

Retention of highway runoff pollutants by plants and soils as affected by Best Management Practices: A Literature Review

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Introduction

Runoff from roads and highways contains constituents that could threaten both surface water and groundwater quality if allowed to flow or leach into these receiving waters (Table 1). To prevent this, Best Management Practices (BMP's) can be implemented in design, installation, management, and maintenance of vegetated highway sites. BMP's are designed to reduce contaminant levels by either (Young et al., 1996):

- containing runoff until contaminants settle out or are adsorbed by soils (*structural* BMP's), or
- reducing initial concentrations (*non-structural* BMP's).

Successful implementation of BMP's, however, requires an understanding of the behavior of the potentially polluting constituents of highway runoff.

Potential pollutants in highway runoff

Overview

Potential pollutants in highway runoff can be divided into five major categories (Table 1):

- Solids: suspended and dissolved sediment
- Nutrients: nitrogen and phosphorus
- Metals: heavy metals and platinum group metals
- Compounds associated with de-icing salts: ionic salts and salt contaminants
- Organic compounds: mostly associated with gasoline and other vehicle fluids

The reactions of nutrients, metals, salts, and organic compounds in highway runoff with water and sediment are complex, and include dissolution, precipitation, ion exchange, adsorption, redox (oxidation/reduction), and complexation (Bricker, 2003). It is important to understand, however, that these processes, and thus the form of constituents in highway runoff, are affected by the activity and concentration of each runoff constituent (including sediment), and by site-specific rainfall, runoff water, and soil conditions.

Note: Solids, metals, nutrients, and other compounds are often reported as being in "*suspended*" or "*dissolved*" form. The accepted definition of a dissolved substance is one which can pass through a 0.45 micron filter (Eaton et al., 2005). In practice, solids in the "dissolved" fraction are still in particulate form, and nutrients and metals in the dissolved fraction are often adsorbed to sediment or organic matter, rather than being present in ionic form (Dean et al., 2005). With the advent of ultrafiltration, some researchers are using a 10 kDa (kilodalton) filter to separate dissolved metals (Tucillo, 2006), but, in this review, the 0.45 micron limit will be used to distinguish "dissolved" materials.

Table 1. Constituents of concern in highway runoff, and their sources. (Adapted from information given in U.S. EPA, 1993; Barrett et al., 1995; Granato, 1996; Thomson et al., 1997; Davis et al., 2001a; Beaton and Dudley, 2004; Huang et al., 2004; Ozaki et al., 2004; Ravindra et al., 2004; Venner et al., 2004.)

Constituent	Source
-----Solids-----	
Solids, including total suspended solids (TSS) and total dissolved solids (TDS)	Atmospheric deposition, solids transported by vehicles from other locations, sanding, pavement wear, vehicle part wear, roadside sediment disturbance.
-----Nutrients-----	
Nitrogen (N)	Atmospheric deposition, roadside fertilizer application, transported solids.
Phosphorus (P)	Atmospheric deposition, roadside fertilizer application, anti-rust agents in de-icing salts, transported solids.
-----Metals-----	
Cadmium (Cd)	Atmospheric deposition, tire wear, road marking paint.
Chromium (Cr)	Metal plating, moving engine parts, brake lining wear, impurities in de-icing salts.
Copper (Cu)	Atmospheric deposition, brake emissions, metal plating and engine part wear, some fungicides and insecticides.
Iron (Fe)	Auto body rust, brake linings, steel highway structures such as bridges and guardrails, engine parts.
Lead (Pb)	Atmospheric deposition, road marking paint, lead wheel weights, lubricating oil, bearing wear.
Manganese (Mn)	MMT (methylcyclopentyl manganese tricarbonyl) gasoline additive, engine part wear.
Nickel (Ni)	Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear and asphalt paving, impurities in de-icing salts.
Zinc (Zn)	Tire wear, atmospheric deposition, brake linings, exhaust emissions.
Platinum group metals (platinum, rhodium, palladium)	Catalytic converters.
-----Compounds associated with de-icing salts-----	
Sodium (Na), calcium (Ca), chloride (Cl) and magnesium, sulfate, potassium, fluoride, and others.	De-icing salts, impurities in de-icing salts, atmospheric deposition.
Sulfates	De-icing salts, roadway beds, fuel.
Cyanide	Anti-caking compounds in de-icing salts.
-----Organic Compounds-----	
Semi-volatile organic compounds (petroleum hydrocarbons, oil and grease, polycyclic aromatic hydrocarbons)	Crankcase oil, engine leaks, vehicle emissions, tire wear, asphalt pavement.
Volatile organic compounds [toluene, xylene, benzene, ethyl benzoate, MTBE (methyl tert-butyl ether)]	Atmospheric (in industrial areas), gasoline oxygenates, vehicle fluids.
Herbicides	Roadside maintenance activities.

Suspended and dissolved solids

Runoff of suspended and dissolved solids can cause water quality issues by impeding the light penetration necessary for plant growth, and by causing siltation, which destroys the habitat of aquatic organisms. However, many runoff pollutants are often associated with sediment, and BMP's that trap sediment will also trap a large percentage of these pollutants.

Runoff constituents that can be bound to either suspended or dissolved solids are:

- semi-volatile organic compounds such as polyaromatic hydrocarbons (PAH's) (Shinya et al., 2003)
- metals, such as zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni) and cadmium (Cd) (Hewitt and Rashed, 1992; Sansalone and Buchberger, 1997a; Furumai et al., 2002; Shinya et al., 2003; Han et al., 2006)
- phosphorus (P) (Venner et al., 2004)

Asplund et al. (1982) found that total suspended solids (TSS) in Washington State highway runoff came from the following sources, in order of importance of contribution:

- sanding and de-icing: although seasonal, this contributes most of the TSS to runoff during the period it is used
 - dust fall
 - traffic: vehicles contribute TSS that are acquired elsewhere
 - pavement deterioration (minor)
-

Nutrients (N and P)

Although nitrogen (N) and phosphorus (P) are essential nutrients for plant growth, they are also a major pollutant of U.S. surface waters (Carpenter et al., 1998). Excess N and P cause *eutrophication*, the over-enrichment of an ecological system with nutrients. This results in excess algal growth, reduced dissolved oxygen and water clarity, and subsequent lack of growth of aquatic plants and other organisms. Excess nitrate (NO_3^-) in water is also toxic to humans and animals, and impacts human and animal health (Carpenter et al., 1998; Evanylo and Beegle, 2006).

Much of the N in urban highway runoff in the eastern U.S. comes from wet and dry atmospheric deposition (USEPA, 2002). The source of this atmospheric N is nitrogen oxide (usually referred to as NO_x) emitted by vehicles, industrial and agricultural engines, and fuel combustion by electric utilities, and, to a lesser extent, nitrous oxide (N_2O) and ammonia (NH_3) volatilization resulting from farming operations (Puckett, 1994; USEPA, 2002). Wu et al. (1998) found that combined wet and dry deposition contributed 70-90% of the total N in urban highway runoff.

Roadside fertilizer application is another source of N in runoff (USEPA, 1993), especially if more fertilizer is applied than can be taken up by roadside vegetation, or if fertilizer is applied at a time of year when plant uptake of nutrients is slow (Mullins and Hansen, 2006). Both fertilizer N and N deposited by atmospheric deposition are easily transformed to ammonium (NH_4^+) and nitrate by biological processes in soil. Nitrate is the most mobile form of N in soils, and is highly susceptible to loss by leaching.

Atmospheric deposition is a source of P in runoff as well (USEPA, 1993), although atmospheric deposition of P is less than that of N (Jassby et al., 1994). Roadside fertilizer application also contributes P to highway runoff, as may the deposition from surrounding agricultural areas (Wu et al., 1998). While P is often sparingly soluble in soil, soluble P runoff may occur if roadside soils become saturated with P due to frequent fertilizer applications. Phosphorus bound to soil particles can be removed during runoff and subsequent erosion (Mullins and Hansen, 2006).

Metals

Heavy metals in highway runoff come from a number of different sources (Table 1). Most research on metals in highway runoff has focused on the heavy metals cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) (CH2MHill, 1998). All can be toxic to plants, animals, or humans if they are taken up or ingested in high concentrations, although Cu, Ni, and Zn are also essential at trace levels for plant growth. Manganese (Mn), also an essential trace element for plant growth, has become an element of concern since MMT replaced Pb as a gasoline anti-knocking element during the 1970's and 1980's (Brault et al., 1994; Lytle et al., 1994; Beaton and Dudley, 2004).

There has been recent research on the palladium group metals (platinum, palladium, and rhodium), which are deposited by catalytic converter degradation. The concentration of these palladium group metals in runoff has increased in the last few decades (Rhavindra et al., 2004), and elevated concentrations have been found in roadside soils (Ely et al., 2003; Sutherland, 2003), but the environmental consequences of this have not been quantified yet.

Although dissolved metals have the most detrimental effect on aquatic organisms (CH2MHill, 1998), research on the relative concentrations of dissolved and suspended metals in runoff has produced varying conclusions (Hewitt and Rashad, 1992; Sansalone and Buchberger, 1997b; Shinya et al., 2000; Furumai et al., 2002; Shinya et al., 2003; Han et al., 2006; and others). Apparently, the partitionment of metals in runoff is affected by factors such as rainfall pH, type of washoff (snow or rain), the presence or absence of other dissolved compounds that can bind the metals (Ca, Mg, organic matter), and type of roadway (Sansalone and Buchberger, 1996; Dean et al., 2005; Tucillo, 2006). For example, acidic rainwater will solubilize metals, but will be buffered to a neutral pH when it contacts cement pavement (Dean et al., 2005). In general, it appears that Cr, and Fe tend to be present mainly in particulate (> 0.45 micron) form, while Pb, Cd, Cu, Zn, and Ni may be found either in dissolved or particulate forms, depending on site conditions.

De-icing salts

De-icing salts such as sodium chloride (NaCl), calcium chloride (CaCl₂), and magnesium chloride (MgCl₂) are present in runoff in soluble, ionic form. The environmental effect of chloride de-icing salts have been summarized by Grueb et al. (1985), Granato (1996), Norrstrom and Jacks (1998), Novotny et al. (1998), Norrstrom and Bergstedt (2001), and Ramakrishna and Viraraghavan (2005) as:

- elevated, possibly toxic, salt levels in surface water and groundwater
- elevated sodium (Na) levels in soils, resulting in decreased soil permeability
- increased metal solubility in saline runoff, and in soils affected by salt runoff
- degradation of ferrocyanides (used as anti-caking agents) to toxic cyanides
- possibility of accumulation of trace impurities such as sulfate, bromide, vanadium, magnesium, fluoride, and strontium

Calcium magnesium acetate has been recommended as a more environmentally friendly de-icing chemical but more field studies need to be done to confirm this (Ramakrishna and Viraraghavan, 2005).

Obviously, the concentrations of de-icing salts in highway runoff, and subsequent environmental problems, are greater in areas with high snowfall and ice accumulation. Regions where the use of de-icing salts is more intermittent, however, may still have similar problems with runoff from highway salt storage facilities (Fitch et al., 2004), or in environmentally sensitive areas such as karst terrain where groundwater is directly affected by highway runoff (Donaldson, 2004).

Organic compounds

The most common organic contaminants in highway runoff are *semi-volatile organic compounds* (SVOC), such as petroleum hydrocarbons, oil and grease, and polyaromatic hydrocarbons. High concentrations of SVOC's can cause endocrine disruptions in aquatic and other organisms (Lopes and Dionne, 2003).

Most SVOC's in highway runoff originate from crankcase oil leaks and vehicle emissions. SVOC's tend to be associated with both suspended and dissolved solids (Hewitt and Rashad, 1992; Shinya et al., 2000; Venner et al., 2004; Aryal et al., 2006).

Volatile organic compounds (VOC) are also present in runoff, and include toluene, xylenes, benzene, and ethyl benzene (also known as BTEX compounds). These derive from atmospheric deposition in industrial areas, and from some gasoline compounds. VOC's tend to volatilize, and the concentrations in runoff are generally too low to be toxic to aquatic organisms in surface waters. Drinking water derived from ground water contaminated with VOC's, however, could have chronic health effects in humans (Lopes and Dionne, 2003).

Methyl tert-butyl ether (MTBE), a gasoline oxygenate, is probably the VOC with the most negative environmental consequences, since it is less biodegradable than other VOC's (Delzer et al., 1996; Venner et al., 2004). Although MTBE has been detected in ground and surface waters, and in urban runoff (Moran et al., 2005), the exact source was unclear. To date, there has been little research on MTBE and other VOC's in highway runoff (Lopes and Dionne, 2003).

Factors that affect pollutant concentration in highway runoff

Average values

Highway runoff is a *non-point* source of pollutants, meaning that it does not derive from a single, continuous source (Carpenter et al., 1998). Thus, pollutant concentrations may be irregular, and will vary depending on a number of different, often site-specific, factors. Although “average” pollutant values that have been reported in studies by different researchers have been summarized by Driscoll et al. (1990a), Barrett et al. (1995), and other research, it can be difficult to compare these values because sampling and analysis methods differ (Granato, 2003). In an effort to catalog and validate these studies, the Federal Highway Administration’s National Highway Runoff Water-Quality Data and Methodology Synthesis (NDAMS) project (Granato et al., 2003a; Granato et al., 2003b; Granato, 2003) has produced a searchable database of 2600 bibliographic entries, 1300 abstracts, and metadata for 262 research reports. This study also documented the technical issues inherent in monitoring highway runoff water quality, including sampling, sample-handling, and quality control.

First flush

The *first flush* effect has been documented by many researchers, and has been defined as being “the high pollutant load in the runoff water at the beginning of a rainfall event” (Shinya et al., 2003). A review of the literature by Kim et al. (2005) found that estimates for distinguishing the first flush of runoff from the rest of the runoff event range from 20% to 30% of the initial runoff volume. The level of pollutants in first flush runoff is usually affected by rainfall intensity and duration, and the length of the preceding dry period (Gupta and Saul, 1996), and the first flush effect appears to be more marked in areas with a high percentage of impervious cover (Young et al., 1996)

Although the existence of the first flush phenomena appears to be generally accepted, it has been debated by some researchers (Deletic and Maksimovic, 1998). Barrett et al. (1998a) did observe a first flush for many pollutants at the beginning of runoff events. However, they also found that most pollutants continued to run off through the duration of the rainfall event at the sites sampled, as vehicles continued to contribute pollutants throughout the event. They cautioned that constant pollutant input throughout a runoff event should be planned for in treatment systems.

A strong first flush does not occur with every runoff constituent, and the first flush concentrations of some runoff constituents vary depending on the specific study. It appears that site-specific factors also affect the concentration of pollutants in runoff first flush. For example, Sansalone and Buchberger (1997b) found that “dissolved” (< 0.45 micron) Zn, Cd, and Cu, showed a strong first flush effect, while Fe and Al did not. On the other hand, Shinya et al. (2003) found that total suspended solids, total P, and Fe were strongly concentrated in runoff first flush, apparently because approximately 50% of the total P and 92% of the total Fe were associated with TSS. In the same study, total N showed only a weak first flush effect because 80% was present in dissolved form. Han et al. (2006) also observed a strong first flush effect for TSS and for all particulate-bound metals except Pb, but also found that total N concentrations were relatively high in the first flush, possibly because N was sorbed to dissolved organic carbon.

Site-specific factors

The effect of any one site-specific factor on runoff pollutant concentration varies depending on location, time of year, and site characteristics. However, some site-specific factors that many researchers agree have an effect on the concentrations of at least one common runoff pollutant are:

- **Average daily traffic (ADT):** While some researchers have found that ADT has a direct effect on runoff pollutant concentration (Irish et al., 1995), others have obtained contradictory results (Driscoll et al., 1990b; Barrett et al., 1995; Patel, 2005). Kayhanian et al. (2003) concluded that, although there was no direct correlation between ADT and level of runoff pollutants, ADT was one of a number of factors that, taken together, did influence pollutant concentration.
- **Surrounding land use** (for example, urban vs. rural sites): Driscoll et al. (1990b) found this to be one of the most important variables affecting runoff pollutant concentrations, with urban sites generally, although not always, having higher concentrations of pollutants than rural sites.
- **Permeability or perviousness of surrounding area:** This factor is related to land use, but also applies to runoff from highway structures such as bridge decks and impervious medians (Wu et al., 1998).
- **Number of antecedent dry days (or intensity of previous storm):** Like average daily traffic, this factor may or may not have a direct effect on runoff pollutant concentration (Deletic and Maksimovic, 1998; Kayhanian et al., 2003; Venner et al., 2004), possibly because pollutants can be removed by wind, vehicles, or other means (Barrett et al., 1995; Patel, 2005).
- **Maximum rain volume, duration, and/or intensity:** (Driscoll et al., 1990b; Thomson et al., 1997; Deletic and Maksimovic, 1998; Kayhanian, 2003; Shinya et al., 2003).
- **Number of vehicles during storm:** Although Barrett et al. (1995) summarized research which found this to be a consistent factor in runoff load, it is also an extremely unpredictable factor.
- **Ratio of *pervious* to *impervious* material in a particular location:** This would include the presence of bridges and other large paved areas, or the presence or absence of roadside shoulders or medians (Deletic and Maksimovic, 1998; Wu et al., 1998).

Note that each of these factors, however, may not affect each runoff constituent at the same site in the same way, as demonstrated in Thomson et al.'s (1997) research in Washington State (Table 2).

Table 2. Identification of independent variables affecting constituent concentration in Washington State highway runoff during multiple regression analysis (adapted from Thomson et al., 1997 and Venner et al., 2004).

Constituent	Storm Duration	Storm Volume	Storm Intensity	Vehicles During Storm	Length of Antecedent Dry Period	Antecedent Traffic Count	Previous Storm Intensity
Fe		X	X		X		
TSS		X	X		X		X
Zn	X	X				X	X
P	X	X	X			X	
Nitrate		X	X			X	
Pb		X	X	X			X
Cu	X	X		X			
Oil and Grease		X		X			

Pollutant retention in vegetated BMP's: general principles

Introduction

As stated earlier, BMP's can be structural or non-structural. *Structural BMP's* are designed to control and confine highway runoff until pollutants settle out and infiltrate into the soil. These structures can be either vegetated or non-vegetated (Table 3). All vegetated BMP's are designed to remove pollutants by detaining runoff, filtration by vegetation, surface sedimentation, and infiltration into soil (Young et al., 1996). **If the BMP is not designed properly, however, there will be little pollutant retention because the hydraulic residence time, or the length of time runoff remains in the BMP, will be too short.**

Although specific details regarding the non-vegetated BMP's listed in Table 3 is beyond the scope of this review, the intended function of these structures is similar to that of vegetated BMP's, and many are combined with grass filter strips or buffer areas in runoff *treatment trains*, or series of BMP's for sequential runoff treatment. Detailed information on design of both vegetated and non-vegetated structural BMP's can be found in Schueler et al. (1992), Young et al. (1996), and Clar et al. (2004).

Non-structural BMP's are designed to remove pollutants at their source and include (Barrett et al., 1995; Young et al., 1996):

- planning of surrounding land use, including roadside landscaping.
 - source control, such as controlled application of fertilizers (nutrient management) and pesticides to roadsides and medians, and controlled salt application.
 - litter and debris control.
 - control of highway structure maintenance activities such as bridge cleaning and painting.
-

Table 3. Types of structural BMP's used to control pollution from highway runoff (adapted from Young et al., 1996).

Vegetated BMP's	Non-vegetated BMP's
<ul style="list-style-type: none"> • Filter strips • Grassed swales • Infiltration basins • Constructed wetlands • Bioretention areas (small-scale BMP's for urban areas) 	<ul style="list-style-type: none"> • Dry (detention) pond* • Wet ponds* • Infiltration trenches* • Sand filters** • Water quality inlets (oil and grit separators) • Porous pavement • Various small-scale non-vegetated filters used in urban areas.

* Usually surrounded by grass filter strips or other vegetation.

Pollutant retention by roadside plants

Although some uptake of metals and organic pollutants occurs in vegetated BMP's (Clar et al., 2004), the primary function of plants in BMP's appear to be (Maestri et al., 1988; Barrett et al., 1995; Piretz, 2001; Huang et al., 2004):

- soil stabilization
- decreasing runoff flow rate and increasing sedimentation and infiltration
- physical filtration of runoff
- nutrient uptake and transformation
- contributions made by root metabolism and organic matter to soil processes (including herbicide degradation)

There has been much recent research on phytoremediation, or the uptake and/or transformation of metals and other pollutants from contaminated soils by certain plant species. (For a detailed discussion of phytoremediation, see Appendix 1). This technique is still mainly experimental, and while it may be applicable to small, intensively managed, highly contaminated areas, it is unlikely to be effective in controlling metal levels in highway runoff.

Plants metabolize small amounts of metals from the soil as they grow, requiring low levels of Cu, Co (cobalt), Fe, Mo (molybdenum), Mn, Ni, and Zn as essential plant nutrients. Excess soil concentrations of most of these metals are generally either:

- rendered insoluble by soil chemical processes,
- or, if plant-available, are toxic to most plant species at very low concentrations.

This combination of low metal solubility/availability in soils, and the phytotoxic effect of high metal levels is known as the *soil-plant barrier* (Chaney and Giordano, 1977). It generally prevents toxic levels of trace elements from entering the food chain via consumption of plants by animals or humans. Some wetland plants have been shown to take up heavy metals such as Zn (Yu et al., 1995), presumably because metals are more available under reducing conditions. However, the amount of metal uptake in wetland plants is still limited by potential plant toxicity.

Pollutant retention by roadside soils

Nitrogen:

Nitrogen goes through more transformations in soil than any other plant nutrient (Mullins and Hansen, 2006). Plants take up N as either ammonium (NH_4^+) or nitrate (NO_3^-). Ammonium that is not taken up by plants can be *volatilized*, and nitrate can undergo *denitrification*: both processes resulting in a loss of N to the atmosphere as N_2 gas. Both ammonium and nitrate can be *immobilized*, or transformed into organic N forms that are unavailable to plants. Ammonium also undergoes biologically mediated *nitrification*, or transformation to nitrate. Nitrate that is not taken up by plants is very mobile and can easily be lost through leaching or runoff. These losses can be minimized by source control: adding less N to the soil and fertilizing at appropriate times of the year (Evanylo and Beegle, 2006). The leaching risk is greatest on sandy soils where N is applied at high rates at times when plant uptake is low (Mullins and Hansen, 2006).

Phosphorus:

In acid soils (pH <5.5), P tends to precipitate as Fe or aluminum (Al) phosphates, while in alkaline soils (pH >6.8), P precipitates as Ca phosphates (Mullins and Hansen, 2006). However, if the soil is saturated with P, excess P will be subject to leaching as dissolved reactive orthophosphate. This often happens in sandy soils because levels of native Fe and Al oxides are low, resulting in little P binding (Pierzynski and Gale, 2005.) The diffusion of P in the soil is limited, and it is only taken up by root hairs if it is located within ¼ inch of the root (Mullins and Hansen, 2006).

Loss of P from soil can be prevented by limiting the use of P fertilizers and organic amendments. The Virginia Phosphorus Index (Mullins et al., 2005) is a tool that is used to calculate the risk of P loss from roadside soils based on the amount of P applied plus erosion risk (sediment bound P loss), risk of runoff of dissolved reactive orthophosphate, and subsurface risk P leaching as dissolved reactive orthophosphate.

Heavy metals:

In soils, heavy metals are generally present in one of the following fractions (Brady and Weil, 2001):

- *Adsorbed or exchangeable (ionic)*: This fraction is relatively mobile, and is available for uptake by plants or for leaching, but is only a small portion of total soil metals.
- *Organic matter bound*: This fraction can be slowly released to plants with time as the organic matter decomposes.
- *Associated with carbonates or iron/manganese oxides*: These fractions are generally not plant-available unless soil pH becomes quite low.
- *Residual*: This fraction consists of sulfates and other insoluble compounds, and is the least plant-available.

Metals in soils can become more available if (Bartenhagen et al., 1995):

- Soil pH decreases, which increases hydrogen ions on exchange sites (displacing metals), and dissolves oxide and carbonate metal complexes.
- Soil redox potential decreases, resulting in less metal complexing.
- Soil salinity increases, causing competition for sites on the exchange complex.

After a review of the literature, Turer and Maynard (2003) concluded that it is generally accepted that heavy metals originating from highway runoff are higher in the upper part of the soil profile, and decrease with increasing distance from highway, indicating that most metals from highway runoff are not very mobile. They found that Cu, Pb, and Zn were enriched in the upper 6 inches of roadside soils in Cincinnati, OH and Corpus Christi, TX. These metals were relatively immobile and unlikely to be resolubilized because they were tightly bound to organic compounds which apparently originated from vehicle exhaust or asphalt pavement. Nickel and Cr in the roadside soils in these areas appeared to be native to the soil rather than originating from highway runoff.

Lee and Touray (1998) found that Mn and Cd were potentially most mobile in slightly acid solutions (such as acid rain). Zn was somewhat less mobile, and Pb and Fe had very limited mobility, possibly because they were in carbonate or iron oxide form. Dierkes and Geiger (1999) found that Cd and Zn were the most mobile metals in roadside embankments in Germany with high organic matter levels and near neutral pH. Approximately 20% of the Cd in these soils was present in plant-available form.

Salts:

Both sodium (Na) and calcium (Ca) dissolve from de-icing salts as cations, and will accumulate on the exchange complex of roadside soils. Excess Na in the soil may result in decreased permeability, (Novotny et al., 1998; Ramakrishna and Viraraghavan, 2005), but if salt is only applied occasionally, this effect is temporary. As stated above, metals such Pb, Cu, and Zn in roadside soils could be vulnerable to leaching if soils were subjected to high concentrations of de-icing salts, since both Na and Ca will displace metals from the exchange complex, and Na may cause dispersion of metal-organic and metal-oxide complexes (Norrstrom and Jacks, 1998). Again, this is unlikely to be a problem where de-icing salts are not used frequently (Ramakrishna and Viraraghavan, 2005).

PAH's and other organic compounds:

In soil, organic compounds can (Brady and Weil, 2001):

- *volatilize* into the atmosphere,
- be *adsorbed* and held in the soil by soil organic matter and clays,
- *leach* from the soil to ground or surface waters,
- be *decomposed* (biodegraded) by soil microorganisms, or
- be *taken up by plants or soil animals* (such as earthworms), and enter the food chain.

As stated earlier, VOC's in highway runoff tend to volatilize while SVOC's tend to be associated with both suspended and dissolved solids (Hewitt and Rashad, 1992; Shinya et al., 2000; Lopes and Dionne, 2003; Venner et al, 2004; Aryal et al., 2006). Research by Dierkes and Geiger (1999) in Germany on some SVOC's has demonstrated that PAH's will accumulate in the upper 4 inches of soils, because they adsorb strongly onto soil organic matter and clay and then do not biodegrade rapidly. Oil-type hydrocarbons (from leaks, etc.) are found mainly on soil surfaces near roads, and appear to mainly undergo volatilization and biodegradation before they enter the soil.

Note: Compost has been used by some states to control runoff and erosion on highway construction sites, and can be used as an alternative to commercial fertilizer to assist in the establishment of roadside vegetation. Glanville et al. (2004) examined the effect on water quality of composts used to control erosion from highway construction sites using three types of compost: biosolids compost, yard waste compost, and paper mill plus grain-processing waste composts. Although the runoff from composted areas had higher concentrations of heavy metals and nutrients than the runoff from non-amended sites, the total mass of these pollutants in runoff from non-amended areas was much higher because far more runoff and erosion occurred in these areas.

Pollutant retention in vegetated BMP's: specific structures

Filter strips Filter strips are ideally flat or gently sloping areas that are densely vegetated with grass, shrubs or trees, and are probably the least expensive structural BMP's to build and maintain (Young et al., 1996). Filter strips are designed to handle overland sheet flow rather than directed flows, and work best in areas that do not receive high velocity runoff flows (Barrett et al., 1995). Although some researchers have recommended that filter strips have a slope of no greater than 9-12% (Walsh et al., 1997), existing road shoulders with slopes greater than this can be used as filter strips if width is increased to allow for increased slope, and if vegetative cover is maintained (Kearfott et al., 2005; Barrett et al., 2006).

Filter strips can remove substantial amounts of suspended solids and associated metals if correctly designed, but do not generally provide good nutrient removal, and can even add nutrients to runoff because of contributions from roadside fertilizer application and decomposing vegetation (Table 4; also Gannon et al., 1995; Barrett et al., 2006). Maintaining dense vegetation is important, because removal efficiencies are considerably reduced if vegetative cover is less than 80% and maximum pollutant removal is achieved if cover is 90% or more (Kearfott et al., 2005; Barrett et al., 2006). Filter strip efficiency is also dependent on width, slope, soil permeability, runoff velocity, and size of contributing runoff area (Young et al., 1996).

Note: The performance of runoff treatment BMP's is usually expressed as *percent removal* of a specific pollutant. Venner et al. (2004) and Barrett (2005) have pointed out that this may not be an accurate method of measuring BMP efficiency, since percent removal of a specific pollutant tends to be lower if influent concentration of that pollutant is low. Since most of the literature uses percent removal to quantify BMP performance, however, the term will be used in this review.

Table 4. Pollutant removal efficiencies for filter strips in Texas. (Note: numbers in parentheses show “negative removal” where the filter strip itself added the pollutant to the runoff.) nd=not determined.

Filter strip study reference	TSS	Total N	NO ₃ ⁻ -N	Total P	Cu	Pb	Zn
	----- % removal -----						
2 strips, TX (Walsh et al., 1997; Barrett et al., 1997)	85-87	33-44	23-50	34-44	nd	17-41	75-91
3 strips, TX (Kearfott et al., 2005)	73-89	(-154) - 19*	(-132) - 6*	(-250) - (-90)	75-90	84-95	**

*In some locations, total N, nitrate-N, and total P were generally higher after runoff traveled through the filter strip, and were likely contributed by either roadside fertilizer and/or decomposing vegetation.

** Zn leached from the collecting apparatus in this study, causing elevated total and dissolved Zn concentrations in runoff.

Grassed swales

Grassed swales are similar to filter strips but are constructed with a shallow channel to hold runoff, thus can also convey flows. Ideally, grassed swales should have slopes <3-6% and a length greater than 200-250 feet (Schueler et al., 1992; Yu et al., 2001). Grassed swales must be maintained by mowing and periodic sediment removal (Finley and Young, 1993; CH2MHill, 1998).

Hydraulic residence time and swale soil infiltration rate may be the most important factors affecting pollutant removal efficiency in swales (Yousef et al., 1985; Barrett et al., 1997; CH2MHill, 1998). Infiltration rate can be increased by selecting proper soil for swale construction, and by avoiding soil compaction during construction. To increase hydraulic residence time, check dams within the swale are highly recommended (Yu et al., 1995; Kaighn and Yu, 1996).

Both Yu et al. (2001) and Mazer et al. (2001) noted that swales tended not to reduce pollutants if inflow rate of runoff is too high (as in strong storms). Sediment and associated pollutants within the swale can be re-suspended and lost if the swale is inundated with water. Mazer et al. (2001) recommended that estimated *hydraulic loading rate*, as determined by flow rate and treatment area, be used as a predictor of swale performance.

Swales can remove a high percentage of total suspended solids and associated metals if they are properly designed. A review of the literature (CH2MHill, 1998), showed that metal removal percentages in swales was quite variable. Swales surveyed in the review removed from 14 to 67 % of total runoff Cu, 4 to 90% of total Zn, and 15 to 99% of total Pb. The removal of metals in swales was shown to depend highly on factors which affected hydraulic residence time, including the slope ratio, density of vegetative cover, high infiltration rate of underlying soil, the length of swale, and the presence or absence of check dams. Barrett et al. (1997) and CH2MHill (1998) have recommended at least a 9 minute hydraulic residence time.

Nutrient removal in swales can be quite low, especially for nitrogen. Both

Yousef et al. (1985) and Barrett et al. (1997) found that the swale actually added nitrogen removal to the runoff, apparently because dead and decomposing vegetation on the swale contributed nitrate to the drainage water. Other swales have been shown to remove at least some N and P (Barrett et al., 1998b; Yu et al., 2001), but in general, source control of these nutrients may be a better way of reducing their concentrations in highway runoff.

Infiltration basins

An infiltration basin is a “surface pond which captures the first flush of stormwater and treats it by allowing it to percolate into the ground and through permeable soils” (Young et al., 1996). Generally, infiltration basins are designed to hold the first ½ inch of rainfall associated with the first flush (Barrett et al., 1995). Infiltration basins treat runoff pollutants by sedimentation, adsorption onto soil particles, and by biological degradation (decomposition and plant uptake of nutrients), and can be quite efficient in pollutant removal (Table 5). Most of these structures fail within 5 years, however, because they are clogged by fine sediments, and then must be altered so they function as wet ponds or wetlands (Schueler et al., 1992). Because of the high reported failure rate and high cost, infiltration basins tend not to be a good option for a vegetated BMP (CH2MHill, 1998).

Table 5. Specific pollutant removal estimates for infiltration basins (adapted from data presented in Young et al., 1996.)

Type of infiltration basin	Total suspended solids (TSS)	Total N	Total P	Heavy metals
	-----% removal -----			
Basin designed to store 0.5" runoff per acre	75	45-55	50-55	75-80
Basin designed to store 1" runoff per acre	90	55-60	60-70	85-90

Constructed wetlands

Constructed wetlands specifically designed for highway runoff treat pollutants by settling, soil filtration, decomposition, plant uptake (especially of nutrients), and other processes (Table 6). Unlike wetland mitigation sites, wetlands for runoff treatment do not have to be designed to provide all wetland ecosystems functions (Barrett et al., 1995). The water table in the wetland should be at or near the surface, the soils should have low permeability, and the wetland should be designed so that runoff retention time is approximately 6 to 14 days (Schueler et al., 1992; Barrett et al., 1995; Young et al., 1996). Wetland construction is relatively expensive, and wetlands require intensive maintenance for the first three years after construction. Wetlands may not function as effectively in winter when vegetation is dormant and soil processes are slowed (Gannon et al., 1995).

Constructed wetlands have been shown to be quite effective at reducing levels of TSS, N, P, metals, and organic compounds in runoff **if runoff retention time is long enough to allow wetland soil processes to take place** (Gannon et al., 1995; DeBusk, 1999; Shutes et al., 2001; Farrell and Scheckenberger, 2003). Birch et al. (2004) found relatively low and considerably variable pollutant removal efficiencies for TSS, N, P, and other pollutants in a constructed wetland in Australia and concluded that the runoff detention time was too short. The wetland was too small for the size of the catchment area, especially during storms. Shutes et al. (2001) and Revitt et al. (2004) found that properly designed wetlands receiving highway runoff removed most pollutants during large storms.

Yu et al. (1998a, 1998b) examined artificial wetlands in Virginia that were constructed to meet wetland mitigation requirements in order to determine if they could also serve as highway runoff treatment BMP's. Most sites removed relatively large percentages of TSS, P, orthophosphate, and Zn from highway runoff without appearing to decrease wetland ecological function. Removal rates were increased in wetlands where design maximized hydraulic residence time.

Some plant uptake of soluble metals, particularly Zn, by certain plant species such as *Typha latifolia* (cattail) and *Phragmites australis* (common reed) may occur in wetlands receiving highway runoff (Ellis et al., 1994, Mungur et al., 1995; Yu et al., 1995; CH2MHill, 1998; Shutes et al., 2001). Although this plant uptake may reduce soil levels of metals, it increases levels in plant vegetation. Decomposing vegetation will then release accumulated metals into sediment (Mungur et al., 1995) unless the plant material is harvested.

For example, Shutes et al. (2001) found that one constructed wetland they studied actually released Cu during high flow runoff events, presumably because Cu was released from decomposing vegetation.

Overall, it appears that properly designed and constructed wetlands can remove relatively high rates of contaminants from highway runoff. Further research, however, is needed to quantify the performance of these wetlands with time, since changes in sediment depth, sediment concentration of metals and salts, accumulation of organic matter, and possible re-suspension of contaminants, may occur as the wetland ages (Pontier et al., 2004).

Table 6. Pollutant removal mechanisms in constructed wetlands (Gannon et al., 1995; DeBusk, 1999).

Pollutant	Removal process
Total suspended solids (TSS)	Sedimentation
Total P	Sedimentation; adsorption; complexation as Ca or Fe/Al phosphates; plant uptake
Total N	Denitrification of NO ₃ ⁻ ; adsorption and volatilization of NH ₄ ⁺ ; plant uptake
Metals	Sedimentation; adsorption; complexation with carbonates, Fe/Al oxides, and organic matter; precipitation with sulfides; some plant uptake
Oil and grease	Degradation by light; microbial decomposition; some volatilization
Volatile organic compounds (VOC)	Volatilization

Bioretention areas

A bioretention area is a small BMP structure that uses both woody and herbaceous plants with layered substrate materials such as mulch, organic matter, and/or soil and sand to provide runoff treatment for space-limited urban areas, such as parking lots and median strips, where other BMP's might be inappropriate (Davis et al., 2001b; Davis et al., 2003). The prototypical bioretention area design was developed in the 1990's by the Prince Georges County, Maryland Department of Environmental Resources. In this design, runoff flows from an impervious surface over a sand trench to a planting area consisting of mulch over soil over a sand trench. The planting area is designed to hold 6 inches of ponded runoff so that it can slowly infiltrate into the organic materials and soil below (USEPA, 1998). The design can be modified to include gravel and/or underdrains.

Bioretention areas have been shown to provide removal of suspended and dissolved heavy metals (Davis et al., 2003) and TSS and associated pollutants, especially for small storms (Yu and Stopinski, 2001). Removal percentages for organic N and total P were also relatively high, but nitrate removal percentages were low, since N build-up in the bioretention area tends to surpass vegetative uptake (Davis et al., 2003).

Accumulation of metals in BMP's

If vegetated BMP's are designed so they are efficient at trapping high percentages of metals, there is a possibility that metals may accumulate to potentially toxic levels in the BMP soils. Walsh et al. (1997) and Barrett et al. (1997) used the U.S. Standards for the Use or Disposal of Sewage Sludge (Title 40 of the Code of Federal Regulations, Part 503; also known as the "Part 503 rule") to evaluate annual and cumulative Pb and Zn loadings in filter strips in Texas, and found that annual loading rates were less than a tenth of those permitted by the Part 503 rule. They estimated that it would take 200 years before these metals reached the cumulative loading rate limits mandated in the Part 503 rule.

Wigington et al. (1986) measured heavy metals in swales in suburban Fairfax County, VA, and found that, although metals did accumulate in the top 5 cm (2 inches) of swale soils, the pattern of accumulation was similar to that seen in roadside soils, and no subsurface metal enrichment attributable to runoff was found. Soils examined were relatively fine-textured, however, with low infiltration rates.

Yousef et al. (1994) measured heavy metals in the bottom sediments of Florida detention ponds (non-vegetated) receiving highway runoff, and determined that most of the metals were tightly bound to the sediments and would not be prone to leaching into groundwater. Toxicity characteristic leaching procedures (TCLP) performed on the sediments revealed that they were not hazardous wastes. They recommended cleaning out detention ponds at intervals of 25 years to reduce the potential for groundwater contamination.

It appears, based on estimates of metal accumulation with time, that BMP's that receive highway runoff will tend not to accumulate toxic levels of heavy metals. However, this issue will require further on-site research as existing BMP's become older.

Summary and conclusions

- Primary constituents of concern in highway runoff are suspended and dissolved solids, nitrogen (N), phosphorus (P), heavy metals, de-icing salts, semi-volatile organic compounds (SVOC), and volatile organic compounds (VOC).
- In general, metals, SVOC's and some P in highway runoff tend to be associated with suspended sediments; thus Best Management Practices (BMP's) that are designed to trap suspended sediments will provide reasonably good removal of these contaminants.
- The functions of plants in vegetated BMP's are mainly soil stabilization, decreasing runoff flow rate, increasing sedimentation and infiltration, physical filtration of runoff, nutrient uptake and transformation, and the contribution of root metabolism and organic matter to soil processes. While some metal uptake occurs (particularly in wetland species), this is limited by the soil-plant barrier.
- Soils in vegetated BMP's retain and transform pollutants in many ways, although this is dependent on soil pH, soil texture, and other chemical and physical soil properties.
- Filter strips and grassed swales have been shown to remove total suspended solids (TSS) and associated metals if properly designed, but generally do not provide good removal of nutrients. Source control is recommended to reduce nutrient levels in highway runoff.
- Infiltration basins have relatively high pollutant removal efficiencies but are expensive and clog easily. Constructed wetlands are a better alternative. Wetlands generally provide adequate removal of most pollutants, but further research is needed to quantify the sustained performance of constructed wetlands as a runoff treatment with time.
- Small scale bioretention areas appear to work as BMP's in urban areas, but can be expensive and maintenance-intensive.
- Vegetative BMP's receiving highway runoff do not appear to retain toxic levels of metals over time.

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Appendix: Phytoremediation of pollutants

Introduction *Phytoremediation* has been defined as “the use of plants to partially or substantially remediate selected contaminants in soil, sludge, sediment, groundwater, surface water, and waste water” (Pivetz, 2001). At present, phytoremediation is largely an experimental technique. Although laboratory and field studies have shown positive results, various phytoremediation techniques are still being refined (Trapp and Karlson, 2001). The term phytoremediation encompasses several different techniques, which are summarized below.

Phytoextraction Plants that grow naturally on soils that contain high levels of metals have developed evolutionary responses to deal with potentially phytotoxic metal concentrations (Baker, 1981). *Accumulators* or *hyper-accumulators* are able to take up levels of metals that would be toxic to other plants. For example, some species in the plant genus *Thlaspi* have been shown to be Zn and Cd hyper-accumulators and some species in the genus *Alyssum* will hyper-accumulate Ni and Co (Angle et al., 2003). *Excluders* have developed physiological mechanisms that prevent metal translocation from roots to above-ground plant tissue.

Species of plants that are metal hyper-accumulators have been used experimentally to remove metals from soil in a technique known as *phytoextraction* (Salt et al., 1995; Dzantor and Beauchamp, 2002; Lasat, 2002), but there are still questions that need to be answered about this technique. It may be a viable method for slowly extracting metals from soils with high metal levels, but careful management is necessary. For example, since only a small percentage of total soil metals are available for plant uptake, it may necessary to treat the soil with chelating agents (DTPA-TEA, EDTA, organic chelators, etc.) or other agents to increase metal bioavailability (Barter, 1999; Lasat, 2002). The total biomass produced by hyperaccumulator plants is generally low, so remediation may take a number of years (Beauchamp and Dzantor, 2002). Hyperaccumulator plants must be harvested and disposed of properly, and site access must be restricted to animals and humans during the growing season, in order to prevent metals from entering the food chain (UNEP, 2003).

Phyto-stabilization In phytostabilization, metal-tolerant plant species are used to revegetate soils with toxic levels of heavy metals. This results in the immobilization of metals by root absorption and adsorption or precipitation in the root zone (Barter, 1999), and also helps prevent erosion of contaminated soil (Salt et al., 1995). Plants used for this technique should ideally be metal excluders so that above-ground portions do not become toxic. More research is required on this method of phytoremediation before it becomes a feasible option (Dzantor and Beauchamp, 2002).

Rhizofiltration

Rhizofiltration involves the use of plant roots to absorb and precipitate pollutants from effluents (Salt et al., 1995). Rhizofiltration is used for contaminants that are in solution in water, and has been used experimentally to remove radionuclides from ponds (Barter, 1999). Hydroponically grown plants have also been shown to remove heavy metals from water (Raskin et al., 1997). Again, plants are harvested and removed when root metal levels become high (Barter, 1999).

Remediation of organic compounds

There are several methods that have been used to phytoremediate organic compounds: phytodegradation, rhizodegradation, phytovolatilization (Pivetz, 2001). The basic principle, however, is that certain plant species are able to break down organic compounds in contaminated soils by metabolic processes, either in the shoots or roots; or by increasing microbial activity in the rhizosphere (Salt et al., 1995; Barter, 1999; Dzantor and Beauchamp, 2002.) These methods have been used experimentally to remove herbicides, VOC's, PAH's, PCB's, and other contaminants from soil (Beauchamp and Dzantor, 2002), but are still being refined.
