Correlations Between Heavy Metals and Suspended Solids in Highway Runoff: Implications for Control Strategies

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Stormwater runoff from heavily travelled urban highways can adversely affect the quality of receiving waters. Nonpoint pollutants in highway runoff include heavy metals, suspended solids, micro-organics, oils and chlorides. These anthropogenic pollutants result from traffic activities, atmospheric deposition, engine exhaust, roadway degradation and highway maintenance. An effective control strategy for trapping runoff pollutants, especially heavy metals and suspended solids, is a partial exfiltration trench (PET). A PET is an engineered trench designed to exfiltrate some of the runoff captured during "first-flush" periods or long duration hydrographs. Narrow PETs installed outside the travelled pavement serve as a multipurpose replacement for underdrains and can be located in restricted rights-of-way where space constraints preclude other pollutant control options. The hypothesis that heavy metal concentrations are significantly correlated to suspended solids in highway runoff is investigated in this paper. Runoff data from eight highway sites in the United States and Europe are analyzed to test this hypothesis. Results indicate a strong positive correlation between heavy metals and suspended solids for snow washoff events and a weaker positive correlation for rainfall events. Similar results are observed for correlations between heavy metals and suspended solid particle sizes. It is argued that a PET holds promise as an effective device for immobilizing heavy metals and trapping suspended solids generated during snow washoff, pavement "first-flush" and long duration rainfall events.

Stormwater runoff from heavily travelled urban highways can adversely affect the quality of adjacent receiving waters (*1*). Urban highway runoff often contains significant concentrations of soluble, insoluble and speciated fractions of heavy metals; suspended, colloidal and volatile fractions of inorganic and organic particulates; organic compounds such as polycyclic (polynuclear) aromatic hydrocarbons (PAHs); anions such as chlorides; and oil and grease.

These nonpoint pollutants result from traffic activities and maintenance operations. Typical sources of highway pollutants include vehicular component wear, fluid leakage and engine exhaust; roadway abrasion and degradation; wet and dry atmospheric deposition; and highway maintenance such as de-icing salt application and roadway reconstruction. The potential impacts of highway nonpoint pollution are greatest in heavily travelled urban corridors. Impacts on receiving waters from runoff of rural Interstates and highways which carry less than 30,000 vehicles per day are minimal (*2*).

Passage of the Clean Water Act (CWA) in 1972 established the National Pollutant Discharge Elimination System (NPDES) to regulate industrial and municipal point sources discharging into waters of the United States. By the mid-1980s, it became evident that control of nonpoint source pollutants was crucial to meeting CWA objectives (*3*). Therefore, in 1987 the CWA was amended to include NPDES permits for stormwater discharges from industrial activities and municipal separate stormwater systems. Soon thereafter, the U.S. Environmental Protection Agency promulgated regulations governing permits for stormwater discharges.

This evolving regulatory framework has prompted some state departments of transportation to implement proactive efforts to characterize highway stormwater discharges and to identify best management practices (BMPs). A variety of passive BMPs have already been used as effective control strategies for runoff from urban areas and roads in the United States, Europe and Japan. In view of the nonpoint pollutant loads that originate in highway corridors and the emerging NPDES stormwater criteria, it is likely that use of BMPs to control highway nonpoint pollution will grow in the future.

The purpose of this paper is twofold. First, using water quality data monitored at eight roadways in the United States and Europe, we test the hypothesis that heavy metal concentrations are significantly correlated to the concentrations and the particle size of suspended solids transported in highway runoff. Second, we discuss the implications of our findings on identification and development of effective strategies for controlling nonpoint pollutants from urban highways.

CHARACTERIZATION OF HIGHWAY NONPOINT POLLUTANTS

Highway nonpoint pollutants are transported off roadway pavements during rainfall runoff and snow washoff events. Even though nonpoint pollutant concentrations often vary by several orders of magnitude during a runoff event, a single index, known as event mean concentration (EMC) (*4*) is often used to characterize nonpoint source pollution. The EMC for an individual storm event is defined as the total pollutant load (mass) divided by the total runoff volume, or

$$EMC = \bar{C} = \frac{M}{V} = \frac{\int C(t)Q(t)dt}{\int Q(t)dt} \quad (1)$$

where:

M = total mass of pollutant,
V = total liquid volume of flow or sample,
$\bar{C}$ = flow weighted average concentration,
$C(t)$ = time variable concentration, and
$Q(t)$ = time variable flow.

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From a practical point of view, EMCs are obtained from a flow weighted composite of concentration samples taken at intervals throughout the entire storm event. Individual storm events are either rainfall or snow. Estimated EMCs vary from event to event. Due to this variability, EMCs are often assumed to be a random variable with a lognormal probability distribution (*5*).

CONTROL STRATEGIES FOR HIGHWAY NONPOINT POLLUTANTS

Table 1 summarizes the potential effectiveness of several control strategies that have been used to immobilize pollutants transported in urban runoff (*6*). Here, effectiveness is defined as the trap efficiency of the device (*7*). In Table 1, the chloride removal efficiency is based on the potential physico-chemical reaction processes likely to occur with each control strategy.

Besides trap efficiency, the applicability of each control strategy under diverse highway conditions is important. Table 2 summarizes the suitability of each control strategy as a function of site specific highway conditions. Urban highways often have relatively narrow rights-of-way. Therefore, control devices with long linear configurations, such as a partial exfiltration trench (PET) or an infiltration trench, may be the most suitable alternatives. In less congested urban areas where sufficient shoulder or median space is available, a vegetated swale may be the preferred control strategy because of the low maintenance and cost, depending on the soil cover conditions, infiltration characteristics and slope.

HIGHWAY RUNOFF WATER QUALITY DATA

The data analyzed in this paper are taken in part from the FHWA research program and from two European studies. Both data bases are briefly described below.

United States Data

During the 1970s and 1980s the FHWA and state agencies carried out a field program to characterize the water quality impacts of highway runoff. This research program collected runoff water quality data during 993 storm events at 31 highway sites in 11 states (*8*). The storms included both rainfall and snow events. Highway water quality parameters included heavy metals, suspended solids, oxygen demand, nitrates, phosphates, chlorides and oil and grease. Most of these water quality constituents were presented as EMCs as defined in Equation 1. However, some were determined from a sequential series of concentration and flow data (*8*). It should be noted that there are data reporting errors in this report. The original correct data should be obtained from the individual state departments of transportation.

From the 31 FHWA highways sites, the following six sites were selected: Milwaukee I-794, Milwaukee I-94, Milwaukee HWY-45, Spokane I-90, Seattle SR-520 and Minneapolis I-5. These sites were chosen because they had sufficient data to allow a comparison between snow washoff and rainfall runoff EMCs.

European Data

Our data set also includes water quality information collected during two European studies conducted in Jessheim, Norway from 1979 to 1981 and Karlsruhe, Germany from 1991 to 1992. Besides measuring many of the same pollutants included in the FHWA program, the European studies also monitored conductivity, total organic carbon (TOC), nickel (Ni), and PAHs. In addition, the European investigations characterized suspended solid particle size distributions.

At the Jessheim E6 site, EMCs and sedimentation velocities were analyzed (*9*). Suspended solid concentrations associated with a sedimentation velocity range were given. The Karlsruhe data presented coefficients of determination (R^2 values) obtained from a linear regression of heavy metal concentrations against suspended solid particle sizes (*9*).

Characteristics of U.S. and European Data

Table 3 summarizes the median EMCs (EMC_{50}) and selected site data for the FHWA and Jessheim studies. Here it is important to recall that EMC_{50} represents the EMC from the median runoff event at a particular site. Since the focus of this paper is to compare pollutant removal during rainfall runoff and during snow washoff,

TABLE 1 Effectiveness of Urban Runoff Control Strategies

URBAN RUNOFF PARAMETER	Heavy Metals	Suspended Solids	Colloidal Solids	PAHs	Chloride	Peak Flow
CONTROL STRATEGY	PERCENT REMOVAL (%)					
Infiltration Trench	70 - 100	70 - 100	50 - 80	80 - 100	unknown	reduced
Porous Pavement	20 - 100	90 - 100	unknown	unknown	unknown	reduced
PET	70 - 100	70 - 100	50 - 80	80 - 100	unknown	reduced
Detention Basin	40 - 60	40 - 60	0 - 20	unknown	0 - 20	reduced
Retention Basin	60 - 80	80 - 100	20 - 60	unknown	0 - 20	reduced
Vegetated Swale	20 - 100	20 - 100	20 - 60	unknown	0 - 20	reduced
Wetland	60 - 100	80 - 100	60 - 80	unknown	unknown	reduced

TABLE 2 Suitability of Control Strategies for Highway Site Conditions

HIGHWAY SITE CONSTRAINT	Areal Size	Maintenance & Cleaning	Flow Type Suitability	Safety & Concerns	Native Soil Conductivity	Cost
CONTROL STRATEGY						
Infiltration Trench	minimal	periodic	snow washoff, rainfall-runoff	clogging	important	low to moderate
Porous Pavement	minimal	periodic	entire runoff hydrograph	clogging	some importance	low to moderate
PET	minimal	periodic	snow washoff, first-flush	clogging	some importance	low to moderate
Detention Basin	large	periodic	entire runoff hydrograph	water surface	slight importance	moderate
Retention Basin	large	infrequent	entire runoff hydrograph	water surface	important	moderate
Vegetated Swale	small	infrequent	snow washoff, rainfall-runoff	none	some importance	low
Wetland	large	infrequent	entire runoff hydrograph	water surface	some importance	moderate to high

TABLE 3 Site Median EMCs (EMC_{50}) and Corresponding Site Data

SNOW WASHOFF & RAINFALL SITE MEDIAN CONCENTRATION, EMC(50) COMPARISON

Highway Sites	Milwaukee I-94		Milwaukee I-794		Milwaukee Hwy 45		Spokane I-90		Seattle SR520		Jessheim E6	
Parameters: [mg/L]	Rain	Snow	Rain	Snow	Rain	Snow	Rain	Snow	Rain	Snow	Rain	Snow
Copper	0.155	0.233	0.088	0.285	0.075	0.196	0.041	0.136	0.072	0.094	0.111	0.062
Lead	0.817	2.285	1.457	6.239	0.738	1.510	0.173	1.213	1.065	2.004	0.218	0.196
Zinc	0.465	1.537	0.336	1.415	0.371	0.750	2.892	6.786	0.280	0.577	0.172	0.320
Cadmium	0.011	0.021	0.032	0.088	0.029	0.053	- -	- -	- -	- -	0.008	0.008
Susp. Solids	143	240	140	701	334	375	119	752	244	435	316	645
Volatile SS	47	178	47	139	72	94	29	139	59	103	- -	- -
Event Data:												
Precip (mm)	831	93	461	36	312	55	269	330	438	332	- -	- -
Event Dur.	- -	- -	2.2	5.6	2.8	5.7	47.6	79.5	12.0	27.0	- -	- -
# of Events	107	30	35	5	29	7	12	4	37	9	7	6
Date (19##)	78-81	78-81	76-77	76-77	76-77	76-77	79-81	79-81	79-80	79-80	80-81	80-81
Site Data:												
ADT	116		53		85		35		84		8	
% impervious	64		100		31		100		100		100	
Area (ha)	3.10		0.85		42.90		0.08		0.04		- -	
Flow Length	419		248		2898		55		46		- -	
Traffic Lanes	8		8		6		6		4		4	
Land Use	urban		urban		urban		urban		urban		rural	
Curbed	yes		yes		yes		yes		yes		yes	
Pavm. Type	Asph		Conc		Conc		Conc		Conc		Asph	

NOTES :
: The Event Duration is the median duration of the events, measured in hours
: Average Daily Traffic, ADT values presented are divided by 1000.
: Flow length in meters
Date (19##) : years data were collected
: - - : Incomplete or insufficient data

EMC_{50} statistics for both types of precipitation events are presented. The data in Table 3 date back to the late 1970s and early 1980s. The EMC_{50} of certain pollutants, specifically lead, would likely be different if measured today. The snow washoff EMC_{50}'s are significantly greater than the rainfall runoff EMC_{50}'s. The sample sizes for the snow washoff events are smaller than the rainfall runoff event sample sizes as shown in Table 3. EMC data were not provided for the Karlsruhe site.

ANALYSIS OF HIGHWAY WATER QUALITY DATA

Previous Work

Principal factors affecting the quality of highway runoff include precipitation type (rain or snow) and pattern, traffic count, highway surface and subsurface drainage design, highway maintenance practices, pollutant accumulation and deposition, local land use, geological and geographic characteristics, and pavement type and condition. Many previous studies have investigated the relation between nonpoint pollutant washoff from highways and some measure of traffic intensity such as Average Daily Traffic (*5*) or, more recently, Cumulative Vehicles During Storms (*10,2*). Other investigators have established conclusive correlations between metal pollutant loadings and suspended solids concentrations (*11*).

Here we examine further the relation between concentrations of metals and suspended solids in highway runoff. However, our approach departs from most previous studies in two ways. First, we make a distinction between rainfall and snowmelt events when analyzing the correlation between mass loadings and suspended solids. Second, we investigate the influence of particle size on heavy metal concentrations for both rainfall and snowmelt events.

Regression of Metals Against Suspended Solids

It is hypothesized that there is a statistically significant linear relationship between heavy metal EMCs and suspended solid EMCs. To test this hypothesis, total heavy metal EMCs were linearly regressed against suspended solid EMCs. These regressions were performed separately for snow washoff and rainfall runoff events using water quality data collected at the six selected FHWA sites and the Jessheim E6 site. The linear regression model is written as:

$$Y = \alpha + \beta X + \epsilon \tag{2}$$

where

- Y = computed metal EMC,
- X = measured suspended solid EMC,
- α, β = regression parameters estimated from the sample data, and
- ϵ = total error associated with predicting Y at a given X.

The error is assumed to be a linear combination of "measurement" error and "modeling" error. Error associated with data acquisition, measurement and testing procedures was unknown. Lumped together, these potential errors constitute the overall "measurement" error.

Clearly the linear model is an expedient. Other more complex regression models such as nonlinear or multiple regression approaches could be used. However, some data sets lacked sufficient observations to justify multiparameter models. To maintain consistency among the study sites and between types of storm events and to afford comparison with other published results, the simple linear model is sufficient for our purposes.

Table 4 contains the resulting coefficients of determination obtained from least squares analysis performed using the software package Statgraphics. These R^2 values represent the proportion of the total variation in the dependent variable, Y, that can be accounted for by a linear relationship with the independent random variable, X (*12*). Results indicate a significant correlation between concentrations of metals and suspended solids in snow washoff and long duration rainfall runoff events. Significance was evaluated with a null hypothesis that the slope of the regression line was equal to zero, using the test statistic

$$T = R\sqrt{\frac{n-2}{1-R^2}} \sim t_{(1-\frac{\alpha}{2},\, n-2)} \tag{3}$$

where:

- T = test statistic
- R = correlation coefficient
- n = sample size
- α = significance level
- t = variable from t distribution with $n - 2$ degrees of freedom

In contrast, R^2 values for chloride and nitrate show very weak EMC correlations with suspended solids for both rainfall runoff and short duration snow washoff events. These findings are consistent with observations reported elsewhere (*13*).

Regression of Metals Against Particle Size

The Jessheim data set contained measured sedimentation velocities. Based on particle Reynolds numbers these velocities are in the laminar regime. It is straightforward to estimate approximate particle sizes based on rates of settling in laminar flow. From an equilibrium force balance, assuming discrete suspended solid particles, Newton's law gives (*14*)

$$V = \sqrt{\frac{4g(\rho_p - \rho_w)d_p}{3C_D\,\rho_w}} \tag{4}$$

For laminar flow, Equation 4 leads to Stokes law, solved for particle diameter (*14*):

$$d_p = \sqrt{\frac{18\mu V}{g(\rho_p - \rho_w)}} \tag{5}$$

where:

- C_D = drag coefficient for laminar flow,
- ρ_w = density of water (1000 kg/m^3),
- ρ_p = density of particle (2,600 kg/m^3),
- μ = dynamic viscosity of water (0.000152 kg/m·s),
- V = settling velocity (m/sec), and
- d_p = particle diameter (m).

Equation 5 was used to convert Jessheim sedimentation velocities to equivalent particle diameters. The particle diameters were

TABLE 4 Coefficients of Determination for Runoff Water Quality Constituents

CORRELATIONS TO SUSPENDED SOLIDS - COEFFICIENTS OF DETERMINATION									
PARAMETERS		Cu	Pb	Zn	Cl	Fe	Cd	Cr	NO3
HIGHWAY SITES									
Milwaukee I-94	Rain	0.669	0.903	0.805	0.051	0.914	0.119	0.007	0.019
	Snow	0.950	0.981	0.970	0.605*	0.936	---	---	0.151
Milwaukee I-794	Rain	0.161	0.383	0.262	0.058	0.007	0.151	0.010	---
	Snow	0.907	0.988	0.966	0.032*	0.983	0.109	0.891	---
Milwaukee Hwy-45	Rain	0.068	0.463	0.181	0.009	0.808	0.000	0.120	---
	Snow	0.937	0.961	0.968	0.038	0.983	0.002	0.908	---
Spokane I-90	Rain	0.990	0.983	0.752	0.71*	---	---	---	0.040
	Snow	0.999	0.991	0.995	0.711	---	---	---	0.090
Seattle SR-520	Rain	0.320	0.616	0.337	0.094*	---	---	---	0.010
	Snow	0.890	0.941	0.470	0.098*	---	---	---	0.028
Jessheim E6	Rain	0.854	0.263	0.265	0.162*	0.301	0.86*	0.06*	---
	Snow	0.871	0.645	0.864	0.957	0.897	0.023	0.909	---

NOTES:
: Coefficients of Determination are designated as "R-Squared" in Figure 1
: --- : Incomplete or insufficient data
: Cu : Copper Pb : Lead Zn : Zinc Cl : Chlorides
: Fe : Iron Cd : Cadmium Cr : Chromium NO3 : Nitrates
: * indicates a negative correlation coefficient , r

TABLE 5 R^2 Values for Constituents Regressed Against Suspended Solid Particle Sizes, Jessheim Site

CORRELATIONS TO SUSPENDED SOLID PARTICLE SIZES - COEFFICIENTS OF DETERMINATION								
PARAMETERS:	Cu	Pb	Zn	Fe	Cd	Cr	Ni	PAHs
PARTICLE SIZE:	R-Squared results for data from 6 Jessheim (E6) SNOW washoff events							
TSS [mg/L]	0.871	0.645	0.995	0.905	0.023	0.909	0.317	0.937
< 15 microns	0.954	0.723	0.983	0.972	0.008	0.933	0.306	0.921
15 to 25 microns	0.239	0.235	0.331	0.269	0.003	0.234	0.232	0.479
25 to 50 microns	0.299	0.352	0.120	0.328	0.011	0.273	0.107	0.474
50 to 130 microns	0.681	0.671	0.698	0.720	0.006	0.613	0.093	0.720
> 130 microns	0.267*	0.49*	0.083*	0.225*	0.540	0.296*	0.000	0.073*
PARTICLE SIZE:	R-Squared results for data from 7 Jessheim (E6) RAIN washoff events							
TSS [mg/L]	0.854	0.263	0.265	0.301	0.863*	0.055*	0.431*	0.730
< 15 microns	0.504	0.791	0.376	0.575	0.444*	---	---	0.005
15 to 25 microns	0.390	0.056*	0.002	0.000	0.531*	---	---	0.667
25 to 50 microns	0.956	0.162	0.443	0.410	0.903*	---	---	0.789
50 to 130 microns	0.934	0.178	0.441	0.400	0.942*	---	---	0.760
> 130 microns	0.589	0.016*	0.057	0.034	0.596*	---	---	0.845

NOTES :
: Coefficients of Determination are designated as "R-Squared" in Figures 2 & 3
: --- : Linear regression analysis was not performed for these particle sizes
: TSS : Total Suspended Solids Fe : Iron
: Cu : Copper Pb : Lead Zn : Zinc
: Cd : Cadmium Cr : Chromium Ni : Nickel
: PAHs : Polycyclic (Polynuclear) Aromatic Hydrocarbons
: Calculations and results are based on Jessheim E6 site runoff water quality data
: * indicates a negative correlation coefficient

then used as the independent variables in a linear regression with heavy metal concentrations. Results are summarized in Table 5.

RESULTS

Three main findings emerge from our analysis of correlations between heavy metal EMCs and suspended solid EMCs for rainfall runoff and snow washoff events. Each is discussed below.

Lognormal EMCs

It is often assumed that EMC data from a particular site have a lognormal distribution irrespective of the type of runoff generating event(s). All of the sites analyzed here included EMCs from rainfall runoff and snow washoff. Using the chi^2 goodness of fit statistic at the 90 percent confidence level, the combined precipitation events at a given location did not yield lognormal EMCs. When separated between rainfall runoff and snow washoff, however, the EMCs did follow a lognormal distribution. This finding suggests that EMCs pooled from rainfall and snow events at a particular location represent a mixed rather than a homogeneous population. For purposes of EMC characterization, it may be advisable to carry out separate statistical analyses for the split rainfall runoff and snow washoff EMC populations.

Correlation of Heavy Metal EMCs to Suspended Solid EMCs

Estimated correlations between heavy metal EMCs and suspended solid EMCs are summarized in Table 4 and plotted in Figure 1. Correlations were significant between concentrations of heavy metals and suspended solids in snow washoff and long duration rainfall runoff events. In contrast, R^2 values for chloride and nitrate show very weak EMC correlations with suspended solids for both rainfall runoff and snow washoff events. Both of these findings are consistent with observations reported by other investigators (*13*).

Generally speaking, the EMC correlations are higher for snow washoff events than for rainfall runoff events. The single exception to this trend is the Spokane I-90 site, where the EMC correlations are very high for both rainfall runoff and snow washoff events. At most sites, rainfall events tend to have much shorter durations than snow washoff events. At the Spokane site, however, rainfall events tend to be very long (see Table 3), especially compared to rain events at the other sites. It seems plausible that strong correlations for rainfall events at Spokane may be attributed in part to long duration storms which perhaps enhance pollutant washoff from highway areas. A kinematic wave model of pollutant washoff from impervious surfaces has demonstrated that rainfall duration and rainfall intensity strongly affect runoff pollutant concentration (*15*).

In addition, differences in the size distributions of suspended solids in pavement washoff could be another factor contributing to the observed discrepancies in rainfall and snow washoff EMC correlations given in Table 4. This is an issue that deserves more attention.

Correlation of Heavy Metal EMCs to Suspended Solid Particle Size

Estimated correlations between heavy metal EMCs and particle size from the European sites are summarized in Table 5 and Figures 2 and 3. Here too, there are significant correlations between concentrations of heavy metals and particle sizes in highway runoff. As before, these correlations are more significant for snow washoff events than for rainfall runoff events.

There is a strong correlation between heavy metal concentrations and small particle sizes (<15 microns) at the Jessheim E6 site for snow washoff. From physical considerations, this strong correlation is expected because the specific surface area of the solids fraction increases as the particle size decreases. Surprisingly, heavy metal correlations were more strongly correlated with particle sizes in the 50 to 130 micron range than with particle sizes in the 15 to 50 micron range. This trend was also observed between PAHs and particle size at Jessheim.

In contrast to the snow washoff results, particle size correlations for rainfall runoff events at Jessheim E6 exhibit a rather inconsistent pattern across each of the heavy metals and the PAHs. This

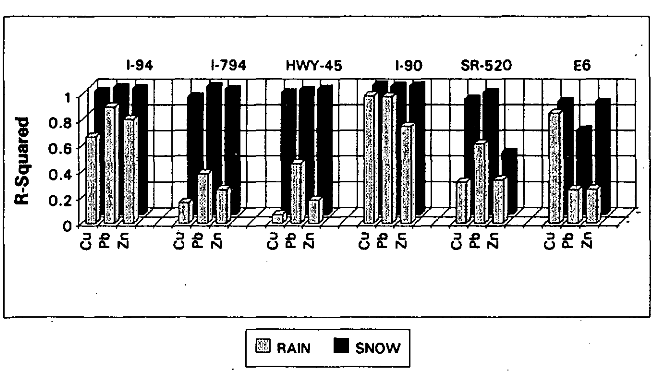

FIGURE 1 R^2 **values for heavy metals regressed against suspended solids**

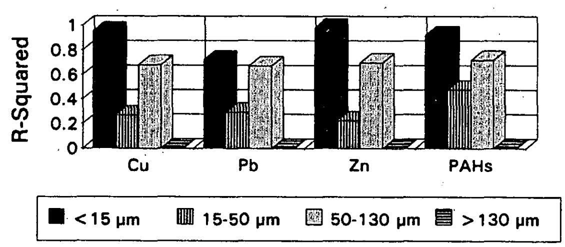

FIGURE 2 Snow washoff R^2 **values for runoff water quality parameters at Jessheim**

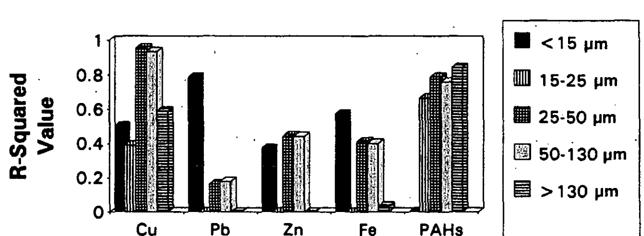

FIGURE 3 Rainfall-runoff R^2 **values for rainfall runoff water quality parameters at Jessheim**

finding, however, is not unexpected based on the erratic correlations obtained for total suspended solids given in Table 4 for Jessheim. The Karlsruhe data, limited to rainfall events only, show that correlations between heavy metals and particle size tend to decrease as particle sizes increase. These results are expected from physical considerations and are much more consistent than the corresponding correlations derived for rainfall events at Jessheim.

Aside from sampling variability, several key factors may have contributed to the differences in correlations observed at the Jessheim and Karlsruhe sites. The Jessheim particle sizes and concentrations were estimated from sedimentation column tests, whereas the Karlsruhe particle sizes and concentrations were measured using a light blocking particle counter. Since the light blocking method is a superior particle counting technology, it is likely that the Karlsruhe data have greater accuracy than the Jessheim data. Finally, obtaining representative suspended solids and pollutant samples in stormwater runoff is a recognized problem. Many sampling devices do not account for changes in flow velocity that occur during a runoff event (*5*). Inconsistent heavy metal correlations observed at Jessheim may indicate that field sampling did not obtain representative samples of suspended solid gradations.

IMPLICATIONS FOR CONTROLLING HIGHWAY RUNOFF QUALITY

The preceding analysis shows that heavy metals and suspended solids in highway runoff are significantly correlated. From a physical standpoint, this is expected since metals preferentially sorb to the finer fractions of the suspended solids. PAHs with low aqueous solubilities and high octanol-water partition coefficients also strongly sorb to suspended solid-associated organic matter (*6*). The fraction of the heavy metal that is sorbed to particulates has great potential to exert a long-term toxicity impact depending on changes in the speciation environment such as pH. Therefore, one important key to effective control of heavy metals and PAHs is to trap the suspended solids transported in highway runoff. In addition, effective control could be further enhanced if the soluble fraction of heavy metals were immobilized. The soluble fraction of a heavy metal is mainly a function of pH and the speciation environment.

Control strategies that have great potential to trap suspended solids, heavy metals bound to suspended solids and soluble heavy metals are infiltration methods and PETs. Both control options essentially function as filters, trapping larger suspended solids through surface straining as well as finer suspended solids and colloidal particles through various mechanisms occurring in deep-bed filtration (*16*).

PETs located along the edge of the paved berm offer several promising advantages. These devices are ideally suited to intercept snow washoff and the "first flush" from the pavement. When properly designed, they can trap solids and particulates of less than 40 microns. PETs would function as a multipurpose replacement to the current practice of underdrain installation. Finally, a PET would intercept subgrade interflow, which can be significant for deteriorated pavement or roadways with unsealed joints (*17*).

PETs can also effectively trap soluble heavy metals through the mechanisms of adsorption, ion-exchange and precipitation. PETs are one of the most effective control options given in Table 1 under conditions in which the suspended solid gradation approaches the colloidal size and heavy metals occur predominantly in soluble form. Wet and dry extended detention basins are not likely to be effective in removing the colloidal size particles compared to control strategies that function as filters (*5*). Any device that does effectively trap suspended solids and heavy metals must be designed so that periodic cleaning and maintenance is feasible.

Swedish researchers have shown that porous pavement, a type of infiltration device, effectively removes pollutants in highway runoff. The Swedish porous pavement, known as the Swedish Unit Superstructure, was developed as both a water quantity and quality control device. Simulations using 30 years of exposure to "stormwater rain" indicated the Unit Superstructure performed as effectively as any other control option listed in Table 1. The simulation produced negligible clogging and these results were confirmed by testing of in situ porous pavement (*17*). The PET blends aspects of typical infiltration trenches and porous pavement. As shown in Figure 4, a PET is designed as a relatively narrow trench with an upper surface consisting of a precast porous pavement block. It is located along the outer edge of the paved berm of an urban highway. The PET is designed to capture the pavement "first-flush" of large runoff events and fully capture snow washoff and rainfall runoff events of low intensity. PETs would be installed in place of underdrains during highway rehabilitation work.

The porous pavement block functions as a rigid surface finish, allows the infiltration of runoff and acts as a straining layer for the surficial trapping of the larger size suspended solids. The porous pavement block is a critical element of the PET for both the effectiveness and maintenance aspects of the control strategy. In order to be hydraulically effective the porous pavement block must have adequate infiltration capacity yet be designed such that the suspended solid particle sizes responsible for long-term deep bed clogging are strained or captured in the porous pavement. Suspended solids trapped in the porous pavement have been easily removed with modified street cleaning techniques such as water spray injection and subsequent vacuuming (*18*). Such surficial cleaning techniques would be applied on a periodic basis. Experience indicates that clogging of porous pavements is minimal. Loss of infiltration capacity is readily restored by surficial cleaning. Nonetheless, the potential for clogging at PETs requires investigation. Unlike drinking water rapid sand filters, which are regularly backwashed to remove suspended solids and other pollutants, a PET cannot be backwashed; therefore, deep bed clogging needs to be minimized. Additionally, the potential for pollutant migration to shallow groundwater requires investigation, especially for clean granular soils with few fines (*19*). Recent computer simulations in Germany indicate a minimal potential for infiltrated pollutant leaching. Experimental bench scale and in situ work is needed for verification (*20*).

CONCLUSIONS

Nonpoint source pollution from urban highways often contains significant levels of heavy metals, suspended solids, PAHs, oils and chlorides. The most common index for quantifying nonpoint source loads is based on the EMC concept. EMC data for heavy metals and suspended solids were obtained from eight highway sites in the United States and Europe. For a given location, the EMCs appear to follow a lognormal distribution, provided the samples arise from similar generating events. When the EMCs from rainfall runoff and snow washoff events at a given site are mixed, the pooled data set deviates from the lognormal distribution. There is a consistent and significant correlation between EMCs for heavy metals and suspended solids in highway runoff. This correlation is strongest for

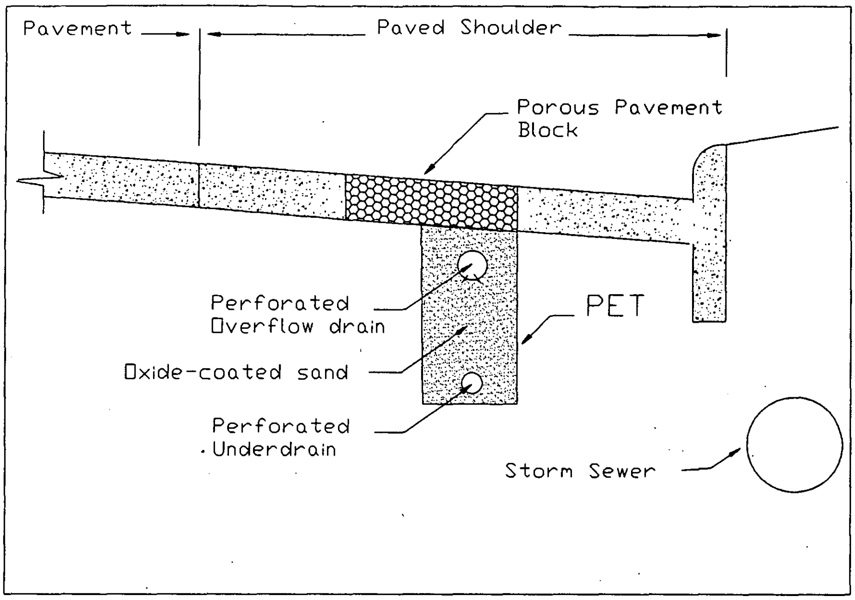

FIGURE 4 Schematic section of a proposed partial exfiltration trench (PET)

snow washoff events, long duration rainfall events and for very small (<15 microns) particle sizes. Considering nonpoint pollutant characteristics and highway site constraints, long, narrow devices called PETs seem to offer a cost effective and efficient means to immobilize heavy metals and to trap suspended solids transported in runoff from urban highways. The potential for clogging and pollutant leaching requires further investigation.

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