, emissions standards, catalytic converter requirements, acceleration/deceleration zones, preference of traffic circles over stop lights, and brake pad or tire material composition can all affect the quantity and quality of traffic generated contaminants contributing to any given section of roadway. For example, the elimination of tetra ethyl lead from gasoline in some areas has resulted in significant reduction in lead loadings (Helmers et al., 1995; Legret and Pagotto, 1999; Turer et al., 2001), illustrating how aggressive regulatory control can substantially reduce environmental impact. However, as metal migration is generally reported as a relatively slow process, current and historically generated metals contaminants are most likely still present not far from where they were first deposited.

2.3 Transport of contaminants to roadside environments

Once metal and particulates are generated and introduced to the contaminant plume associated with a transportation corridor, they are susceptible to macro, meso, and micro scale transport mechanisms to the roadside environment. Macro scale mechanisms are a function of regional meteorology and land use. Meso scale mechanisms include localized traffic conditions and physical roadway geometry. Micro scale transport mechanisms from road surfaces and within natural environments are highly dynamic and complex functions of physical, chemical and temporal characteristics. These transport mechanisms are discussed in detail below.

2.3.1 Macro scale mechanisms

2.3.1.1 <u>Regional precipitation patters</u>

Regional meteorology affects the quantity, frequency and duration of runoff events. These factors strongly influence contaminant concentrations. Contaminant-laden particulates, aerosols, and ions are scoured from the atmosphere and flushed from roadway surfaces by precipitation as runoff. Long antecedent dry periods facilitate accumulation of contaminants on road surfaces, resulting in a correlation with higher concentrations of some contaminants in stormwater runoff (Hewitt and Rashed, 1992). Long duration storms have the overall result of producing dilute runoff, as the finite contaminant load is dispersed within the runoff volume. Long duration storms also contribute to pavement wear, as wet weather road wear is two to six times greater than dry weather road wear (Backstrom et al., 2003). High intensity storms result in high runoff velocities, increasing sediment transport of particulates (Deletic, 1999).

2.3.1.2 <u>Regional wind patterns and land use</u>

Regional meteorology also affects prevailing wind speed and direction, which influences the distance and direction particles are transported (Piron-Frenet et al., 1994; Ylaranta, 1995). Some conditions may be mutually affective. For example, the combination of the agricultural activities of eastern Washington and the regional Palouse Loess soil type, coupled with the prevalence of the blustery winds of the high plains, succeeds in dusting the area with fine organic rich soil (Horner and Mar, 1984), to which metal species from roadways may readily adsorb. Regional atmospheric chemistry, either degraded by

anthropogenic pollution or simply influence by a nearby marine environment will alter rainwater quality, and will thus affect the partitioning of metals to particulates in runoff (Glenn III et al., 2001).

2.3.1.3 *Seasonal variability*

Seasonal variability in northern climates causes precipitation in the form of snow, necessitating the use of deicing salts on roadway surfaces, some of which contribute directly to impaired runoff quality as chloride and cyanide ions (Novotny et al., 1998; Marsalek, 2003). In some locations sand or gravel is used to increase traction during winter seasons. Not only do these materials contribute to the particulate load to roadside environments (Oberts, 1986), but they have a secondary degradative mechanism - sand and gravel assist in abrading road surfaces, creating more particulates. Studded tires that are widely used in some northern climates during winter months also increase the particulate load from roadways due to increased winter wear, while summer road surface wear is minimal in comparison (Backstrom et al., 2003).

2.3.2 *Meso scale mechanisms*

2.3.2.1 *Localized traffic conditions*

Traffic generated winds can provide sufficient kinetic energy to keep small particulates in suspension in the turbulent region within traffic paths until they are blown far enough away to settle onto vegetation and soils as dry deposition. Re-suspension of particulates by road traffic during dry conditions is influenced by particle size, vehicle speed, and the number of vehicle passes (Nicholson and Branson, 1990). Deposited metals concentrations on vegetation and soils (Ter

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Haar, 1970; Dedolph, 1970; Daines and Motto, 1970; Ward et al., 1975; Ward et al., 1977; Wheeler and Rolfe, 1979; Ylaranta, 1995) exhibit characteristic decreases in concentration with distance from the road, as have directly measured atmospheric deposition (Backstrom et al., 2003). During wet weather, traffic generated spray scours the undercarriage of vehicles increasing metals and particulate release, with the intensity of the spray being a function of the traffic speed. In addition to releasing contaminants, spray influenced by traffic volume and speed can be a significant mechanism for delivering contaminant laden stormwater to roadside environments (Cristina and Sansalone, 2003).

2.3.2.2 *Localized road corridor geometry*

Metals and particulates may also settle and aggregate on the road surface (Harrison et al., 1981). Location of dominant particulate deposition and particle size distribution is a function of roadway geometry and transverse and longitudinal slope (Sansalone and Tribouillard, 1999). Transportation corridor geometries influenced by stands of trees has also been demonstrated to reduce the atmospheric transport of contaminant laden particulates by reducing wind velocities (Heath et al., 1999).

2.3.3 *Micro scale mechanisms*

2.3.3.1 *Factors influencing metal speciation and behavior*

While a detailed description of the complex settling and scouring processes of dry and wet atmospheric deposition of metals and particulates to the roadside environment could be provided, it is beyond the scope of this report. Delivery of these contaminants via stormwater runoff is more relevant and

warrants discussion. Metals speciation in stormwater is a function of residence time, pH, particulate size and organic content of suspended particulates, alkalinity, salinity and temperature (Warren and Zimmerman, 1994; Sansalone and Buchberger, 1997a; Sansalone and Glenn III, 2000; Glenn III et al., 2001). Pavement type, either asphalt or Portland cement, may also influence metals speciation as a result of the influence of Portland cement on carbonate chemistry (Dean et al., 2005). These physical, chemical and temporal factors will cause the metal species to dynamically adsorb onto and desorb from particulates according to conditionally specific reaction kinetics and partitioning coefficients (Sansalone and Glenn III, 2000). If under a steady state, low alkalinity and slightly acidic conditions, partitioning equilibrium can be reached in as little as six hours (Sansalone and Buchberger, 1997a), with a small fraction existing in a dissolved phase and the major fraction being bound to particulates. The order of partitioning affinity for each metal species varies according to system specific conditions (pH, soil type, etc.) mentioned above.

2.3.3.2 *First flush of contaminants*

Metal species and particulates are lifted and scoured from the road surface, predominantly during the initial interval of a precipitation event, exhibiting what is characteristically known as a 'first flush' phenomenon (Sansalone and Buchberger, 1997a). Metals species may be primarily in the dissolved form in runoff at the pavement edge, and are more apt to exhibit a first flush phenomenon than particulates, as particulate transport is a function of runoff velocity and hence precipitation intensity (Sansalone et al., 1998). Initial

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transport of dissolved metals may therefore be considered flow driven while particulate transport is primarily intensity driven (Cristina and Sansalone, 2003). As smaller particles are more readily transported by lower rainfall intensities and smaller particles have greater surface area to volume ratios and thus a higher metal adsorption capacity, a dominant portion of the particulate bound metals fraction is also more strongly correlated with first flush phenomena as a result of being bound to more readily transported particulates (Sansalone and Buchberger, 1997b). However, another study indicated that mid range sized particles actually have a greater specific surface area due to the rough physical characteristics of that particulate fraction and thus more adsorption sites for metal species (Sansalone and Tribouillard, 1999).

With short duration events, contaminant mass may not be fully washed from the roadway surface, resulting in a flow limiting event with regard to the complete and characteristic development of what is known as a 'pollutograph' – a graphical representation of contaminant concentration versus time. Conversely, long duration events may succeed in removing the mass of contaminants from the roadway surface deposited during the antecedent period, and a runoff event may be considered contaminant limited. With contaminant limited events, once antecedently deposited contaminants are removed from road surfaces, and as the contaminants generated during an event are concurrently flushed from roadways with runoff, the pollutograph asymptotically approaches equilibrium (Cristina and Sansalone, 2003).

2.3.3.3 _Overland flow of metals to roadside environments_

As stormwater leaves the pavement edge as overland flow, aqueous phase and particulate bound metals contaminants introduced to the roadside environment are subject to complex and dynamic functions of sediment transport, filtration, and adsorption onto soil matrices and existing vegetation. Hydraulically, sediment transport and erosive potential is a function of runoff velocity which is a function of precipitation intensity, roadside slope, and surface roughness. Surface roughness is dominated by the fraction of bare ground and litter cover (Hart and Frasier, 2003).

Much research has been done on sediment transport through vegetation in both simulated laboratory experiments (Pearce et al., 1997; Munoz-Carpena et al., 1999; Deletic, 1999) and in simulated field experiments (Pearce et al., 1998; Backstrom, 2002). Generally, greater slopes increase flow velocities, and higher velocities can transport larger particles. With increasing vegetated thickness (increased Mannings number) sediment transport capacity is reduced (Gross et al., 1991). Velocity slows with greater roughness, and particles are subject to sedimentation processes, with the heavier (typically larger) particles settling out first, followed by smaller particles which settle out further down-slope as velocities are reduced.

2.3.3.4 _Infiltration of stormwater_

Typically, overland flow only occurs when run–on rates are greater than infiltration rates. Infiltration is dependant on soil type, vegetated cover (Greene et al., 1994), litter cover(Agassi et al., 1998; Costantini and Lcoh, 2002; Hart and

Frasier, 2003) surficial crusting (Lasanta et al., 2000), water quality (Kim and Miller, 1996; Borselli et al., 2001), and most importantly, the presence and abundance of macro-pores (Haria et al., 1998; Heppell et al., 2000; Weiler and Naef, 2003; Di Pietro et al., 2003). Macro-pores can be responsible for up to 86% of infiltration (Heppell et al., 2000).

Infiltration rates of mineral rich water possessing a high electrical conductivity, such as tap water, can be 2-3 times higher than water with a low electrical conductivity such as distilled water (Borselli et al., 2001). Silty clay soils are more affected by this phenomenon than silty loam soils. This has important implications for field determinations of hydraulic conductivity and simulated rainfall infiltration studies. However, it is unknown how significantly metal species affect the electrical conductivity of stormwater runoff and hence the infiltration rate. Temporal and spatial metal concentration gradient of metals in stormwater may induce a similar temporal and spatial infiltration gradient within the roadside environment throughout the duration of the storm, all other things being equal. If tap water and stormwater runoff induces similar infiltration rates due to similarities in electrical conductivity, than tap water may be an acceptable surrogate. Due to the potential for substantial overestimation, additional research is warranted.

Infiltration also plays a part in metals transport. Particulate bound metals delivered via overland flow are essentially strained by the soil matrix as stormwater is infiltrated. Aqueous phase metals are adsorbed onto and retained by the soil matrix during infiltration (Dierkes and Geiger, 1999; Turer et al., 2001)

or adsorb onto vegetation, most preferentially senescent vegetation (Ratcliffe and Beeby, 1980).

2.3.3.5 *Erosion of metals laden particulates*

Once metals laden particulates are deposited, they can be subjected to both overland flow and, when vegetation is minimal, raindrop erosive forces, both of which will transport particulates further down-slope. Erosive capacity of overland flow is a function of velocity and existing sediment load (Zheng et al., 2000). Overland flow carrying a maximum sediment load has little erosive ability, while sediment free overland flow of the same velocity can cause considerably more erosion. Varying only sediment load in introduced overland flow will result in constant down-slope sediment delivery. Bare soils are also subject to particulate dislodgement and scouring by the kinetic energy of rain drops (Meyer and Harmon, 1992; Thompson et al., 2001). This process increases particulate availability to the transport mechanisms of overland flow.

2.3.3.6 *Metals transport within the soil matrix*

Once retained by the soil matrix, either through deposition via overland flow of particulate bound metals or adsorption of aqueous phase metals following infiltration, metals are susceptible to various transport or leaching mechanisms. Transport of metals through soils is enormously complex. Much research has been done regarding metals transport through soil columns (Igloria et al., 1996b; Papini and Majone, 1997; Delmas et al., 2002; Marcos et al., 2002). Transport of some metals is a function of pH (Sauve et al., 2000), soil organic matter (Igloria et al., 1996a), dissolved soil organic matter (Jordan et al., 1997; Liu and

Gonzalez, 2000), solute colloid concentration (Amrhein et al., 1993), salinity from deicing salts (Amrhein et al., 1992), temperature (Vandenabeele and Wood, 1972), and reducing conditions caused by inundation (Charlatchka and Cambier, 2000; Ma and Dong, 2004). Adsorption/desorption kinetic processes are very dynamic, and while metal species are largely immobile once they adsorb onto the soil matrix, they are susceptible to some mobilization under certain conditions as described above. Metal species in roadside soils deposited over the past century have not had sufficient time to migrate far, as there is little evidence in the literature of metals migrating beyond depths of 1 m. Under normal circumstances, barring the use of deicing salts, the potential for transportation generated stormwater runoff to contaminate groundwater through infiltration is limited (Mikkelsen et al., 1997; Barraud et al., 1999).

2.3.3.7 *Influence of winter conditions*

Winter conditions invoke a number of factors that affect micro scale transport mechanisms. Frozen ground can inhibit infiltration of stormwater, and once saturated, can behave like an impervious surface, transporting contaminant laden stormwater further within the roadside environment or directly to receiving waters. If precipitation is in the form of snow, metals and sediment are transported to roadside environments via plowing to snow banks, which accumulate metals and particulates (Sansalone and Buchberger, 1996; Sansalone and Glenn III, 2002; Glenn III and Sansalone, 2002), deicing salts (Buttle and Labadia, 1999), and cyanide de-bulking agents (Paschka et al., 1999).

Soluble components are readily released with meltwater, while insoluble and particulate bound species are more slowly released (Marsalek et al., 2003) or remain once the snowbank disappears (Sansalone et al., 2003). With applications of deicing salts, aqueous phase metals concentrations increase in snowbank meltwater (Novotny et al., 1998). Regardless of phase, contaminant concentrations may be one to two orders of magnitude higher during the winter (Glenn III and Sansalone, 2002; Backstrom et al., 2003). Concentrations of metals and salts associated with snowbank meltwater may have the most significant impact on receiving waters (Lygren et al., 1983). As a result, there has been increased usage of calcium magnesium acetate (CMA), as it is less toxic to aquatic life and does not contain cyanide de-bulking agents (Amrhein et al., 1993). However, high concentrations of metals and salts that are not discharged to receiving waters infiltrate into the soil matrix as frozen grounds thaw, and both NaCl and CMA salts increase the mobility of metals in roadside soils (Amrhein et al., 1992; Bauske and Goetz, 1993; Norrstrom and Jacks, 1998; Norrstrom and Bergstedt, 2001; Backstrom et al., 2004). Increased metal mobility through roadside soils due to the use of deicing compounds may result in groundwater contamination (Granato et al., 1995).

2.3.3.8 *Integrated metals budget*

When developing an integrated budget for the transport of highway generated metals to roadside environments, one study found that ~8% of metals were removed in runoff, ~6% were removed via atmospheric deposition to environments within 50 m of the roadway, and the remaining ~86% were

distributed away from the transportation corridor (Hewitt and Rashed, 1990).

This has significant implications for the application of LIAs as a sink for the

contaminants in stormwater runoff. If runoff contains ~8% of transportation

generated metals, then natural dispersion of this stormwater roughly doubles the

metal load to roadside environments (adding to the ~6% of metals deposited via

atmospheric deposition).

2.4 Impact of metals on terrestrial organisms

If immediately discharged to receiving waters directly from the road

surface, metals in stormwater may be predominantly in a dissolved form, and

thus available for uptake by and subsequently toxic to aquatic organisms,

although with no significant effect on rural stream invertebrates exposed to runoff

from lightly traveled or rural highways (Smith and Kaster, 1983) . In contrast,

metals in runoff are quickly rendered relatively immobile in terrestrial

environments, as they are readily adsorbed to organic matter and retained in

soils. While this limits exposure of terrestrial organisms, metals are still

bioavailable for uptake and biomagnification (Scanlon, 1986). Quantifiable tissue

concentration gradients of metals with distance from the road have been

documented for all manners of organisms, including plants (Cannon and Bowles,

1962; Lagerwerff and Specht, 1970; Dedolph, 1970; Motto et al., 1970;Chow,

1970; Ward et al., 1975; Ward et al., 1977; Haqus and Hameed, 1986; Ylaranta,

1995; Parkpian et al., 2003), invertebrates (Williamson and Evans, 1972; Gish

and Christensen, 1973; Ash and Lee, 1980; Wade et al., 1980; Weigmann, 1991)

and mammals (Jefferies and French, 1972; Welch and Dick, 1975; Scanlon,

1986; Nyangababo, 2001). Lead and Cd have also been recorded in the milk of dairy cows grazing on fertilized pastures with elevated Pb and Cd levels in forage and soils next to roads, but concentrations were well below health standards and did not differ from pastures not subjected to metals contamination (Parkpian et al., 2003). With regard to vegetation, generally one to two thirds of metals are associated with atmospheric deposition rather than uptake, and different species have widely varying abilities to uptake metals. Metals that are taken up by vegetation are re-released as vegetation dies and decomposes. It is then subject to continued biotic uptake, particulate adsorption, leaching or overland transport. Some plant species have shown an adaptive tolerance to both metals (Schmidt, 2003) and deicing salts (Beaton and Dudley, 2004), although both can inhibit seed germination (Hsu and Chou, 1992; Beaton and Dudley, 2004).

While increased accumulation of metals for most biota with road proximity has been amply demonstrated, toxicological research was not reviewed and would best be found in toxicology literature and not transportation research. Interestingly, while there has been no demonstrated significant population number or density differences for vegetation, mammals, and certain invertebrates with increasingly metal contaminated soils, some studies found that certain invertebrate populations increase with proximity to the road (Muskett and Jones, 1980; Braun and Fluckiger, 1984), speculatively due to decreased predation from organisms not capable of living at the road edge and from increased susceptibility of vegetation due to a decline in health. Finally, with regard to soil microorganisms, biomass has been shown to decrease with increasing metals

concentration (Khan and Scullion, 2000). Certain strains of microorganisms are

also capable of enhancing the leaching of metals by reducing pH, altering metals

partitioning to the aqueous phase (Anderson et al., 1998), which, while probably

playing only a small roll in natural environments, has significant implications for

other engineered bioreactor metals removal methods.

2.5 Previous research on vegetated swales and filter strips

Numerous studies have been conducted to demonstrate that

contaminants can be retained in engineered LID stormwater dispersion and

infiltration BMPs known as swales and vegetated filter strips (Yousef et al., 1985;

Wigington et al., 1986; Finley and Young, 1993; Kaighn and Yu, 1996; Barrett et

al., 1998; Yu et al., 2001; Backstrom, 2002; Backstrom, 2003). Generally for

most conditions and based on concentration, particulate removal was greater

than 60%, while total metals removal was greater than 50%. However, one study

indicated that as contaminant concentration in runoff decreases, removal

efficiency decreases, and these vegetative controls may actually be a source of

contaminants rather than a sink (Backstrom, 2003). All studies found that

removal efficiencies were highest with complete infiltration, and that shallow

sloped (<12%), densely vegetated, long filter strips (>8 m) and swales (> 60 m)

were most effective in allowing infiltration, particulate sedimentation and metals

adsorption. However, these studies were broad-based, site specific conceptual

illustrations that the scientific principles addressed previously can indeed be

applied with a reasonably expected outcome. Many of the important variables

governing overland flow, sediment transport and infiltration, were not considered

or addressed. Regardless, demonstrations of this nature are essential in verifying that soft engineering applications can be effective.

3 METHODS

3.1 Site description

Three roadside monitoring sites were chosen that exhibited features ideal for demonstrating the applicability of LIAs for roadside stormwater runoff quantity and quality attenuation. Physical features included a quantifiable impervious surface area and the existence of a natural, unaltered roadside environment that could attenuate roadside runoff. A site was chosen on SR 270, 5.5 km east of Pullman, WA; on US 2, 24 km north of Spokane, WA, and on I 90, 300 meters west of Exit 45 eastbound outside of North Bend, WA (Figure 1, Figure 2, and Figure 3, respectively). These three sites had different contributing impervious surface areas but were all moderately sloped with vegetated shoulders. The Pullman site was heavily vegetated with a slope of ~4:1 with loess soil, the North Bend site was moderately vegetated with a slope of ~5:1 with loam soil, and the Spokane site was moderately vegetated with a slope ~6:1 and sandy loam soil. Average daily traffic flows were 13,000, 29,000, and 23,000 for the Pullman, North Bend and Spokane LIA sites, respectively (WSDOT, 2004). The Pullman and North Bend sites had distinctive gravel strips between the edge of the pavement and the soil type of the natural areas, while the Spokane site had no such delineation.

Figure 1. Pullman LIA site.

Figure 2. Spokane LIA site.

Figure 3. North Bend LIA site.

3.2 Field installation

Field site installations were completed on 6/30/04, 8/20/04, and 9/10/04 for the Pullman, Spokane, and North Bend LIA sites, respectively. Multiple equipment, material and procedural iterations were experimented with until an arrangement was arrived at that would allow for collection of the desired event parameters. Each site was outfitted to collect overland flow within these vegetated natural areas at three distances from the impervious surface edge, with each collection slot drain longitudinally spaced so as not to influence the

adjacent drains. Additionally, longitudinal road slopes were minimal at all sites,

and runoff could be assumed to be perpendicular to the road surface. In this

manner the need for plot area border guides could be avoided. A generic

schematic is represented in Figure 4. Corresponding dimensions for the three

field sites and material/equipment descriptions are presented in Table 1 and

Table 2 respectively.

Table 1. LIA field site dimensions.

Variable	Description	Roadway		
		Pullman SR 270	Spokane US 2	North Bend I 90
a	Distance from crown to edge of pavement	5.9m	8.6m	10m
b	Length of slot drain	2m	2m	2m
c	Distance from edge of pavement to 2nd slot drain	2.0m	3.2m	1.7m
d	Distance between 1st and 2nd slot drain	2.5m	3.0m	1.5m
e	Distance from edge of pavement to 3rd slot drain	4.0	6.1m	3.5m
f	Distance between 2nd and 3rd slot drain	2.5m	3.0m	1.5m
g	Rain gauge height	3.1m	3.5m	~10m

Table 2. LIA field site equipment.

Variable	Description
1	Slot Drain – (NDS, Inc. Mini Channel) 2m x 0.01m
2	2" PVC pipe
3	Custom built tipping bucket 0-3 L/min capacity
4	5 gallon composite sampler bucket
5	8" tipping bucket rain gauge (American Sigma)
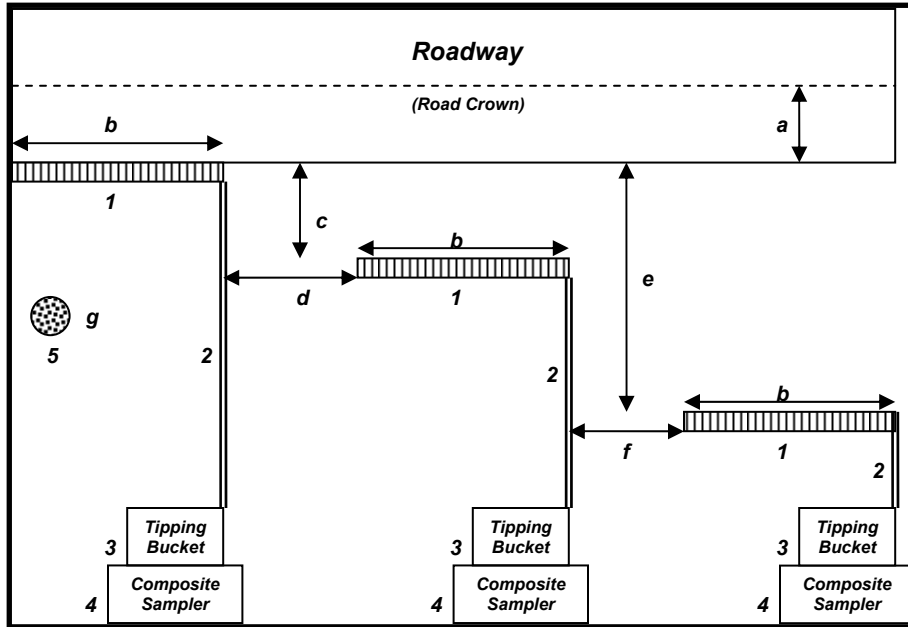
Figure 4. General schematic of the three LIA field sites.

Precipitation events were recorded with an 8 inch tipping bucket rain gauge (American Sigma, Inc.) (Figure 5). For the Pullman and Spokane sites, gauges were mounted on 12 ft posts sunk ~3 ft in the ground. A 50 lb bag of ready mix concrete was used to solidly anchor the post in place. Gauges were positioned so as to minimize influenced by surrounding vegetation. For the North Bend site the gauge was mounted on top of a 10 m road sign. Gauges were connected to HOBO event data loggers (Onset Computer Corporation) that recorded time intervals between tips. Each tip represented 0.254 mm of precipitation.

Runoff was collected in 2 m x 0.1 m Mini Channel slot drains (NDS, Inc.) that were flush mounted with either the surrounding soil or the edge of the pavement. Slot drains at the two most distant locations were covered to prevent the influence of precipitation. The surface area of the slot drains at the edge of

the road surface was included in calculation of the contributing impervious

surface area when calculating theoretical runoff and was not covered. Slot

drains were sufficiently longitudinally spaced so as not to influence runoff

received by adjacent drains. Drain outlets were flush mounted with the surface,

and if no natural lateral slope existed, they were slightly adjusted out of parallel to

the edge of pavement so as to yield a low end that the collection pipe could be

attached to. Collection piping was mounted above ground, and collected runoff

was diverted from the slot drains through 2 inch PVC pipes outfitted with 90

degree elbows that fit snugly over funnels connected to custom built low flow

tipping buckets, which operated similarly to a tipping bucket rain gauge.

Figure 5. Tipping bucket rain gauge.

Figure 6. Tipping bucket/composite sampler.

For the Pullman and Spokane sites, where sample retrieval was feasible, the low flow tipping buckets were positioned above 5 gallon buckets which served as composite samplers (Figure 6). The tipping bucket/composite sampler assembly was located sufficiently down the lateral side-slope so as to fit under the runoff piping without excavation. Holes in the lid of the 5 gallon bucket allowed the tipping bucket to divert runoff directly into the bucket. The entire apparatus was strapped to a 2 ft x 2 ft concrete paver with a bungie cord, and then covered with a modified 50 gallon drum or a 30 gallon trash can (not shown) to protect it from the influence of precipitation.

3.3 Flow sampling

Custom tipping buckets were designed and implemented to quantify low runoff flow rates for this study (Figure 7). The design was inspired by tipping bucket rain gauges and refined from equipment designs used in runoff and

erosion research and published in the literature (Johnson, 1942; Edwards et al., 1974; Chow, 1976; Barfield and Hirschi, 1986; Loch et al., 1998; Zhao et al., 2001). Bucket sizing and operation was calculated by solving a static moment equation. The assembly was constructed by the author, using 0.25 inch acrylic for all planar components but the base which was 0.5 inch acrylic. Inexpensive level bubbles (obscured from view) were mounted in a perpendicular arrangement on the base, and screws were positioned on the corners to adjust level orientation. Due to the high tipping angle of 40 degrees, misalignment could prevent the bucket from tipping, and therefore a level orientation was critical for accurate operation. A funnel centered flow over the tipping axis. A magnet mounted on the bucket triggered a reed switch allowed for each tip to be registered by a contact closure of a magnetic reed switch with a HOBO Event Data Logger (Onset Computer Corporation).
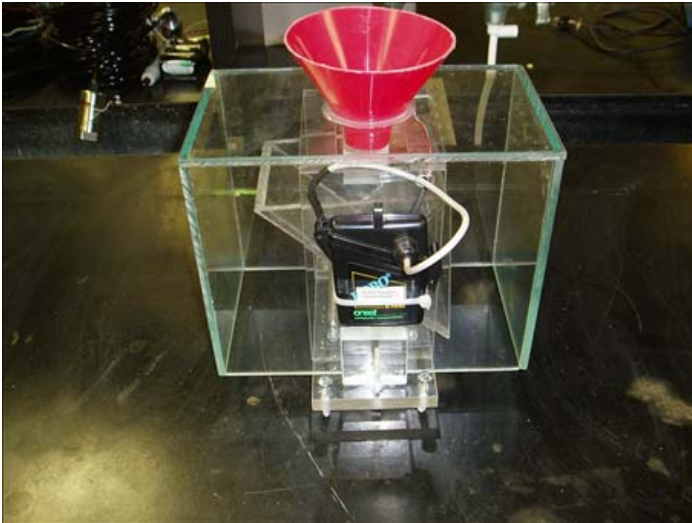
Figure 7. Custom low flow Lancaster tipping bucket.

Specifics of the design included a high tilt angle which would accommodate a high sediment load from road surface scour during the first flush

phenomena. This feature would induce vigorous flushing of particulates during the tipping action. High sediment/debris load is problematic in traditional flow measurements where a weir such as a V-notch weir in a channel causes flow to go through critical depth. A strategically placed pressure transducer can measure this depth, which can be converted to a flow rate by application of the energy equation, a method commonly used in hydraulic design. However, high sediment/debris loads cause interferences by changing the channel geometry with sedimentation and/or obstructing the V notch weir with debris. Low flows are difficult to measure this way due to the extremely small changes in critical depth with small changes in flow. Accurate measurements are a function of the pressure transducer sensitivity and unimpeded flow. Debris such as a small twig or wheat stalks caught in a V-notch weir could severely alter the measured critical depth, resulting in inaccurate readings. Additionally, as total solids is an important water quality parameter, and as heavy metals, also an important water quality parameter, adsorb to particulates, obtaining a complete and representative composite sample is crucial for accurately defining runoff water quality. A properly sized tipping bucket overcomes these limitations and is ideal for measuring the low flow rates of runoff observed in this study.

The time interval between tips was correlated with a given flow rate based on calibration curves determined prior to testing. Triplicate calibrations runs were performed for 5 flow rates based on 5 peristaltic pump settings. Tipping buckets were placed over an empty bucket, and for a given number of tips (>10), both time and mass of water in the bucket was recorded. Tips per minute and L/tip

could then be calculated, and the corresponding flow rate relating to tips/min could be determined. Both x and y error bars were determined, and are within the data point if they can not be seen. Tipping buckets were calibrated up to 3 L/minute, which corresponded to approximately one tip every 3-5 seconds. Greater flow rates produced non-quiescent flow, and tips resulting from irregular sloshing had reduced measurement accuracy. Adjusting for the varying contributing surface areas, runoff depths in excess of 15 mm/hour at the Pullman site, 10 mm/hour at the Spokane site, and 4.5 mm/hour at the North Bend site exceeded the 3 L/min capacity of the tipping buckets. However, most runoff flow rates were within the acceptable range. Tipping bucket location and calibration data is presented in Table 3. Complete tipping bucket calibration data can be found in Appendix A.

Table 3. Tipping bucket location and calibration data.

Tipping Bucket ID #	Location	Calibration flow range, L/min	Calibration equation to determine L/min	Average L/tip over range
2	SR 270 4 m slot drain	0.24-3.10	= 0.1799 * (tips/min)	0.1752
3	SR 270 2 m slot drain	0.25-2.49	= 0.1658* (tips/min)	0.1622
4	SR 270 0 m slot drain	0.24-2.75	= 0.1735 * (tips/min)	0.1673
5	US 2 3.2 m slot drain	0.27-2.69	= 0.1923 * (tips/min)	0.1873
6	US 2 0 m slot drain	0.27-2.50	= 0.187 * (tips/min)	0.1846
7	US 2 6.1 m slot drain	0.25-2.70	= 0.173 * (tips/min)	0.1687
8	I90 0 m slot drain	0.45-2.74	= 0.1805 * (tips/min)	0.1765
9	I90 1.7 m slot drain	0.26-2.29	= 0.1749 * (tips/min)	0.1692
10	I90 3.5 m slot drain	0.63-2.17	= 0.2053 * (tips/min)	0.1966

3.4 Runoff aqueous sampling

Composite samples were collected periodically for analysis. While collection immediately following an event would have been ideal, this was not always possible. When composite samples were collected, a representative aliquot was obtained by first thoroughly mixing the contents of the sampler so as to suspend all settled material without inducing a vortex which could result in a

particle gradient radiating from the center based on size and density. A sample

bottle was then submerged into this turbulent suspension and allowed to fill.

Samples were brought back to the lab and stored for analysis. Sample volumes

were initially 50 ml, but were increased to 1L towards the end of the study.

Water quality analysis included soluble and total metals (Cu, Zn, Cd, and Pb) by

ICP-MS according to EPA Method 200.7. Total metals concentration is defined

as both dissolved species and those species bound to particulates and colloids.

Dissolved, or soluble metals concentration is defined as those that pass through

a 0.45 um filter. For soluble metals determination, 20 ml of each 0.45 um filtered

sample was preserved with 0.4 ml of 1+1 nitric acid and analyzed by ICP-MS.

Not all aqueous samples were properly filtered, as will be discussed in section

4.2.2, Metals Analysis. For total metals determination, 50 ml of unfiltered sample

was added to an Erlenmeyer flask along with 2 ml of 1+1 nitric acid and 1 ml of

1+1 hydrochloric acid and heated on an 85° C hotplate until the sample volume

was reduced to 20 ml (~30 min). A watch glass was then placed over the top of

the Erlenmeyer flask and the acidified sample was refluxed for an additional 30

minutes. The solution was then transferred quantitatively to a 100 ml volumetric

flask and diluted to volume with ultrapure DI water. After allowing any

particulates to settle overnight in a 4° C cold room, a 15 ml aliquot was

transferred to a test tube and the sample was analyzed for metals by ICP-MS.

All glassware, for all metals analyses, were washed, rinsed, triple DI rinsed,

soaked in 1+6 nitric acid over night, and then triple ultrapure DI rinsed.

Due to volume limitations, total suspended solids by gravimetric determination of solids retained on a 0.45 um filter and particle size distribution analyses were performed on only three samples obtained towards the end of the study. Particle size distribution (PSD) was determined by static light scattering methodology using a Malvern MasterSizer (Malvern Instruments, UK). Preparation for PSD determination involved filtration of 200 ml of a homogenized event sample through a 100 um filter, as the detectable range for this instrument is 1-100 um.

3.5 Slot drain sediment sampling

As overland flow containing particulates entered the slot drains, velocity slowed, which allowed particulates to settle out. In this way the slot drains acted as a pretreatment device, removing a readily settleable fraction from the heterogeneous flow regime. Therefore slot drain sediment was collected routinely for analysis at the Pullman site and once at the end of the study at the Spokane site. Analyses included total mass, sieve analysis with six fractions, and determinations of Cu, Zn, Cd, and Pb by ICP-MS for each fraction. Each sediment sample was first dried at 60° C for 24 hours. The entire sample was then sieved through a 3 inch diameter, #5, #10, #35, #60, and #140 standard size sieve set, and each fraction was weighed on a lab scale. Approximately 1 g of sediment sample fraction was then placed in an Erlenmeyer flask with 4 ml of 1+1 nitric acid and 10 ml of 1+10 hydrochloric acid, covered with a watch glass, and refluxed at 85° C for 30 minutes. After cooling, the aqueous portion was transferred quantitatively to a 100 ml volumetric flask, carefully rinsing the solids

in the Erlenmeyer flask with DI water to extract as much of the acidified sample as possible. The volumetric flask was then diluted to volume. Any remaining particulates were allowed to settle overnight in a 4° C cold room, and approximately 20 ml was then transferred to a test tube for ICP-MS analysis.

3.6 LIA soil sampling

In order to quantify the horizontal migration of metals via atmospheric deposition and overland flow to the LIAs, soil samples were collected at three distances corresponding to the three slot drain distances at both the Pullman and the Spokane sites. Additionally, to evaluate the vertical migration of metals, samples were collected at the surface and at 10 cm and 20 cm depths, for a matrix of nine samples at each of the two sites. Analyses included sieve analysis with six fractions and determinations of Cu, Zn, Cd, and Pb by ICP-MS for each fraction. Each soil sample was first dried at 60° C for 24 hours. Approximately 75 grams of a sample was then sieved through a 3 inch diameter, #5, #10, #35, #60, and #140 standard size sieve set, and each fraction was weighed on a lab scale. Approximately 1 g of each sample fraction was then placed in an Erlenmeyer flask with 4 ml of 1+1 nitric acid and 10 ml of 1+10 hydrochloric acid, covered with a watch glass, and refluxed at 85° C for 30 minutes. After cooling, the aqueous portion was transferred quantitatively to a 100 ml volumetric flask, carefully rinsing the solids in the Erlenmeyer flask with DI water to extract as much of the acidified sample as possible. The volumetric flask was then diluted to volume. Any remaining particulates were allowed to settle overnight in a 4° C

cold room, and approximately 20 ml was then transferred to a test tube for ICP-MS analysis. Triplicate analysis was performed for one sample at each site.

3.6.1 Method standards and blanks - metals

Standards were run in triplicate for total metals analysis to validate the preparation method. Stock solutions were prepared containing 0.2mg/L of each constituent from commercially available high purity aqueous stock standards (High Purity Standards, Inc., 1000 ug/ml of Cu, Cd, Zn, and Pb). These were prepared similarly to actual total metals aqueous samples. Method standards data are presented in Figure 8 and Table 4. Copper, Cd and Pb tested within generally accepted criteria (+/- 10%), while Zn exhibited an average well above accepted tolerances (121%). Interestingly, most other total Zn concentrations of aqueous samples were also higher than should have been possible, although typically by a much greater percentage. Also presented in Table 4 are method blank and equipment blank total metals values. Method blanks were run with nanopure DI water and underwent the same procedures as method standards, while equipment blanks were comprised of rinse water of the 15 ml glass tubes used for transport of samples to the ICP-MS lab which had been rinsed in 1:6 nitric acid and subsequently nanopure water prior to use. Both method blanks

and equipment blanks were run in triplicate.
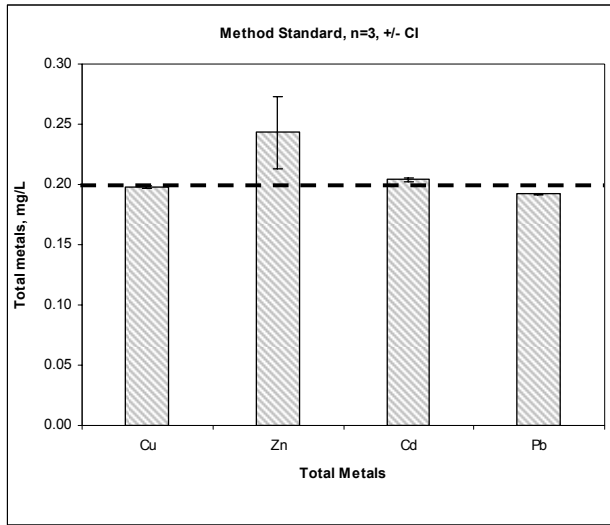
Figure 8. Aqueous total metals analysis, method standards.

Table 4. Aqueous total metals analysis, standards and blanks.

	Method Standards			MS	Method Blanks		Equipment Blanks	
	Average	CI	% of Calculated	MDL	Average	CI	Average	CI
Cu, mg/L	0.198	0.001	99%	0.005	0.011	0.000	0.011	0.000
Zn, mg/L	0.243	0.030	121%	0.005	0.006	0.001	0.008	0.008
Cd, mg/L	0.204	0.001	102%	0.005	0.014	0.000	0.015	0.000
Pb, mg/L	0.192	0.001	96%	0.005	0.002	0.001	0.001	0.000

4 RESULTS AND DISCUSSION

4.1 Event precipitation and runoff data

4.1.1 Event summaries

The events covered during the course of this study summarized in Table 5 and Table 6 for the Spokane LIA site, Table 7 and Table 8 for the Pullman LIA site, and Table 9 for the North Bend LIA site. For this study, events were delineated by a period of at least three hours of no rain gauge activity. The

Pullman site was monitored for 15 weeks, receiving approximately 148 mm of precipitation with an average of 4.4 mm per event, and the Spokane site was for 10 weeks, receiving 99 mm of precipitation with an average of 5.5 mm per event. The North Bend site provided only two days worth of reliable data due to numerous complications. The Pullman LIA site also experienced problems, including slot drain bypass and tipping bucket malfunctions. Despite these complications, of the events that provided reliable data sets, the Pullman and Spokane LIA site pavement runoff measurements typically documented fairly consistent runoff fractions of the theoretical runoff, calculated based on the contributing surface area. These values were 39% +/- 6% and 78% +/- 6% of the theoretical runoff for the Pullman and Spokane LIA sites, respectively. The North Bend LIA site runoff fraction averaged 55% between the two documented events. The remaining fractions are assumed to have bypassed the slot drains as spray due to passing traffic. The differences in this fraction between the two sites are a function of road geometry, traffic density, and rainfall intensity. Only the Spokane site measured runoff at distances other than at 0 m from the pavement edge. Five events resulted in runoff at the 3.2 m distance, and only one of these events resulted in runoff at the 6.1 m distance. All the measured runoff at these distant slot drains was less than 3% of the runoff that was measured at the 0 m distance, indicating that greater than 97% was infiltrated.

Table 5. Spokane site precipitation summary.

Date	Duration, Hours	Good Rainfall data	Total Rainfall, mm	Peak Intensity, mm/hour	Peak 5 Min Intensity, mm/hour	Antecedent Dry Period, hours
9/11/04 5:09	**3.9**	**yes**	**10.16**	**18.85**	**12.19**	**-**
9/12/04 16:38	**0.4**	**yes**	**2.54**	**16.18**	**12.19**	**31.6**
9/13/04 11:05	1.3	yes	1.78	12.53	6.10	18.0
9/13/04 16:16	0.9	yes	3.05	16.04	12.19	3.9
9/15/04 4:34	**6.6**	**yes**	**5.33**	**2.46**	**3.05**	**35.4**
9/15/04 14:48	**2.8**	**yes**	**3.05**	**13.75**	**9.14**	**3.7**
9/17/04 11:24	**4.5**	**yes**	**3.56**	**2.87**	**3.05**	**41.8**
10/6/04 7:38	-	windy	<1.0	-	-	447.7
10/9/04 3:47	**5.2**	**yes**	**5.33**	**2.89**	**3.05**	**55.9**
10/16/04 12:18	**2.1**	**yes**	**3.56**	**9.10**	**9.14**	**171.4**
10/16/04 23:19	**14.2**	**yes**	**9.40**	**10.95**	**9.14**	**8.9**
10/17/04 19:07	**6.5**	**yes**	**8.13**	**11.08**	**6.10**	**5.6**
11/1/04 22:33	**2.0**	**yes**	**1.02**	**1.35**	**3.05**	**44.9**
11/2/04 11:26	**11.0**	**yes**	**11.18**	**6.90**	**3.05**	**10.9**
11/6/04 17:39	0.9	insignificant	<1.0	-	-	-
11/15/04 17:56	**12.0**	**yes**	**10.92**	**2.23**	**3.05**	**307.5**
11/18/04 7:14	**3.2**	**yes**	**6.35**	**6.72**	**6.10**	**49.3**
11/23/04 22:24	**6.9**	**yes**	**11.42**	**3.18**	**3.05**	**131.9**
Bold events have been graphed						

Table 6. Spokane site runoff summary.

Date	0 m Slot Drain			3.2 m Slot Drain		6.1 m Slot Drain	
	Good Runoff data	Runoff Depth, mm[1]	% Captured (78+/- 6%)[2]	Runoff Depth, mm[1]	% Infiltrated	Runoff Depth, mm[1]	% Infiltrated
9/11/04 5:09	**yes**	**7.94**	**78**				
9/12/04 16:38	**yes**	**1.62**	**64**				
9/13/04 11:05	yes	0.61	34				
9/13/04 16:16	yes	2.49	82				
9/15/04 4:34	**yes**	**4.69**	**88**				
9/15/04 14:48	**yes**	**2.12**	**70**				
9/17/04 11:24	**yes**	**2.40**	**68**				
10/6/04 7:38	yes	0.11	-				
10/9/04 3:47	**yes**	**4.64**	**87**	**0.02**	**99.67%**		
10/16/04 12:18	**yes**	**2.76**	**78**				
10/16/04 23:19	**yes**	**7.60**	**81**				
10/17/04 19:07	**yes**	**7.44**	**92**	**0.16**	**97.86%**	**0.02**	**99.36%**
11/1/04 22:33	**yes**	**0.64**	**63**				
11/2/04 11:26	**yes**	**10.51**	**94**				
11/6/04 17:39	yes	0.07	-				
11/15/04 17:56	**yes**	**9.54**	**87**	**0.01**	**99.92%**		
11/18/04 7:14	**yes**	**6.23**	**98**	**0.03**	**99.51%**		
11/23/04 22:24	**yes**	**10.07**	**88**	**0.02**	**99.77%**		

[1] Runoff Depth = Volume calculated by # of tips/contributing surface area
[2] % Captured=(Runoff Depth)/(Rainfall Depth x Contributing Area), average +/- CI, n = 16, α = 0.05
Bold events have been graphed

Table 7. Pullman site event precipitation and runoff summary, 1 of 2.

Date	Duration, Hours	Good Rainfall data	Total Rainfall, mm	Peak Intensity, mm/hour	Peak 5 Min Intensity, mm/hour	Antecedent Dry Period, hours	Good Hydrograph data?	Runoff Depth, mm[1]	Peak Runoff, mm/hr	% Captured (39 +/- 6%)[2]
8/17/04 16:52	6.13	no	<5.0	-	-	-	yes	0.48	10.8	-
8/6/04 3:57	1.47	yes	3.3	10.0	9.1	244.9	bypassed	-	-	-
8/19/04 15:15	2.22	yes	2.5	32.1	6.1	57.8	bypassed	-	-	-
8/22/04 0:42	**2.54**	**yes**	**3.3**	**3.6**	**3.0**	**55.2**	**yes**	**0.57**	**1.2**	**17**
8/22/04 4:07	**20.57**	**yes**	**11.9**	**20.3**	**18.3**	**3.9**	**yes**	**3.10**	**9.9**	**26**
8/24/04 0:02	**0.97**	**yes**	**1.5**	**18.5**	**6.1**	**20.3**	**yes**	**0.58**	**7.2**	**38**
8/24/04 4:00	4.87	no	<0.5	-	-	3.0	insignificant	-	-	-
8/24/04 18:12	**1.57**	**yes**	**1.8**	**2.9**	**3.0**	**9.3**	**yes**	**0.50**	**0.7**	**28**
8/25/04 4:16	**8.88**	**yes**	**8.1**	**67.7**	**21.3**	**8.5**	**yes**	**3.61**	**36.1**	**44**
8/25/04 17:19	1.43	no	<1.0	-	-	4.6	yes	1.42	36.1	-
9/13/04 15:12	**2.67**	**yes**	**7.4**	**13.3**	**6.1**	**428.4**	**yes**	**2.91**	**12.1**	**39**
9/13/04 21:34	**1.47**	**yes**	**2.5**	**6.5**	**6.1**	**3.7**	**yes**	**0.88**	**3.9**	**35**
9/15/04 7:48	**3.65**	**yes**	**4.1**	**5.8**	**6.1**	**32.8**	**yes**	**1.62**	**4.5**	**40**
9/18/04 1:22	**4.85**	**yes**	**8.6**	**31.5**	**21.3**	**61.9**	**yes**	**3.71**	**15.5**	**43**
9/19/04 15:36	**4.53**	**yes**	**2.5**	**8.7**	**6.1**	**33.4**	**yes**	**0.94**	**2.7**	**37**
9/23/04 1:09	0.83	no	<1.0	-	-	77.0	insignificant	-	-	-
10/9/04 4:57	6.95	yes	11.9	6.6	6.1	386.9	incomplete	-	-	-
10/16/04 9:54	8.63	yes	6.9	4.5	3.0	166.0	malfunction	-	-	-
10/17/04 7:02	2.32	yes	1.8	1.6	3.0	12.5	malfunction	-	-	-
10/17/04 20:45	10.81	yes	10.9	8.1	9.1	11.4	malfunction	-	-	-
10/18/04 16:58	3.68	yes	2.0	1.2	3.0	39.4	malfunction	-	-	-
10/20/04 12:00	0.56	yes	1.0	2.2	3.0	39.3	malfunction	-	-	-
10/20/04 23:54	6.06	yes	5.1	12.4	9.1	11.3	malfunction	-	-	-
10/21/04 9:20	1.44	yes	1.0	3.2	3.0	3.4	malfunction	-	-	-
10/21/04 17:33	0.10	yes	0.6	16.9	12.2	6.8	malfunction	-	-	-

Table 8. Pullman site precipitation and runoff summary, 2 of 2.

Date	Duration, Hours	Good Rainfall data	Total Rainfall, mm	Peak Intensity, mm/hour	Peak 5 Min Intensity, mm/hour	Antecedent Dry Period, hours	Good Hydrograph data?	Runoff Depth, mm[1]	Peak Runoff, mm/hr	% Captured (39 +/- 6%)[2]
10/22/04 9:43	5.85	yes	6.4	2.3	3.0	16.1	malfunction	-	-	-
10/30/04 15:51	**0.26**	**yes**	**1.8**	**9.8**	**6.1**	**192.3**	**yes**	**0.38**	**3.3**	**22**
10/31/04 8:19	7.57	yes	1.3	1.0	3.0	16.2	insignificant	-	-	-
11/1/04 21:40	1.19	yes	1.0	0.9	3.0	29.8	malfunction	-	-	-
11/2/04 15:18	9.32	yes	6.6	2.0	3.0	16.3	malfunction	-	-	-
11/15/04 22:04	**3.06**	**yes**	**2.8**	**1.7**	**3.0**	**309.6**	**yes**	**1.53**	**1.3**	**55**
11/18/04 9:35	**1.14**	**yes**	**3.3**	**3.8**	**6.1**	**56.5**	**yes**	**1.36**	**4.2**	**41**
11/23/04 23:27	**8.54**	**yes**	**13.7**	**4.0**	**3.0**	**132.7**	**yes**	**7.16**	**2.0**	**52**
11/24/04 12:54	**6.17**	**yes**	**3.6**	**2.2**	**3.0**	**4.9**	**yes**	**1.10**	**1.4**	**31**
11/24/04 23:33	**7.06**	**yes**	**7.4**	**2.0**	**3.0**	**4.5**	**yes**	**2.86**	**1.7**	**39**
11/25/04 15:46	**0.99**	**yes**	**5.3**	**19.9**	**12.2**	**9.1**	**yes**	**3.60**	**8.3**	**67**

[1] Runoff Depth = Volume calculated by # of tips/contributing surface area
[2] average +/- CI, n = 17, α = 0.05
Bold events have been graphed

Table 9. North Bend precipitation and runoff summary.

Date	Duration, Hours	Good Rainfall data	Total Rainfall, mm	Peak Intensity, mm/hour	Peak 5 Minute Intensity, mm/hour	Antecedent Dry Period, hours	Good Hydrograph data?	Runoff Depth, mm[1]	Peak Runoff, mm/hour	% Captured (55% Average)
9/10/04 19:44	**11.2**	**yes**	**51.31**	**32.08**	**18.29**	**3.5**	**yes**	**26.24**	**11.06**	**51**
9/11/04 23:50	**4.0**	**yes**	**6.35**	**17.58**	**12.19**	**16.9**	**yes**	**3.73**	**8.29**	**59**

[1] Runoff Depth = Volume calculated by # of tips/contributing surface area
Bold events have been graphed

4.1.2 Event hyetograph/hydrograph

Hyetographs were calculated based on the time interval between rain-gauge tipping bucket tips, as were runoff intensity measurements. Each precipitation event separated by a minimum of three hours that provided reliable data was processed in spreadsheets and rainfall and runoff were normalized to the contributing surface area, thus expressing values as an intensity depth vs. time. An example event hyetograph/hydrograph from the Spokane LIA site is presented in Figure 9. Hyetographs and their corresponding hydrographs for complete events (indicated by the bold designation in the Tables 4 through 8) are presented in their entirety in Appendix B, C, and D for the Pullman, Spokane and North Bend LIA sites, respectively. Most events produced runoff exclusively at the pavement edge, and at intensities within the calibrated range of the tipping buckets. Where the 15 mm/hour, 10 mm/hour, and 4.5 mm/hour tipping bucket calibration limits were exceeded for the Pullman, Spokane and North Bend LIA sites, respectively, and may appear to have produced valid hydrographs, the accuracy of these intensity depth measurements are unknown. As nearly all events produced runoff only at the pavement edge and the contributing surface area was entirely impervious, it would be expected that the hyetographs and hydrographs are very similar. Any difference could be exclusively attributed to spray.
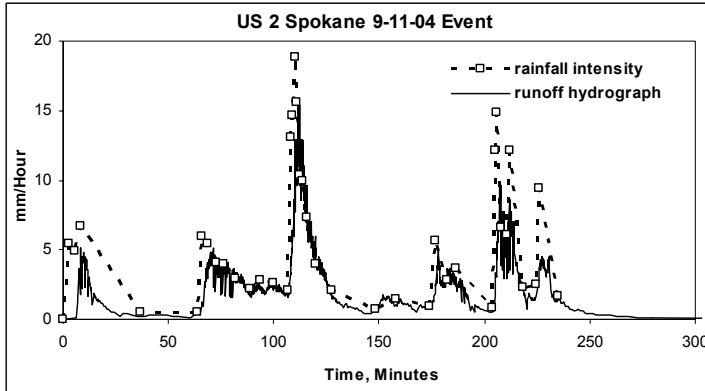
Figure 9. Spokane LIA site event hyetograph/hydrograph.

4.2 Stormwater Quality Data

4.2.1 Composite samples – the contribution of multiple events

Multiple precipitation events contributed to most aqueous samples. The precipitation events that contributed to each composite sample are documented in Table 11 and Table 10 for the Pullman and Spokane LIA sites, respectively. Analyses comparing these two data sets is presented in section *4.2.4, Overflowed vs. non overflowed comparison*. Ideally, a complete or representative composite would have been collected by the composite sampler for each event, and a sample would have been obtained for analysis of each event.

Table 10. Contributing events to stormwater samples, Pullman LIA site.

Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date
8/23/04[1]	8/24/04	8/26/04[1]	9/16/04[1]	9/24/04[1]	10/12/04[1]	10/22/04[1]	10/30/04	11/3/04[1]	11/16/04	11/19/04	11/25/04[1]
Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events	Contributing Storm Events
8/22/04 0:42	8/24/04 0:02	8/24/04 18:12	9/13/04 15:12	9/18/04 1:22	10/9/04 4:57	10/16/04 9:54	10/30/04 15:51	10/31/04 8:19	11/15/04 22:04	11/18/04 9:35	11/23/04 23:27
8/22/04 4:07		8/25/04 4:16	9/13/04 21:34	9/19/04 15:36		10/17/04 7:02		11/1/04 21:40			11/24/04 12:54
		8/25/04 17:19	9/15/04 7:48	9/23/04 1:09		10/17/04 20:45		11/2/04 15:18			11/24/04 23:33
						10/18/04 16:58					11/25/04 15:46
						10/20/04 12:00					
						10/20/04 23:54					
						10/21/04 9:20					
						10/21/04 17:33					
						10/22/04 9:43					
Total Precipitation, mm											
15.26	1.52	10.91	13.98	12.18	11.94	35.65	1.78	8.89	2.79	3.30	29.97
Total Runoff, mm											
3.67	0.58	5.53	5.41	4.65	4.66[2]	13.90[2]	0.38	3.46[2]	1.53	1.36	14.72

[1] Sampler overflow
[2] Calculated by multiplying precipitation depth by 39%

Table 11. Contributing events to stormwater samples, Spokane LIA site.

Sample Date	Sample Date	Sample Date	Sample Date
9/19/2004	10/12/2004	10/20/2004	11/19/2004
Contributing Storm Events	**Contributing Storm Events**	**Contributing Storm Events**	**Contributing Storm Events**
9/11/04 5:09	10/6/04 7:38	10/16/04 12:18	11/1/04 22:33
9/12/04 16:38	10/9/04 3:47 [1]	10/16/04 23:19	11/2/04 11:26
9/13/04 11:05		10/17/04 19:07 [1,2]	11/6/04 17:39
9/13/04 16:16			11/15/04 17:56 [1]
9/15/04 4:34			11/18/04 7:14 [1]
9/15/04 14:48			
9/17/04 11:24			
Total Precipitation, mm			
29.47	**6.33**	**21.09**	**30.47**
Total Runoff, mm[3]			
21.87	**4.75**	**17.80**	**26.99**

[1] Only contributing event(s) to the 3.2 m slot drain composite sample
[2] Only contributing event to the 6.1 m slot drain composite sample
[3] Runoff at the 0 m slot drain (pavement edge)

4.2.2 Metals analysis

Results between total and dissolved metals were not typical, as measured dissolved concentrations for Zn and Pb often exceeded total metals values, which is theoretically impossible. This could have been due to a number of reasons. Sample volumes collected (mostly 50 ml) could have been inadequate to perform the total metals digestions as prescribed in the method (100 ml), and most filtered samples were erroneously filtered using the paper disc that separates the 0.45 um filters from each other instead of the actual 0.45 um paper. However, even properly filtered samples resulted in fractions of dissolved metals to total metals that exceeded the theoretical maximum of 100% for Zn and Pb. A review of the metals analyses method blanks indicates that there was no contamination introduced in the preparation method, and dilution calculations were rigorously reviewed. Unfortunately, standard additions to samples were not performed, as is common in environmental analyses. This would have identified

potential matrix interference. While the source of error can not be clearly

identified, it has been assumed that the more reliable of the two analyses is the

total metals analysis, and that is the one that will be referred to most often in this

report.

Partitioning between the dissolved and particulate phase is highly

dynamic, based on the temporal, physical and chemical variables mentioned in

the literature review. Metals may be primarily in the dissolved phase once lifted

from the road surface, and partitioning to particulates will predominate upon

entering the roadside environment, on the order of hours and to an extent that

is dependent on site specific and conditionally specific reaction kinetics. At

best, dissolved metals data obtained from a composite sample bucket hours

after an event only indicates the metals partitioning behavior within the bucket.

Since it is assumed that nearly all runoff will be infiltrated within LIAs, total metal

loading to roadside environments is ultimately the more important parameter.

Finally, the experimental design did not lend itself to obtaining a time series for

partitioning behavior throughout runoff events. Dynamic partitioning behavior of

highway runoff may be best understood by reviewing other research

(Sansalone and Buchberger, 1997a; Glenn III et al., 2001; Dean et al., 2005).

4.2.3 Total metals

Average concentrations of total metals in stormwater samples are

presented in Figure 10 for the Pullman LIA site samples and in Figure 11 for the

Spokane LIA site samples. Comparisons to reported values are reported in

Table 12. While Cu and Zn are within the expected range, Pb is considerably

lower (possibly due to elimination of Pb additives in gasoline) while TSS is higher

(possibly due to local agricultural activities). Certain samples had multiple

contributing events, as documented in *4.2.1 Composite samples – the*

contribution of multiple events and summarized in Table 11 and Table 10. Total

aqueous sample metals data is summarized in Table 13 and Table 14 for the

Pullman and Spokane LIA sites, respectively. While a large and diverse number

of factors influence the concentration of metals in a particular composite

stormwater sample and concentrations between events may vary considerably, it

is interesting to note that concentrations for twelve Pullman LIA site samples

(Figure 10) did not vary substantially. This result may be influenced not only by

the fact that some samples were composites of multiple events, but also by the

fact that some samples were subject to overflow, a factor which will be discussed

in the following section, *4.2.4 Overflowed vs. non overflowed comparison*. Figure

11 presents average total metals concentrations of stormwater runoff samples for

the three different distances for the Spokane site composite samples. There is a

general trend of increasing concentrations with distance, indicating that metals

deposited from previous events are desorbed and/or re-suspended and

transported down gradient.

Table 12. Range of runoff concentrations vs. reported values.

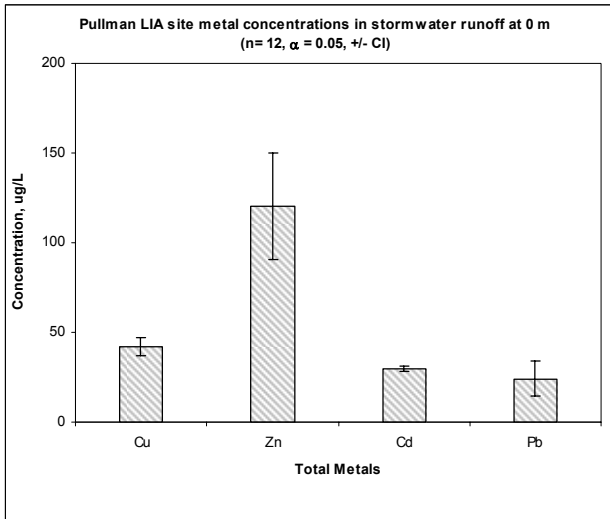| Contaminant	8 WA sites[1]	Pullman SR 270	Spokane US 2
	mg/L	mg/L	mg/L
TSS	34-126	103-250	-
Cu	0.017-0.072	0.028-0.055	0.045-0.078
Zn	0.040-2.892	0.042-0.192	0.043-0.104
Pb	0.046-1.065	0.007-0.067	0.026-0.050
[1] Driscoll, et al. 1990			

Figure 10. Pullman LIA site metals concentrations in stormwater runoff.
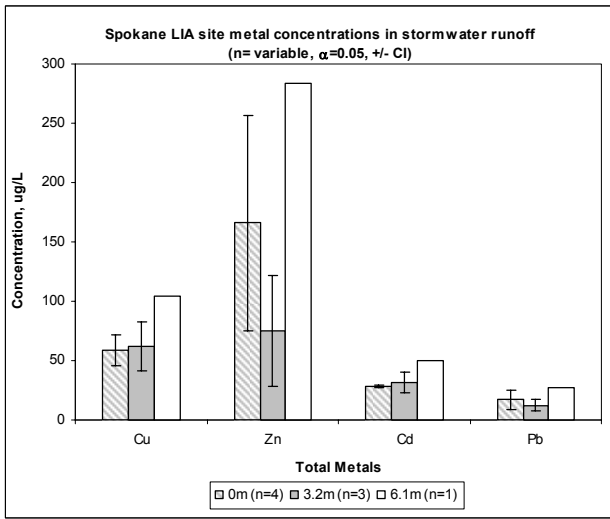

Figure 11. Spokane LIA site metals concentration in stormwater runoff.

Table 13. Pullman site stormwater composite samples metals data.

Sample Date	Slot drain Location	Rainfall, mm[1]	Runoff, L[1]	Runoff Depth, mm[1]	Total metals concentration, mg/L				Total Mass, mg[3]			
					Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
8/23/04	0m	15.26	43.1	3.67	0.030	0.052	0.027	0.011	1.28	2.26	1.18	0.46
8/24/04	0m	1.52	6.8	0.58	0.034	0.074	0.028	0.013	0.23	0.51	0.19	0.09
8/26/04	0m	10.91	65.1	5.53	0.050	0.150	0.030	0.067	3.24	9.76	1.93	4.34
9/16/04	0m	13.98	63.7	5.41	0.045	0.133	0.028	0.037	2.86	8.47	1.78	2.38
9/24/04	0m	12.18	54.6	4.65	0.055	0.171	0.034	0.037	2.98	9.32	1.84	2.02
10/12/04	0m	11.94	54.8[2]	4.66[2]	0.053	0.152	0.035	0.030	2.88	8.31	1.89	1.67
10/22/04	0m	25.65	163.5[2]	13.90[2]	0.050	0.166	0.028	0.032	8.11	27.06	4.64	5.19
10/30/04	0m	1.78	4.5	0.38	0.046	0.158	0.027	0.023	0.21	0.71	0.12	0.10
11/3/04	0m	8.89	40.8[2]	3.46[2]	0.034	0.079	0.027	0.010	1.40	3.24	1.09	0.42
11/16/04	0m	2.79	18.0	1.53	0.047	0.192	0.031	0.014	0.84	3.46	0.55	0.26
11/19/04	0m	3.30	16.0	1.36	0.034	0.074	0.030	0.008	0.54	1.18	0.47	0.13
11/25/04	0m	29.97	173.1	14.72	0.028	0.042	0.029	0.007	4.88	7.26	5.05	1.27
	Total	**148.16**		**59.87**				**Total**	**29.45**	**81.54**	**20.73**	**18.33**

[1] Sum of contributing events
[2] Assuming 39% capture of theoretical runoff calculated from total event depth (actual runoff was not quantified)
[3] Calculated by multiplying the concentration (mg/L) by the runoff volume (L)

Table 14. Spokane site stormwater composite samples metals data.

Sample Date	Slot Drain Location	Rainfall, mm[1]	Runoff, L[1]	Runoff Depth, mm[1]	Total metals concentration, mg/L				Total Mass, mg[2]			
					Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
9/19/04	0m	29.47	384.1	21.87	0.055	0.055	0.123	0.029	21.23	47.40	11.14	5.10
10/12/04	0m	6.33	83.4	4.75	0.045	0.045	0.064	0.027	3.75	5.34	2.25	0.64
10/12/04	3.2m	6.33	0.4	0.02	0.080	0.080	0.122	0.029	0.03	0.04	0.01	0.00
10/20/04	0m	21.09	312.5	17.80	0.056	0.056	0.197	0.028	17.60	61.49	8.90	6.45
10/20/04	3.2m	21.09	3.8	0.16	0.043	0.043	0.045	0.026	0.17	0.17	0.10	0.06
10/20/04	6.1m	21.09	0.7	0.02	0.104	0.104	0.283	0.050	0.07	0.20	0.03	0.02
11/19/04	0m	30.47	474.1	27.00	0.078	0.078	0.279	0.028	36.75	132.37	13.45	12.85
11/19/04	3.2m	30.47	0.9	0.04	0.064	0.064	0.058	0.040	0.06	0.05	0.04	0.01
	Total[3]	87.36		71.42				Total[3]	79.33	246.6	35.74	25.04

[1] Sum of contributing events
[2] Calculated by multiplying the concentration (mg/L) by the runoff volume (L)
[3] Totals only of edge of pavement values

4.2.4 Overflowed vs. non overflowed comparison

A comparison was made of Pullman site data between the total metals concentrations in runoff composite samples resulting from overflow and those that were non-overflow, or complete samples. Preventing overflow required that the precipitation event produced less than 5 gallons of runoff, since that is the size of the composite sample bucket used in this study. The first flush phenomena predicts that high concentrations of contaminants, including sediments and metals (both particulate bound and dissolved), are transported during the first time increments of a runoff event. Subsequent time intervals result in substantially more dilute contaminant concentrations, since there is a finite quantity of contaminants that have been deposited on the road surface. This quantity is a function of a variety of factors, as previously discussed in the literature review. Therefore, it would be expected that, all other things being equal, composite samples of short duration runoff events would have higher concentrations of contaminants than would longer events – a function of hydraulic dilution. However, as a result of the limited composite sample bucket size, this bucket was apt to overflow. The significance of overflow on obtaining a representative sample is unknown. If overflow were representative (i.e., if metals phase partitioning between the adsorbed and dissolved phases was in equilibrium and the particulate fraction was homogenously suspended (which could occur either with complete mixing or if the particulate fraction was comprised entirely of non-settle-able colloids, which would not be likely), and/or if metals were primarily in the aqueous phase in runoff as has been suggested in

the literature), then overflow would not be detrimental to obtaining an accurate sample. If overflow were not representative (i.e., metals were predominantly particulate bound in runoff, and particulates were readily settle-able), then the composite samplers would accumulate the constituents of concern. It is unclear how much or how little these factors influenced contaminant analysis results, as phase distribution is physically, chemically, and temporally dependant and particulate quality is function of a host of factors. Additionally, metal species are strongly associated with smaller particles, which inherently have lower settling velocities within a 5 gallon bucket. On occasion, multiple short duration events were composited and resulted in overflow, which were then collected as a single sample (Table 15). This study was not instrumented adequately to obtain complete or representative composite (or discrete time series) samples for long duration events. An attempt was made, however, to identify differences between complete composite short duration event samples, and events (either singly or multiply), that resulted in overflow of the composite sample bucket. These results are presented in Table 15 and Figure 12. It can be seen that, of the data that was obtained, differences in the metals concentrations of overflowed and not overflowed samples are not substantially different.
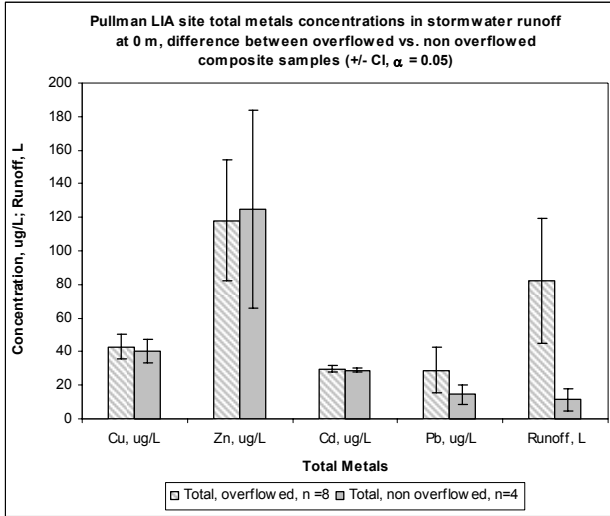
Figure 12. Comparison of metals concentrations between overflowed and non- overflowed composite samples.

Table 15. Contributing events for overflowed vs. not overflowed samples.

Overflowed		Not overflowed	
Sample Date	# of contributing events	Sample Date	# of contributing events
8/23/04	3	8/24/04	1
8/26/04	3	10/30/04	1
9/16/04	3	11/16/04	1
9/24/04	3	11/19/04	1
10/12/04	1		
10/22/04	9		
11/3/04	3		
11/25/04	4		

Table 16. Overflowed vs. not overflowed sample statistics.

	Overflowed		Not Overflowed	
	Average	Confidence	Average	Confidence
Cu, ug/L	42.94	7.36	40.21	6.91
Zn, ug/L	118.07	36.08	124.62	58.76
Cd, ug/L	29.68	2.00	28.94	1.32
Pb, ug/L	28.90	13.65	14.45	5.95
Runoff, L	82.34	37.28	11.33	6.54

4.2.5 Contaminant mass vs. event depth regression equations

If it was assumed that aqueous runoff concentrations of samples resulting from overflow were not significantly different from values that would have resulted from a complete composite sample, i.e., that these overflow samples were representative, then a mass balance could be performed and the mass of total metals could be compared with runoff depth to develop regression curves for each constituent. It could be expected that, if the first flush phenomenon is an accurate dynamic characterization of contaminant behavior in runoff, then a graph of this relationship would asymptotically approach some maximum with increasing event depth, if all other factors (contributing traffic count, antecedent dry period, etc.) were similar. Events could then be characterized as being pollutant limited or flow limited with regard to a typical pollutograph, based on where on the asymptotic regression curve each event fell.

An evaluation of this type was performed relating runoff depth to total contaminant mass in runoff at the 0 m distance from the Pullman LIA site. A regression curve for Cu is presented in Figure 13 from data supplied in Table 13. For the four data sets resulting from less than 2 mm of runoff depth, runoff volumes were sufficiently small so as not to overflow the composite sample bucket and therefore the composite sample could be considered complete. There were two explanations why the observed regression curve does not follow the expected asymptotic maximum model. Either the overflow samples were not representative, or the event depths were not of sufficient quantity to have removed the mass of metals in their entirety, characterizing all of the events as

being flow limited events. It is unclear which possibility more accurately
describes these results.

This analysis is exhibitory in nature, demonstrating the type of analysis
that can be performed. If precipitation events were sampled more definitively
and results were more exact, these regression curves could be reliable. As total
contaminant mass becomes increasingly skewed with increasing total runoff
volume with overflowed samples, the validity of incorporating any samples that
included multiple events is questionable, despite any previously identified
assumptions. Regression curves for the Pullman LIA site are presented in
Appendix F. While total mass data for Spokane events is presented in Table 14,
no regression curves were developed, as there were only four aqueous samples
taken, and all were generated from multiple events.

Pullman site runoff depth vs. mass Cu load in runoff at 0 m

$y = 0.477x^{1.0099}$
$R^2 = 0.96$

(x-axis: Runoff Depth, mm; y-axis: Mass of Cu in Runoff, mg)
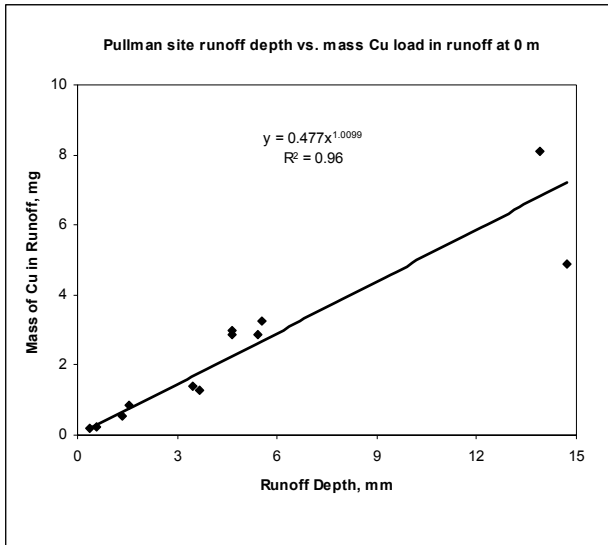
Figure 13. Pullman site LIA runoff depth vs. mass Cu load in runoff at 0 m.

4.2.6 Runoff vs. total deposition

Prior to installation of the slot drain covers at the 2 m and 4 m distances at the Pullman LIA site, two events produced aqueous samples at two locations. It was suspected that the collected volume was merely a result of rainfall entering the slot drains, as the volumes were low and of similar quantity. Once the slot drain covers were installed, and events with far greater event depths occurred that resulted in no volume generated at these two locations, it was confirmed that the previously collected volumes were exclusively from rainfall. As this was the case, the resulting metals within those samples had been derived from spray, wet deposition during the precipitation event, and dry deposition during the antecedent dry period. The contributing storm events resulted in similar total precipitation depths and runoff volumes, as can be seen in Table 17. While the contaminants collected at the pavement edge could be considered a combination of what is found in both runoff and total deposition, it is presumed that the dominant component is runoff and will be referred to exclusively as runoff.

A comparison was therefore made between the concentrations of metals in the runoff collected at the 0 m slot drain and of the total deposition collected at the 2 m and 4 m location at the Pullman LIA site. Concentration results are summarized in Table 18 and presented graphically in Figure 14 and Figure 15. A clear trend is not apparent, but it is evident that metals are indeed transported to the 2 m and 4 m distance from automotive spray and/or wet and/or dry deposition. A mass balance was performed evaluating the total mass delivered to roadside environments at the three distances (Table 19). Greater than 93% of

all metals delivered to the 4 m swath adjacent to the Pullman LIA site are delivered through immediate runoff from the pavement. The remaining fraction is attributed to traffic spray and wet and dry deposition.

Table 17. Runoff vs. total deposition, Pullman LIA site.

Sample Date	Contributing Storm Events	Storm Depth, mm	Volume in 0 m Slot Drain (attributed to runoff)	Volume in 2 m Slot Drain[2] (attributed to deposition)[1]	Volume in 4 m Slot Drain[2] (attributed to deposition)[1]
8/26/04	8/24/04 18:12 8/25/04 4:16 8/25/04 17:19	10.96	65.1L	0.5 L	0.7 L
9/16/04	9/13/04 15:12 9/13/04 21:34 9/15/04 7:48	13.97	61.9L	1.1 L	0.6 L

[1] Including dry atmospheric deposition, wet weather fallout, and traffic induced spray, collected from corresponding slot drain composite samplers prior to slot drain cover installation
[2] Calculated by # of tips, confirmed by visual inspection of composite samplers

Table 18 . Metals concentrations of runoff vs. total depostion, Pullman LIA site.

Sample Date	Slot Drain	Sample Type	Total Metals, ug/L			
			Cu	Zn	Cd	Pb
8/26/04	0 m	Runoff	49.8	149.8	29.7	66.6
	2 m	Total Deposition	64.0	99.8	60.7	18.5
	4 m	Total Deposition	34.8	99.5	28.2	5.3
9/16/04	0 m	Runoff	44.9	132.9	28.0	37.3
	2 m	Total Deposition	57.8	420.5	29.8	8.6
	4 m	Total Deposition	72.2	258.4	34.5	12.7

Table 19. Metals mass in runoff vs. total deposition, Pullman LIA site.

Sample Date	Slot Drain	Total Volume, L	Cu		Zn		Cd		Pb	
			Mass, ug	% total	Mass, ug	% total	Mass, ug	% total	Mass, ug	% total
8/26/04	0 m	65.1	3239	98.3%	9755	98.8%	1931	97.5%	4336	99.7%
	2 m	0.5	32	1.0%	50	0.5%	30	1.5%	9	0.2%
	4 m	0.7	24	0.7%	70	0.7%	20	1.0%	4	0.1%
9/16/04	0 m	61.9	2778	96.3%	8226	93.0%	1732	97.0%	2311	99.3%
	2 m	1.1	64	2.2%	463	5.2%	33	1.8%	9	0.4%
	4 m	0.6	43	1.5%	155	1.8%	21	1.2%	8	0.3%
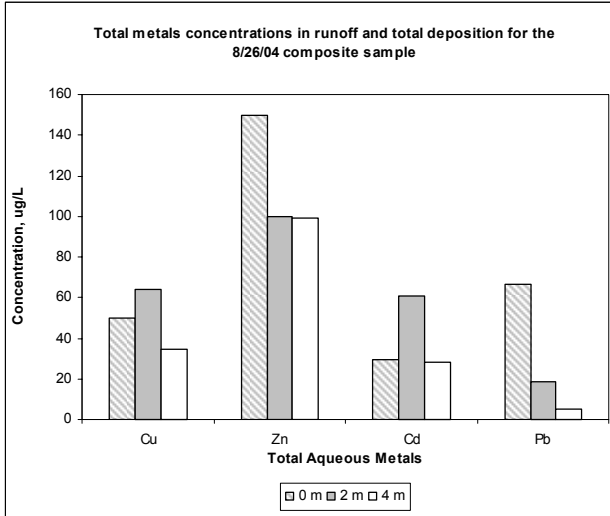
Figure 14. Total metals in runoff vs. total deposition, 8/26/04 composite sample, Pullman LIA site.
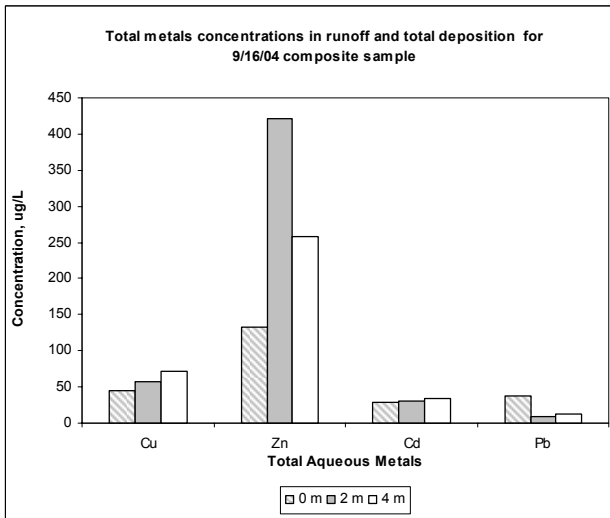
Figure 15. Total metals in runoff vs. total deposition, 9/16/04 composite sample, Pullman LIA site.

4.2.7 Suspended solids and particle size distribution analysis

Particle size distribution (PSD) analysis was performed on three precipitation event runoff samples from the Pullman site. These event samples, collected from the 11/16,/04, 11/19/04, and 11/25/04 events, were of sufficient volume to perform PSD analysis. Volume weighted mean sizes ranging from 5.43 -12.35 um. An example PSD analysis for the 11/16/04 event is presented in Figure 16. Of the three samples analyzed, suspended solids retained on a 0.45 um filter resulted in concentrations that ranged from 173.3 -250.4 mg/L, and concentrations of particulates that passed through a 100 um filter ranged from 115.72 – 155.69 mg/L, determined by multiplying the particulate fraction by volume by an assumed particulate density of 2.65 g/cm^3. Volume weighted mean sizes ranged from 5.43 to 12.35 um. Complete PSD and suspended solids data is presented in Table 20, and all PSD graphs for the three events are presented in Appendix E.

Table 20. Aqueous particulate data for three event samples.

Sample collection date	Static Light Scattering PSD determination					Gravimetric TSS determination
	Particles passed through a 100 um filter (n=3)					Particles retained on a 0.45 um filter (n=1)
	concentration by volume	Concentration, assuming a density of 2.65 g/cm^3		Volume weighted mean size		300 ml sample volume
	Average	Average	CI	Average	CI	Single value
	%	mg/L	mg/L	um	um	mg/L
11/16/04	0.0044	115.72	35.78	5.43	0.17	250.4
11/19/04	0.0059	155.69	13.96	7.88	2.54	173.3
11/25/04	0.0049	130.73	28.81	12.35	0.14	103.3
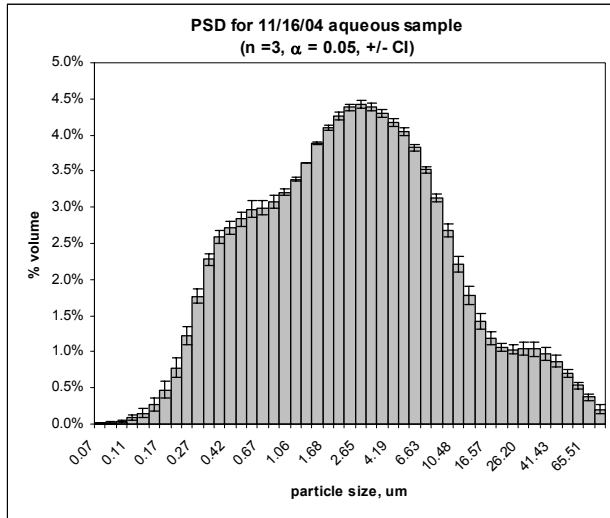
Figure 16. Sample PSD of an aqueous event sample by static light scattering.

4.3 Slot drain sediment data

4.3.1 Contribution of multiple events

Composite slot drain sediment samples were collected periodically for the Pullman LIA site and once at the end of the study for the Spokane LIA site. For the Pullman LIA site, multiple precipitation events contributed to each sediment sample, but differently than for aqueous samples due to a different sampling regime. Some events failed to yield appreciable quantities of sediment, and some sediment that was deposited existed as a slurry, making collection difficult. Under these circumstances collection was postponed to allow for the sediment to desiccate naturally. Inevitably, during this interim an additional event or two would occur. The precipitation events that contributed to each composite sediment sample collected at the Pullman LIA site are documented in Table 21. While sediment was only observed in the 0 m slot drain at the Pullman site since it alone received runoff, sediment was found in all three slot drains at the

Spokane LIA site. All events at the Spokane LIA site contributed to these composite sediment samples.

4.3.2 Sieve analysis and metals concentrations/fraction data

Sieve analysis was performed on each sediment sample, and each fraction of each sample was analyzed for Cu, Zn, Cd and Pb by ICP-MS according to EPA Method 200.7 as described in the methods section. The results for the 0 m slot drains are graphically presented in Figure 17 for the Pullman LIA site, and Figure 18 for the Spokane LIA site. A total of nine samples were collected from the Pullman 0 m slot drain, and it can be seen by looking at the confidence intervals for these samples that metals concentration and particle size distribution were remarkably uniform between samples. Metals concentrations increased characteristically with decreased particle size for nearly all samples and fraction sizes. There were no samples collected at the 2 m and 4 m distances. There was only one sample collected from the Spokane LIA site slot drains at the end of the study, but sediment was collected from all three slot drains. Fraction distribution between the three distances is presented in Figure 19. It can be seen that the sediments collected at the 0 m slot drain had a higher fraction of fine particles. Complete Pullman and Spokane LIA site slot drain data for is presented in Appendix G.

Table 21. Contributing events to slot drain sediment samples, Pullman LIA site

Sample Date 8/23/2004	Sample Date 8/24/2004	Sample Date 8/26/2004	Sample Date 9/16/2004	Sample Date[1] 10/22/2004	Sample Date[1] 11/3/2004	Sample Date 11/16/2004	Sample Date 11/19/2004	Sample Date[1] 11/25/2004
Storm Events	**Storm Events**	**Storm Events**	**Storm Events**	**Storm Events**	**Storm Events**	**Storm Events**	**Storm Events**	**Storm Events**
8/22/04 0:42	8/24/04 0:02	8/24/04 18:12	9/13/04 15:12	9/18/04 1:22	10/30/04 15:51	11/15/04 22:04	11/18/04 9:35	11/23/04 23:27
8/22/04 4:07		8/25/04 4:16	9/13/04 21:34	9/19/04 15:36	10/31/04 8:19			11/24/04 12:54
		8/25/04 17:19	9/15/04 7:48	9/23/04 1:09	11/1/04 21:40			11/24/04 23:33
				10/9/04 4:57	11/2/04 15:18			11/25/04 15:46
				10/16/04 9:54				
				10/17/04 7:02				
				10/17/04 20:45				
				10/18/04 16:58				
				10/20/04 12:00				
				10/20/04 23:54				
				10/21/04 9:20				
				10/21/04 17:33				
				10/22/04 9:43				
Total Precipitation, mm								
15.26	1.52	10.91	13.98	59.76	10.67	2.79	3.30	29.97
Total Runoff, mm								
3.67	0.58	5.53	5.41	23.21[2]	3.84[2]	1.53	1.36	14.72

[1] Samples with greater than 3 contributing events not included in correlation determinations between runoff depth and contaminant mass delivered
[2] Assuming 39% capture of theoretical runoff calculated from total event depth (actual runoff was not quantified)

Figure 17. Pullman LIA site 0 m slot drain sediment sieve analysis and metals concentration/fraction.
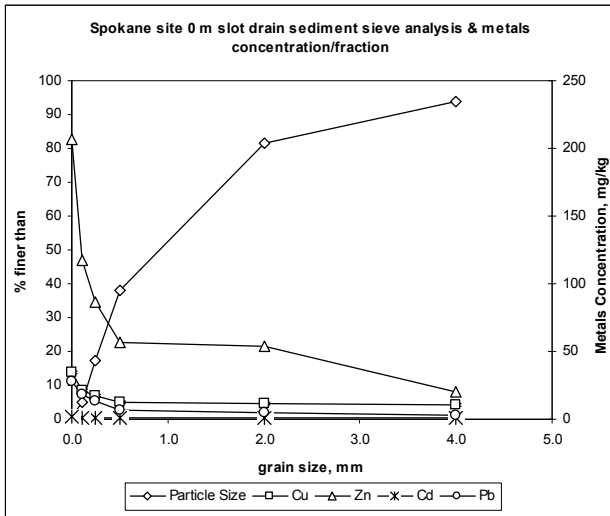
Figure 18. Spokane LIA site 0 m slot drain sediment sieve analysis and metals concentration/fraction.
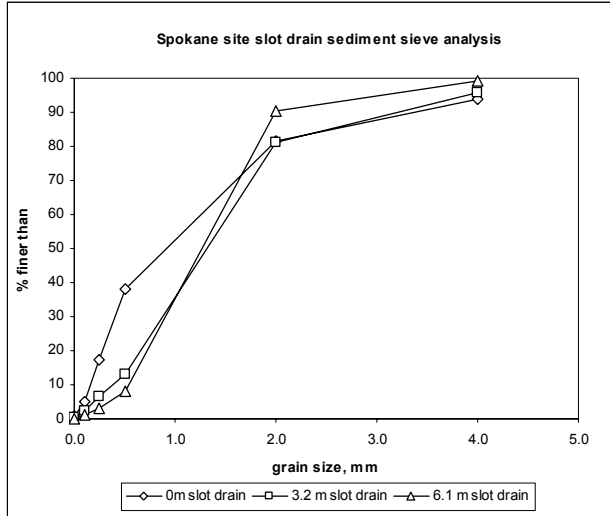
Figure 19. Spokane LIA site slot drain sediment sieve analysis.

4.3.3 Total metals concentrations

Slot drain sieve fractions were multiplied by the metal concentration of each fraction to calculate a total metals concentration for each sample. Averages of the nine Pullman site 0 m slot drain sediment samples are presented in Figure 20 and Table 22. Average total metals concentrations were 23.01 +/- 1.47 mg/kg for Cu, 73.16 +/- 4.40 mg/kg for Zn, 1.01 +/- 0.19 mg/kg for Cd, and 44.43 +/- 5.57 mg/kg for Pb. Of particular interest is that total metals concentration varies little between samples. Figure 21 and Table 23 presents total metals concentrations for the single sampling of sediment collected from the three slot drain distances at the Spokane site. Total Zn concentrations decreased with distance from the road, total Cu decreased slightly, and total Cd and Pb concentrations were relatively unchanged.
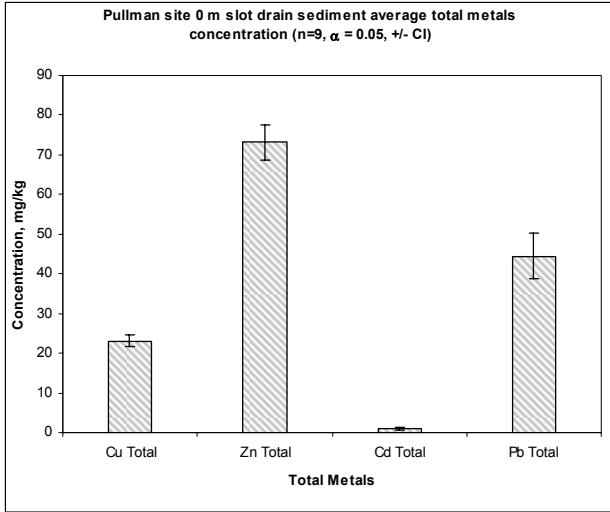
Figure 20. Pullman LIA site 0 m slot drain sediment average total metals concentration.
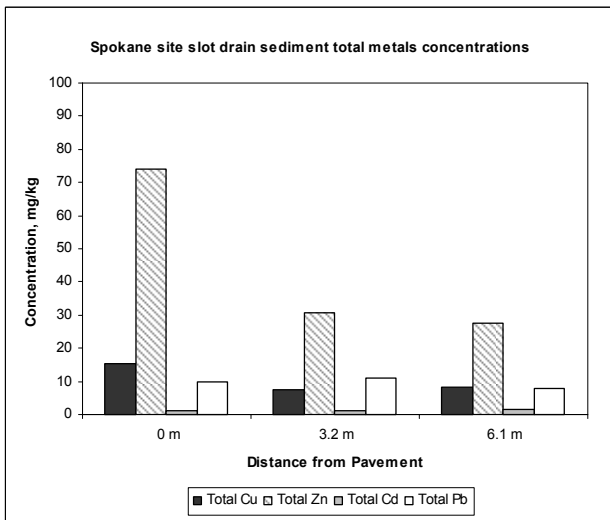
Figure 21. Spokane site slot drain sediment total metals concentrations.

Table 22. Pullman LIA site 0 m slot drain sediment average total metals concentrations.

Constituent	Average (n=9)	CI
	mg/kg	mg/kg
Cu Total	23.01	1.47
Zn Total	73.16	4.40
Cd Total	1.01	0.19
Pb Total	44.43	5.73

Table 23. Spokane LIA site slot drain sediment total metals concentrations.

Slot drain	0m	3.2 m	6.1 m
Constituent	mg/kg	mg/kg	mg/kg
Cu Total	15.16	7.32	8.25
Zn Total	73.86	30.75	27.74
Cd Total	1.31	1.33	1.42
Pb Total	9.83	10.90	7.81

4.3.4 Contaminant mass vs. event depth regression curves

Slot drain sediment total mass and total metals loadings from mass balance determinations could potentially be correlated with event runoff depth. Sediment was collected derectly from the slot drain, and was comprised of material that did not pass through to the composite sampler. For this study, this evaluation may be more reliable than the correlation between total metals loadings in stormwater runoff and event runoff depth, as sediment collection was not subject to potential skewing through dilution or concentration as a result of overflow. Admittedly these are completely different evaluations; sediment regression curves simply may be more accurate when comparing accuracy alone.

Regression curves were therefore prepared that compared runoff depth with the total mass of a contaminant in sediment samples from the Pullman LIA site 0 m slot drain. Results comparing the total mass of sediment and the total mass of Cu with runoff depth are presented in Figure 22 and Figure 23. As most metals concentrations were fairly uniform regardless of mass, it is logical that regression curves comparing metals mass with runoff depth closely resemble the regression curve comparing sediment mass with runoff depth. All regression curves developed comparing runoff depth to contaminant load for the Pullman

LIA site collected from the 0 m slot drain are presented in the Appendix. As there was only a single sample collected from the Spokane site, no regression analysis could be performed. Tabular data of contaminant masses in sediment calculated for the Pullman and Spokane sites are presented in Table 24 and Table 25, respectively.
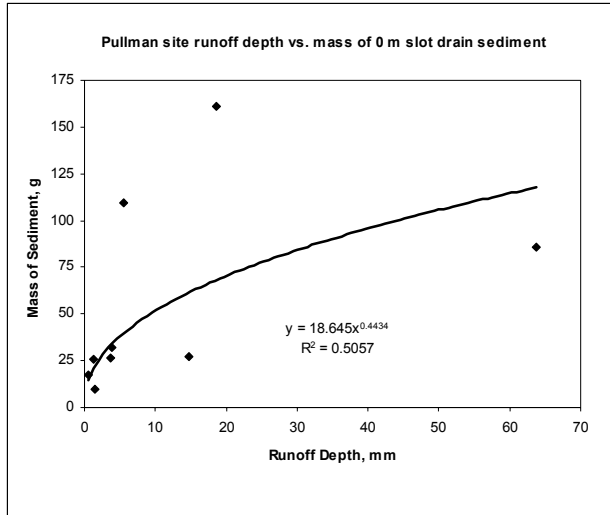
Figure 22. Pullman site runoff depth vs. mass of 0 m slot drain sediment.
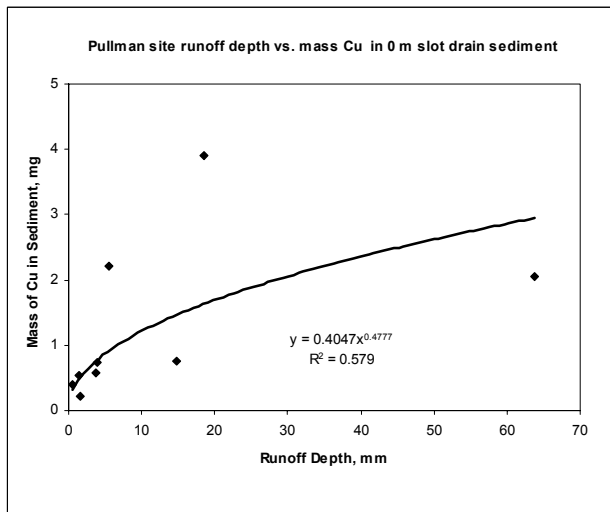
Figure 23. Pullman site runoff depth vs. mass Cu in 0 m slot drain sediment.

Table 24. Pullman site total mass of metals in 0 m slot drain sediment.

Sample Date	Total Storm Depth, mm	Runoff Depth, mm	Total Sediment Mass, g	Total Cu, mg	Total Zn, mg	Total Cd, mg	Total Pb, mg
8/23/2004	15.26	3.67	26.54	0.58	1.81	0.02	1.17
8/24/2004	1.52	0.58	17.52	0.39	1.16	0.01	0.96
8/26/2004	10.91	5.53	109.78	2.20	7.38	0.08	5.01
9/16/2004	13.98	63.7	85.63	2.05	6.28	0.06	3.84
10/22/2004	37.59	18.56[2]	161.03	3.91	12.95	0.12	8.30
11/3/2004	10.67	3.84[2]	31.78	0.74	2.34	0.04	1.25
11/16/2004	2.79	1.53	9.84	0.22	0.67	0.01	0.24
11/19/2004	3.30	1.36	25.63	0.54	1.93	0.03	1.13
11/25/2004	29.97	14.72	27.50	0.76	2.37	0.04	1.40
Total:	**148.16**	**59.87**	**495.25**	**11.39**	**36.89**	**0.41**	**23.3**

[1] Sum of contributing events
[2] Assuming 39% capture of theoretical runoff calculated from total event depth (actual runoff was not quantified)

Table 25. Spokane LIA site total mass of metals in three slot drain sediments.

Slot Drain	Total Mass	Total Storm Depth	Runoff Depth	Cu	Zn	Cd	Pb
				Total Mass	Total Mass	Total Mass	Total Mass
Distance	g	mm	mm	mg	mg	mg	mg
0 m	427.88		81.49	6.49	31.60	0.56	4.21
3.2 m	140.86	98.76	0.24	1.03	4.33	0.19	1.53
6.1 m	5.97		0.02	0.05	0.17	0.01	0.05

4.4 Comparison of metals in runoff vs. slot drain sediment samples

A comparison was made between the metals in aqueous samples collected in the composite sampler and metals in sediment collected in the 0 m slot drain at the Pullman LIA site for each sample set. As runoff entered the slot drain, a certain fraction of particulates settled out, and runoff would filter through the sediment as it was transported through the slot drain and conveyance piping to the composite sampler. In this way the slot drain acted as a pre-treatment device, as there was a residence time within the slot drain that enhanced metals partitioning from the aqueous phase to the particulate phase. This comparison was performed in order to determine whether certain constituents had a greater affinity for existing in the dissolved or adsorbed phase at the time the aqueous sample left the slot drain for conveyance to the tipping bucket and composite sampler. As the sampling schedule for these two different parameters were slightly different, attempts were made to sum certain aqueous samples and their corresponding event depths for continuity. Event and sample values contributing to aqueous samples collected on 9/24 and 10/12 were combined with and designated as the 10/22 sample date, and the those from 10/30 were combined with and designated as the 11/3 sample date. Two events could not provide runoff quantification due to tipping bucket error, and it was assumed that 39% of the measured precipitation was captured as runoff, as the average of all other events resulted in a capture of 39% +/- 6%. Total metals masses could then be calculated for the stormwater associations.

Comparisons were made for all metals for nine sample dates. The comparison of the mass of Cu in runoff and in sediment is presented in Figure 24. All metals comparisons are presented in the Appendix. The total mass between the two associations was summed for each event (Table 26) and fraction distributions between the two associations were calculated (Table 27). Averages of these percentages are presented graphically in Figure 25. It can be seen that Cu and Zn was predominantly associated with runoff (60-65%), Cd was almost exclusively associated with runoff (97%), and Pb was primarily associated with slot drain sediment (65%).
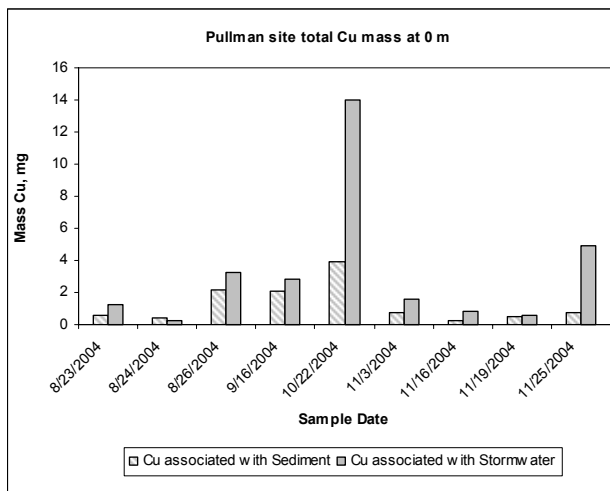
Figure 24. Distribution of Cu between slot drain sediment and stormwater collected at the Pullman LIA site 0 m distance.
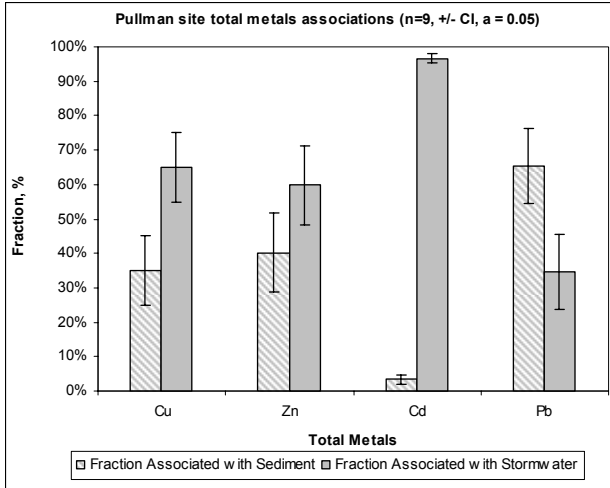
Figure 25. Distribution summary of metals between sediment and stormwater collected at the Pullman LIA site 0 m distance.

Table 26. Pullman LIA site total mass of metals in both sediment and stormwater.

Sample Date	Total Storm Depth, mm[1]	Runoff Depth, mm[1]	Total Cu, mg	Total Zn, mg	Total Cd, mg	Total Pb, mg
8/23/2004	15.26	3.67	1.86	4.07	1.20	1.63
8/24/2004	1.52	0.58	0.62	1.66	0.21	1.04
8/26/2004	10.91	5.53	5.44	17.13	2.01	9.34
9/16/2004	13.98	5.41	4.91	14.74	1.85	6.22
10/22/2004	59.76	23.21[2]	17.87	57.65	8.49	17.17
11/3/2004	10.67	3.84[2]	2.35	6.29	1.25	1.77
11/16/2004	2.79	1.53	1.06	4.13	0.56	0.50
11/19/2004	3.30	1.36	1.08	3.11	0.51	1.26
11/25/2004	29.97	14.72	5.65	9.63	5.10	2.67
Total:						
15 weeks	148.16	59.87	40.85	118.43	21.17	41.61
[1] Sum of contributing events [2] Assuming 39% capture of theoretical runoff calculated from total event depth (actual runoff was not quantified)						

Table 27. Distribution of metals between sediment and stormwater.

Contaminant	Fraction Associated with Sediment	Fraction Associated with Stormwater	+/- CI (n=9, α = 0.05)
Cu	35%	65%	10%
Zn	40%	60%	12%
Cd	3%	97%	1%
Pb	65%	35%	11%

4.5 Roadside soil metals data

 4.5.1 Sieve analysis

Soil samples were taken at the Pullman and Spokane sites at locations equivalent to the three slot drain distances at the surface, at 10 cm, and at 20 cm depths. An example comparison between sieve samples at different depths for the 0 m distance for the Pullman LIA site is presented in Figure 26. Complete sieve analyses comparisons of fraction distributions with depth for both sites are presented in Appendix J. Generally, the Pullman site 0 m and 2 m distances had finer fractions at the surface locations, while the reverse was true for the Spokane 0 m distance.

 4.5.2 Metals concentration/fraction

Metals concentration for each fraction of a soil sample taken at the 0 m distance from the roadway at the soil surface for the Pullman site is presented in Figure 28. Total data for both sites (nine such data sets for each site, three depths and three distances from the road surface) are presented in Appendix K. Metals concentrations increased characteristically with decreased particle size for most samples.
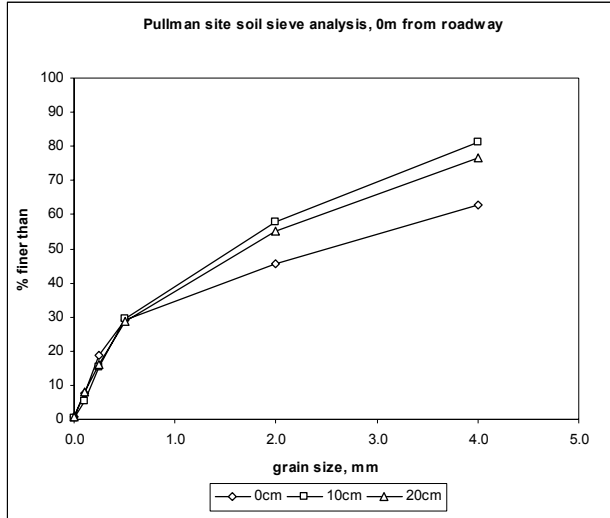
Figure 26. Pullman site sieve analysis, three depth comparison, 0 m from roadway.

4.5.3 Replicate analysis

Replicate analyses were performed for sieve analysis and metals determination per fraction for each site. The Pullman site replicate was performed in quadruplicate and is presented in Figure 27. The Spokane site replicate was performed in triplicate, and all replicate data is presented in Appendix L. As can be seen, replicate sieve analysis is variable, possibly due to the fairly heterogeneous nature of soils. This variability may explain the widely varying metals concentrations of certain size fractions.

4.5.4 Total metals

Total metals concentrations were determined for each distance and depth by multiplying the size fraction by the metals concentration for each fraction. An example graph for total soil Cu concentration found at the three distances and depths at the Pullman site is presented in Figure 29. A summary of total metals concentrations at all depths and distances from the roadway are presented in Table 29 and Table 30 for the Pullman site and Spokane LIA sites, respectively.

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Complete soil total metals concentration data is presented in Appendix M. For the Pullman LIA site, no clear trend exists for any metal species, although the highest concentrations of Cu and Zn were found at the road surface.

Interestingly, the highest Pb concentration found at the Pullman LIA site, 161 mg/kg, was found at the road edge, but not at the surface (Figure 30). The highest lead concentration was found at the 20 cm depth, as concentrations increased with depth at both the 0 m and 2 m distance. There are two possible explanations for this. Lead, typically the most immobile of the heavy metals found in runoff, may have migrated through the soil at that location, as the soil was poorly graded, being comprised mostly of larger gravel aggregates; however, an equally likely explanation is that Pb, deposited historically at a time when tetraethyl lead was an additive in fuels, was buried by years of graveling for traction, operation and maintenance, and sediment deposition. As Pb is no longer emitted in large quantities, the deposited matrix had considerably lower concentrations of Pb. Lead also decreased with distance from the road at the 20 cm depth. For the Spokane LIA site, a decreasing trend in surface concentrations was observed for Cu and Zn, and decreasing trend in concentration with depth for Zn and Pb at the 3.2 m distance. The highest Pb concentration was found at the 3.2 m distance at the surface. Ranges of total metals for all samples locations compared with background ranges reported in the literature is presented in Table 28. While Cu and Zn concentration ranges were slightly lower, Cd and Pb values were slightly higher than background concentrations.

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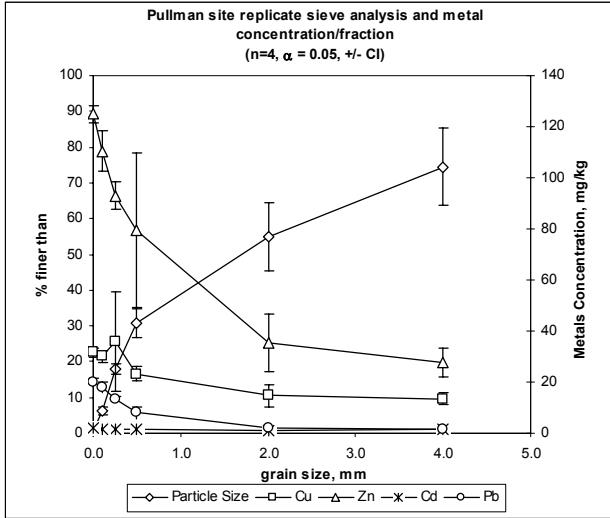
Figure 27. Pullman site replicate soil sieve analysis and metal concentration/fraction.
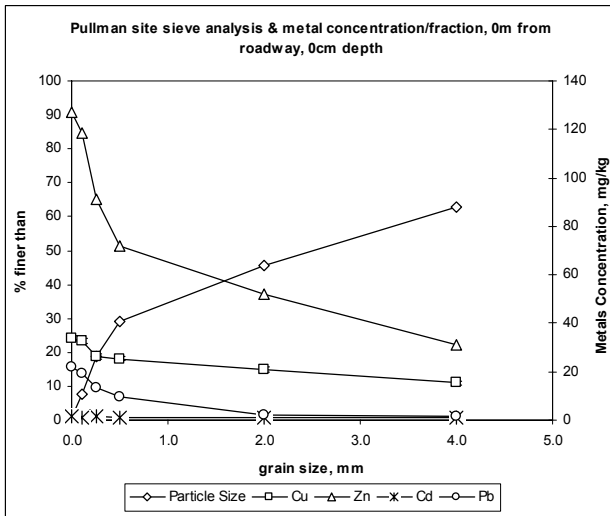
Figure 28.   Pullman site 0 m distance, 0 cm depth soil sieve analysis and metal concentration/fraction.
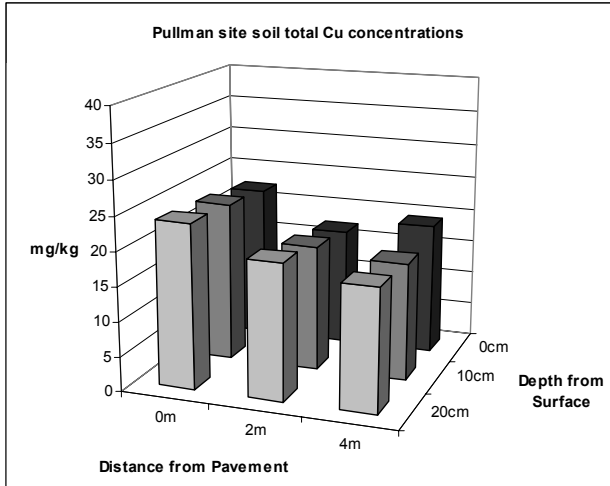
Figure 29. Pullman site soil total Cu concentrations.
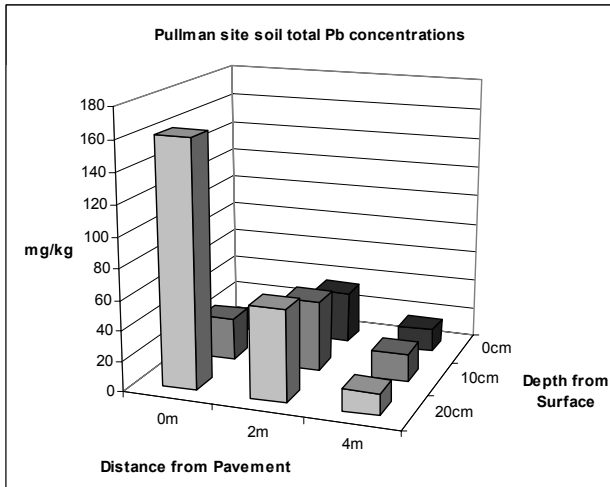
Figure 30. Pullman site soil total Pb concentrations.

Table 28. Soil total metals concentrations compared to background concentrations.

Contaminant	Eastern WA Background[1] mg/kg	Pullman LIA site mg/kg	Spokane LIA site mg/kg
Cu	28.4	17.0-23.9	7.9-19.2
Cd	0.81	1.1-1.4	1.1-1.4
Zn	80.9	40.7-76.5	24.6-72.8
Pb	13.1	14.4-161.2	2.3-22.1
[1] Yonge, 2000.			

Table 29. Pullman LIA site soil total metals concentrations

Slot Drain Distance	Cu Total			Zn Total			Cd Total			Pb Total		
	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
0m	22.24	23.32	23.88	63.91	76.51	63.73	1.23	1.33	1.41	7.54	27.81	161.18
2m	17.01	18.26	19.67	42.21	47.22	50.91	1.13	1.22	1.41	34.31	46.68	60.21
4m	19.21	17.20	17.85	48.47	40.71	42.76	1.32	1.32	1.31	15.09	18.47	14.38

Table 30. Spokane LIA site soil total metals concentrations

Slot Drain Distance	Cu Total			Zn Total			Cd Total			Pb Total		
	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
0m	19.23	7.59	7.88	72.82	24.56	30.28	1.39	1.16	1.23	7.40	2.33	4.18
3.1m	11.93	12.34	11.46	62.37	39.24	32.40	1.37	1.20	1.12	22.09	13.20	7.45
6.1m	8.71	10.02	10.12	30.49	30.59	30.72	1.38	1.16	1.33	7.98	7.69	6.98

5 CONCLUSION

5.1 Summary

For the events recorded, all of the 59.87 mm of runoff generated over 15 weeks at the Pullman LIA site was infiltrated within the first 2 m of the roadway, and 99 % of the 81.49 mm of runoff generated over 10 weeks at the Spokane LIA site was infiltrated within the first 6 m of the roadway at the Spokane site. If all metals were assumed to be associated with the aqueous phase, then the fraction of contaminants retained should match the fraction of runoff infiltrated. However, as metals partitioning to the particulate phase, albeit a highly complex and dynamic process, begins to occur once metals are lifted from the road surface and continues throughout overland flow and infiltration processes, it can be assumed that metals retention within the first few meters of the road surface is considerably higher. This is a remarkable conclusion, demonstrating the applicability of using natural roadside environments as LIAs as part of a LID stormwater mitigation strategy that can successfully concentrate metals and practically eliminate their discharge to receiving waters.

5.2 Recommendations for future work

A number of modifications to the experimental design are suggested for future studies. They are presented here in attempt to direct future researchers by what was learned from the literature and field work. Namely, suggestions target improving aqueous sampling methods for more reliable and accurate determinations, reducing the number of unknown parameters, and collection of

data of sufficient quantity and quality so as to perform statistical evaluations in order to verify correlations made between precipitation, runoff, antecedent try period, traffic density, rainwater quality, and the host of other significant variables that have been documented in the literature.

Suggestions include:

1. Selection of a single site for more thorough evaluation and monitoring.

2. Selection of a site that exhibits evidence of overland flow (riling).

3. Selection of a site on a roadway that has been constructed within the past 10 years to eliminate the influence of historic metals accumulation (particularly lead).

4. Evaluation of background rainwater quality.

5. Evaluation of rainwater quality at multiple distances from the roadway via collection troughs that would be replaced after every event in order to characterize dry deposition of contaminants prior to an event, contaminants delivered via spray, and wet deposition of contaminants during an event (total deposition).

6. Evaluation of air quality at multiple distances from the roadway to characterize dry deposition prior to an event.

7. Characterization of vegetation type and stem count density within the experimental plot.

8. Characterization of macro-pores within the experimental plot to determine influence on infiltration capacity.

9. Determination of hydraulic conductivity at multiple locations within the test plot using water with similar quality to rainwater and runoff water (not tap water).

10. Installation of traffic strips to obtain vehicle counts prior to and during precipitation events.

11. Cleaning roadway surface following an event.

12. Improve tipping bucket design to ensure all runoff flow rates are within calibration range, and develop a flow partitioning apparatus to collect representative fraction of flow to obtain time series samples.

13. Evaluation of time series of water quality parameters during events.

14. Installation of soil moisture probes at multiple distances and depths to determine infiltration characteristics during events.

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Appendix A – Tipping Bucket Data

Custom low - flow tipping bucket schematic.

Collecting funnel

Tip sensor

40°

9.1cm

1.4cm

Tipping bucket

Cover box

Interior bucket width =8.8 cm

19.5cm

20 cm

9cm

10cm

24cm

Tipping Bucket #2 Calibration

L/min, +/- confidence interval

tips/min, +/- confidence interval

$y = 0.1779x$
$R^2 = 0.9994$

Tipping Bucket #2 ml/tip vs. tips/minute

tips/minute, +/- confidence interval

ml/tip, +/- confidence interval

Tipping Bucket #3 Calibration

y = 0.1658x
R² = 0.9995

Tipping Bucket #3 ml/tip vs. tips/minute

Tipping Bucket #4 Calibration

y = 0.1735x
R² = 0.9982

Tipping Bucket #4 ml/tip vs. tips/minute

Tipping Bucket #5 Calibration

$y = 0.1923x$
$R^2 = 0.9975$

Tipping Bucket #5 ml/tip vs. tips/minute

Tipping Bucket #6 Calibration

$y = 0.187x$
$R^2 = 0.9996$

Tipping Bucket #6 ml/tip vs. tips/minute

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Tipping Bucket #7 Calibration

$y = 0.173x$
$R^2 = 0.999$

Tipping Bucket #7 ml/tip vs. tips/minute

Tipping Bucket #8 Calibration

$y = 0.1805x$
$R^2 = 0.9993$

Tipping Bucket #8 ml/tip vs. tips/minute

Tipping Bucket #9 Calibration

y = 0.1749x
R^2 = 0.9987

Tipping Bucket #9 ml/tip vs. tips/minute

Tipping Bucket #10 Calibration
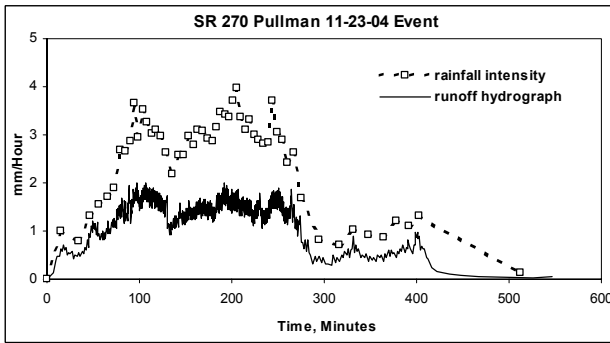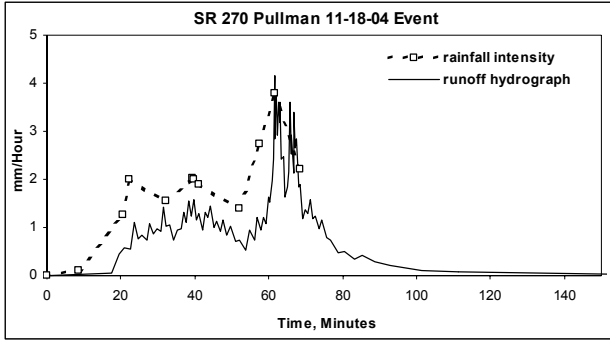
y = 0.2053x
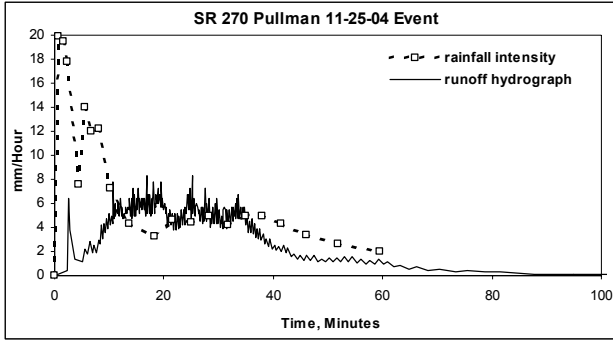R^2 = 0.9996

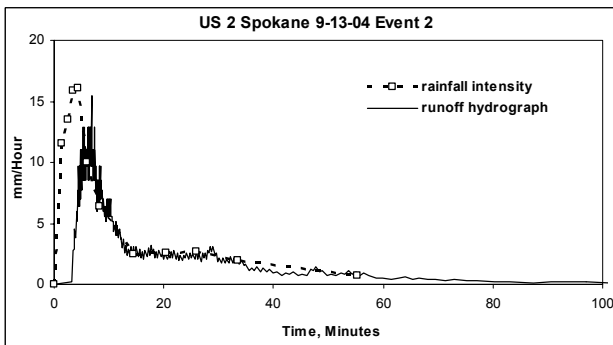**Tipping Bucket #10 ml/tip vs. tips/minute**

Appendix B – Pullman LIA site event graphs

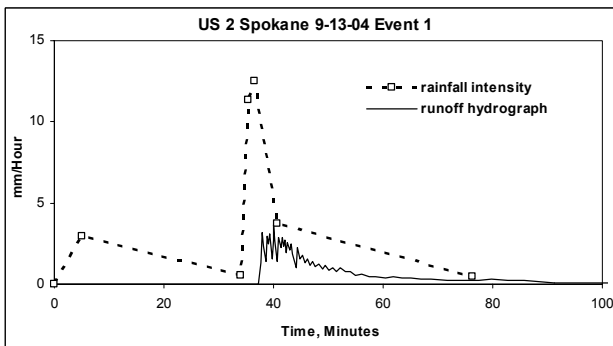SR 270 Pullman 8-22-04 Event 1

SR 270 Pullman 8-22-04 Event 2

SR 270 Pullman 8-24-04 Event 1

SR 270 Pullman 8-24-04 Event 2

SR 270 Pullman 8-25-04 Event 1

SR 270 Pullman 9-13-04 Event 1

SR 270 Pullman 9-13-04 Event 2

SR 270 Pullman 9-15-04 Event

SR 270 Pullman 9-18-04 Event

SR 270 Pullman 9-19-04 Event

SR 270 Pullman 10-30-04 Event

SR 270 Pullman 11-15-04 Event

SR 270 Pullman 11-18-04 Event

SR 270 Pullman 11-23-04 Event

SR 270 Pullman 11-24-04 Event 1

SR 270 Pullman 11-24-04 Event 2

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SR 270 Pullman 11-25-04 Event

- - ☐ - rainfall intensity
—— runoff hydrograph

mm/Hour

Time, Minutes

Appendix C - Spokane LIA site event graphs

US 2 Spokane 9-11-04 Event

US 2 Spokane 9-12-04 Event

US 2 Spokane 9-13-04 Event 1

US 2 Spokane 9-13-04 Event 2

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US 2 Spokane 9-15-04 Event 1

US 2 Spokane 9-15-04 Event 2

US 2 Spokane 9-17-04 Event

US 2 Spokane 10-9-04 Event

US 2 Spokane 10-16-04 Event 1

US 2 Spokane 10-16-04 Event 2

US 2 Spokane 10-17-04 Event

US 2 Spokane 11-1-04 Event

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US 2 Spokane 11-2-04 Event

US 2 Spokane 11-15-04 Event

US 2 Spokane 11-18-04 Event

US 2 Spokane 11-23-04 Event

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Appendix D – North Bend LIA site event graphs

US I90 North Bend 9-10-04 Event

US I90 North Bend 9-11-04 Event

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Appendix E – PSD of aqueous samples

PSD for 11/16/04 aqueous sample
(n =3, α = 0.05, +/- CI)

PSD for 11/19/04 aqueous sample
(n =4, α = 0.05, +/- CI)

PSD for 11/25/04 aqueous sample
(n =3, α = 0.05, +/- CI)

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Appendix F - Runoff depth vs. aqueous mass

contaminant regression curves

Pullman site runoff depth vs. mass Cu load in runoff at 0 m

$y = 0.477x^{1.0099}$
$R^2 = 0.96$

Mass of Cu in Runoff, mg

Runoff Depth, mm

Pullman site runoff depth vs. mass Zn load in runoff at 0 m

$y = 1.3338x^{0.956}$
$R^2 = 0.816$

Mass of Zn in Runoff, mg

Runoff Depth, mm

Pullman site runoff depth vs. mass Cd load in runoff at 0 m

$y = 0.3399x^{1.0134}$
$R^2 = 0.9954$

Mass of Cd in Runoff, mg

Runoff Depth, mm

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Pullman site runoff depth vs. mass Pb load in runoff at 0 m

$y = 0.1929x^{1.1346}$
$R^2 = 0.7723$

Mass of Pb in Runoff, mg

Runoff Depth, mm

Appendix G - Slot drain sediment sieve analysis and

metals concentration/fraction

Pullman site 0 m slot drain sediment sieve analysis & metals concentration/fraction (n=9, α = 0.05, +/- CI)

Spokane site 0 m slot drain sediment sieve analysis & metals concentration/fraction

Spokane site 3.2 m slot drain sediment sieve analysis and metals concentration/fraction

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Spokane site 6.1 m slot drain sediment sieve analysis & metals concentration/fraction

Pullman LIA site sediment sieve analysis and metals concentration/fraction

Sieve Size	size >than, mm	Location	%finer		Cu		Zn		Cd		Pb	
			average	CI	average	CI	average	CI	average	CI	average	CI
			%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	0m	95.0	2.0	16.40	5.83	43.51	17.63	1.67	1.48	8.23	7.25
#10	2.0	0m	82.5	3.9	16.62	1.95	46.86	8.48	0.91	0.14	17.56	4.77
#35	0.5	0m	38.2	4.1	20.59	1.42	64.51	6.88	0.94	0.19	35.33	8.64
#60	0.3	0m	20.7	2.9	24.86	1.65	85.58	4.74	1.02	0.20	63.11	12.77
#140	0.1	0m	8.1	1.4	32.35	3.51	101.55	8.29	1.12	0.20	66.69	10.10
Pan	0.0	0m	0.7	0.3	35.01	3.13	117.80	7.09	1.39	0.29	82.73	12.28

Spokane LIA site sediment sieve analysis and metals concentration/fraction

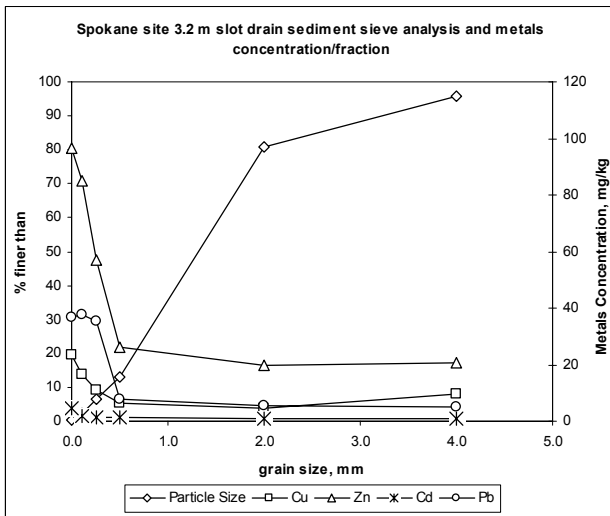| Size >than, mm	% finer			Cu			Zn			Cd			Pb		
	0m	3.2 m	6.1 m	0m	3.2 m	6.1 m	0m	3.2 m	6.1 m	0m	3.2 m	6.1 m	0m	3.2 m	6.1 m
	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
4.0	93.7	95.8	99.1	10.29	9.65	5.06	20.01	20.52	9.84	0.94	1.06	3.02	3.09	5.05	3.65
2.0	81.6	81.0	90.3	11.45	4.72	6.94	53.40	19.98	23.00	1.20	1.13	1.43	4.97	5.73	4.90
0.5	38.1	13.0	7.9	12.50	6.37	7.36	56.78	26.19	24.89	1.35	1.29	1.30	6.33	7.69	7.19
0.3	17.4	6.6	3.0	17.27	11.19	11.30	86.07	57.12	47.56	1.19	1.22	1.20	13.81	35.58	9.75
0.1	5.2	2.3	1.3	20.80	16.77	30.01	117.56	85.15	71.54	1.40	1.69	2.55	17.80	37.93	23.18
0.0	0.7	0.4	0.0	35.05	23.52	33.18	206.61	96.38	112.86	2.12	4.68	7.21	27.93	36.73	39.51

Appendix H - Runoff depth vs. sediment mass

contaminant regression curves

Pullman site runoff depth vs. mass of 0 m slot drain sediment

Mass of Sediment, g

$y = 18.645x^{0.4434}$
$R^2 = 0.5057$

Runoff Depth, mm

Pullman site runoff depth vs. mass Cu in 0 m slot drain sediment

Mass of Cu in Sediment, mg

$y = 0.4047x^{0.4777}$
$R^2 = 0.579$

Runoff Depth, mm

Pullman site runoff depth vs. mass Zn in 0 m slot drain sediment

Mass of Zn in Sediment, mg

$y = 1.2878x^{0.4773}$
$R^2 = 0.5506$

Runoff Depth, mm

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Pullman site runoff depth vs. mass Cd in 0 m slot sediment

$y = 0.0195x^{0.3963}$
$R^2 = 0.5612$

Mass of Cd in Sediment, mg

Runoff Depth, mm

Pullman site runoff depth vs. mass Pb in 0 m slot drain sediment

$y = 0.763x^{0.4815}$
$R^2 = 0.4504$

Mass of Pb in Sediment, mg

Runoff Depth, mm

Appendix I - Comparison of metals in aqueous vs.

sediment samples

Pullman site total Cu mass at 0 m

Mass Cu, mg

Sample Date

□ Cu associated with Sediment □ Cu associated with Stormwater

Pullman site total Zn mass at 0 m

Mass Zn, mg

Sample Date

□ Zn associated with Sediment □ Zn associated with Stormwater

Pullman site total Cd mass at 0 m

Mass Cd, mg

Sample Date

□ Cd associated with Sediment □ Cd associated with Stormwater

Pullman site total Pb mass at 0 m

Appendix J – Sieve analysis of roadside soils

Pullman site soil sieve analysis, 0m from roadway

Pullman site soil sieve analysis, 2m from roadway

Pullman site soil sieve analysis, 4m from roadway

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Spokane site soil sieve analysis, 0m from roadway

Spokane site soil sieve analysis, 3.2m from roadway

Spokane site soil sieve analysis, 6.1m from roadway
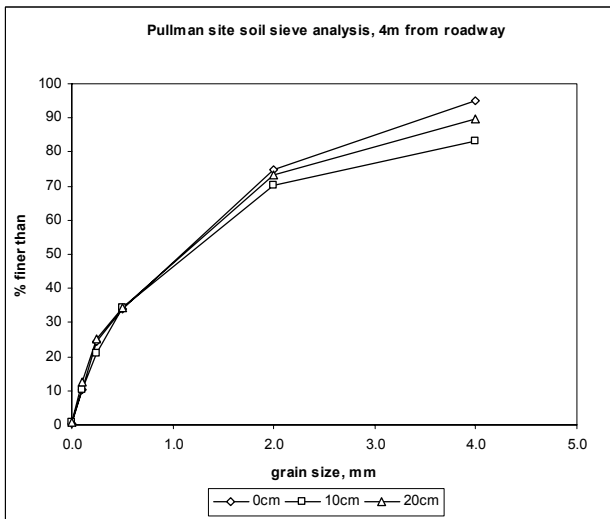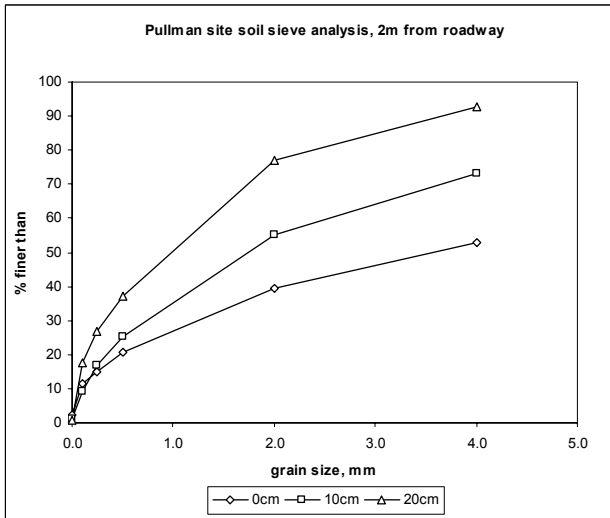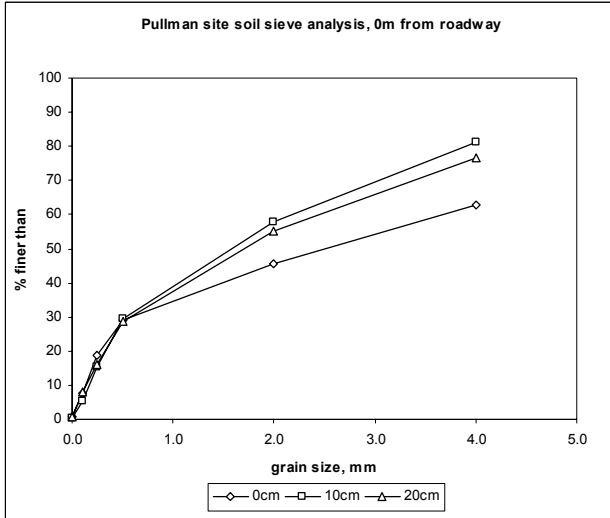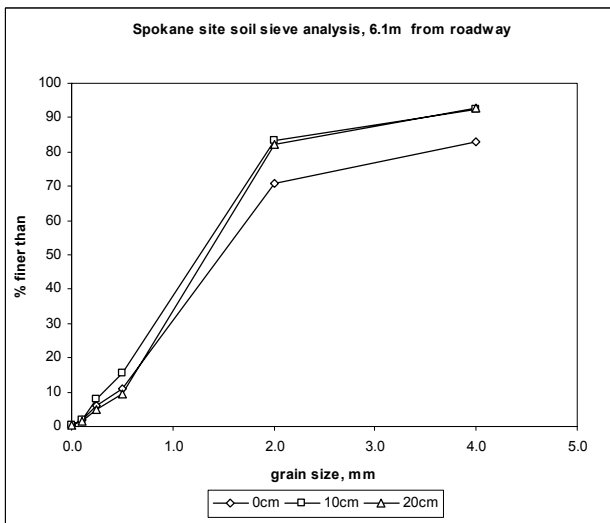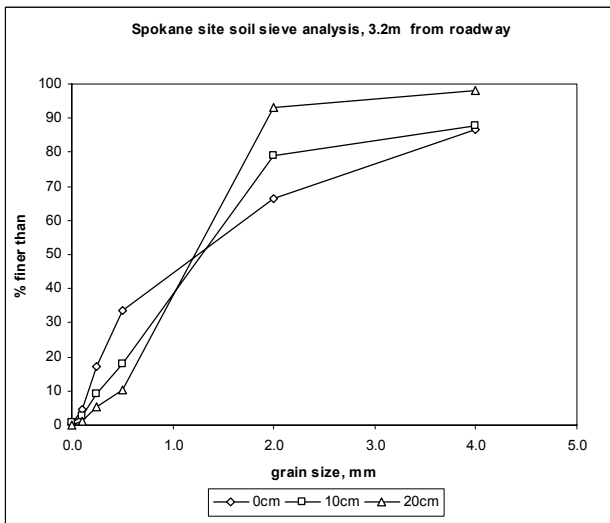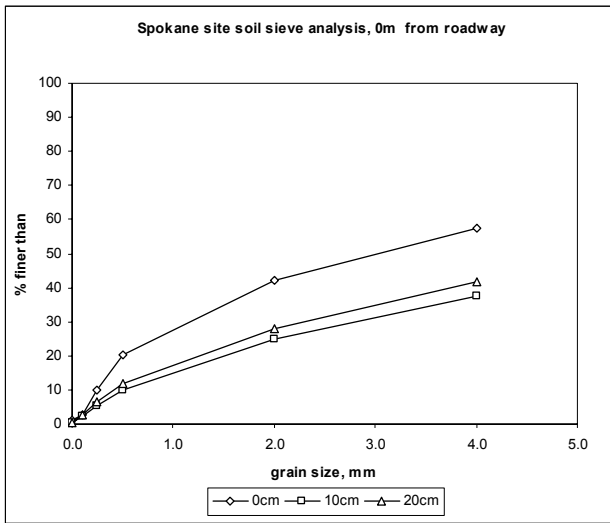
Pullman LIA site soil sieve analysis, depths and distances from roadway

Sieve #	Sample Distance	0m			2m			4m		
	Size greater than	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm
	mm	%	%	%	%	%	%	%	%	%
#5	4.0	62.9	81.1	76.8	53.0	73.3	92.7	94.9	83.3	89.7
#10	2.0	45.8	57.8	55.3	39.4	55.0	76.9	74.9	70.3	73.4
#35	0.5	29.1	29.6	28.7	20.5	25.4	37.2	34.1	34.2	34.5
#60	0.3	18.9	15.3	16.0	15.0	16.8	26.8	24.3	20.9	25.2
#140	0.1	7.6	5.2	8.1	11.5	9.2	17.8	10.5	10.3	12.8
Pan	0.0	0.7	0.4	0.6	2.5	1.1	0.9	0.4	0.8	0.6

Spokane LIA site soil sieve analysis, depths and distances from roadway

Seive #	Slot Drain Distance	0m			3.2m			6.1m		
	Size greater than	0cm	10cm	20cm	0cm	10cm	20cm	0cm	10cm	20cm
	mm	%	%	%	%	%	%	%	%	%
#5	4.0	57.3	37.4	41.9	86.8	87.9	98.0	82.8	92.3	92.9
#10	2.0	42.2	24.7	27.9	66.6	79.0	93.0	70.7	83.2	82.3
#35	0.5	20.3	9.9	11.9	33.5	17.9	10.4	11.0	15.6	9.4
#60	0.3	10.0	5.4	6.4	17.1	9.2	5.2	6.2	8.1	5.0
#140	0.1	2.6	2.1	2.7	4.6	2.5	1.2	2.0	1.8	1.7
Pan	0.0	1.0	0.2	0.4	0.5	0.6	0.2	0.5	0.4	0.2

Appendix K – Metals concentration/size fraction for

roadside soils

Pullman site sieve analysis & metal concentration/fraction, 0m from roadway, 0cm depth

Pullman site sieve analysis & metal concentration/fraction, 0m from roadway, 10cm depth

Pullman site sieve analysis & metal concentration/fraction, 0m from roadway, 20cm depth

129

Pullman site sieve analysis & metal concentration/fraction, 2m from roadway, 0cm depth

Pullman site sieve analysis & metal concentration/fraction, 2m from roadway, 10cm depth

Pullman site sieve analysis & metal concentration/fraction, 2m from roadway, 20cm depth

130

Pullman site sieve analysis & metal concentration/fraction, 4m from roadway, 0cm depth

Pullman site sieve analysis & metal concentration/fraction, 4m from roadway, 10cm depth

Pullman site sieve analysis & metal concentration/fraction, 4m from roadway, 20cm depth

131

Spokane site sieve analysis & metal concentration/fraction, 0m from roadway, 0cm depth

Spokane site sieve analysis & metal concentration/fraction, 0m from roadway, 10cm depth

Spokane site sieve analysis & metal concentration/fraction, 0m from roadway, 20cm depth

132

Spokane site sieve analysis & metal concentration/fraction, 3.2m from roadway, 0cm depth

Spokane site sieve analysis & metal concentration/fraction, 3.2m from roadway, 10cm depth

Spokane site sieve analysis & metal concentration/fraction, 3.2m from roadway, 20cm depth

133

Spokane site sieve analysis & metal concentration/fraction, 6.1m from roadway, 0cm depth

Spokane site sieve analysis & metal concentration/fraction, 6.1m from roadway, 10cm depth

Spokane site sieve analysis & metal concentration/fraction, 6.1m from roadway, 20cm depth

Seive #	Size greater than (mm)	Cu mg/kg	Zn mg/kg	Cd mg/kg	Pb mg/kg	Cu mg/kg	Zn mg/kg	Cd mg/kg	Pb mg/kg	Cu mg/kg	Zn mg/kg	Cd mg/kg	Pb mg/kg

Pullman LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 0 m sample distance

Seive #	Sample Distance	0m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than (mm)	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	15.34	31.19	1.15	1.52	17.10	21.36	1.08	1.49	10.18	19.63	1.20	30.30
#10	2.0	20.98	51.82	1.15	2.25	17.37	34.74	1.28	4.69	18.36	42.25	1.49	84.13
#35	0.5	25.43	71.98	1.24	9.44	27.48	51.33	1.40	39.46	24.26	64.36	1.34	121.14
#60	0.3	26.30	91.32	1.43	13.20	25.67	80.64	1.47	44.93	39.79	114.64	1.62	296.18
#140	0.1	32.83	118.71	1.30	19.08	28.93	87.34	1.54	57.22	37.83	110.78	1.67	409.32
Pan	0.0	33.82	127.09	1.51	22.12	35.80	123.30	1.49	65.34	41.24	129.54	1.59	454.95

Pullman LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 2 m sample distance

Seive #	Sample Distance	2m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than (mm)	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	13.81	28.25	0.89	8.56	16.11	31.93	1.09	13.61	15.12	33.22	1.12	14.87
#10	2.0	18.50	47.05	1.25	26.32	14.19	38.64	1.12	37.25	17.57	42.53	1.26	42.29
#35	0.5	21.66	61.36	1.51	75.12	20.04	55.49	1.22	65.81	20.50	55.49	1.39	68.59
#60	0.3	21.97	64.31	1.40	69.82	23.07	65.93	1.52	71.81	20.21	50.88	1.48	67.20
#140	0.1	25.55	73.20	1.41	79.86	23.14	64.25	1.46	73.21	22.91	61.34	1.51	76.75
Pan	0.0	20.11	53.80	1.43	65.23	20.95	57.66	1.49	62.13	20.59	52.71	1.69	66.81

		Pullman LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 4 m sample distance											
Seive #	Sample Distance	4m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than (mm)	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	16.24	39.12	1.11	12.18	13.39	28.55	1.13	9.71	12.81	25.55	1.39	5.95
#10	2.0	18.07	47.04	1.36	11.91	16.28	35.95	1.42	17.44	18.41	41.61	1.34	18.65
#35	0.5	19.27	51.39	1.30	14.68	19.19	48.92	1.32	20.71	17.22	42.72	1.25	12.24
#60	0.3	20.87	47.17	1.25	17.44	18.72	42.07	1.35	22.28	22.31	52.97	1.35	18.29
#140	0.1	21.52	49.37	1.50	19.44	16.67	38.88	1.43	19.72	21.32	52.97	1.42	19.33
Pan	0.0	18.65	45.99	1.27	16.83	17.50	40.99	1.47	21.60	17.36	42.94	1.31	15.26

		Spokane LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 0 m sample distance											
Seive #	Sample Distance	0m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	17.34	53.14	1.06	4.49	5.20	11.01	1.07	0.28	4.66	10.13	1.13	1.01
#10	2.0	17.79	54.26	1.19	5.11	6.15	21.56	1.27	1.96	7.61	25.27	1.29	4.38
#35	0.5	16.48	66.90	1.39	5.60	9.42	40.98	1.27	4.20	12.36	60.23	1.37	5.61
#60	0.3	22.86	107.52	1.86	13.29	24.60	77.32	1.34	10.55	14.85	80.50	1.24	17.89
#140	0.1	33.32	168.08	2.65	22.34	17.60	93.02	1.36	13.25	19.28	101.11	1.61	15.06
Pan	0.0	44.30	233.70	3.87	29.08	25.52	123.08	1.73	20.04	27.06	135.48	1.82	24.10

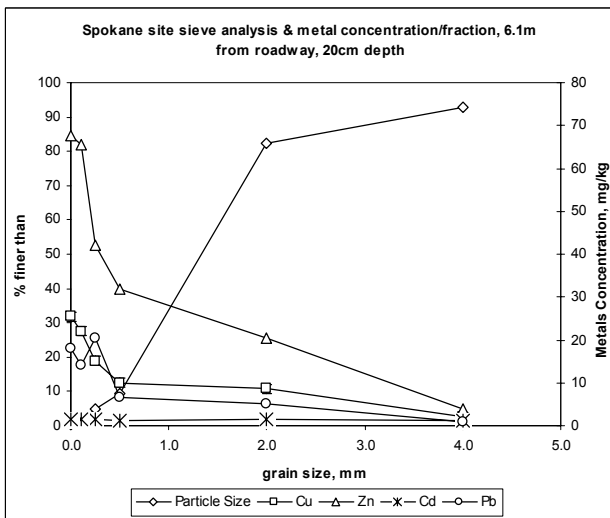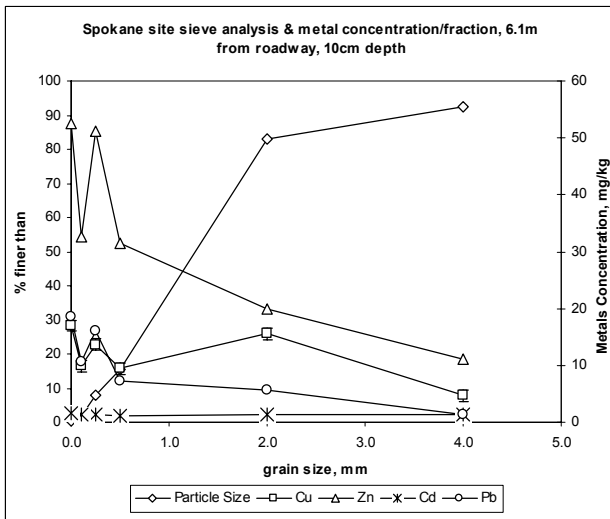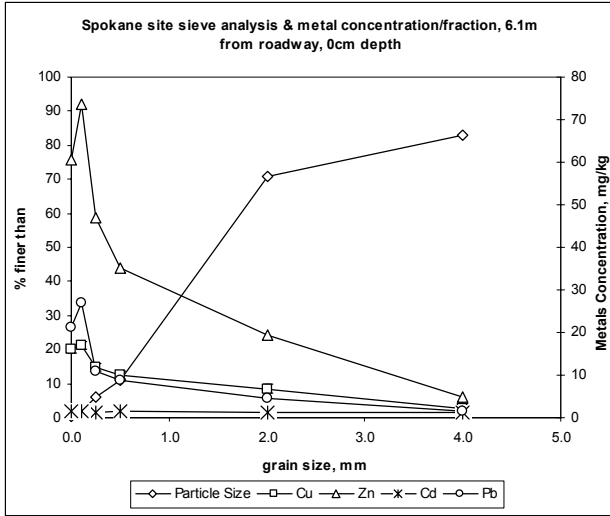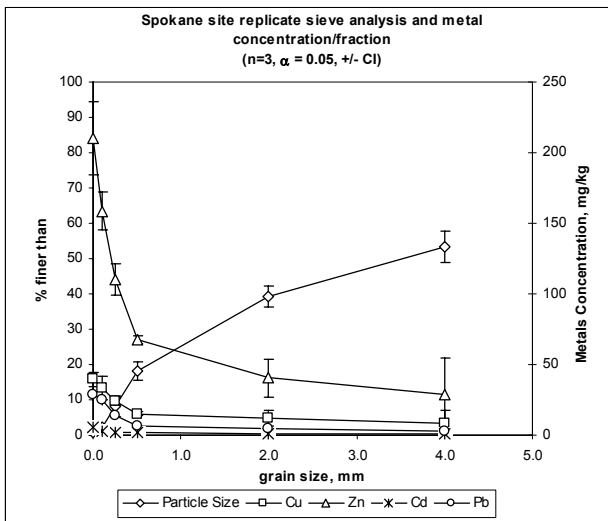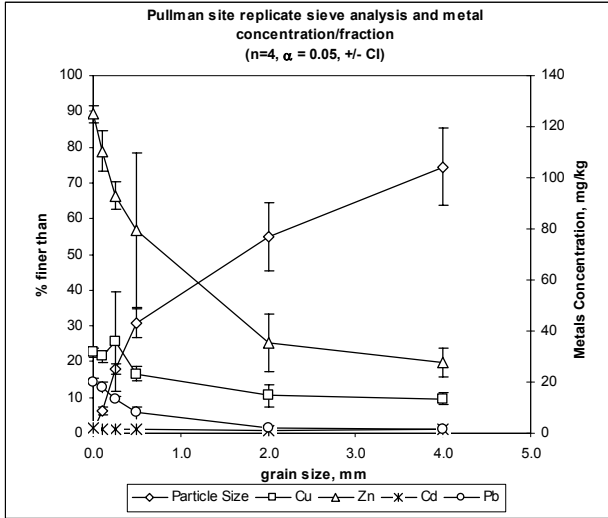| Seive #	Sample Distance	3.2m											

Spokane LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 3.2 m sample distance

Seive #	Sample Distance	3.2m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	5.94	18.82	1.27	11.68	4.67	15.21	1.00	3.92	6.11	16.14	1.45	29.25
#10	2.0	8.57	26.57	1.42	5.83	6.54	18.56	1.13	5.93	6.64	20.42	1.33	5.01
#35	0.5	9.89	48.18	1.16	15.72	12.74	37.59	1.18	11.46	11.40	30.78	1.05	6.10
#60	0.3	15.66	91.97	1.52	39.95	14.25	60.90	1.48	21.02	13.51	50.52	1.41	12.56
#140	0.1	19.99	132.76	1.60	44.76	26.30	87.39	1.52	39.65	17.40	60.76	1.36	18.44
Pan	0.0	26.53	170.00	2.11	49.75	21.63	86.35	1.61	37.88	18.55	55.77	2.19	18.39

Spokane LIA site soil metal concentrations/fraction, 0 cm, 10 cm, and 20 cm depths at the 6.1 m sample distance

Seive #	Sample Distance	6.1m											
	Sample Depth	0cm				10cm				20cm			
	Constituent	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu	Zn	Cd	Pb
	Size greater than	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
#5	4.0	2.20	4.83	1.31	1.60	4.66	11.10	1.37	1.43	2.15	4.02	1.29	0.93
#10	2.0	6.82	19.32	1.21	4.49	15.60	19.97	1.28	5.59	8.67	20.50	1.41	5.08
#35	0.5	10.02	35.25	1.44	8.67	9.40	31.49	1.07	7.31	10.00	31.91	1.32	6.52
#60	0.3	11.79	46.84	1.33	10.90	13.64	51.15	1.40	16.02	15.11	42.13	1.39	20.36
#140	0.1	16.93	73.66	1.45	27.02	9.92	32.69	1.36	10.62	22.07	65.54	1.43	14.24
Pan	0.0	16.04	60.63	1.64	21.08	16.99	52.47	1.66	18.59	25.42	67.81	1.46	18.09

Appendix L – Replicate metals concentration/size fraction for roadside soils

Pullman site replicate sieve analysis and metal concentration/fraction
(n=4, α = 0.05, +/- CI)

Spokane site replicate sieve analysis and metal concentration/fraction
(n=3, α = 0.05, +/- CI)

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		% finer than		Cu		Zn		Cd		Pb	
Pullman LIA site replicate soil sieve analysis and metal concentration/fraction data												
Seive Size	Size greater than (mm)	Average %	CI	Average mg/kg	CI	Average mg/kg	CI	Average mg/kg	CI	Average mg/kg	CI
#5	4.0	74.4	10.8	13.6	2.3	27.6	5.7	1.4	0.2	1.5	0.5
#10	2.0	55.1	9.5	14.8	4.4	35.5	11.3	1.2	0.1	1.9	0.5
#35	0.5	30.7	4.0	23.3	2.6	79.5	30.2	1.4	0.2	8.1	2.3
#60	0.3	18.0	1.4	35.7	19.4	93.0	5.5	1.4	0.0	13.4	1.1
#140	0.1	6.3	1.2	30.2	2.3	110.4	8.0	1.5	0.2	18.0	1.9
Pan	0.0	0.7	0.1	31.7	1.8	124.9	3.3	2.0	0.4	20.0	1.8
Replicate data set: n= 4, α = 0.05												

		% finer than		Cu		Zn		Cd		Pb	
Spokane LIA site replicate soil sieve analysis and metal concentration/frction Data												
Seive Size	Size greater than (mm)	Average %	CI	Average mg/kg	CI	Average mg/kg	CI	Average mg/kg	CI	Average mg/kg	CI
#5	4.0	53.3	4.4	8.3	9.0	28.8	25.5	1.1	0.0	2.4	2.2
#10	2.0	39.3	3.1	12.0	5.7	40.4	13.7	1.3	0.1	4.4	1.0
#35	0.5	18.2	2.5	15.0	1.5	68.0	2.7	1.4	0.1	6.8	1.3
#60	0.3	8.1	2.9	23.7	2.7	110.0	11.0	1.7	0.3	14.3	2.1
#140	0.1	2.1	0.6	33.6	8.2	158.8	13.4	2.5	0.3	25.2	3.8
Pan	0.0	0.6	0.4	39.4	4.9	210.2	25.8	5.6	1.7	28.6	1.7
Replicate data set: n= 3, α = 0.05												

Appendix M – Soil total metals concentrations

Pullman site soil total Cu concentrations

Pullman site soil total Zn concentrations

Pullman site soil total Cd concentrations

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Pullman site soil total Pb concentrations

Spokane site soil total Cu concentrations

Spokane site soil total Zn concentrations

Spokane site soil Total Cd concentrations

Spokane site soil total Pb concentrations

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