WATERSHED SCIENCE BULLETIN

Center for Watershed Protection Association

Journal of the Center for Watershed Protection Association

The Effectiveness of Stormwater BMPs in Reducing Toxic Contaminants in Urban Runoff: A Literature Review for the Chesapeake Bay Watershed

Schueler, T.[a]*, A. Youngk[a], L. Williamson[b]

Watershed Science Bulletin is a publication of the Center for Watershed Protection Association

"*The Effectiveness of Stormwater BMPs in Reducing Toxic Contaminants in Urban Runoff: A Literature Review for the Chesapeake Bay Watershed*" was first published in the *Watershed Science Bulletin* June 2017.

Front cover photo courtesy of Center for Watershed Protection

The Effectiveness of Stormwater BMPs in Reducing Toxic Contaminants in Urban Runoff: A Literature Review for the Chesapeake Bay Watershed

Schueler, T.[a], A. Youngk[a], L. Williamson[b]*

[a]Chesapeake Stormwater Network, Ellicott City, MD

[b]Center for Watershed Protection, Ellicott City, MD

**Corresponding author, watershedguy@hotmail.com*

Abstract

Toxic contaminants, such as pesticides, pharmaceuticals, and metals, are of interest to many watershed managers who want to safeguard aquatic and human health. This article summarizes literature findings on the degree to which structural urban best management practices (BMPs) that are currently intended to decrease nutrient and sediment pollution can also reduce toxic contamination of waterways. Such multiple benefits could provide significant cost savings to regulatory agencies, such as the Chesapeake Bay Partnership, that must meet nutrient and sediment total maximum daily loads and also want to reduce toxic contaminants in the water environment. The literature review focused on 12 categories of urban toxic contaminants (UTCs) and involved review of more than 250 research papers and reports. The available data on BMP removal of UTCs was sparse for many of the UTCs. However, sufficient data was available to demonstrate capture and/or retention of polycyclic aromatic hydrocarbons, petroleum hydrocarbons, and urban trace metals (e.g., cadmium, copper lead and zinc) by urban BMPs. The limited available data also provide evidence that these BMPs capture and retain polychlorinated biphenyls, mercury, other trace metals (e.g., arsenic, chromium, iron and nickel), pyrethroid pesticides, legacy organochlorine pesticides, plasticizers and polybrominated diphenyl ether (a flame retardant). Given the limited data available to quantify removal of UTCs by urban BMPs, a key finding from the literature review was that because UTCs have many "sediment-like" properties, a rationale may be provided for using sediment removal rates as the initial benchmark for estimating UTC removal rates by urban BMPs, when little or no monitoring data are available. The article suggests an approach for inferring UTC removal rates based on TSS removal rates. Although the Chesapeake Bay Partnership does not officially regulate toxics, they have adopted the approach recommended here.

Introduction

The Chesapeake Bay total maximum daily load (TMDL) for nutrients and sediment was approved in 2010 to provide an accountable means to achieve the water quality standards for the Chesapeake Bay and its tidal tributaries (US Environmental Protection Agency [USEPA] 2010). The EPA Chesapeake Bay Program's Toxic Contaminant Work Group was established to achieve the goals and outcomes set forth in the 2014 Chesapeake Bay Watershed Agreement, one of which is to "identify which best management practices might provide multiple benefits of reducing nutrient and sediment pollution as well as toxic contaminants in waterways." Such multiple benefits could provide significant cost savings to the Chesapeake Bay Partnership to simultaneously meet the Bay TMDL and reduce toxic contaminants in the environment.

Although toxic contaminants, such as pesticides, pharmaceuticals, and metals, are not regulated under the Bay TMDL, they are still of interest to many watershed managers who want to safeguard aquatic and human health. In 2012, close to 74% of the tidal water segments of the Chesapeake Bay were fully or partially impaired by toxic contaminants (Chesapeake Bay Program [CBP] n.d.). These contaminants can harm the health of both humans and wildlife. Therefore, the 2014 Chesapeake Watershed Agreement includes the following goal: "Ensure that the Bay and its rivers are free of effects of toxic contaminants on living resources and human health."

Table 1: Priority urban toxic contaminants in the Chesapeake Bay Watershed.[1]

#	Toxics Category	Individual Contaminants	Major Sources	Environmental/Health Impacts
1	PCBs	Total PCBs	Old transformers and capacitors (banned in 1977); old industrial areas; atmospheric deposition	Bioaccumulation in human, fish, and wildlife tissue; cancer (ATSDR 2000; USEPA et al. 2012; Davis et al. 2007)
2	PAHs	Total PAH, benzo(a) pyrene, napthalene	Coal tar sealcoats on asphalt; coal burning; fossil fuel combustion; creosote treated wood; vehicle emissions; street solids	Cancer; cardiovascular disease; developmental impacts (ATSDR 1995; French-McCay 2002)
3	Petroleum Hydrocarbons	TPH, oil and grease, benzene	Fuel leaks/spills; vehicle emissions; tire particles	Toxic to aquatic life at high levels (USEPA 1976)
4	Mercury	Hg, Me-Hg	Atmospheric deposition (power plant emissions)	Bioaccumulation in human, fish, and wildlife tissue; central nervous system and kidney impacts (USGS 2000; Wentz et al. 2014)
5	Urban Trace Metals	Cd, Cu, Pb, Zn	Atmospheric deposition; brakes and rotors; metal roofing; asphalt shingles; siding; downspouts	Toxic to aquatic life in dissolved forms (LeFevre et al. 2015)
6	Other Trace Metals	As, Cr, Fe, Ni	Industrial operations; automotive batteries; fabricated metals; stainless steel	Drinking water contamination (Kitchell 2001)
7	Pyrethroid Pesticides	Bifenthrin, permethrin	Maintained landscapes	Toxic to aquatic invertebrates even at low levels (USEPA et al. 2012)
8	Legacy OC Pesticides [2]	DDT/DDE, dieldrin, lindane, chlordane	Erosion of previously contaminated soil	Bioaccumulation in vertebrates such as fish, eagles, and marine mammals (Lazarus et al. 2016)
9	Legacy OP Pesticides [2]	diazinon, chloropyrifos	Erosion of previously contaminated soil	Toxic to aquatic invertebrates even at low levels (USEPA et al. 2012)
10	Plasticizers	Phthalates	Flexible PVC products (e.g., roof coating, cable coating, garden hoses and vehicle under-coating)	Endocrine disruption (Mathieu-Denoncourt et al. 2015)
11	Flame Retardants	PBDE	Computer and television wiring; plastics; foam cushions; insulation foams	Bioaccumulation in fish and wildlife tissue (ATSDR 2004; Kupper et al. 2008; Wenning et al. 2011)
12	Dioxins	Dioxins and furans	Waste incineration; legacy chemical manufacturing sites; paper mills; atmospheric deposition	Human carcinogen; other human and animal health impacts (Horstmann and McLachan 1995; USEPA 2001, 2012)

Codes: *PCBs = polychlorinated biphenyls, PAH = polycyclic aromatic hydrocarbons, PBDE = polybrominated diphenyl ether, TPH = total petroleum hydrocarbons, OC = organochlorine, OP = organophosphate, PVC = polyvinyl chloride.*

Notes:

[1] As defined by the extent and prevalence of the contaminant in the Bay watershed, as well as actual impairments or fish advisories, as defined in CBP (no date).

[2] Legacy pesticides refer to insecticides that have been banned or phased out but have such long half-lives that they are still detected in the environment; this list is based on a national assessment of pesticide prevalence in streams and groundwater by Stone et al. 2014a).

The Chesapeake Stormwater Network conducted an international literature review for the Chesapeake Bay Partnership to identify key research papers on the priority toxics. The review investigated:

- key characteristics, sources, generating sectors, and watershed pathways associated with priority toxics;
- measured concentrations in stormwater runoff, groundwater, and sediments;
- measured or inferred removal of toxics associated with current urban and agricultural best management practices (BMPs);
- measured concentrations and retention of toxics within BMP sediments; and
- additional pollution prevention practices that can prevent the amount of toxics that are released to the environment.

Schueler and Youngk (2015, 2016) detail the full results of this review. This article summarizes literature findings on the degree to which structural urban BMPs that are currently intended to decrease nutrient and sediment pollution in the Chesapeake Bay can also reduce toxic contamination of waterways. This paper does not analyze pollution prevention or source control practices (which are critical to reducing toxics). It also identifies data gaps and research needs to further improve our understanding of the risks associated with toxic contaminants and how best to manage them. Note that investigation of herbicides as urban toxic contaminants was outside of the scope of this review; however, they are discussed in agricultural applications in Schueler and Youngk (2016).

Methods

Out of thousands of potential toxic contaminants in the water environment, the literature review focused on 12 categories of urban toxic contaminants (UTCs) (Table 1), based on environmental risk in the Chesapeake Bay Watershed. These priority UTCs were identified using criteria established by the Chesapeake Bay Program (USEPA et al. 2012). Similar efforts have been conducted in other regions, such as the European Water Framework for Selected Stormwater Priority Pollutants (Eriksson et al. 2007). More than 250 reports on monitoring research pertaining to the priority UTCs in the Chesapeake Bay Watershed were reviewed, and a spreadsheet was developed to organize the papers by the toxics category, author, title, and geographic region.

One of the primary goals of the review was to evaluate the quality of the available monitoring data for each class of toxic contaminants, with respect to its concentration in stormwater runoff and urban sediments, and its removal and/or retention within urban BMPs. Figure 1 illustrates the number of studies evaluated by each UTC category. Table 2 compares the relative quality of available monitoring data for the 12 urban toxic contaminants; data quality ranges from very low to very high, depending on the contaminant category.

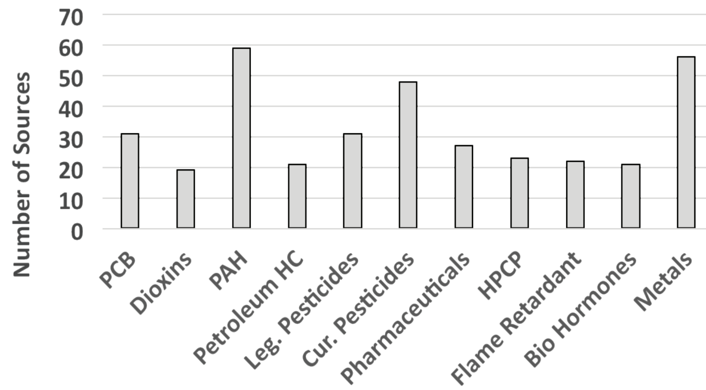

Figure 1: Number of studies evaluated by category of toxic contaminant.

Findings

Polychlorinated Biphenyls (PCBs)

PCBs are a group of synthetic organochlorine chemicals widely used as a dielectric and coolant fluid in transformers and capacitors. The United States banned the production of PCBs in 1977 out of concern for their persistence in the environment and their bioaccumulation in human, fish, and wildlife tissue. PCBs are listed as a probable human carcinogen by USEPA. Old electrical transformers (Davis et al. 2007), atmospheric deposition (Bressy et al. 2012), and erosion of historically contaminated soils (King et al. 2004; Velinsky et al. 2011) are the primary sources of PCBs in the urban environment.

Gilbreath et al. (2012) concluded that urban stormwater runoff was the most dominant source of PCBs in the San Francisco Bay during the last decade. The typical PCB concentration in stormwater runoff in urban watersheds ranged from 4 to 110 ng/l (median event mean concentration [EMC] of 14.5 ng/L), with the highest concentrations found in older urban areas with legacy industrial sites. That study also noted a strong association between high turbidity levels and elevated PCB concentrations.

Remarkably little monitoring has been conducted to assess whether urban stormwater BMPs can remove PCBs. Yee and Mckee (2010) conducted a series of settling column experiments

Table 2. Data quality for urban toxic contaminants.

Urban Toxics Category	Runoff EMCs	Sediment Conc.	Air Deposition	Street Solids	BMP Removal	BMP Sediment
PCBs	VL	M	VL	VL	VL	L
PAH	M	H	L	M	M	M
TPH	M	VL	ND	L	M	L
Mercury	H	H	H	VL	L	L
UTM	VH	VH	H	M	VH	H
OTM	H	H	M	L	M	M
PP	M	M	NA	VL	L	L
Legacy OCP	VL	L	NA	ND	ND	L
Legacy OPP	M	L	NA	ND	VL	VL
Plasticizers	VL	L	NA	ND	ND	VL
PBDE	VL	L	VL	ND	VL	VL
Dioxins	VL	VL	VL	ND	ND	ND

PCBs = polychlorinated biphenyls
PAH = polycyclic aromatic hydrocarbons
TPH = total petroleum hydrocarbons
UTM = urban trace metals (Cd, Cu, Pb, and Zn)
OTM = other trace metals (As, Cr, Fe and Ni)
PP = pyrethroid pesticides
OCP = organochlorine pesticides
OPP = organophosphate pesticides
EMC = event mean concentration
PBDE = polybrominated diphenyl ether

Shaded rows are toxics categories with the lowest data quality

VL = Very low (<3 studies, none from Chesapeake Bay)
L = Low (<5 studies, some from Chesapeake Bay)
M = Moderate (5 to 10 studies)
H = High (10 to 25 studies)
VH = Very high (>25 studies)
NA = Not applicable
ND = No data

to measure PCB settling rates for stormwater runoff and stream sediments from urban watersheds in the San Francisco Bay area. They found that 55% of PCB particles in stormwater settled out within 30 minutes, and 30% of re-suspended creek sediments settled out within two minutes. They concluded that effective settling of moderate-to-larger sediment particles can remove at least 50% of PCB loads in stormwater. Parker et al. (2000) evaluated PCB levels in stormwater pond sediments in Arizona and concluded many of them exceeded preliminary sediment remediation guidelines, which would require special handling and disposal techniques when accumulated sediments are removed from stormwater ponds.

A European study found that urban tree pits and their associated bacteria have the capability to degrade PCBs in the soil (Leigh et al. 2006). This finding suggests that practices such as bioretention, which have aerobic media conditions, may also promote the growth of PCB-reducing bacteria.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a class of hundreds of compounds that are composed of carbon and hydrogen in structures of two or more benzene rings. Various human health risks of PAH exposure include cancer, cardiovascular disease, and developmental effects. PAHs readily adsorb to sediments in water and persist for a long time (half-lives of up to five years).

PAH sources include combustion of fossil fuels, fires, driveway and parking lot sealcoats, and creosote-treated wood. In urban areas, coal-tar sealcoats and vehicle emissions are the primary sources of PAHs (Hwang and Foster 2006; Brown and Peake 2006; Stein et al. 2006; Bressy et al. 2012; Gilbreath et al. 2012; Nowell et al. 2013). Nowell et al. conducted a comprehensive review of toxic contaminant levels in stream sediments within seven metropolitan areas across the United States and detected PAHs in 98% of the urban stream samples. The study also found that PAHs contributed more to total toxicity than all other contaminants combined (e.g., PCBs, trace elements, organochlorine and other pesticides).

PAH compounds are generally hydrophobic and in runoff are most often found in a particulate phase. Bathi et al. (2012) found that in streams, PAHs attach to both very fine sediment particles and very coarse organic particles. A San Francisco Bay stormwater sampling study (Gilbreath et al. 2012) routinely found high PAH concentrations in urban stormwater runoff with a mean flow-weighted concentration of 9,600 ng/l.

Only a handful of research studies have evaluated whether stormwater BMPs have the capability to remove PAHs. Roinas et al. (2014) found that stormwater ponds and swales were highly effective at removing heavier, hydrophobic PAHs (e.g., phenanthrene, flouranthene, pyrene), but less effective at removing lighter and more soluble PAHs, such as napthalene. DiBlasi et al. (2008) reported an 87% reduction in the mass of PAH in stormwater in a field study of a bioretention practice in College Park, Maryland. LeFevre et al. (2015) investigated the primary pollutant removal mechanisms responsible for the high performance of bioretention areas, focusing on experiments with napthalene. Most of the napthalene adsorbed to mulch and media (56 to 73%), about 12 to 18% biodegraded within the practice, about 10% was taken up by plants, and less than 1% volatilized into the atmosphere.

Kamlakkannan et al. (2004) concluded that stormwater ponds are very effective at trapping PAHs, but do not readily break them down because of the hypoxic conditions of the water and sediment at the bottom of the ponds.

Total Petroleum Hydrocarbons (TPH)

In this paper, the TPH category refers to a broader group of petroleum hydrocarbons than just PAHs. This group includes a variety of compounds (e.g., benzene, toluene, ethylbenzene, xylene) derived from crude oil that have considerable variation in chemical properties. Land uses associated with vehicle activities, such as freeways, streets, and parking lots, are the primary sources of petroleum hydrocarbons in urban areas. Specifically, these contaminants enter stormwater from fuel leaks and spills, vehicle emissions, and even tire particles. James et al. (2010) found that runoff from impervious areas had a mean concentration of TPH of 62 mg/L—much higher than is typically found in runoff from pervious areas.

Available monitoring studies have found that several mechanisms can be at play in stormwater management BMPs to remove hydrocarbons: settling, filtering, adsorption, biodegradation, and volatilization. Hong et al. (2006) conducted a series of bench-scale column tests to evaluate the effectiveness of bioretention in reducing levels of oil and grease in stormwater runoff. Oil and grease removal rates of 80 to 95% were observed, with most of the removal resulting from sorption and filtration, much of which occurred on the surface mulch layer. In addition, 90% of the hydrocarbons trapped in the bioretention area were effectively biodegraded within several days after each simulated runoff event. LeFevre et al. (2012) concluded that rain gardens and bioretention were an ideal practice to both remove and break down urban hydrocarbons, especially if planted with deep-rooted prairie plant species (as opposed to just mulch or turf cover).

In constructed wetlands, the predominant removal mechanisms are aerobic biodegradation and volatilization, and the TPH removal performance levels are close to those of bioretention. Tang et al. (2009) looked at the capability of vertical flow constructed wetlands to reduce benzene. Overall, they reported benzene removal ranging from 73 to 90%. Higher removal efficiencies were observed for wetlands located indoors with controlled temperature, light, and humidity compared to wetlands located outdoors under natural environmental conditions. The presence of aggregates improved the benzene removal efficiency through adsorption. However, the presence of plants had no significant impact on benzene removal.

Mercury

Mercury is a ubiquitous pollutant that today primarily enters watersheds via atmospheric deposition from power plant emissions. Methyl-mercury (which forms when mercury resides in anoxic and organic rich sediments) accumulates in fish tissue. Nationally, mercury is responsible for more river miles and lake acres being under fish consumption advisories than all other contaminants combined (Wentz et al. 2014). Monitoring studies have shown that mercury levels in storm flow are strongly correlated with turbidity (Gilbreath et al. 2012) and suspended particulate matter and particulate organic matter (Mason et al. 1999). Mangarella et al. (2010) established that the highest unit-area mercury loads in runoff were produced from industrial and commercial land uses with legacy mercury contamination in the soil, as compared to residential and open space.

Table 3. Comparative ability of stormwater BMPs to remove selected urban trace metals.

Stormwater BMP	Urban Trace Metals			
	Cadmium	Copper	Lead	Zinc
Bioretention	H	VH	VH	VH
Wet Pond	M	H	H	H
Wetland	M	H	M	M
Sand Filter	H	M	VH	H
Permeable Pavement	L	M	VH	VH
Dry Swale	L	H	--	VH
Grass Channel	M	L	L	M
Grass Filter	L	M	L	M
Dry Pond	L	L	M	M

VH = Very high removal (76 to 100%)
H = High removal (50 to 75%)
M = Moderate removal (26 to 50%)
L = Low removal (0 to 25%)
Source: Schueler and Younk (2015)

Few studies have monitored stormwater management BMPs for mercury removal. Yee and Mckee (2010) conducted a series of settling column experiments using stormwater runoff and sediment samples collected from urban watersheds. They found that 10 to 30% of mercury entrained in stormwater settled out within 20 minutes, and 90% of mercury resuspended from creek sediments settled out within 10 minutes. The authors concluded that that any urban BMP that promotes settling of fine sediment particles or captured fine-grained street solids (e.g., street cleaning) should be effective at reducing mercury loads in urban watersheds.

Monson (2007) monitored the effect of ten constructed wetlands in Minnesota to remove mercury in urban stormwater runoff and found that they were extremely effective in trapping and retaining mercury inputs (e.g., 80 to 90% removal, primarily due to particle sedimentation).

Urban Trace Metals

Cadmium, copper, lead, and zinc are considered urban trace metals because they are detected in virtually every urban stormwater sample. LeFevre et al. (2015) notes that the greatest toxicity risk is associated with dissolved forms of trace metals, which are more bioavailable to aquatic life. The sources and pathways of these metals vary. Atmospheric deposition contributes copper, lead, and zinc, while vehicle tires release these same metals. Brake pads and rotors are a major source of cadmium, copper, and possibly zinc. Several building materials also contribute trace metals: metal roofing (depending on the type) is a source of cadmium, zinc, and copper; asphalt shingles are a source of lead; and siding and downspouts release cadmium, copper, lead, and zinc. Median event mean concentrations of urban trace metals in stormwater runoff are 1 µg/L for cadmium, 16 µg/L for copper, 17 µg/L for lead, and 115 µg/L for zinc (National Stormwater Quality Database at http://www.bmpdatabase.org/nsqd.html).

More than 50 studies were found that evaluate how urban BMPs remove urban trace metals from stormwater. In general, the highest overall removal rates were reported for bioretention, wet ponds, and sand filters (see Table 3).

Because bioretention appears to be the most effective BMP for removing all four trace metals, this practice merits some special attention. Li and Davis (2008) found that most trace metals are captured on the surface mulch layer or the top few inches of the bioretention media, thus concluding that 12 to 18 inches of bioretention media were sufficient to maximize removal. Jang et al. (2005) found the greatest mulch sorption for lead, followed by copper and then zinc. Several studies have revealed design features that enhance trace metal removal in bioretention and sand filter practices. For example, Hunt et al. (2012) found that the metal binding capabilities of bioretention media can be increased by adding more organic matter to the mix. Reddy et al. (2014) found that adding calcite, zeolite, and/or iron filings to media mix sharply increased cadmium, copper, lead, and zinc removal rates compared to the conventional sand media (which is used in both sand filters and bioretention areas).

Other Trace Metals

Other trace metals include arsenic, chromium, iron, and nickel. Although some of these metals are naturally produced through geological weathering and soil erosion, their concentrations tend to be much higher in urban watersheds, especially those with extensive industrial operations, because of the wide variety of sources present there (e.g., automotive batteries, fabricated metals, stainless steel). These metals are exposed on many surfaces in the urban landscape where they can be "weathered" or corroded, often enhanced by acid rain. The main environmental risk associated with this group of trace metals is potential drinking water contamination, although the metal concentrations during most storm events fall well below most primary and secondary drinking water standards.

The four trace metals are highly treatable with new or existing stormwater practices in urban watersheds. The highest removal rates (50 to 80%) are reported for iron, which is not surprising given its very limited solubility. On the other hand, removal of arsenic, chromium, and nickel by stormwater BMPs ranges from 15 to 65%. The type of stormwater practice has a strong influence on metal removal rates, with wet ponds, infiltration, sand filters, and grass channels recording the highest removal rates. Surprisingly, bioretention areas, which were highly effective in removing cadmium, copper, lead, and zinc, were ineffective at removing nickel and iron, with several negative removal rates reported. On the other hand, bioretention was highly effective at removing chromium.

There were not enough data to assess the risk that either arsenic, chromium, iron, or nickel might break out or be released from BMP sediments or media, although the fact that several studies reported negative removal efficiency for some bioretention areas implies that the possibility does exist (Leisenring et al. 2014). Stronger evidence exists for trace metal accumulation in the bottom sediments of stormwater ponds. Gallagher et al. (2011) sampled the bottom sediments for trace metal levels at 68 stormwater ponds located in Baltimore County, Maryland. They found that nickel and chromium levels in stormwater pond sediments exceeded sediment contamination guidelines. For nickel, the threshold effect concentration level was exceeded in 82% of the stormwater ponds, and the probable effects concentration was exceeded at 35% of the ponds. In the case of chromium, the threshold effect concentration level was exceeded in 49% of the ponds, whereas the probable effects concentration was exceeded at 4% of the ponds. More research is needed to assess the risk of pond sediment contamination for these two metals, but it clearly shows the need to exercise care when handling and disposing of sediments during stormwater pond cleanouts.

Pyrethroid Pesticides

Pyrethroids (e.g., bifenthrin, permethrin) are a group of insecticides used for pest control in buildings, landscape maintenance, and home and garden use, and numerous formulations are sold at the retail level. As a group, pyrethroids are relatively non-persistent in the environment and are unlikely to bioaccumulate in vertebrates. Nonetheless, pyrethroids are extremely lethal at very low concentrations to aquatic invertebrates in urban streams. Pyrethroids are hydrophobic, preferentially adsorb to sediment particles, and are often found in urban stream sediments. Stormwater runoff is the primary source of pyrethroids in urban watersheds. Monitoring studies of urban surface waters and sediments have detected pyrethroid pesticides at high frequencies and at levels that are toxic to aquatic organisms (Ensminger et al. 2013; Holmes et al. 2008; Lao et al. 2010; Kuivila et al. 2012; Amwag et al. 2006; Ding et al. 2010).

The monitoring data on whether BMPs can effectively remove pyrethroid pesticides consists of three studies that investigated constructed wetlands and swales that were treating agricultural runoff. Moore et al. (2009) investigated the capability of a constructed wetland to remove pyrethroid pesticides in agricultural runoff in Mississippi. They determined that the wetland trapped the pesticides effectively, with most of them sorbing either to wetland sediments or vegetation. Budd et al. (2011) monitored the impact of a constructed wetland in reducing pyrethroid pesticides generated from agricultural irrigation return flows in the Central Valley of California. The constructed wetland was found to be very effective at trapping pyrethroids in its bottom sediments. Budd et al. (2011) found low to moderate rates of microbial biodegradation of pyrethroid pesticides within the constructed wetland. The pesticides had measured half-lives of several months to a year in the wetland sediment. Given the low rate of biodegradation, Budd et al. expressed some concern that pyrethroids could persist and possibly accumulate in the sediments of the constructed wetland, increasing the potential toxicity risk for the fish and wildlife that utilize these habitats. Werner et al. (2010) evaluated the capability of a 400-meter vegetated swale to reduce toxicity from alfalfa and tomato fields that were treated with permethrin. Based on their tests, they concluded that the swale had very little capability to reduce permethrin toxicity.

Delorenzo et al. (2012) monitored for the presence of urban pesticides in the water column of stormwater ponds that drained residential catchments in coastal South Carolina. Pyrethroids were detected in 10% of the ponds sampled and occasionally exceeded benchmarks to protect aquatic life.

Legacy Organochlorine (OC) Pesticides

OC pesticides include insecticides such as DDT, DDE, chlordane, and dieldrin that have been banned for decades but still persist in the environment. Although these pesticides were banned many years ago (DDT and DDE in 1972, dieldrin in 1987, and chlordane in 1988) they are still an urban water quality concern because they are highly persistent in the environment, with half-lives typically measured at a thousand days or more, have a high affinity for soil organic matter, and tightly bind to soil and sediment particles. Therefore their primary source and pathway in urban areas is erosion of contaminated soils and transport by stormwater runoff.

OC pesticides are a classic example of how highly persistent and lipophilic insecticides can have an enduring environmental impact nearly a half-century after their use was banned. For example, Connor et al. (2007) investigated DDT and dieldrin sources in the San Francisco Bay area more than 30 years after their use was banned and concluded that sediments carried in urban stormwater runoff were the greatest source of DDT and dieldrin in the region, far exceeding the inputs from agricultural runoff and irrigation return flows from the Central Valley of California. Stormwater runoff also dominated all other sources of DDT and dieldrin in the San Francisco Bay region, such as atmospheric deposition and discharges from municipal or industrial wastewater treatment plants. Gilbreath et al. (2012) also monitored legacy pesticides in urban runoff from the San Francisco Bay region and found that DDT and dieldrin were routinely detected during storm events. The EMC for DDT ranged from 5.1 to 59 ng/l (median: 15 ng/l) and was positively correlated with elevated turbidity and flow levels. The encouraging news is that nearly all monitoring studies have shown sharply declining trends in OC pesticides in urban stormwater runoff and creek sediments since they were banned. This appears to have greatly reduced their bioaccumulation and toxicity in vertebrates such as fish, eagles, and marine mammals (Stone et al. 2014a; Van Metre and Mahler 2005).

No monitoring studies could be found that investigated OC pesticide removal rates for urban BMPs. The monitoring evidence for OC pesticides being trapped in BMP sediments is also rather sparse. Parker et al. (2000) measured OC pesticides in stormwater pond sediments in the arid Arizona environment. They discovered that OC pesticides were routinely detected in nearly every stormwater pond that they sampled (DDT degradates, DDE, and dieldrin). Overall, Parker et al. noted that OC pesticide levels were all found at fairly low levels when the data were collected some 20 years ago.

Legacy Organophosphate (OP) Pesticides

OP pesticides refers to a group of insecticides that include chlorpyrifos, diazinon, and dichlorovos that were introduced toward the middle of the last century to replace the more persistent OC pesticides. These insecticides are delivered via urban runoff from upland lawns, gardens, and landscape areas where they are applied. They are very soluble and highly mobile; for example, diazinon has a half-life of about 40 days in both soil and water (Schueler 1999).

Research emerged toward the later part of the century that confirmed that that these relatively non-persistent insecticides were highly toxic to aquatic invertebrates in urban streams at extremely low concentrations (several studies are profiled in Schueler 1998). Due to this and concerns about cancer risk and human exposure, the use of most OP pesticides has been banned or highly restricted (chlorpyrifos and diazinon were banned for residential use in 2000–2002). The use of dichlorvos is still allowed, although it is more restricted than in the past.

Stone et al. (2014a) reported that diazinon and chlorpyrifos were among the most frequently detected and most consistently toxic insecticides measured in urban streams in the 1990s and the first few years of the new century. Subsequent national monitoring from 2002 to 2011, however, confirms that chlorpyrifos and diazinon are rarely detected in either urban or agricultural streams (Stone et al. 2014b). The number of urban streams that exceeded aquatic life benchmarks also dropped sharply for both insecticides. Both trends were directly attributed to the stringent restrictions imposed on their use at the turn of the century. Stone et al. (2014b) reported that dichlorvos was the second most frequently detected insecticide in urban streams across the nation from 2002 to 2011. More than 45% of urban streams across the nation exceeded their aquatic life benchmark for dichlorvos (fipronil exceeded benchmarks at more than 70% of urban streams).

No monitoring data were available to assess the ability of urban BMPs to remove OP pesticides. Two studies examined the capability of agricultural BMPs to remove OP pesticides. Budd et al. (2010) found that a constructed wetland was effective in removing chlorpyrifos in California, whereas Werner et al. (2010) reported that a grass swale had little value in reducing toxicity from irrigation return flows containing high levels of chlorpyrifos. In addition, no monitoring data were available to determine the presence and persistence of OP pesticides in urban or agricultural BMP sediments over time.

Plasticizers

Phthalates are a type of plasticizer that are emitted from a diverse array of flexible PVC products, such as roof coating, cable coating, garden hoses, and vehicle under-coating. The effect of phthalates on human health is still being assessed, and no benchmarks have been established for acceptable human exposure.

Once released into the environment, phthalates tend to sorb to sediment particles (Clara et al. 2010) and can then be mobilized in urban stormwater. The limited available research indicates that phthalates are ubiquitous in the urban environment and are detected in urban rain water, surface water, wastewater, stormwater, and sediments.

Only one study has monitored phthalate removal in an urban BMP. Zhang et al. (2014) reported greater than 80% removal of phthalates in an Australian biofilter. A number of European researchers have tried to model how urban BMPs remove phthalates (and other micropollutants), but data limitations prevented them from providing reliable estimates of removal efficiency (Björklund et al. 2011; DeKeyser et al. 2010; Vezzaro et al. 2010, 2011).

Flame Retardants

Polybrominated diphenyl ether (PBDE) is a flame retardant that includes chemical compounds that are persistent, lipophilic, and hydrophobic and tend to bioaccumulate in the tissues of fish and wildlife (Kupper et al. 2008). Flame retardants are commonly used in household items such as computer and television wiring, plastics, foam cushions, and insulation foams. PBDE is emitted from several sources, including atmospheric deposition over urban watersheds. Some studies indicate that wastewater discharges and/or land application of municipal biosolids could also be a significant potential source of flame retardants at the watershed scale (Gorgy et al. 2011; Rief et al. 2012). Like many other UTCs, PBDE strongly sorbs to soil, sediments, and organic matter and moves through the watershed when these particles are mobilized by stormwater runoff.

Because PBDEs have similar characteristics as PCBs and dioxins, it is anticipated that PBDE runoff can be effectively reduced by urban BMPs that are able to trap or filter out sediment particles. The limited research seems to support this contention.

Three European studies investigated whether urban BMPs can effectively remove flame retardants (Table 4). Sébastian et al. (2014) reported that a retention pond removed 20 to 66% of PBDE during the one year monitoring period. They noted that while PBDE was clearly associated with sediment particles, it did not always behave like them when it came to settling out in the pond. Biofilters had high to very high PBDE removal efficiencies (Table 4), depending on the type of compound.

Dioxins

Dioxins and furans are generic terms for a group of toxics that contain chlorine and carbon atoms associated with dibenzodioxin and dibenzofurans. They are inadvertently produced by combustion processes that involve chlorine in uncontrolled reactions. Dixons are mostly found in the particulate phase (Suarez et al. 2006) and tend to be lipophilic, which increases the potential bioaccumulation in fish tissue (Horstmann and McLachan 1995).

The sources of dioxins include incomplete waste combustion (e.g., municipal, medical, and hazardous waste incineration), legacy chemical manufacturing sites, paper mills, and atmospheric deposition. Some are even produced by night-time fireworks, and others are found as impurities in certain organochlorine pesticides (e.g., 2-4-D). Wash-off of dioxins deposited onto impervious surfaces, as well as erosion or wash-off of older contaminated soils, are the major pathways for transport of these pollutants in urban watersheds.

No monitoring data were discovered to determine whether urban BMPs can remove dioxins in urban runoff. The lack of data is due to the difficulty and expense to obtain reliable dioxin samples in the field during storm conditions. No data

Table 4. Summary of PBDE removal efficiencies.

Author	Year	Location	Removal	Contaminant	BMP
Bester and Schäfer	2009	Germany	96–99%	Lipophilic compounds	Biofilter peat and sand
			81–98%	Hydrophilic compounds	Biofilter peat and sand
Gilbert et al.	2012	Paris	44–87%	Light congeners	Biofiltration
			75%	Heavy congeners	Biofiltration
Sébastian et al.	2014	France	20–66%	PBDEs	Dry retention pond

were available to document whether dioxins are trapped in BMP sediments or media and whether they have the potential to accumulate and persist over time.

Discussion

Although the data on BMP removal of UTCs were sparse, sufficient evidence was available to demonstrate effective removal of certain UTCs by urban BMPs. Studies that quantify the accumulation of UTCs in BMP sediments and concentrations in urban runoff also support the notion that urban BMPs are removing UTCs in urban runoff and preventing many of them from reaching the receiving waters. Table 5 summarizes the degree to which urban BMPs capture or retain each UTC, based on the literature review.

It is important to keep in mind that even though urban BMPs may be effective at trapping and retaining UTCs, they are not necessarily removing them from the environment. These persistent compounds could accumulate in BMP sediments over many decades to the point that they might trigger sediment toxicity guidelines. Older stormwater ponds built in the 1980s and 1990s appear to have the greatest risk of sediment toxicity. Monitoring has revealed that as many as eight UTCs could potentially reach toxic levels in pond sediments, including PCB, PAH, mercury, nickel, chromium, copper, cadmium, and zinc. Some UTCs appear to be slowly declining in pond sediments (e.g., legacy pesticides), whereas the potential risk associated with other UTCs is simply not known at this time (e.g., PBDE, dioxins, pyrethroid pesticides).

Despite these risks, pond sediments remain an acceptable option to (temporarily) trap toxics in the urban landscape for several reasons. First, the actual toxicity risk to aquatic life in the stormwater pond environment may be limited. The simplified food webs and low species diversity found in ponds may reduce the potential for bioaccumulation in urban fish and wildlife tissues. In particular, the benthic community in pond sediments

Table 5. Degree to which urban BMPs capture or retain UTCs.

Toxics Category	Urban BMP Capture or Retention?
PCBs	Yes, supported by limited monitoring data
PAH	Yes, based on strong evidence
TPH	Yes, based on strong evidence
Hg	Yes, supported by limited monitoring data
UTM	Yes, based on strong evidence
OTM	Yes, supported by limited monitoring data
PP	Yes, supported by limited monitoring data
OCP	Yes, supported by limited monitoring data
OPP	No data available to assess
Plasticizer	Yes, supported by limited monitoring data
PBDE	Yes, supported by limited monitoring data
Dioxins	No data available to assess

that would be most exposed to UTCs is already highly degraded. Regarding human health, fish consumption is extremely limited in stormwater ponds and recreational contact with sediments is uncommon.

On a more positive note, the research indicates that green infrastructure BMPs (e.g., bioretention, biofilters, swales) are very effective at trapping certain UTCs and may actually break them down as a result of microbial biodegradation and phytoremediation processes that occur in the soil media and/or vegetation. The risk of UTC bioaccumulation also appears to be less pronounced in BMPs such as bioretention. These smaller practices do not create aquatic habitat, and their maintenance schedule calls for frequent removal and replacement of surface mulch and sediments where most UTCs will be preferentially trapped.

Recommendations

Estimating UTC Reductions from Urban BMPs

While there are very limited data available to quantify removal of UTCs by urban BMPs, a key finding from the literature review was that UTCs have many "sediment-like" properties and, therefore, a rationale may be provided for using sediment removal rates as the initial benchmark for estimating UTCs removal rates by urban BMPs, when little or no monitoring data are available.

There are extensive monitoring data to establish sediment removal rates for a wide range of urban BMPs (Schueler and Lane 2015). Most urban BMPs have a high capability to remove suspended sediment from urban runoff. Suspended sediments and many UTCs share common characteristics—they are hydrophobic, are non-soluble, have a strong affinity for organic matter, and bind, adsorb, or otherwise become attached to sediment particles. In addition, both sediments and most UTCs are relatively inert and persistent and have low rates of biodegradation. Both are also associated with fine- and medium-grained particles that can be entrained in urban stormwater runoff. Most importantly, both are subject to the same pollution "removal" mechanisms (i.e., settling and filtering).

In the absence of reliable data on UTC removal, it is recommended that the default value be set to the associated total suspended solids (TSS) removal rate of each urban BMP. The basic idea is that the UTC removal rate can be adjusted upward or downward from the sediment removal benchmark, depending on the characteristics and properties of the individual toxics type. For example, the UTC removal rate should be adjusted *lower* than the sediment benchmark if any of the following conditions apply:

- A significant fraction of the UTC is present in soluble form (i.e., 25% or more).
- The UTC is predominantly associated with very fine-grained particles (i.e., silt and clay particles less than 62 microns in diameter).
- Is prone to release after being trapped in BMP sediments (e.g., methylation in hypoxic and organic-rich environment of constructed wetland sediments).

By contrast, the UTC removal rate can be adjusted *higher* than the sediment removal benchmark when the UTC is:

- seldom or never found in soluble form,
- predominantly associated with medium or coarse-grained particles that are easier to settle (i.e., more than 250 microns in diameter), or
- documented to persist and accumulate within BMP sediments over time.

This benchmark approach can be used to estimate UTC reductions associated with stormwater BMPs for local TMDLs and to estimate the additional toxic removal benefits achieved by the Chesapeake Bay TMDL. Table 6 estimates the treatability of urban toxic contaminants relative to the removal rates of TSS by stormwater practices. This approach has been accepted by the Chesapeake Bay Program and Bay jurisdictions.

Future Research Needs

More research is needed to directly quantify the removal of UTCs by urban BMPs. Research is also needed to measure toxics concentrations in pond sediments to fully assess the real toxicity risk and develop safer methods to maintain BMPs and clean out their sediments. Work is needed to determine which types of stormwater ponds pose the greatest risk (e.g., age, contributing land use, surface area, other factors) and to define the optimal places in the urban landscape where pond sediments can be safely disposed after they are cleaned out (e.g., fill, mix with biosolids, landfill). In addition, further tissue tests are recommended to determine whether toxics are bioaccumulating in the fish and wildlife that utilize the habitat created by urban BMPs.

Table 6: Comparison of BMP treatability for the 12 urban toxic contaminant groups.

Toxics Category	BMP Removal Rate?	Measured or Estimated?	Behaves like Sediment?	BMP Retention?	Sediment Toxicity Concern?
PCBs	TSS	E	Y	Y	PR
PAH	>TSS	E	Y	Y	CR
TPH	>TSS	M	Y	Y	MR
Hg	>TSS	E	Y	Y	PR
UTM	<TSS	M	Y	Y	PR
OTM	<TSS	M	Y	Y	PR
PP	TSS	E	Y	y	CR
OCP	>TSS	E	Y	y	MR
OPP	<TSS	E	Y	ND	MR
Plasticizers	<TSS	E	Y	y	ND
PBDE	<TSS	E	Y	Y	ND
Dioxins	<TSS	E	Y	ND	ND

Removal Rate:

>TSS = Higher than TSS removal
TSS = Similar to TSS removal
<TSS = Less than TSS removal

M = Measured
E= Estimated

Y = Yes, based on strong evidence
Y = Yes, limited monitoring data provides support
ND = No data available to assess

PR = Potential risk
CR = Clear risk
MR = Minimal risk

Summary

This literature review on the degree to which urban BMPs that are intended to decrease nutrient and sediment can also reduce toxic contamination of waterways showed a limited number of studies for many of the UTCs. However, sufficient data were available to demonstrate capture and/or retention of PAHs, TPH, and UTMs by urban BMPs. The limited available data also provide evidence that these BMPs capture and retain PCBs, mercury, OTMs, PP, OCP, plasticizers, and PBDE. These findings suggest that efforts to reduce nutrients and sediments can produce other significant water quality benefits, such as reducing toxicity to fish, wildlife, and humans.

Continued implementation of BMPs in urban areas is a key element of a comprehensive strategy to reduce loads of UTCs (along with existing strategies such as pollution prevention and product substitution). Expert panels of the Chesapeake Bay Partnership have developed TSS removal rates for more than a dozen different types of approved urban BMPs. Although the Partnership does not officially regulate toxics, it has adopted the approach recommended here for estimating UTC removal rates based on TSS removal.

References

Amweg, E., D. Weston, J. You, and M. Lydy. 2006. Pyrethroid insecticides and sediment toxicity in urban creeks from California and Tennessee. Environmental Science & Technology. 40: 1700–1706.

ATSDR (Agency for Toxic Substances and Disease Registry). 1995. Toxicological profile for polycyclic aromatic hydrocarbons (PAHs) update. Atlanta, GA: ATSDR.

ATSDR (Agency for Toxic Substances and Disease Registry). 2000. Toxicological profile for polychlorinated biphenyls (PCBs). Atlanta, GA: ATSDR.

ATSDR (Agency for Toxic Substances and Disease Registry). 2004. Toxicological profile for polybrominated biphenyls and polybrominated diphenyl ethers. Atlanta, GA: ATSDR.

Bathi, J., R. Pitt, and S. Clark. 2012. Polycyclic aromatic hydrocarbons in urban stream sediments. Advances in Civil Engineering. Article ID 372395.

Bester, K. and D. Schäfer. 2009. Activated soil filters (bio filters) for the elimination of xenobiotics (micro-pollutants) from storm- and waste waters. Water Research. 43(10): 2639-2646.

Björklund, K., P. Malmqvist, and A. Stromvall. 2011. Simulating organic pollutant flows in urban stormwater: Development and evaluation of a model for non-phenols and phthalates. Water Science & Technology 63(3): 508–515.

Bressy, A., M. Gromaire, C. Lorgeoux, M. Saad, F. Leroy, and G. Chebbo. 2012. Towards the determination of an optimal scale for stormwater quality management: Micro-pollutants in a small residential catchment. Water Research 46: 6799–6810.

Brown, J., and B. Peake. 2006. Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff. Science of the Total Environment 359: 145–155.

Budd, R., A. O'geen, K. Goh, S. Bondarenko, and J. Gan. 2011. Removal mechanisms and fate of insecticides in constructed wetlands. Chemosphere 83: 1581–1587.

CBP (Chesapeake Bay Program). No date. Toxic contaminants research. http://www.chesapeakebay.net/managementstrategies/strategy/toxic_contaminants_research.

Clara, M., G. Windhofer, W. Hartl, K. Braun, M. Simon, O. Gans, C. Scheffknecht, and A. Chovanec. 2010. Occurrence of phthalates in surface runoff, untreated and treated wastewater and fate during wastewater treatment. Chemosphere 78: 1078–1084.

Connor, M., J. Davis, J. Leatherbarrow, B. Greenfield, A. Gunther, D. Hardin, D., T. Mumley, J. Oram, and C. Werme. 2007. The slow recovery of San Francisco Bay from the legacy of organochlorine pesticides. Environmental Research 105: 87–100.

Davis, J., F. Hetzel, J. Oram, and L. McKee. 2007. Polychlorinated biphenyls (PCBs) in San Francisco Bay. Environmental Research 105: 67–86.

De Keyser, W., V. Gevaert, F. Verdonck, I. Nopens, B. De Baets, P. Vanrolleghem, P. Mikkelsen, and L. Benedetti. 2010. Combining multimedia models with integrated urban water system models for micropollutants. Water Science & Technology 62(7): 1614–1622.

DeLorenzo, M., B. Thompson, E. Cooper, J. Moore, and M. Fulton. 2012. A long-term monitoring study of chlorophyll, microbial contaminants, and pesticides in a coastal residential stormwater pond and its adjacent tidal creek. Environmental Monitoring & Assessment 184(1): 343–359.

DiBlasi, C., H. Li, A. Davis, and U. Ghosh. 2008. Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility. Environmental Science & Technology 43(2): 494–502.

Ding, Y., A. Harwood, H. Foslund, and M. Lydy. 2010. Distribution and toxicity of sediment-associated pesticides in urban and agricultural waterways from Illinois, USA. Environmental Toxicology and Chemistry 29(6): 149–157.

Ensminger, M., R. Budd, K. Kelley, and K. Goh. 2013. Pesticide occurrence and aquatic benchmark exceedances in urban surface waters and sediments in three urban areas of California, USA, 2008–2011. Environmental Monitoring & Assessment 185(5): 3697–3710.

Eriksson, E., A. Baun, L. Scholes, A. Ledin, S. Ahlman, M. Revitt, C. Noutsopoulos, and P.S. Mikkelsen. 2007. Selected stormwater priority pollutants—A European perspective. Science of the Total Environment 383: 41–51.

French-McCay, D.P. 2002. Development and application of an oil toxicity and exposure model,
OilToxEx. Environmental Toxicology and Chemistry 21: 2080–2094.

Gallagher, M., J. Snodgrass, D. Ownby, A. Brand, R. Casey, and S. Lev. 2011. Watershed-scale analysis of pollutant distributions in stormwater management ponds. Urban Ecosystems 14(3): 469–484.

Gilbert, S., J. Gasperi, V. Rocher, C. Lorgeoux and G. Chebbo. 2012. Removal of alkylphenols and polybromodiphenylethers by a biofiltration treatment plant during dry and wet-weather periods. Water Science & Technology 65(9): 1591-1598.

Gilbreath, A., D. Yee, and L. McKee. 2012. Concentrations and loads of trace contaminants in a small urban tributary, San Francisco Bay, California. Technical report of the Sources Pathways and Loading Work Group of the Regional Monitoring Program for Water Quality: SFEI Contribution No. 650. Richmond, CA: San Francisco Estuary Institute.

Gorgy, T., L. Li, J. Grace, and M. Ikonomou. 2011. Polybrominated diphenyl ethers mobility in biosolids-amended soils using leaching column tests. Water, Air & Soil Pollution 222: 77–90.

Holmes, R., B. Anderson, B. Phillips, J. Hunt, D. Crane, and A. Mekebri. 2008. Statewide investigation of the role of pyrethroid pesticides in sediment toxicity in California's urban waterways. Environmental Science & Technology 42(18): 7003–7009.

Hong, E., E. Seagren, and A. Davis. 2006. Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. Water Environment Research 78(2): 141–155.

Horstmann, M., and M. McLachlan. 1995. Concentrations of polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF) in urban runoff and household wastewaters. Chemosphere 31(3): 2887–2896.

Hunt, W., A. Davis, and R. Traver. 2012. Meeting hydrologic and water quality goals through targeted bioretention design. Journal of Environmental Engineering 138(6): 698–707.

Hwang, H., and G.D. Foster. 2006. Characterization of polycyclic aromatic hydrocarbons in urban stormwater runoff flowing into the tidal Anacostia River, Washington, DC, USA. Environmental Pollution 140(3): 416–426.

James, R., P. Wilbon, and J. DiVincenzo. 2010. Pervious and impervious urban stormwater runoff in a rapidly urbanizing region: Occurrence of fluoranthene and pyrene. Bulletin of Environmental Contamination and Toxicology 85: 32–36.

Jang, A., Y. Seo, and P. Bishop. 2005. The removal of heavy metals in urban runoff by sorption on mulch. Environmental Pollution 133: 117–127.

Kamalakkannan, R., V. Zettel, A. Goubatchev, K. Stead-Dexter, and N. Ward. 2004. Chemical (polycyclic aromatic hydrocarbon and heavy metal) levels in contaminated stormwater and sediments from a motorway dry detention pond drainage system. Journal of Environmental Monitoring 6(3): 175–181.

King, R., J. Beaman, D. Whigham, A. Hines, M. Baker, and D. Weller. 2004. Watershed land use is strongly linked to PCBs in white perch in Chesapeake Bay subestuaries. Environmental Science & Technology 38(24): 6546–6552.

Kitchell, A. 2001. Managing lakes for pure drinking water. Watershed Protection Techniques 3(4):797–812

Kuivila, K., M. Hladik, C. Ingersoll, N. Kemble, P. Moran, D. Calhoun, L. Nowell, and R. Gilliom. 2012. Occurrence and potential sources of pyrethroid insecticides in stream sediments from seven U.S. metropolitan areas. Environmental Science and Technology 46(6): 4297–4303.

Kupper, T., L. de Alencastro, R. Gatsigazi, R. Furrer, D. Grandjean, and J. Tarradellas. 2008. Concentrations and specific loads of brominated flame retardants in sewage sludge. Chemosphere 71: 1173–1180.

Lao, W., D. Tsukada, D. Greenstein, S. Bay, and K. Maruya. 2010. Analysis, occurrence, and toxic potential of pyrethroids, and fipronil in sediments from an urban estuary. Environmental Toxicology and Chemistry 29(4): 843–851.

Lazarus, R., B. Rattner, and M. Ottinger. 2016. Chesapeake Bay fish-osprey food chain: Evaluation of contaminant exposure and genetic damage. Environmental Toxicology and Chemistry 35(6): 1560–1575.

LeFevre, G., R. Hozalski, and P. Novak. 2012. The role of biodegradation in limiting the accumulation of petroleum hydrocarbons in rain garden soils. Water Research 46: 6753–6762.

LeFevre, G., K. Paus, P. Natarajan, J. Gulliver, P. Novak, and R. Hozalski. 2015. Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells. Journal of Environmental Engineering 141(1).

Leigh, M., P. Prouzová, M. Macková, T. Macek, D. Nagle, and J. Fletcher. 2006. Polychlorinated biphenyl (PCB)-degrading bacteria associated with trees in a PCB contaminated site. Applied and Environmental Microbiology 72(4): 2331–2342.

Leisenring, M., J. Clary, and P. Hobson. 2014. Pollutant category status report: Solids, bacteria, nutrients and metals. International Stormwater Best Management Practices Database. http://www.bmpdatabase.org.

Li, H., and A. Davis. 2008. Heavy metal capture and accumulation in bioretention media. Environmental Science and Technology 42(14): 5247–5253.

Mangarella, P., K. Havens, W. Lewis, and L. McKee. 2010. Task 3.5.1: Desktop evaluation of controls for polychlorinated biphenyls and mercury load reduction. Technical report of the Regional Watershed Program: SFEI Contribution 613. Oakland, CA: San Francisco Estuary Institute.

Mason, R., and A. Lawrence. 1999. Concentration, distribution, and bioavailability of mercury and methylmercury in sediments of Baltimore Harbor and Chesapeake Bay, Maryland, USA. Environmental Toxicology and Chemistry 18(11): 2438–2447.

Mathieu-Denoncourt, J., S.J. Wallace, S.R., de Solla, and V.S. Langlois. 2015. Plasticizer endocrine disruption: Highlighting developmental and reproductive effects in mammals and non-mammalian aquatic species. General and Comparative Endocrinology 219: 74–88.

Monson, B. 2007. Effectiveness of stormwater ponds/constructed wetlands in the collection of total mercury and production of methylmercury. St. Paul, MN: Minnesota Pollution Control Agency.

Moore, M., C. Cooper, S. J. Smith, R. Cullum, S. Knight, M. Locke, and E. Bennett. 2009. Mitigation of two pyrethroid insecticides in a Mississippi Delta constructed wetland. Environmental Pollution 157(1): 250–6.

Nowell, L., P. Moran, R. Gilliom, D. Calhoun, C. Ingersoll, N. Kemble, K. Kuivila, and P. Phillips. 2013. Contaminants in stream sediments from seven United States metropolitan areas: Part 1: Distribution in relation to urbanization. Archives of Environmental Contamination and Toxicology 64: 32–51.

Parker, J., K. Fossum, and T. Ingersoll. 2000. Chemical characteristics of urban stormwater sediments and implications for environmental management, Maricopa County, Arizona. Environmental Management 26: 99–115.

Reddy, K., T. Xie, and S. Dastgheibi. 2014. Removal of heavy metals from urban stormwater using different filter materials. Journal of Environmental Chemical Engineering 2(1): 282–292.

Reif, A., J. Crawford, C. Loper, A. Proctor, R. Manning, and R. Titler. 2012. Occurrence of pharmaceuticals, hormones, and organic wastewater compounds in Pennsylvania waters, 2006–09. US Geological Survey (USGS) Scientific Investigations Report 2012-5106. Washington, DC: USGS.

Roinas, G., A. Tsavdaris, J., J. Williams, and C. Mant. 2014. Fate and behavior of pollutants in a vegetated pond system for road runoff. CLEAN: Soil, Air, Water 42(2): 169–177.

Schueler, T. 1999. Diazinon sources in runoff from the San Francisco Bay region. Watershed Protection Techniques 3(1): 613–616.

Schueler, T.R., 1998. Urban pesticides: From the lawn to the stream. Watershed Protection Techniques 2(1): 247–253.

Schueler, T.R., and A. Youngk. 2016. Potential benefits of nutrient and sediment practices to reduce toxic contaminants in the Chesapeake Bay Watershed. Part 2: Removal of toxic contaminants from the agriculture and wastewater sectors. Annapolis, MD: Chesapeake Bay Partnership Toxics Workgroup. http://chesapeakestormwater.net/wp-content/uploads/dlm_uploads/2016/03/Final-Report-on-Ag-and-Wastewater-Toxics.pdf.

Schueler, T.R., and A. Youngk. 2015. Potential benefits of nutrient and sediment practices to reduce toxic contaminants in the Chesapeake Bay Watershed. Part 1: Removal of urban toxic contaminants. Annapolis, MD: Chesapeake Bay Partnership Toxics Workgroup. http://chesapeakestormwater.net/wp-content/uploads/dlm_uploads/2016/02/Toxics-Report-1.pdf.

Schueler, T.R., and C. Lane. 2015. Recommendations of the expert panel to define removal rates for state stormwater performance Standards. Annapolis, MD: Chesapeake Bay Partnership Water Quality Goal Implementation Team.

Sébastian, C., S. Barraud, C. Gonzalez-Merchan, Y. Perrodin, and R. Visiedo. 2014. Stormwater retention basin efficiency regarding micro-pollutant loads and ecotoxicity. Water Science & Technology 69(5): 974–981.

Stein, E., L. Tiefenthaler, and K. Schiff. 2006. Watershed-based sources of polycyclic aromatic hydrocarbons in urban storm water. Water Science and Technology 25(2): 373–385.

Stone, W., R. Gilliom, and K. Ryberg. 2014a. Pesticides in U.S. streams and rivers: Occurrence and trends during 1992–2011. Environmental Science & Technology 48(19): 11025–11030.

Stone, W., R. Gilliom, and J. Martin. 2014b. An overview comparing results from two decades of monitoring for pesticides in the nation's streams and rivers, 1992–2001 and 2002–2011 US Geological Survey (USGS) Scientific Investigations Report 2014-5154. Washington, DC: USGS.

Suarez, M., H. Rifai, J. Schimek, M. Bloom, P. Jensen, and L. Koenig. 2006. Dioxin in storm-water runoff in Houston, Texas. Journal of Environmental Engineering 132(12): 1633–1643.

Tang, X., P. Eke, M. Scholz, and S. Huang. 2009. Processes impacting on benzene removal in vertical-flow constructed wetlands. Bioresource Technology 100: 227–234.

US Environmental Protection Agency, US Geological Survey, and US Fish and Wildlife Service. 2012. Toxic contaminants in the Chesapeake Bay and its watershed: Extent and severity of occurrence and potential biological effects. Annapolis, MD: USEPA Chesapeake Bay Program Office.

USEPA (U.S. Environmental Protection Agency). 2012. Priority PBTs: Dioxins and furans fact sheet. Washington, DC: USEPA Office of Pollution Prevention and Toxics. https://archive.epa.gov/epawaste/hazard/wastemin/web/pdf/dioxfura.pdf.

USEPA (U.S. Environmental Protection Agency). 2010. Chesapeake Bay total maximum daily load for nitrogen, phosphorus, and sediment. https://www.epa.gov/chesapeake-bay-tmdl/chesapeake-bay-tmdl-document.

USEPA (U.S. Environmental Protection Agency). 2001. Information sheet 2 dioxin: Scientific highlights from draft reassessment (2000). Washington, DC: USEPA Office of Research and Development.

USEPA (U.S. Environmental Protection Agency). 1976. Quality criteria for water. Washington, DC: USEPA. EPA 440/9-76-023.

USGS (U.S. Geological Survey). 2000. Mercury in the environment. USGS Fact Sheet 146-00. Washington, DC: USGS.

Van Metre, P., and B. Mahler. 2005. Trends in hydrophobic organic contaminants in urban and reference lake sediments across the United States, 1970–2001. Environmental Science and Technology 39: 5567–5574.

Velinsky, D., G. Riedel, J. Ashley, and J. Cornwell. 2011. Historical contamination of the Anacostia River, Washington, D.C. Environmental Monitoring & Assessment 183: 307–328.

Vezzaro, L., E. Eriksson, A. Ledin, and P.S. Mikkelsen. 2010. Dynamic stormwater treatment unit model for micropollutants (STUMP) based on substance inherent properties. Water Science & Technology 62(3): 622–629.

Vezzaro, L., E. Eriksson, A. Ledin, and P.S. Mikkelsen. 2011. Modeling the fate of organic micropollutants in stormwater ponds. Science of the Total Environment 409(13): 2597–2606.

Wenning, R.J., L. Martello, and A Prusak-Daniel. 2011. Dioxins, PCBs, and PBDEs in aquatic organisms. In: Environmental contaminants in biota, interpreting tissue concentrations, second sdition, ed. W.N. Beyer, and J.P. Meador, 103–166. Boca Raton, FL: CRC Press.

Wentz, D., M. Brigham, L. Chasar, M. Lutz, and D. Krabbenhoft. 2014. Mercury in the nation's streams—levels, trends, and implications. U.S. Geological Survey (USGS) Circular 1395. Washington, DC: USGS.

Werner, I., L. Deanovic, J. Miller, D. Denton, D. Crane, A. Mekebri, M. Moore, and J. Wrysinski. 2010. Use of vegetated agricultural drainage ditches to decrease toxicity of irrigation runoff from tomato and alfalfa fields in California, USA. Environmental Toxicology and Chemistry 29(12): 2859-2868.

Yee, D., and L.J. McKee. 2010. Task 3.5: Concentrations of PCBs and Hg in soils, sediments and water in the urbanized Bay Area: implications for best management. A technical report of the Watershed Program: SFEI Contribution 608. Oakland, CA: San Francisco Estuary Institute.

Zhang, K., A. Randelovic, D. Page, D. McCarthy, and A. Deletic. 2014. The validation of stormwater biofilters for micropollutant removal using in situ challenge tests. Ecological Engineering 67(2014): 1–10.