EPA Public Access

Author manuscript

Water Res. Author manuscript; available in PMC 2019 October 30.

About author manuscripts

Submit a manuscript

Published in final edited form as:

Water Res. 2018 June 01; 136: 41–53. doi:10.1016/j.watres.2018.02.050.

Performances of metal concentrations from three permeable pavement infiltrates

Jiayu Liu^a, Michael Borst^b

^aOak Ridge Institute for Science and Education Postdoctoral Fellow at the U.S. Environmental Protection Agency, 2890 Woodbridge Ave., MS-104, Edison, NJ, 08837, United States

^bU.S. Environmental Protection Agency, 2890 Woodbridge Ave., MS-104, Edison, NJ, 08837, United States

Abstract

The U.S. Environmental Protection Agency constructed a 4000-m² parking lot in Edison, New Jersey in 2009. The parking lot is surfaced with three permeable pavements [permeable interlocking concrete pavers (PICP), pervious concrete (PC), and porous asphalt (PA)]. Samples of each permeable pavement infiltrate, surface runoff from traditional asphalt, and rainwater were analyzed in duplicate for 22 metals (total and dissolved) for 6 years.

In more than 99% of the samples, the concentration of barium, chromium, copper, manganese, nickel and zinc, and in 60%–90% of the samples, the concentration of arsenic, cadmium, lead, and antimony in infiltrates from all three permeable pavements met both the groundwater effluent limitations (GEL) and maximum contaminant levels (MCL). The concentration of aluminum (50%) and iron (93%) in PICP infiltrates samples exceed the GELs; however, the concentration in more than 90% samples PA and PC infiltrates met the GELs.

No measurable difference in metal concentrations was found from the five sources for arsenic, cadmium, lead, antimony, and tin. Large concentrations of eleven metals, including manganese, copper, aluminum, iron, calcium, magnesium, sodium, potassium, silica, strontium and vanadium, were detected in surface runoff than the rainwater. Chromium, copper, manganese, nickel, aluminum, zinc, iron and magnesium concentrations in PICP infiltrates; calcium, barium, and strontium concentrations in PA infiltrates; sodium, potassium and vanadium concentrations in PC infiltrates were statistically larger than the other two permeable pavement infiltrates.

Graphical abstract

Disclaimer

The U.S. EPA, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described in this paper. It has been subjected to the Agency's administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the writers and do not necessarily reflect the views of the Agency; therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Keywords

Stormwater; Permeable pavements; Metals; Water quality

1. Introduction

During urbanization, traditionally undeveloped lands became impervious. This change dramatically reduces rainfall pathways for storage, infiltration, and groundwater recharge. In the meantime, surface runoff is mixed with many new materials and components used in land development, contributing to higher stressor loads during rainfall and subsequent stormwater runoff (Davis, 2005; Li and Davis, 2009). Traditional stormwater management (gray infrastructure) focuses on moving runoff away quickly to prevent ponding and flooding (Davis, 2005), however, this approach has limitations on both effectiveness and cost due to the growing rates and volumes of stormwater runoff. Low impact development (LID) integrates environmental concerns as part of land development. It is designed to maximize preservation, undisturbed area, and reduce the impact on the soils, vegetation, and aquatic systems to help to maintain the pre-development runoff volume (Dietz, 2007). LID is a promising approach for urban stormwater management (USEPA, 2016).

Permeable pavement is an infiltration-based LID technique, which includes a permeable pavement surface, aggregate sub-base, and sometimes includes geotextiles and underdrains (Drake et al., 2014). During a storm event, stormwater first infiltrates into an underground storage area and then is either conveyed by perforated pipes or exfiltrates to the surrounding soil and ultimately recharges in the groundwater (Brattebo and Booth, 2003; Sansalone and Buchberger, 1995). Permeable pavements are considered a good alternative for urban stormwater drainage management because they provide water quality treatment and they restore the predevelopment hydrology (Bean et al., 2007; Borst and Brown, 2014; Sansalone et al., 2008). Possible pollutant removal mechanisms in permeable pavements include filtration, adsorption, transformation, biological degradation, and volatilization. Permeable interlocking concrete pavers (PICP), pervious asphalt (PA), and porous concrete (PC) are three commonly-used permeable pavements. PA and PC are variations of the typical hot mix asphalt (HMA) and typical concrete mixture, respectively. The mix for PA omits the fine portion of the aggregate. The mix for PC omits fine aggregate and the slurry is tamped or rolled in placed (Dietz, 2007).

Stormwater runoff from urban roadways is often contaminated by significant loads of metal elements (Brown and Peake, 2006; Davis, 2005; Legret et al., 1999; Sansalone and Buchberger, 1997b). Commonly detected metals include sodium (Na), calcium (Ca), aluminum (Al), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), and zinc (Zn) (Granato et al., 1995). Some metals are toxic, affecting aquatic life and human health when concentrations are above the criterion, causing a negative impact on the central nervous system, lungs, kidneys, liver, blood composition, urinary system, and reproductive systems at sub-lethal levels (NYS, 2014; USEPA, 2009, 2012). Pb, Cu and Zn were detected in more than 90% of stormwater samples in the Nationwide Urban Runoff Program (NURP) study (USEPA, 1983), however, Pb pollution is rapidly declining in stormwater runoff due to stringent federal controls over lead in gasoline (Blick et al., 2004; Pitt et al., 2004b).

The deposition and accumulation of metals are from multiple sources, such as automobiles, pavement degradation, decorative flashing, and roadway maintenance (Davis, 2005; Davis et al., 2001; Sansalone and Buchberger, 1997a; Tsihrintzis and Hamid, 1997). The total metals transported by stormwater runoff is comprised of dissolved metals and particulate bound metals. These two phases could transfer between each other in aqueous environment. Permeable pavement systems show ability to trap dissolved heavy metals to their media (Dierkes et al., 2000) and act as filters for particulate-associated metals (Sansalone, 1999). Although underdrains were applied to permeable pavement systems in some projects, infiltrate water commonly directly drains into the existing underlying soil. Metals in the infiltrating water interact with vadose zone soils, but some metals from the permeable pavement systems may reach the groundwater that serve as a source of drinking water. In order to protect human health and the environment, EPA and state governments set concentration limits for different types of water. Groundwater effluent limitations (GEL) set the criterion for discharges to Class GA (fresh groundwater) waters (Part 703.6) (NYS, 2014), and national primary drinking water regulations (NPDWR) (USEPA, 2009) set maximum contaminant levels (MCLs) for contaminants that may pose health risk when present in drinking water supplies.

A lot of research has been done on removal of metals by permeable pavement, most studies focus on Pb, Cu, Cd, Zn or metals related to deicing salts. Legret and Colandini (1999) studied the effects of a porous pavement with reservoir structure on runoff water quality of heavy metals (Pb, Cu, Cd, and Zn) in France and found that metal concentrations were reduced by the passage through the porous pavement. Berbee et al. (1999) reported that runoff from well-maintained PA contains a relatively small concentration of heavy metals than traditional HMA in the research conducted in Netherlands. In the Rushton (2001) research study at the Florida Aquarium in Tampa, FL, metal load reductions of Cu, Fe, Pb and Mn were all more than 75% after passing through porous paving with a swale. Brattebo and Booth (2003) did six years of research in Renton, WA on four different types of permeable pavements and found that Cu and Zn concentrations are significantly lower in infiltrate water from permeable pavements than in runoff from adjacent asphalt lot. PICP was monitored in Waterford, CT, and concentrations of Cu, Pb, and Zn were significantly less than runoff from asphalt driveways (Gilbert and Clausen, 2006). In a field research in Auckland, New Zealand, the event mean concentrations of zinc and copper in discharge

from a permeable modular concrete paver were statistically less than that from the reference conventional asphalt (Fassman and Blackbourn, 2011). Drake et al. (2014) compared the winter quality of stormwater outflows from three permeable pavement systems (one PC and two PICP) with runoff from an asphalt control pavement and found that the permeable pavement systems performed similarly in reducing the event mean concentrations (EMC) and total pollutant loadings for Cu, Fe, Mn and Zn. In recent research, novel techniques such as carbon-negative aggregate, or high-sulfur and high-carbon fly ashes were used to retrofit the traditional permeable pavement systems to enhance the heavy metal removal (Holmes et al., 2017; Tota-Maharaj et al., 2017).

Sodium chloride (NaCl), calcium chloride (CaCl₂) and magnesium chloride (MgCl₂) are commonly-used deicers applied to roadways to increase driving safety during winter season (Borst and Brown, 2014). The deicing salts can damage vegetation, corrode concrete and vehicles, and contaminate groundwater and freshwater (Granato et al., 1995; Suraneni et al., 2017). Moreover, they cause leaching or mobilization of heavy metals by cation replacement (Na⁺ for Ca²⁺ and Mg²⁺) in underlying soils (Marsalek et al., 2003). Granato et al. (1995) investigated groundwater samples adjacent to a highway in southeastern Massachusetts during winter and summer seasons in 1991 and 1993 and found that concentrations of major and trace chemical constituents of highway runoff in groundwater are substantially larger downgradient than upgradient from the highway. Novotny et al. (2008) studied thirteen lakes with annual road deicing application nearby in the Twin Cities Metropolitan Area of Minnesota over 46 months, and found Na and Cl concentrations were 10–25 times larger in these lakes than in other non-urban lakes.

In this paper, six years of monitoring data for 22 metals in the infiltrate from three permeable pavements (PA, PC and PICP) are summarized. Values are contrasted with the corresponding traditional HMA surface runoff (CC) and rainwater (RW). The objectives are:

- (1) to give characterized metals concentrations in rainwater, stormwater surface runoff, and infiltrate from different types of permeable pavements in commercial area;
- (2) to use total metal EMC values from permeable pavement infiltrates to compare with existing standards (GEL and MCL) to determine the potential impact on groundwater and drinking water supply; and
- (3) to compare metal concentrations in infiltrates among three permeable pavements, as well as in surface runoff and rainwater to identify if the permeable pavements is a promising stormwater management strategy.

2. Methods

2.1. Site description and sampling methods

During 2009, the U.S. EPA constructed a 4000m² parking lot at the Edison Environmental Center (EEC) in Edison, New Jersey (Fig. 1). It is used by EEC staff and visitors during workdays. The parking lot is surfaced with three permeable pavements (PICP, PC and PA) from north to south. The storage gallery under the parking lot is constructed of American

Association of State Highway and Transportation Officials (AASHTO) No. 2 size compacted recycled concrete aggregate (RCA). The PC and PA were placed directly on the compacted RCA. The PICP was placed on a AASHTO No. 8 aggregate bedding course with AASHTO No. 57 aggregate used as a choker above the AASHTO No. 2. Each permeable surface has four EPDM (ethylene propylene diene monomer) lined sections numbered 1–4 from west to east. The liner isolates the upper 0.41m of the storage gallery. Infiltrating water from each lined section was piped to a 5.7-m³ high-density polyethylene (HDPE) tank for homogenizing and sampling. The tanks completely collected rain events as large as 38mm. Rainfall exceeding 38mm bypasses the collection tanks. Sampling tanks were emptied and cleaned before each event. The driving lanes and the southernmost single row were paved with HMA. The runoff from the southernmost HMA section entered the rain gardens through six curb cuts. The runoff was sampled at two inlets (CC4 and CC5) selected by lot as sampling points at the start of the experiments to serve as a control. The parking lot was built on a 1.6% longitudinal slope from north to south and permeable surface area to drainage area ratio is 60%.

Winter maintenance used a rubber edged plow blade and pelletized CaCl₂ with no added sand applied from a typical truck-mounted, impeller-based spreader. The impeller turns at a constant speed so more pellets are applied per unit area as the truck slows leading to uneven distribution.

From January 2010 to October 2015, samples were collected from infiltrates of the three permeable pavement (PICP, PC, PA), surface runoff from curb cuts draining from traditional asphalt (CC), and rainwater (RW). Samples were analyzed for 22 metals in both total and dissolved phases by ICP-AES (EPA method 200.7) (USEPA, 1994). The sampling timeline and strategy is presented in Fig. 2.

Samples were immediately carried to the on-site laboratory after collection. Sample pH was analyzed at the on-site laboratory using an ion-specific electrode (Orion DUAL STAR pH/ISE Meter, Thermo Fisher Scientific Inc., Beverly, MA). Dissolved samples were first passed through a 0.45µm polypropylene membrane (GHP membrane, pall Corp., Port Washington, NY), and all metal samples (total and dissolved) were acidified (pH<2 with HNO₃) for preservation. Samples were refrigerated until shipped in coolers with cold packs for overnight delivery to EPA's laboratory in Cincinnati, Ohio for analysis.

The metals list, including the number of samples, their detection limits (DL), and the censored percentage for each metal from each source can be found in Table S1 in the supplementary information.

Metals in new permeable pavement surface materials were extracted using DI water at a weight/volume ratio (g/mL) of 1: 4 for 24h to help understand the potential surface material contribution of metal concentrations in permeable pavement infiltrates. Then the liquid samples were treated and analyzed the same as metal infiltrate samples.

2.2. Data handling and statistical analyses

Data in this research are “left-censored”, indicating some values are less than the DL. Substitution, maximum likelihood estimation (MLE) and nonparametric methods are three basic methods for analyzing data with non-detects. Substitution is recommended by USEPA (2000) when censored data are a small proportion (less than 15%) of the total population. This approach artificially affects both mean and variance estimates and has been shown to give poor results in simulation studies (Huston and Juarez-Colunga, 2009). For this study, the robust regression-on-order statistics (ROS), demonstrated to work well for both small and large data sets (Helsel, 2011), was selected to estimate summary statistics when censored data proportion was less than 80%. When the data set contained more than 80% censored data, the percentage of uncensored data was reported without the summary descriptive statistics. Total metal (M_T) and dissolved metal (M_D) concentrations were analyzed separately for summary statistics.

Hypothesis comparisons were performed using both parametric and non-parametric methods (Table 1). MLE is a parametric method used to compare center differences between two or more independent groups of censored data. MLE is a large-sample method (uncensored samples > 30–50%), based on parametric distributions and sensitive to outliers (Helsel, 2011). Wilcoxon rank sum tests are non-parametric methods for testing differences between two groups, and the Wilcoxon score test is a multivariate extension of it for comparisons among multiple groups. Although non-parametric methods are not as powerful as parametric methods at detecting difference, they require fewer assumptions about the underlying data distribution and are less sensitive to sample size and outliers (Huston and Juarez-Colunga, 2009). Non-parametric methods provide a check for its corresponding parametric method, although the confidence interval estimate is not available. There may be evidence of assumption violations if these two methods provided different results (Huston and Juarez-Colunga, 2009). When comparisons were applied between paired observations, the difference between each pair, which are interval censored, were calculated first, and then either the parametric paired MLE test or non-parametric modified sign test was performed on differences between measurements.

The dissolved fraction, f_d , is defined as:

$$f_d = \frac{C_d}{C_t}$$

Where C_d =dissolved concentration of a metal element (mg/L); C_t =total concentration of a metal element (mg/L). Since concentrations may be lower than DL in some cases, the range of the median f_d was reported.

The exceedance probability plots were created by ranking the measured values from the largest to the smallest and plotted in a semi-log scale (Li and Davis, 2009) to compare concentrations distribution in different sources. Box and whisker plots were used to show the shape of the distribution, the central value, and its variability. Censored values were modeled

by ROS method (Lee, 2013): the procedure first computes the Weibull-type plotting positions of all observations. A linear regression was performed using the plotting positions of the uncensored observations and their normal quantiles. This model was then used to estimate the concentration of the censored observations as a function of their normal quantiles.

Statistical analysis was performed using R (R Development Core Team, 2014), with the NADA package (Lee, 2013) for computing statistics with non-detects. A significance level of $\alpha = 0.05$ was set for all statistical comparisons. Hypotheses tests were applied on stressors with non-detectable samples less than 80%.

3. Results

3.1. General statistical analysis result

Table S1 in the supplementary information lists the summary statistics (number of observations (N), percentage of censored observations (<DL), median ($\tilde{M}$), mean ($\bar{M}$), standard deviation (SD)) calculated for all 22 metals in both total and dissolved phases. Other than beryllium (Be), all metals have censored percentages less than 80%. No summary statistics or statistical comparison were applied on Be. Results will be discussed later by metal groups.

As shown in Fig. 2 and 100% duplicate samples were collected during the first 1.5-year period. The large duplication rate was established to demonstrate adequate homogenization and sampling techniques for the 5.7m³ tanks. The Wilcoxon signed rank test for uncensored paired samples and non-parametric modified sign test for censored paired samples indicate that only 2 out of 105 (21 stressors×5 sources) groups of duplicate samples showed significant differences for either filtered or unfiltered samples. This demonstrated that the procedures of sample collection, storage, and analysis were adequate to obtain representative samples, and supported the decision in the following period to collect 10% duplicate samples.

Total and dissolved concentrations for each metal were compared pairwise to identify if there was a difference. Metals with a significant difference between the dissolved and total concentrations indicate at least some of the metal is particulate-associated. The dissolved fraction is an important indicator of bioavailability and an implication for metal transport and immobilization, which were used by EPA to set and measure compliance with water quality standards (CFR, 1995; Sansalone and Buchberger, 1997a). The range of median dissolved fraction and the comparison of total and dissolved concentrations are summarized in Table S1 in the supplementary information.

Location (section) was not a significant effect for most metals in surface runoff. Total concentrations of Al, Fe, and V collected from CC4 were statistically less than those collected from CC5. For permeable pavement infiltrates, 2 (Ba, Cu), 6 (Al, Ba, Ca, Fe, Mg, Sr), and 5 (Ca, Fe, K, Sr, V) out of 21 metals showed statistical differences by locations in the infiltrates of PICP, PA and PC, respectively. Section 4 showed statistical difference (either larger or smaller) more frequently than other sections. Al, Ba, Ca, and Sr

concentrations in Section 4 in PA infiltrates were the largest among all four sections; whereas Cu concentrations in PICP, as well as Ca and Sr concentrations in PC, Section 4 were the smallest among the four sections. The reasons for the differences in the infiltrate concentrations from this section are unknown. Uneven salt application seems unlikely as Ba, Cu, K and V, which were not detected in the deicing salt, were among the significantly different melts. Metals with statistically significant difference for locations from different sources are shown in Table 2.

Table 3 summarizes the statistical groups among all five sources by Kruskal Wallis test (uncensored data) or Wilcoxon score test (censored data) to investigate if there is a treatment difference between permeable pavements, and if there is a metal concentration difference after passing through the permeable pavements.

3.2. Comparing metals with existing standards

Exceedance probabilities were calculated for metals (total) with criterion of GELs and MCLs in five sources (PA, PC, PICP, CC, RW) (Table S1 in the supplementary information). There are both GELs and MCLs for Ba, Cr, Cu, As, Cd, Pb, and Sb; only GELs for Be, Mn, Ni, Zn, Al and Fe. Other than Cu, the MCLs are smaller than GELs. The exceedance probability plots and boxplots for selected metals are presented in Fig. 3 to Fig. 8. Plots for other metals can be found in the supplementary information (Fig. S1 – Fig. S16). In exceedance probability plots, solid symbols indicate ranked values above the DL, open symbols are values modeled by ROS.

Be, a priority metal pollutant (USEPA, 2012), was detected in less than 10% of the analyses from any source for either the total or the dissolved concentration. The MCL for Be is 0.004mg/L (USEPA, 2009), which is less than the 0.005mg/L DL in this study. An analytical method with a smaller detection limit would be needed to analyze Be in future study. The remaining twelve metals are grouped by their concentrations compared with established standards and the performance of three permeable pavements, and listed in Table 4.

3.2.1. Group I: Ba, Cr, Cu, Mn, Ni, Zn—Although concentrations differed among permeable pavement infiltrates, most metals concentrations in three permeable pavement infiltrates were less than both the GELs and MCLs. Cu is taken as an example to show the exceedance probability plots and boxplots style in this group (Fig. 3). There was no significant difference between the total concentrations in RW and CC for Ba, Cr and Zn. Mn, Cu, and Ni in CC (total concentrations) were statistically larger than in RW, but all at very low level, less than 3% of their GELs. The increase of Cu and Mn was mostly based on particulate metals accumulation from impervious area, since these two metals were almost totally dissolved in RW, whereas $f_d < 50\%$ in CC. The dissolved and total metal (Cr, Cu, Ni, Zn) concentrations in CC were either close to or less than the median values for runoff from commercial areas listed in the National Stormwater Quality Database (NSQD) (Pitt et al., 2004a). Differences in concentrations with the NSQD can be attributed, at least in part, to the reduced traffic at the EEC compared with the coming and goings at many commercial activates such a convenience store.

Zn concentrations (total) in all the three permeable pavement infiltrates, Mn, Cu, and Ni concentrations (total) in PC and PA infiltrates were smaller than in CC. Metals concentrations (total) in PICP infiltrates were usually the largest among the three permeable pavements, with large fraction particulate-bound. Take Mn concentration in PICP infiltrate as an example, the $\overline{Mn}_D$ was less than 0.001mg/L, whereas $\overline{Mn}_T=0.062\text{mg/L}$. This can be mainly attribute to the particulate metals, which were filtered from the runoff in the PC and PA but carried into the PICP infiltrates. However, Ba is an exception. Ba concentrations in PA infiltrate ($\overline{Ba}_T=0.022\text{mg/L}$) was larger than in PICP infiltrate ($\overline{Ba}_T=0.011\text{mg/L}$), which is due to the large fraction of dissolved part in PA ($\overline{Ba}_D=0.021\text{mg/L}$, $f_d > 85\%$).

3.2.2. Group II: As, Cd, Pb, Sb—Nearly 60%–99% metal concentrations in permeable pavement infiltrates are less than GELs and MCLs. No statistically measureable difference was found among the five sources for metals in this group, suggesting permeable pavements in this study had no effect on metals in this group (As: Fig. 4). The concentration of many samples in this group were non-detectable: more than half of As, Cd and Sb samples, and 40% of Pb samples were less than DLs. Pb ($\overline{Pb}_T=0.004\text{mg/L}$, $\overline{Pb}_D=0.003\text{mg/L}$) and Cd ($\overline{Cd}_T < 0.0003\text{mg/L}$, $\overline{Cd}_D < 0.0003\text{mg/L}$) concentrations in CC were much smaller than median values listed in the NSQD for commercial use ($\overline{Pb}_T=0.018\text{mg/L}$, $\overline{Pb}_D=0.005\text{mg/L}$, $\overline{Cd}_T=0.0009\text{mg/L}$, $\overline{Cd}_D=0.0003\text{mg/L}$) (Pitt et al., 2004a). Differences in Pb are likely attributable to the continued steady decline in runoff lead concentrations since the elimination of leaded gasoline. Both the NSQD median As concentration values in surface runoff (0.0024mg/L) and the median CC value in Edison parking lot (<0.004mg/L) were less than As DL (0.004mg/L). More than 80% Cd and Pb samples were smaller than criteria. However, around 40% of As and 30% of Sb were larger than the MCLs.

3.2.3. Group III: Al, Fe—Al and Fe are primary soil/sediment constituents. Approximately eight percent and five percent of lithosphere is Al and Fe, respectively (Lindsay, 1979). They can both cause detrimental effects in receiving waters in their dissolved forms. More than 90% of the Al and Fe (Fig. 5) concentrations in PA and PC infiltrates were less than the GELs, however, only 50% of Al and 7% of Fe concentrations met the standards in PICP infiltrates. The median value of Al and Fe were both almost one order of magnitude larger in surface runoff than rainwater (CC>RW). There was PICP ($\overline{Al}_T=2.009\text{mg/L}$)>PA ($\overline{Al}_T=1.291\text{mg/L}$)>CC ($\overline{Al}_T=0.348\text{mg/L}$)>PC ($\overline{Al}_T=0.181\text{mg/L}$). f_d in PICP and PA are 4% and 94%, respectively, suggesting that Al in PA infiltrates is mainly dissolved, and in PICP infiltrates is mainly particulate-bound. An increase in pH substantially increases the abundance of dissolved Al ($\overline{pH}_{PICP}=9$, $\overline{pH}_{PC}=9.3$, $\overline{pH}_{PA}=11.1$). Al is an amphoteric metal, which is more soluble at higher ($\text{Al}(\text{OH})_4^-$) and lower pH (Al^{3+}), and reaches minimum solubility at a specific pH (around 6.5). This also happens for other metals such as Zn, Cu, and Ni, but not the same as the common finding that metals become soluble and mobile at lower pH (Mikkelsen et al., 1994; Sparks, 2003). Based on the median f_d values, Fe is found mainly particulate-bound in all five sources, which is in accordance with solubility diagram for iron that ferric hydroxide ($\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) is the most common

species in the pH range of 5–11 and Eh range of 0.4–0.6V. Compared with the CC ($\overline{Fe_T}=0.309\text{mg/L}$), Fe concentrations in PICP ($\overline{Fe_T}=3.720\text{mg/L}$) were dramatically larger, whereas in PA ($\overline{Fe_T}=0.063\text{mg/L}$) and PC ($\overline{Fe_T}=0.125\text{mg/L}$) were smaller.

3.3. Metals associated with deicing chemicals

Road salt was the only material intentionally introduced to the system. Na, Mg, and Ca are metals predominantly associated with road salt as a deicing chemical. The concentration of these metals was larger in the surface runoff than rainwater (CC>RW) due to the deicing salts application during snow season. Na (Fig. 6) concentrations in the three permeable pavement infiltrates [PC ($\overline{Na_T}=131.8\text{mg/L}$)>PICP ($\overline{Na_T}=99.6\text{mg/L}$)>PA ($\overline{Na_T}=81.5\text{mg/L}$)] were statistically larger than in CC samples ($\overline{Na_T}=3.5\text{mg/L}$) and RW ($\overline{Na_T}=0.6\text{mg/L}$). Surface material leaching tests showed Na concentrations from PC ($\overline{Na_T}=107.1\text{mg/L}$) were larger than from PA ($\overline{Na_T}=28.4\text{mg/L}$) and PICP ($\overline{Na_T}=8.1\text{mg/L}$). This suggests that part of the Na in the infiltrate may be leaching directly from the materials of construction. Although results from surface material test are only used for qualitative comparison due to the large variation in results, they may explain the large Na concentration in PC infiltrates.

Ca (Fig. 7) concentrations were found PA ($\overline{Ca_T}=34.29\text{mg/L}$)>PICP ($\overline{Ca_T}=7.20\text{mg/L}$)>PC ($\overline{Ca_T}=5.42\text{mg/L}$)~CC ($\overline{Ca_T}=4.61\text{mg/L}$)>RW ($\overline{Ca_T}=0.46\text{mg/L}$), whereas, Ca concentrations in PA were ($\overline{Ca_T}=7.52\text{mg/L}$) much less than PICP ($\overline{Ca_T}=20.90\text{mg/L}$) and PC ($\overline{Ca_T}=18.38\text{mg/L}$) in surface material test. The infiltration test reported PC (4000cm/h)>PICP (2400cm/h)>PA (200cm/h) (Borst, 2010). The smallest infiltration rate in PA resulted in larger concentrations of dissolved Ca in PA ($\overline{Ca_D}=31.59\text{mg/L}$) compared to PICP ($\overline{Ca_D}=4.64\text{mg/L}$) and PC ($\overline{Ca_D}=4.73\text{mg/L}$). The same results was found in chloride (Cl) by Borst and Brown (2014). The Ca, like the Cl, is released slowly from PA and persisted at larger concentrations compared to PICP and PC during no-snow season. This may explain the largest median total Ca concentration in PA infiltrates during the entire study. Mg (Fig. 8) had PICP ($\overline{Mg_T}=4.59\text{mg/L}$)>PC ($\overline{Mg_T}=0.49\text{mg/L}$)~CC ($\overline{Mg_T}=0.51\text{mg/L}$)>PA ($\overline{Mg_T}=0.11\text{mg/L}$)~RW ($\overline{Mg_T}=0.12\text{mg/L}$). PA can effectively remove Mg. Mg concentrations in PICP infiltrates were an order larger than the other two permeable pavement infiltrates. For all three metals in this group, a prominent jump was found in exceedance probability plots (Fig. 6, Fig. 7, Fig. 8) for dissolved metal concentrations at 10% samples in PICP and PC infiltrates, which may indicate the deicing salts application.

3.4. Other metals

This research monitored K, Li, Si, Sn, Sr, and V, which are rarely mentioned by current research. Sn concentrations were small and no statistical differences were found among the five sources. K, Li, Si, Sr, and V in all permeable pavement infiltrates were statistically larger than in CC and RW. Moreover, K, Si, Sr and V accumulated on the surface and runoff concentrations were larger than rainwater (CC>RW).

K and V were not detected in deicing salts. K is an essential element for human, animal and plant tissues, adverse health effects due to K consumption from drinking water are unlikely to occur in healthy individuals. There was $PC (\bar{K}_T = 26.7\text{mg/L}) > PA (\bar{K}_T = 13.5\text{mg/L}) > PICP (\bar{K}_T = 7.5\text{mg/L})$. Surface material test shows that K concentrations in PC ($\bar{K}_T = 176.0\text{mg/L}$) were much larger than in PA ($\bar{K}_T = 0.3\text{mg/L}$) and PICP ($\bar{K}_T = 33.0\text{mg/L}$). Moreover, a prominent jump at 10% in samples for dissolved metals in PICP and PC infiltrates was found for K as well. Extensive cation exchange during snow season may be a possible explanation of it. V concentrations [$PC (\bar{V}_T = 0.024\text{mg/L}) > PICP (\bar{V}_T = 0.021\text{mg/L}) > PA (\bar{V}_T = 0.011\text{mg/L})$] in permeable pavement infiltrates were in the range of V concentrations in drinking water of 0.0002mg/L to more than 0.1mg/L (Vouk, 1979).

Si, Sr and Li were found in both deicers and surface material leachate. Si is the second most abundant element in the earth's crust. The median values of Si concentrations in permeable pavement infiltrates ranged from 6.5 to 10.5mg/L. McNeely et al. (1979) reported that silicon commonly ranges of 1–30mg/L in natural waters in Canada. Sr concentration in PA infiltrates was $\bar{Sr}_T = 1.007\text{mg/L}$ with the $\bar{f}_d = 92\%$, it is one order of magnitude larger than in PICP ($\bar{Sr}_T = 0.020\text{mg/L}$) and PC ($\bar{Sr}_T = 0.019\text{mg/L}$). No water quality criteria is set for Sr, however, the toxicity of Sr is believed very minimal (USEPA, 2007). The median value of Li concentrations in permeable pavement infiltrates is from 0.016 to 0.020mg/L, which is much smaller than the maximum recommended concentration of Li in irrigation water of 2.5mg/L (Environmental Studies Borad, 1972).

4. Conclusions and discussion

Several metals were detected as statistically different by locations (Section) in both surface runoff and permeable pavement infiltrates. Unevenly spread of deicing salts for winter application and preferred vehicle parking pattern may both be the reasons of metal concentrations different among sections. Deicing salts applied in snow season were not evenly spread, which may be one of the reasons for Al, Ca, Fe, Mg, and Sr concentration differences among sections. However, Ba, Cu, K and V, which were not detected in the deicing salt, also showed the concentration differences among sections. Metal release in the parking lots might also be effected by the vehicle parking pattern: preferential parking near the doors of the adjacent building has been observed by Brown and Borst (2015) and moreover, some vehicles are likely to park in the east part of parking lot (Section 4).

The dissolved and total metal (Cr, Cu, Ni, Zn, As, Cd, Pb) concentrations in surface runoff were within one order magnitude of the median values in the NSQD, indicating its representative of national surface runoff for this study.

Eleven metals were detected in surface runoff at larger concentrations than the rainwater. These metals include Mn, Cu, Al, Fe, Ca, Mg, Na, K, Si, Sr and V, with Cu the only priority metal pollutants in the USEPA list (USEPA, 2012) studied in this research. The larger relative concentration indicates surface accumulation between rain events.

Thirteen metals in this study have existing standards such as GELs or MCLs. Be was identified in less than 10% of the samples at concentrations larger than the laboratory reported detection limit. The DL in this study, 0.005mg/L, was larger than MCL (0.004mg/L). Ba, Cr, Mn, Cu, Ni and Zn concentrations in permeable pavement infiltrates were uniformly less than the GELs and MCLs. The concentrations of As, Cd, Pb, and Sb in permeable pavement infiltrates exceeded the GELs and MCLs for 1%–40%. More than 90% of Al and Fe samples in PA and PC infiltrates are less than GELs, however, 50% of Al and 93% of Fe samples in PICP infiltrates exceeded the GELs.

As, Cd, Pb, Sb and Sn samples did not vary by surfaces. This may be 1) because these metals passed through the systems without reaction; 2) or because permeable pavements act as filters for particulate-bound metals (Sansalone, 1999), and could trap dissolved heavy metals to their fixed media (Dierkes et al., 2000) and then keep a steady state adsorption and desorption.

Some metal concentrations (total) in permeable pavement infiltrates were larger than HMA runoff (PICP: Ba, Cr, Mn, Cu, Al, Fe, Ca, Mg, Na, K, Li, Si, Sr, V; PA: Ba, Cr, Al, Ca, Na, K, Li, Si, Sr, V; PC: Cr, Na, K, Li, Si, Sr, V). This may be attributes to 1) surface material of permeable pavement leaching; 2) spatial variability in deicing salt application, and the influence of previous events (Borst and Brown, 2014); and 3) Na and K may exchange for Ca and Mg in underlying aggregates, which promotes leaching or mobilization of heavy metals (Granato et al., 1995; Marsalek et al., 2003).

Cu, Mn, Ni, Al, Fe, Mg concentrations in PICP infiltrates were much larger than the other two permeable pavement infiltrates, most of which are mainly particulate bounded. This may be because suspended solids or salt particles trapped in the gap between PICP and underlying aggregate were directly flushed into the collection tank. PA had the slowest release rate and persisted at larger dissolved Ca concentrations than PICP and PC, which is in accordance with the conclusion found for Chloride (Borst and Brown, 2014). This theory may also explain the relatively larger concentration of Ba and Sr in PA infiltrates. PC infiltrates had the largest metal concentrations of Na, K, and V, which may contribute to the surface material leaching.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgement

This article was supported in part by appointment to the Research Participation Program at the National Risk Management Research Laboratory administered by the Oak Ridge Institute for Science and Education (ORISE, DW-89-92433001) through an interagency agreement between the U.S.DOE and U.S. EPA. The authors acknowledge the support provided by our colleagues in Inorganic Analytical Group of the Water Supply and Water Resources Division led by Keith Kelty and Maily Pham.

References

- Bean E, Hunt W, Bidelsbach D. Field survey of permeable pavement surface infiltration rates J. Irrigat. Drain. Eng, 133 (3) (2007), pp. 249–255

- Berbee R, Rijs G, de Brouwer R, van Velzen Characterization L. and treatment of runoff from highways in The Netherlands paved with impervious and pervious asphalt *Water Environ. Res* (1999), pp. 183–190
- Blick SA, Kelly F, Skupien JJ New Jersey stormwater Best Management Practices Manual (2004)
- Borst M. Surface Infiltration Rates of Permeable Surfaces: Six Month Update (November 2009 through April 2010) National Risk Management Research Laboratory, Water Supply and Water Resources Division, US Environmental Protection Agency (2010)
- Borst M, Brown RA Chloride released from three permeable pavement surfaces after winter salt application *JAWRA Journal of the American Water Resources Association*, 50 (1) (2014), pp. 29–41
- Brattebo BO, Booth DB Long-term stormwater quantity and quality performance of permeable pavement systems *Water Res*, 37 (18) (2003), pp. 4369–4376 [PubMed: 14511707]
- Brown JN, Peake BM Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff *Sci. Total Environ*, 359 (1–3) (2006), pp. 145–155
- Brown RA, Borst M. Nutrient infiltrate concentrations from three permeable pavement types *J. Environ. Manag*, 164 (2015), pp. 74–85
- CFR Title 40, Part 131: Water Quality Standards (1995) (Washington, DC)
- Davis AP Green engineering principles promote low-impact development *Environ. Sci. Technol*, 39 (16) (2005), pp. 338A–344A
- Davis AP, Shokouhian M, Ni S. Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources *Chemosphere*, 44 (5) (2001), pp. 997–1009 [PubMed: 11513434]
- Dierkes C, Göbel P, Benze W, Wells J. Next Generation Water Sensitive Storm Water Management Techniques (2000), pp. 2–4
- Dietz ME Low impact development practices: a review of current research and recommendations for future directions *Water Air Soil Pollut*, 186 (1–4) (2007), pp. 351–363
- Drake J, Bradford A, Van T. Seters Winter effluent quality from partial-infiltration permeable pavement systems *J. Environ. Eng*, 140 (11) (2014) 04014036
- Environmental Studies Borad Water Quality Criteria: 1972 National Service Center for Environmental Publications, Washington, D.C.(1972)
- Fassman EA, Blackburn SD Road runoff water-quality mitigation by permeable modular concrete pavers *J. Irrigat. Drain. Eng*, 137 (11) (2011), pp. 720–729
- Gilbert JK, Clausen JC Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut *Water Res*, 40 (4) (2006), pp. 826–832 [PubMed: 16427680]
- Granato GE, Church PE, Stone VJ Mobilization of major and trace constituents of highway runoff in groundwater potentially caused by deicing chemical migration *Transport. Res. Rec*, 1483 (1995), pp. 92–104
- Helsel DR Statistics for Censored Environmental Data Using Minitab and R John Wiley & Sons (2011)
- Holmes RR, Hart ML, Kevern JT Enhancing the ability of pervious concrete to remove heavy metals from stormwater *Journal of Sustainable Water in the Built Environment*, 3 (2) (2017) 04017004
- Huston C, Juarez-Colunga E. Guidelines for Computing Summary Statistics for Data-sets Containing Non-detects Department of Statistics and Actuarial Science, Simon Fraser University (2009)
- Lee L. NADA: Nondetects and Data Analysis for Environmental Data (2013)
- Legret M, Colandini V. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals *Water Sci. Technol*, 39 (2) (1999), pp. 111–117
- Legret M, Nicollet M, Miloda P, Colandini V, Raimbault G. Simulation of heavy metal pollution from stormwater infiltration through a porous pavement with reservoir structure *Water Sci. Technol*, 39 (2) (1999), pp. 119–125
- Li H, Davis AP Water quality improvement through reductions of pollutant loads using bioretention *J. Environ. Eng*, 135 (8) (2009), pp. 567–576
- Lindsay WL Chemical Equilibria in Soils John Wiley and Sons Ltd (1979)
- Marsalek J, Oberts G, Exall K, Viklander M. Review of operation of urban drainage systems in cold weather: water quality considerations *Water Sci. Technol*, 48 (9) (2003), pp. 11–20

- McNeely RN, Neimanis VP, Dwyer L. Water Quality Sourcebook: a Guide to Water Quality Parameters Environment Canada (1979)
- Mikkelsen PS, Weyer G, Berry C, Waldent Y, Colandini V, Poulsen S, Grotehusmann D, Rohlfing R. Pollution from urban stormwater infiltration Water Sci. Technol, 29 (1–2) (1994), pp. 293–302
- Novotny EV, Murphy D, Stefan HG Increase of urban lake salinity by road deicing salt Sci. Total Environ, 406 (1–2) (2008), pp. 131–144
- NYS Part 703: Surface Water and Groundwater Quality Standards and Groundwater Effluent Limitations (2014)
- Pitt R, Maestre A, Morquecho R. The National Stormwater Quality Database (NSQD, Version 1.1) (2004), pp. 13–51
- Pitt R, Maestre A, Morquecho R, Brown T, Schueler T, Cappiella K, Sturm P, Swann C. Findings from the National Stormwater Quality Database (NSQD) Center for Watershed Protection, Ellicott City, MD (2004)
- Development Core Team R: a Language and Environment for Statistical Computing R Foundation for Statistical Computing, Vienna, Austria (2014)
- Rushton BT Low-impact parking lot design reduces runoff and pollutant loads J. Water Resour. Plann. Manag, 127 (3) (2001), pp. 172–179
- Sansalone J, Buchberger S. An infiltration device as a best management practice for immobilizing heavy metals in urban highway runoff Water Sci. Technol, 32 (1) (1995), pp. 119–125
- Sansalone J, Buchberger S. Partitioning and first flush of metals in urban roadway storm water J. Environ. Eng, 123 (2) (1997), pp. 134–143
- Sansalone J, Kuang X, Ranieri V. Permeable pavement as a hydraulic and filtration interface for urban drainage J. Irrigat. Drain. Eng, 134 (5) (2008), pp. 666–674
- Sansalone JJ Adsorptive infiltration of metals in urban drainage—media characteristics Sci. Total Environ, 235 (1) (1999), pp. 179–188
- Sansalone JJ, Buchberger SG Characterization of solid and metal element distributions in urban highway stormwater Water Sci. Technol, 36 (8) (1997), pp. 155–160
- Sparks DL Environmental Soil Chemistry Elsevier (2003)
- Suraneni P, Azad VJ, Isgor OB, Weiss WJ Use of Fly Ash to Minimize Deicing Salt Damage in Concrete Pavements (2017)
- Tota-Maharaj K, Monrose J, Hills C. Novel Permeable Pavement Systems Utilising Carbon-negative Aggregate (2017)
- Tsihrintzis VA, Hamid R. Modeling and management of urban stormwater runoff quality: a review Water Resour. Manag, 11 (2) (1997), pp. 136–164
- USEPA Results of the Nationwide Urban Runoff Program U.S. Environmental Protection Agency, Water Planning Division, Washington, D.C (1983)
- USEPA (Ed.), Method 200.7: Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-atomic Emission Spectrometry. Agency, U.S.E.P, U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Cincinnati, OH (1994)
- USEPA Guidance for Data Quality Assessment: Practical Methods for Data Analysis U.S. Environmental Protection Agency, Washington, D.C (2000), pp. 1–219
- USEPA (Ed.), Drinking Water Standards and Health Advisories Table. Agency, U.S.E.P (2007), pp. 583–619
- USEPA National Primary Drinking Water Regulations (2009) <https://www.epa.gov/dwstandardsregulations>
- USEPA Code of Federal Regulations, Title 40 (2012) Washington, DC
- USEPA Green infrastructure Research (2016) <https://www.epa.gov/green-infrastructure/green-infrastructure-research>
- Vouk VB Handbook on the Toxicology of Metals Elsevier/North-Holland Biomedical Press (1979)

Highlights

- Ba, Cr, Cu, Mn, Ni, Zn meet GELs and MCLs.
- As, Cd, Pb, Sb have no difference among five sources.
- Large amount of Al and Fe in PICP exceeded the GELs.

Fig. 1.
Plan and cross section view of parking lot at Edison, NJ.

Fig. 2.
Sample collection and analysis strategy.

Fig. 3.
Exceedance probability plots and boxplots for Cu.

Fig. 4.
Exceedance probability plots and boxplots for As.

Fig. 5.
Exceedance probability plots and boxplots for Fe.

Fig. 6.
Exceedance probability plots and boxplots for Na.

Fig. 7.
Exceedance probability plots and boxplots for Ca.

Fig. 8.
Exceedance probability plots and boxplots for Mg.

Table 1.

Hypothesis testing methods selection.

	Uncensored Stressor		Censored Stressor		Application
	Non-parametric	Parametric	Non-parametric		
Two dependent groups	Paired <i>t</i> -test	Wilcoxon signed rank test	Paired MLE	Modified sign test	1) Duplicate samples (Dup) (T, D) ^b 2) Total and dissolved samples;
Two independent groups	Two sample <i>t</i> -test	Wilcoxon rank sum test	MLE	Wilcoxon rank sum test	Concentrations differences between two surface runoff sample points (T). ^b
Multiple independent groups	One-way ANOVA ^a	Kruskal Wallis test	MLE	Wilcoxon score test	1) Concentration difference among five sources (PICP, PA, PC, CC, RW) (T, D) ^b 2) Concentration difference among four locations for each permeable pavement (T). ^b

^aOVA: Analysis of variance.^bT indicates total metal concentration; D indicates dissolved metal concentration.

Table 2.

Metal concentrations (total) statistical significant difference due to sample locations from difference sources.

	PICP				PA				PC				CC	
	<i>M1</i>	<i>M2</i>	<i>M3</i>	<i>M4</i>	<i>M1</i>	<i>M2</i>	<i>M3</i>	<i>M4</i>	<i>M1</i>	<i>M2</i>	<i>M3</i>	<i>M4</i>	<i>M4</i>	<i>M4</i>
Al					A	A	A	B					A	B
					1.249	1.361	1.117	1.617					0.210	0.371
Ba	AB	A	A	B	B	AB	A	C						
	0.013	0.011	0.009	0.019	0.023	0.019	0.015	0.033						
Ca					B	A	A	B	AB	B	B	A		
					37.92	25.77	18.5	53.58	5.148	6.458	5.861	4.022		
Cu	B	B	B	A										
	0.034	0.034	0.035	0.018										
Fe					B	A	AB	B	AB	B	AB	A	A	B
					0.075	0.043	0.061	0.07	0.087	0.157	0.129	0.109	0.226	0.359
K									A	AB	AB	B		
									18.1	25.16	28.8	37.94		
Mg					BC	A	C	AB						
					0.112	0.082	0.124	0.084						
Sr					BC	AB	A	C	B	B	B	A		
					1.029	0.988	0.742	1.628	0.156	0.165	0.152	0.109		
V									A	B	B	B	A	B
									0.013	0.026	0.03	0.032	0.003	0.009

Note.

¹Numbers indicate different sections. PP has four sections: PICP1, PICP2, PICP3, PICP4; PA has four sections: PA1, PA2, PA3, PA4; PC has four sections: PC1, PC2, PC3, PC4; CC has 2 sections: CC4, CC5.

²*M̄* indicates median value.

³Ba, Cu, K, and V were not detected in applied deicer salts.

⁴“A, B, C ...” indicates statistical groups. A<B<C.

Table 3.

Statistical comparison among the infiltrate metal concentrations in three permeable pavement types (PICP, PC, PA), surface runoff (CC) and rainwater (RW) by Kruskal Wallis test (uncensored data) or Wilcoxon score test (censored data).

	Total	Dissolved										
Statistics	PICP	PA	PC	CC	RW	Statistics	PICP	PA	PC	CC	RW	
Al	Chisq (4, 848)=552, p-value<0.001	E	D	B	C	A	Chisq (4, 636)=811, p-value<0.001	C	D	BC	B	A
As	Chisq (4, 848)=5.5, p-value=0.244	A	A	A	A	A	Chisq (4, 636)=8.5, p-value=0.075	A	A	A	A	A
Ba	Chisq (4, 848)=178, p-value<0.001	B	C	A	A	A	Chisq (4, 636)=253, p-value<0.001	AB	C	B	A	AB
Ca	Chisq (4, 848)=522, p-value<0.001	C	D	B	B	A	Chisq (4, 636)=327, p-value<0.001	C	D	BC	B	A
Cd	Chisq (4, 848)=9, p-value=0.062	A	A	A	A	A	Chisq (4, 636)=8.5, p-value=0.075	A	A	A	A	A
Cr	Chisq (4, 848)=71.2, p-value<0.001	D	B	C	A	A	Chisq (4, 636)=39.9, p-value<0.001	B	C	BC	A	A
Cu	Chisq (4, 848)=233, p-value<0.001	C	A	A	B	A	Chisq (4, 636)=18.9, p-value<0.001	AB	BC	A	BC	C
Fe	Chisq (4, 848)=956, p-value<0.001	E	B	C	D	A	Chisq (4, 636)=86.7, p-value<0.001	C	A	B	B	A
K	Chisq (4, 847)=468, p-value<0.001	C	D	E	B	A	Chisq (4, 635)=414, p-value<0.001	C	D	E	B	A
Li	Chisq (4, 848)=47.1, p-value<0.001	C	B	C	A	A	Chisq (4, 636)=21.6, p-value<0.001	B	B	B	A	A
Mg	Chisq (4, 848)=905, p-value<0.001	C	A	B	B	A	Chisq (4, 636)=280, p-value<0.001	C	A	D	C	B
Mn	Chisq (4, 848)=520, p-value<0.001	D	A	B	C	B	Chisq (4, 636)=24.9, p-value<0.001	AB	A	AB	C	BC
Na	Chisq (4, 848)=256, p-value<0.001	D	C	E	B	A	Chisq (4, 636)=217, p-value<0.001	D	C	E	B	A
Ni	Chisq (4, 848)=173, p-value<0.001	C	A	A	B	A	Chisq (4, 636)=37.1, p-value<0.001	A	AB	A	C	BC
Pb	Chisq (4, 848)=0.7, p-value=0.945	A	A	A	A	A	Chisq (4, 636)=7.1, p-value=0.129	A	A	A	A	A
Sb	Chisq (4, 848)=1.8, p-value=0.777	A	A	A	A	A	Chisq (4, 636)=10.4, p-value=0.034	AB	B	A	A	AB
Si	Chisq (4, 848)=297, p-value<0.001	D	C	D	B	A	Chisq (4, 636)=266, p-value<0.001	C	C	D	B	A
Sn	Chisq (4, 848)=7.2, p-value=0.124	A	A	A	A	A	Chisq (4, 636)=2.6, p-value=0.628	A	A	A	A	A
Sr	Chisq (4, 848)=653, p-value<0.001	C	D	C	B	A	Chisq (4, 636)=577, p-value<0.001	C	E	D	B	A
V	Chisq (4, 848)=193, p-value<0.001	D	C	D	B	A	Chisq (4, 636)=138, p-value<0.001	D	C	D	B	A
Zn	Chisq (4, 848)=138, p-value<0.001	C	A	B	D	D	Chisq (4, 636)=252, p-value<0.001	A	AB	B	C	D

Note.

¹“A, B, C ...” indicates statistical groups. A<B<C<D<E.

². Red indicates $p < 0.05$, and blue indicates no statistical difference among the five sources.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

Table 4.

Groups of metal with existing standards.

	More than 99% of metal concentrations less than both GELs and MCLs	At least 1% of metal concentrations larger than GEL, or MCL, or both
No significant difference found among permeable pavements		Group II: As, Cd, Pb, Sb
Significant difference found among permeable pavements	Group I: Ba, Cr, Cu, Mn, Ni, Zn	Group III: Al, Fe