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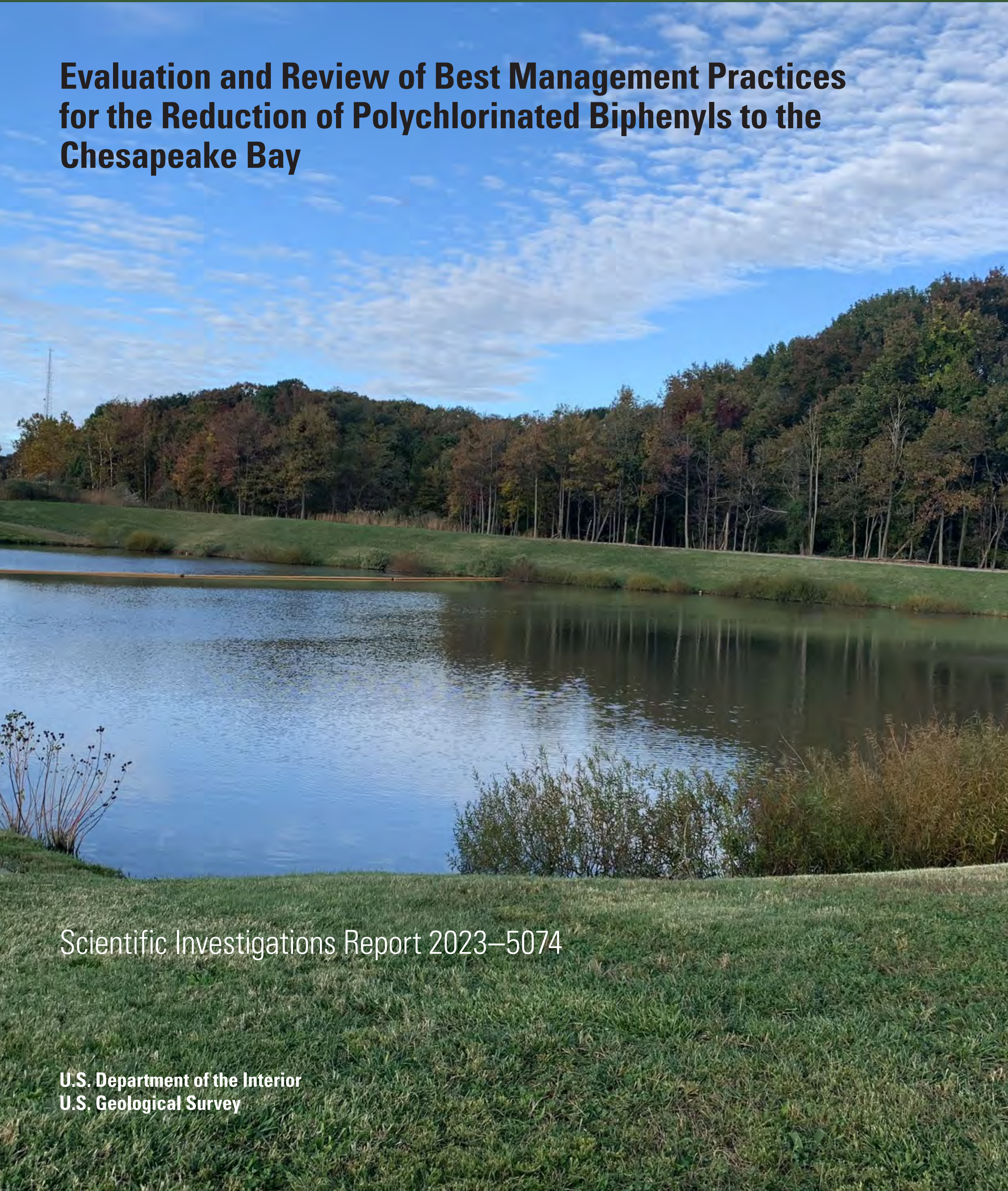
Evaluation and Review of Best Management Practices for the Reduction of Polychlorinated Biphenyls to the Chesapeake Bay



Scientific Investigations Report 2023–5074

U.S. Department of the Interior
U.S. Geological Survey

Cover. Stormwater pond in Baltimore, Maryland. Photograph taken by Caitlyn Dugan, U.S. Geological Survey.

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U.S. Geological Survey, Reston, Virginia: 2024

Suggested citation:
Needham, T.P., Majcher, E., Foss, E., and Devereux, O.H., 2024, Evaluation and review of best management practices for the reduction of polychlorinated biphenyls to the Chesapeake Bay: U.S. Geological Survey Scientific Investigations Report 2023–5074, 18 p., https://doi.org/10.3133/sir20235074.

ISSN 2328-0328 (online)

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Area	
square miles (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
ton, short [2,000 lb]	0.9072	metric ton (t)
ton, long [2,240 lb]	1.016	metric ton (t)

Abbreviations

BMP	best management practices
CAST	Chesapeake Assessment Scenario Tool
CE-QUAL-W2	water quality and hydrodynamic model in 2D
DDT	dichlorodiphenyltrichloroethane
DRBC	Delaware River Basin Commission
EFDC	Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
Hg	mercury
MeHg	methylmercury
mg/kg	milligrams per kilogram
ng/g	nanograms per gram
PAH	polyaromatic hydrocarbon
PCB	polychlorinated biphenyl
ppm	parts per million
QUALs	EPA stream water quality models
RWSM	Regional Watershed Spreadsheet Model
SFEI	San Francisco Estuary Institute
SPARROW	Spatially Referenced Regressions on Watershed
STUMP	Stormwater Treatment unit Model for Micropollutants
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TMDL	total maximum daily load
WATAR	Watershed Approach to Toxic Assessment and Restoration
WWTP	wastewater treatment plant

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By Trevor P. Needham,[1] Emily Majcher,[1] Ellie Foss,[1] and Olivia H. Devereux[2]

Abstract

Polychlorinated biphenyls (PCBs) continue to impact the environment due to historic and ongoing anthropogenic sources (for example, industrial and agricultural), despite their ban. Contaminated stormwater has been identified as a vector for PCB transport to many estuaries impaired by PCBs. Management of these regulated discharges is typically achieved by best management practices (BMPs). This review focuses on PCB reduction practices and BMPs to assist management decision making and provide information on the current state of the science. Studies have quantitatively demonstrated the efficacy of green infrastructure BMPs and gray infrastructure improvements to reduce PCB loads, and other studies have demonstrated qualitative reductions for other BMP types. This review also highlights the disconnect between PCB load reduction and PCB bioavailability when selecting a remediation strategy. Additionally, the review evaluates modeling approaches to assess PCB load reduction to inform management decisions and suggests why there are still significant barriers to implementation.

Introduction

The Chesapeake Bay watershed spans over 64,000 square miles and includes seven different jurisdictions: the District of Columbia, Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia. It is the largest estuary in the United States and the third largest in the world (Chesapeake Bay Program, 2021a). Historic and ongoing anthropogenic sources of contaminants within the watershed have resulted in the impairment of large portions of the waterbody (Chesapeake Bay Program, 2021b). Within the United States, total maximum daily loads (TMDL) have been established to create regulatory limits to meet water quality standards established as part of Clean Water Act Section 303(d) (U.S. Environmental Protection Agency [EPA], 2018a). A Chesapeake Bay-wide TMDL was established in 2010 for nitrogen, phosphorus, and sediment for all waters and jurisdictions within the watershed. Despite the prevalence of toxic contaminants throughout the watershed, no Bay-wide TMDL exists; instead, TMDLs for certain toxic contaminants are implemented by local jurisdictions for sub-watersheds within the Bay through municipal separate storm sewer system (MS4) permits. Toxic contaminants designated by the EPA include a diverse set of compounds that have a toxicological effect on the environment and (or) impact human health. Due to the widespread historical use of toxic contaminants, 88 percent of the tidal Chesapeake Bay watershed is considered impaired or partially impaired under Section 303(d) of the Clean Water Act by the toxic contaminants polychlorinated biphenyls (PCBs), mercury (Hg), and organochlorine pesticides (for example, chlordane and dichlorodiphenyltrichloroethane [DDT]); with PCBs as the dominant cause for impairment (Chesapeake Bay Program, 2021a).

Polychlorinated biphenyls (PCBs) are a group of persistent carcinogenic compounds that bioaccumulate in aquatic and terrestrial ecosystems and are the leading cause of fish consumption advisories in the United States (EPA, 2018a). PCBs were produced commercially in the United States from 1930 to 1977, and globally from 1930 to 1993 with a total estimated production of 1,324,131 metric tons (Breivik and others, 2002). Although PCBs will accumulate in terrestrial ecosystems, the primary exposure pathway that impacts human health is fish consumption. Contaminated stormwater is a vector for PCB transport from terrestrial sources to many impacted watersheds (King and others, 2004; Rossi and others, 2004; Hwang and Foster, 2008; Jartun and others, 2008; David and others, 2014; Schueler and Youngk, 2015; Ivanovsky and others, 2018; Reible and others, 2018; Wu and others, 2019). Transport of PCBs by atmospheric deposition would result in direct transport to an impacted waterbody (Leister and Baker, 1994; Zhang and others, 1999) or deposits on surfaces mobilized by stormwater (Rossi and others, 2004). The impact of contaminated stormwater is magnified in developed urban and residential areas due to the quantities of stormwater runoff from impervious surfaces that mobilize PCB sources within the landscape to receiving waterbodies

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(Rossi and others, 2004; Jartun and others, 2008; Foster and others, 2019; Kaya and others, 2019). Stormwater discharges by municipalities and industries are regulated to meet water quality criteria for PCBs and other pollutants that have an impact on receiving waters (including nutrients, sediment, and bacteria) (EPA, 2022a). Meeting these regulatory goals and limits can require significant reductions in total loads; many discharges are required to reduce total discharged quantities by more than 90 percent. One common approach for managing a regulated stormwater discharge is implementing best management practices (BMP).

A BMP is a specific action (or actions) taken to achieve or aid in the achievement of a management measure (EPA, 2022b). A variety of BMPs exist, ranging from street sweeping to reducing stormwater sediment runoff in bioretention ponds (EPA, 1993, 2022; Chesapeake Bay Program, 2018). For nutrients and sediment load reductions, BMPs have established design removal criteria (or efficiencies), and jurisdictions can receive credit towards reducing a specified load allocation for implementing BMPs for targeted pollutants. Additionally, these removal efficiencies are incorporated into watershed models that inform management decisions to meet water quality criteria. Removal in this context refers to processes that physically remove, sequester, or degrade a target pollutant.

A “co-benefit” can either reduce multiple pollutant loads within a BMP design or provide additional load reduction for a contaminant that was not incorporated into the original design. Little information is available on the co-benefits of PCB removal for many established BMPs in common use. One commonly held assumption is that since PCBs are hydrophobic and often sediment bound in the environment, sediment BMPs should also reduce PCBs bound to the sediment (Schueler and Youngk, 2015), but there are few studies that demonstrate quantifiable efficiencies. Managers need quantifiable data and studies to establish minimum performance targets and estimate efficacy of BMPs.

This review focuses on PCB reduction practices by municipal agencies and provides information on the current state of the science. The purpose of this report is: (1) review and summarize published PCB removal in BMPs; (2) evaluate PCB stormwater modeling efforts and determine the potential to include PCBs; and (3) evaluate lessons learned from monitoring and remediation efforts to improve management decision-making and identify opportunities for integration across programs.

Best Management Practices (BMPs) and Toxic Contaminant Removal

Best management practices (BMPs) are specific actions taken to achieve a management measure which includes removal and prevention of pollutants from entering receiving waters via stormwater (EPA, 1993). Structural BMPs are constructed measures, such as infiltration basins and vegetated filter strips, while nonstructural BMPs are control practices such as pet waste pick-up education, watershed planning, and restoration (EPA, 2018b; Somoza, 2021). Structural BMPs such as grassed swales can reduce the quantity of pollutants that may enter a waterbody, aesthetically improve the landscape, and promote the natural flow of water through the environment (EPA, 2018b).

Numerous studies have been conducted to establish BMP effectiveness values or removal efficiencies for nutrients and sediments (Chesapeake Bay Program, 2018; Washington State Department of Ecology, 2019; North Carolina Department of Environmental Quality, 2020; EPA, 2022b). This approach has widescale adoption and there is interest to expand its use for other contaminants, such as PCBs. The San Francisco Estuary Institute has completed the most comprehensive effort to evaluate BMPs for PCB and mercury (Hg) reduction (San Francisco Estuary Institute, 2010). A literature search identified limited studies that quantify PCB reductions by BMP type (listed in table 1), and these studies primarily provide qualitative results and general guidelines to evaluate the potential efficacy for PCB reductions (Schueler and Youngk, 2015; Wu and others, 2019). A review of the current state of the science by BMP type is summarized and discussed in the following sections.

Stormwater Ponds and Wetlands

Stormwater ponds and wetlands consist of permanent pools or shallow marsh areas to treat urban stormwater. This type of BMP provides stormwater storage during high flow events and can regulate discharge to receiving waterbodies. Physical processes such as sedimentation are typically incorporated into the design for sediment capture. Retention time of stormwater within the BMP is a controlling factor in removal efficiency for suspended sediment. It is assumed that removal efficiencies for sediments are comparable for PCBs due to their hydrophobicity and strong sorption onto sediment; however, studies have found that PCBs within stormwater are associated with different sediment fractions. Yee and McKee (2010) found 31 percent of sediment bound PCBs settled in less than 2 minutes and 53 percent settled within 20 minutes, demonstrating that over half of the PCBs were associated with larger particles in stormwater sediment. Smith (2002) observed higher total organic carbon content in sediment particles greater than 2 millimeters in stormwater sediments captured from highway runoff within oil and grit separator BMPs installed along the Southeast Expressway, Boston, Mass. Elevated levels of PCBs and polyaromatic hydrocarbons (PAHs) in larger diameter sediment was attributed to the higher total organic carbon (TOC) content (Smith, 2002). Smith (2002) also found that oil and grit separators were capable of capturing 20 percent of PCBs in stormwater runoff, but they observed resuspension of the sediment, resulting in increased effluent concentration during high stormflow events. Similar conclusions were drawn from a stormwater

Table 1. Literature review of polychlorinated biphenyl reductions associated with best management practices (BMPs).

[PCB, polychlorinated biphenyl; WWTP, wastewater treatment plant; —, no data; Calif., California; Hg, mercury; PAH, polyaromatic hydrocarbon; TOC, total organic carbon; %, percent; <, less than; min, minute; Tex., Texas; OCDD, octachlorodibenzodioxin ; Cd, cadmium; Pb, lead; Ni, nickel; Zn, zinc; Cu, copper; MethHg, methylmercury; SSC, suspended sediment concentration; Wash., Washington; Va., Virginia; Mass., Massachusetts; Del., Delaware.]

Authors	Location	Types of BMPs	Contaminant types measured	Method of evaluation	PCB reductions	Other reductions
Rossi and others, 2004	Switzerland	Stormwater sewer system and WWTP	PCB	Calculated load	—	—
McKee and others, 2006	San Francisco Bay Area, Calif.	Multiple	PCB and Hg	Qualitative	—	—
Jartun and others, 2008	Bergen, Norway	Stormwater sediment traps	PCB, metals, PAH, and TOC	Sampled and measured	—	—
Mangarella and others, 2010,	San Francisco Bay Area, Calif.	Multiple	PCB and Hg	Qualitative	—	—
SFEI, 2010	San Francisco Bay Area, Calif.	Multiple	PCB and Hg	Qualitative	—	—
Yee and McKee 2010	San Francisco Bay Area, Calif.	Stormwater sediment capture	PCB and Hg	Load reduction	PCB (31–53% reduction) based on <2 min and <20 min settling time	Hg (7–12% average)
Howell and others 2011	Houston, Tex.	Wet and dry in-stream flows	PCB	Calculated load	—	—
David and others, 2014	Daly City, Calif.	Bioretention: rain garden and bioswale	Sediments, PCBs, nutrients, pathogens, and select trace metals	Load reduction	82% reduction of PCB in loading rate	PAHs (97%), OCDD (97%), Cd (96%), Pb (87%), Ni (79%), Zn (98%), Cu (96%), dissolved Hg (64%), total Hg (59%), MethHg (−56%), and SSC (84%)
Schueler and Youngk, 2015	United States	Retention ponds, bioretention cells, stormwater BMP retrofits, stormwater wetlands or diversions	PCB, Pesticides, Hg, and PAH	Qualitative	—	—
Wu and others, 2018	Lower Guadalupe River Watershed, Calif.	Bioretention, infiltration trench, and permeable pavement	PCBs	Modeled load reductions	30–70% modeled reduction	—
Reible and others, 2018	Naval Base San Diego, Calif., and Puget Sound Naval Station, Wash.	Stormwater sediment capture	PCBs, PAHs, and metals	Sampled and measured	—	—

Table 1. Literature review of polychlorinated biphenyl reductions associated with best management practices (BMPs).—Continued

[WWTP, wastewater treatment plant; Calif., California; —, no data; PCB, polychlorinated biphenyl; Hg, mercury; PAH, polyaromatic hydrocarbon; TOC, total organic carbon; %, percent; <, less than; min, minute; Tex., Texas; OCDD, octachlorodibenzodioxin ; Cd, cadmium; Pb, lead; Ni, nickel; Zn, zinc; Cu, copper; MethHg, methylmercury; SSC, suspended sediment concentration; Wash., Washington; Va., Virginia; Mass., Massachusetts; Del., Delaware.]

Authors	Location	Types of BMPs	Contaminant types measured	Method of evaluation	PCB reductions	Other reductions
Ivanovsky and others 2018	Heron Lake, France	Stormwater ponds	PCB, metals, PAH, and nutrients	Sampled and measured	—	—
Jing and others, 2019	Washington D.C.	WWTP bioremediation	PCBs	Sampled and measured	—	—
Gilbreath and others, 2019	El Cerrito, Calif.	Bioretention rain garden	PCBs, Hg, MethHg, Cu, and microplastics	Load reduction	96% PCB	Suspended sediment (94%), Hg (37%), MethHg (49%), CopperCu (68%), and microplastics (91%)
Payne and others, 2019	Quantico, Va.	Wetpond bioremediation	PCB	Reduction	52% PCB bulk sediment and 95% PCB porewater	—
King County Department of Natural Resources and Parks, 2020	King County, Wash.	Bioretention	PCB	Load reduction	90% capture in bioretention soils	—
Smith, 2002	Boston, Mass.	Deep-sump hooded catch basin, Oil-grit separator	PCB, Sediment, TSS, PAH, Metals, TOC, oil and grease, nitrogen, and phosphorus	Load reduction	20% PCB	—
Patmont and others, 2020	Dover, Del.	Wetland restoration	PCB and PAH	Reduction	60% PCB porewater and 80% surface water	—
Flanagan and others 2021	Sweden	Stormwater ponds	259 organic substances	Qualitative	—	—

pond system consisting of five smaller ponds connected to a larger stormwater BMP (Heron Lake, France) (Ivanovsky and others, 2018); the BMP treated both stormwater and raw sewage discharged from combined sewer overflows and broken infrastructure. Suspended sediment PCB concentrations in the channel entrance were at 3,807 nanograms per gram (ng/g) and were reduced to 114 ng/g (±84 percent) by sedimentation within the central portion of Heron Lake. Similar capture efficiencies were observed for other sediment-bound contaminants including metals, heavy PAHs, and phosphorus. The study identified the need to carefully dredge areas to avoid dispersion of pollutants, and also highlighted the potential for releasing captured PCBs during BMP maintenance.

The presence of PCBs within the drainage area of stormwater ponds and wetlands impacts the PCB removal efficacy of these BMPs. Urban inputs to stormwater vary widely and will be discussed in the source removal section. A comparison conducted by Bishop and others (2000) between PAHs, PCBs, and other analytes in stormwater ponds found PAHs were strongly correlated with organic carbon and detected in 14 out of 15 stormwater ponds sampled. Similar correlations to organic carbon were not identified with PCBs. The results of this study suggested that within the urban landscape of Toronto, Ontario (Canada), PAHs are widespread and ubiquitous to the environment. Sources of PCB, however, were episodic and not associated with an annual sediment deposition rate. In the study conducted by Parker and others (2000), PCBs and other persistent organic contaminants were detected throughout various stormwater ponds across Maricopa County, Ariz. with notable levels 200 times above the median concentration in one residential sediment sample with no clear source to the stormwater pond. Additionally, PCBs had one of the highest detection frequencies (75 percent) of the 259 organic substances sampled in 2021 in urban stormwater pond sediment across Sweden (Flanagan and others, 2021). Concentrations of PCBs in the sediments measured by Flanagan and others (2021) varied by more than two orders of magnitude, consistent with previous studies (Parker and others, 2000; Bishop and others, 2000). Due to site-specific variability in delivery of PCBs to BMPs in similar landscapes, removal efficiencies are difficult to assign without sampling individual stormwater ponds and stormwater wetlands to determine if PCBs are being captured. This makes developing a PCB removal efficiency for stormwater ponds and wetlands for use in modeling difficult compared with a more widespread pollutants such as PAHs (DiBlasi and others, 2009; Van Metre and Mahler, 2010).

Stormwater and Municipal Wastewater Sewer Systems Associated BMPs

Stormwater and municipal sewer systems are known conduits for PCBs and other legacy contaminants (Pham and Proulx, 1997; Katsoyiannis and Samara, 2005; Hwang and Foster, 2008; Rodenburg and others, 2010; Balasubramani, Howell, and Rifai, 2014; Needham and Ghosh, 2019). PCBs within the sewer system enter the watershed either through direct discharge in combined sewer outfalls (CSO) and stormwater discharge points, or in treated effluent from a wastewater treatment plant (WWTP). The fate and transport of PCBs within sewer systems can result in significant loads to WWTPs. Needham and Ghosh (2019) measured PCB load (grams per day) in the wastewater influent for a large urban WWTP (Baltimore, Md.) in 2015 at 170 (±16 S.E.) grams of total PCBs per day, which is comparable with major tributaries within the Chesapeake Bay watershed such as the Susquehanna River (208 grams per day) (Ko and Baker, 2004). Rossi and others (2004) found that a significant portion of the PCB load that accumulated in WWTP sludge in Switzerland was the result of urban stormwater and attributed the PCB sources primarily to atmospheric deposition. Their study, however, does not take into consideration PCBs found in building materials within the urban landscape that could wash off during rain events. This source of PCBs will be discussed further in the subsequent source removal section. The connection between urban stormwater fingerprint and WWTP sludge highlights the connection between urban sources and sewer collection systems. Howell and others (2011) observed similar PCB congener profiles and others in urban stormwater in Houston, Tex. that were attributed to building sealants. Increasing the removal efficiency of WWTP to reduce PCB loads discharged in effluent is difficult. Modern WWTP are, however, highly efficient at removing solids which results in PCB removal in generated biosolids (Needham and Ghosh, 2019; Katsoyiannis and Samara, 2004).

An effective strategy of source tracking within municipal sewer systems has been employed by multiple municipalities. Reductions are achieved by locating areas with higher concentrations or loads within gray infrastructure and then conducting maintenance or replacement of the infrastructure. This targeted strategy can be effective in reducing legacy transport of PCBs via sediments in contaminated stormwater and via leaching from fats, oil, and grease deposits in the municipal sewer system (Majcher and others, 2022). The City of Camden, N.J. conducted a pilot scale track-down study to identify sources of PCBs entering the municipal wastewater collection system (Belton and others, 2008). The study found 77 percent of the daily load (31 g/day of PCBs) originated from one branch of the collection system. Phase 2 of this study found PCB contaminated road material entering the stormwater sewer and combined sewer outfall. Similar approaches have been applied to Philadelphia, Pa. (Delaware River Basin Commission, 1998, Rodenburg and others, 2010), Wilmington, Del. (New Castle County, 2014), Middle River, Md. (Lockheed Martin Corporation, 2017), and Baltimore, Md. (Majcher and others, 2022).

Source Removal

While many sites are listed on the National Priorities List (Superfund) for PCB contamination, these sites are a mere fraction of the potential sources to an impaired watershed. Common building materials such as caulks, paints, and coolant oils produced prior to 1979 may contain PCBs and can still be found in many urban landscapes (Kohler and others, 2005; Pokorny and Webster, 2011; U.S. Army Corps of Engineers, 2012; Klosterhaus and others, 2014). PCBs are released through weathering, renovation, or demolition of the structures containing these materials. BMPs designed to address releases during renovation and demolition of PCB-containing buildings were evaluated by Larry Walker Associates (2005) to develop a remediation plan for the San Francisco Estuary Partnership. Proper disposal and containment of these materials are key to reducing conveyance to stormwater. It is difficult to estimate the potential quantity of PCBs that could be removed from the landscape; however, the mass of PCBs in window caulk was estimated between 0.6 and 16 kilograms (kg) per building within the San Francisco Bay Area (Klosterhaus and others, 2014). A study of Houston Harbor, Tex. found similar results identifying building sealants containing Aroclor 1254 and Aroclor 1260, and PCB 11 (a byproduct of yellow pigments often found in road paint) contributing to a large portion of the PCB stormwater load (Howell and others, 2011). The Geological Survey of Norway conducted a study of PCBs in paint on buildings in Bergen, Norway and found PCB concentrations ranging between less than 0.001 and 3,390 milligrams per kilogram (mg/kg) (n=68) for PCB congeners 28, 52, 101, 118, 138, 153, and 180 (Jartun and others, 2009). Their study found correlations between localized elevated levels or “hotspots” within harbor sediments, elevated stormwater concentrations, and building paint concentrations.

Removal of PCB-containing materials can be an effective strategy for PCB load reduction. The widespread use of these materials in many older urban landscapes creates the appearance of a general elevated background level but has specific sources that can be targeted (like caulks and paint). The San Francisco Estuary Institute assessed reducing PCB loads from sources to be one of the most effective means of reducing PCB conveyance in stormwater (San Francisco Estuary Institute, 2010). The EPA recently published guidance on determining and addressing PCB materials in schools and building materials (EPA, 2021a). Source identification and track-down has also been recommended by U.S. Naval Facilities Command (Battelle Memorial Institute, 2012) and the Maryland Department of the Environment (2022). Desktop evaluations by municipalities to identify buildings and areas where these materials may exist can assist in focusing reduction efforts. These exercises can also inform areas where other BMP efforts would have the greatest effect in reducing PCB loads. It is important to note that without removing the source material, stormwater BMPs will continue to receive mobilized PCBs.

Green Infrastructure

Green infrastructure (GI) is defined as, “the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspire stormwater and reduce flows to sewer systems or to surface waters” (EPA, 2020). This type of infrastructure has been studied as a BMP for PCBs and other urban contaminants (David and others, 2014; Schueler and Youngk, 2015; Wu and others, 2018; Gilbreath and others, 2019). PCB reduction by GI is primarily through contaminated sediment capture in stormwater or sorption to natural media. Bioretention is a land-based GI BMP that is installed to improve stormwater quality through natural or enhanced biological processes. Bioretention BMPs consist of a basin or depression that contains a porous soil material capable of sustaining vegetation growth and a mulch layer to promote microbial community growth in order to facilitate nutrient (or contaminant) transformation and increase water holding capacity. Promotion of processes such as evapotranspiration, absorption, adsorption, volatilization, degradation, and decomposition are included in the BMP design.

Although primarily focused on suspended sediment and nutrient capture, bioretention BMPs have been shown to be effective in reducing PCBs and other co-contaminants. David and others (2014) observed reductions in PCBs (82 percent) and multiple other toxic contaminants through installation of bioretention systems; however, the system increased the load associated with methylmercury (MeHg) possibly due to microbial activity in the bioretention system. Total and dissolved Hg both decreased as a result of the bioretention system. In a later study also performed in the San Francisco Bay Area, Gilbreath and others (2019) observed PCB reductions up to 96 percent and MeHg reductions up to 49 percent. The high PCB reductions observed by Gilbreath and others (2019) fit the conceptual model that BMPs that reduce stormwater sediment (94 percent reduction) will also reduce sediment-associated PCBs when present. A study in King County, Wa. in the Lower Duwamish watershed measured an average 90 percent reduction of PCBs in stormwater by bioretention soils with no significant accumulation of PCB mass over the 25-month study period (King County Department of Natural Resources and Parks, 2020). Their study found that the soil was the primary removal mechanism and that vegetation did not significantly improve capture efficiency. Cost and PCB capture efficiency were evaluated by Wu and others (2019) for three GI BMPs consisting of bioretention, an infiltration trench, and permeable pavement using watershed models and by applying an optimization approach for the Lower Guadalupe River, Calif. The study found that bioretention implementation throughout the watershed provided the most cost-effective GI BMP to achieve target PCB reductions (Wu and others, 2019). Study results suggest that strategic placement of GI BMPs in areas identified to contain PCB materials could increase the efficacy and co-benefits of BMPs.

BMP Selection Summary

Limited studies are available to estimate BMP PCB reductions (removal efficiency). Source removal and gray infrastructure improvement has been demonstrated to be effective at reducing loads where sources are present (Belton and others, 2008; Majcher and others, 2022). Sediment BMPs such as stormwater ponds and bioretention systems are effective at capturing PCB-contaminated sediments but only if located in an area with elevated PCB concentrations in stormwater sediment (Smith, 2002; Jartun and others, 2008; Yee and McKee, 2010). When selecting BMPs for the co-benefit of PCB reduction previous studies suggest considering designs that incorporate increased residence time to promote sedimentation and have low risk of resuspension of contaminated sediment captured within the BMP.

Modeling PCB Reduction

Computational models provide a predictive tool for determining estimated pollutant concentrations. Models are a useful management tool for identifying where to target corrective actions and how best to address a defined location given the mix of land use and other factors influencing a particular pollutant's load. Burigato Costa and others (2019) identifies the seven models most applied for water quality parameters worldwide:

- AQUATOX (Park and Clough, 2014),
- water quality and hydrodynamic model in 2D (CE-QUAL-W2; Cole and Buchak, 1995),
- the Environmental Fluid Dynamics Code (EFDC; Tetra Tech, Inc., 2007),
- EPA stream water quality models (QUALs; Brown and Barnwell, 1987),
- The Soil and Water Assessment Tool (SWAT; Neitsch and others, 2001),
- the Spatially Referenced Regressions on Watershed attributes (SPARROW; Schwarz and others, 2006), and
- the Water Quality Analysis Simulation Program (WASP; DiToro and others, 2004).

Of these common models only SPARROW (Schwarz and others, 2006) and SWAT (Neitsch and others, 2001) assess watershed scale pollution transport and management decisions. Neither SPARROW nor SWAT have been applied to PCBs or similar toxic contaminants as the target pollutant. There are multiple approaches for modeling toxic contaminant reductions within watersheds; however, few incorporate PCBs. Subsequent sections will discuss multiple modeling approaches that have been implemented for toxic contaminants and assess the current feasibility of incorporating PCBs into a watershed scale management tool.

Existing PCB Models and Limitations

The San Francisco Estuary Institute developed the Regional Watershed Spreadsheet Model (RWSM) for sediment, PCBs, and Hg (San Francisco Estuary Institute, 2010). This approach was successful in modeling the hydrology of the watershed but was unable to fully incorporate PCBs and Hg. Wu and others (2017) concluded that regional loads of PCBs and Hg calculated by the model generally followed expected concentrations based on land use. This would be expected since the model relies on empirical measurements that would represent a regional load. The model could not account for localized source areas and could not be used to evaluate BMPs due to a lack of data, resulting in the San Francisco Estuary Institute shifting away from the RWSM for PCBs and Hg (Wu and others, 2018).

Similar to the RWSM approach, the VELMA 2.0 model (EPA, 2021b) was successfully implemented to assess multiple stressors and toxic contaminants impacting the Puget Sound by modeling the contaminant fate and transport (McKane and others, 2020). Toxic contaminants assessed included PCBs, PAHs, per- and polyfluoroalkyl substances (PFAS), heavy metals, and 6PPD-quinone (a unique rubber compound found in vehicle tires that is highly toxic to coho salmon) (McKane and others, 2021; Tian and others, 2021). This model was successful in evaluating the impacts of BMPs within a watershed through stormwater reduction for more ubiquitous compounds like 6PPD-quinone that is released by tire wear on roads. Additional studies are needed to determine efficacy in modeling non-ubiquitous compounds like PCBs.

Computational models developed for particulate solids and sediment have been implemented for PCBs by using particulates in stormwater as a proxy for PCBs. WinSLAMM is a hydrologic model for particulate solids that does not directly model toxic contaminants (PV & Associates, LLC, 2019). Brown and others (2019) integrated a statistical model into WinSLAMM to determine the relationship between 82 trace organic compounds and rainfall. Results of the study indicated that when modeling trace organic contaminants in this way, the amount delivered to the watershed outlet was limited only by rainfall amount, not the amount of contaminants available from the source land use. Suspended sediment delivery factors developed for the site-specific Stormwater Treatment unit Model for Micropollutants (STUMP) could be adapted to a watershed model like WinSLAMM to better account for suspension and resuspension (Vezzaro and others, 2011). Models developed for sediments such as the Chesapeake Assessment and Scenario Tool (CAST), SPARROW, and SWAT could be implemented with similar assumptions and limitations.

Within the San Francisco Bay watershed, the EPA Storm Water Management Model (SWMM) was combined with an algorithm to introduce variations to find a suite of near-optimal, low-cost combinations of BMPs for reducing PCBs (Wu and others, 2019). This approach incorporated cost as a parameter so that the recommended BMP combination was the least expensive. The findings indicated an asymptote around 70 percent for the maximum area of land treated by BMPs. This approach is useful but limited by the data for PCB removal efficiency of BMPs (table 1).

Computational models apply a homogeneous distribution of PCBs in stormwater, which is inconsistent with the current understanding of PCB distribution and releases to impacted watersheds as discussed in the previous section. This approach could be improved by incorporating additional factors such as a PCB base load per year of development and PCB loading rate differential per land use. As adequate data to develop PCB loads do not currently exist within many impacted watersheds, a significant sampling effort and model validation would be required.

Options and Limitations for Incorporation of PCBs into CAST

The Chesapeake Bay Program CAST model is a calibrated model using an average of a 10-year hydrological period to estimate nitrogen, phosphorus, and sediment loads delivered to the edge of streams and Chesapeake Bay tidal waters (Chesapeake Bay Program, 2020). This model facilitates development of watershed implementation plans for each of the seven jurisdictions that drain to the Bay and assesses progress toward the planning goals for annual reporting of implemented and inspected BMPs. It is used by multiple local jurisdictions and states to draft watershed implementation plans, milestones, and TMDLs. Planning scenarios can be developed for multiple geographic scales including 12-digit hydrologic unit codes, county, and larger. There is general acceptance and use of CAST within Chesapeake Bay jurisdictions as it is required to be used for annual reporting, assessment of progress, and development of watershed implementation plans resulting from the 2010 Chesapeake Bay TMDL (EPA, 2023).

Currently, CAST solely models nitrogen, phosphorus, and sediment loads (pounds per average hydrological year). One way to target corrective actions (for example, BMPs) to reduce or eliminate PCBs is to introduce PCBs as another modeled pollutant in CAST. A project is currently underway to add multiple co-benefits for other constituents to existing models, including soil carbon storage load reductions. However, BMPs that target PCBs are not under current consideration because the necessary data are not available.

An option for estimating PCB reductions in CAST is to associate the PCB mass with suspended sediment mass. While this method has been evaluated, the associations are not consistent as it assumes that PCB releases are consistent and uniform within a defined area. Alternatively, developing an expected PCB concentration in stormwater based on the age of urban development and land-use type is possible. The age of urban development is estimated by the U.S. Geological Survey Land Data Team that partner with the Chesapeake Bay Program. This annual land use is incorporated with data from the U.S. Department of Agriculture's National Agricultural Statistical Service and state-provided land-use data. By examining the change in developed acres from year to year, the time period when new development began can be determined. This could provide important information for making estimates of likely background levels of PCBs from era materials and is consistent with the methodology Brown and others (2019) used when modeling trace organic contaminants with Win-SLAMM. In this study, the mean annual load variation was determined for commercial and residential areas in Madison, Wis. To use this approach in large watersheds such as the Chesapeake Bay watershed would require the PCB base load per year of development and PCB loading rate differential per land use.

This approach, while possible, has significant obstacles. The delivery factors needed for this type of model exist for nitrogen, phosphorus, and suspended sediment. While not optimal, the suspended sediment delivery factor could be used and is supported by findings from Vezzaro and others (2011). It would only account for suspension and resuspension, but it would not incorporate sorption and desorption which play a major role in PCB transport and bioavailability. Adequate data to develop PCB loads do not currently exist in the Chesapeake Bay and would require a significant sampling effort. The associated cost and time may be better allocated to track-back studies as discussed previously.

The lack of PCB data is less problematic for modeling than the fact that PCBs are not always mobilized by rainstorms of different sizes, and previous studies have shown irregular releases of PCBs to stormwater (Bishop and others, 2000; Parker and others, 2000; Flanagan and others, 2021). The entire basis of CAST is the hydrological model of the amount of flow, which is modeled as storage and release of water in different segments. Adding in a pollutant that is not reliably mobilized by water, but rather by construction/demolition and other types of events would require a model design other than a hydrological model.

Lessons Learned and Opportunities for Integrating Efforts to Reduce PCBs

This section discusses PCB remediation efforts to highlight lessons learned and provide insight into ways to improve future efforts to reduce PCB loads to impacted watersheds. This includes successful PCB load reductions through gray infrastructure improvement, the disconnect between efforts to remediate PCB contaminated sites and contaminated stormwater, and the importance of incorporating bioavailability in PCB management.

Gray Infrastructure Improvement Co-Benefits to PCB Load Reduction

The contribution and potential sources of PCBs associated with WWTP effluents and gray infrastructure contribute to the fate and transport of PCBs to receiving waterbodies (Pham and Proulx, 1997; Rossi and others, 2004; Katsoyiannis; Zouboulis and others, 2006; Guo and others, 2009; Capozzi and others, 2019; Needham and Ghosh, 2019). Successful reductions in PCB loads to WWTPs have been demonstrated through targeted improvements to municipal sewer collection systems. For example, load reductions were observed by Majcher and others (2022) in the Back River, Md. WWTP between 2015 and 2019. Concentration of PCBs in both influent and effluent were reduced by 40 and 70 percent following enhanced nutrient removal (ENR) upgrades and capital improvements to the sewer system (Baltimore City Department of Public Works, 2021). The results indicate that management actions both in the service area to the WWTP and within the plant itself may have reduced PCBs. Targeted cleanouts of stormwater outfalls in Middle River, Md. decreased the PCB concentration in sediment mobilized in the stormwater system from 910 milligrams per kilogram to 0.41 milligrams per kilogram (Lockheed Martin Corporation, 2017). The City of Camden, N.J. successfully conducted a source identification study to identify localized "hotspots" (Belton and others, 2008), and the results found 77 percent of the total load to be localized to one section of the system which could be targeted for improvements. Similar efforts were conducted by Majcher and others (2022) within Baltimore City by deploying equilibrium based passive samplers within the main pump stations of the collection system. The PCB concentration and total mass was dominated by a single pump station within the boundaries of Baltimore City, Md.

Gray-infrastructure improvement and targeted maintenance of areas with high concentrations can reduce PCB loads to a receiving waterbody as a co-benefit. An advantage of this approach for municipalities is that gray infrastructure improvement and maintenance may already be incorporated into their normal operations. Track down studies and an assessment of PCBs entering the receiving sewer infrastructure would be necessary to incorporate this approach into a PCB remediation plan.

Disconnect between Contaminated Sites and Stormwater

Remediation goals for PCB-contaminated soils are different than PCB sediment remediation endpoints. Contaminated sites that contain PCBs can contribute to surface water contamination through stormwater (BrightFields, Inc., 2009, 2015) Regulatory limits under the Toxic Substances Control Act for new PCB spills in soil only requires remedial actions to be taken for concentrations of 50 mg/kg (ppm) total PCB concentration by dry weight or greater and is required to be cleaned to 25 mg/kg (ppm) (40 CFR §761.125). By comparison, the TMDL target criteria for sediments is typically less than 0.5 mg/kg (ppm) total PCB dry weight (EPA, 2011; Maryland Department of the Environment, 2011). Comparing the two different remediation target concentrations, soils mobilized in a rain event from a cleaned PCB spill site could be two orders of magnitude higher than the sediment target criteria of the TMDL.

Stormwater mobilized PCB-contaminated sediments have the potential to contaminate previously remediated sites. Reible and others (2018) captured and measured sediment deposited by stormwater systems in two urban watersheds located in the San Diego Bay, Calif. and Puget Sound, Wash. The study found that PCBs were primarily associated with finer grain particles and deposited in a larger area than PAHs, which are primarily associated with larger particles (greater than 20 micrometers) that deposited close to the outfall. Additionally, their study found that Naval Base San Diego contributes only 13.5 percent of the stormwater input to the watershed but contributed 40 percent of the PCB load.

The Delaware River Basin Commission (DRBC) has taken a more source-oriented approach to managing PCBs in stormwater (Suk and Fikslin, 2006; Yagecic, 2005). The Delaware River has a watershed-wide PCB TMDL. To enable source tracking across multiple jurisdictions and states, the DRBC requires all PCB analysis to be EPA Method 1668A and data is compiled in a central database (DRBC, 2005). Using this database, PCB fingerprints and statistical correlations have been developed to identify and allocate loads associated with different sources (Du and Rodenburg, 2007; Du, Belton, and Rodenburg, 2008; Rodenburg and others, 2010; Praipipat, Rodenburg, and Cavallo, 2013). This approach and the statistical modeling developed for the Delaware River could be applied to other watersheds but requires a more expensive PCB congener analysis and a common repository of data. The Watershed Approach to Toxic Assessment and Restoration (WATAR) program implemented by the state of Delaware is an example of a watershed-scale approach that manages all inputs into the watershed under one program (Department of Natural Resources and Environmental Control, 2018). The program avoids management silos and provides a more complete understanding of the factors impacting a watershed, allowing for targeted allocation of resources and source tracking.

Total Mass Reduction Versus Bioavailability

A primary goal in reducing the mass of PCBs from a watershed is to reduce the biological uptake of PCBs in aquatic food webs of the receiving waterbody that results in concentrations with the potential to cause adverse human health effects through consumption of PCB-contaminated fish tissue. With hydrophobic contaminants such as PCBs, the bioavailability (the fraction that can be incorporated into an organism) is driven by the freely dissolved concentration in the aqueous phase (Arnot and Gobas, 2006). Benthic organisms that live in sediments will be affected by the porewater freely dissolved concentration, and fish at higher trophic levels will be affected by concentrations within the water column and their food sources and will reach equilibrium with the freely dissolved concentration (Arnot and Gobas, 2006, Fadaei and others, 2015). This bioavailable fraction may differ from the total mass present in the sediment and water column depending on the matrix composition. Organic carbon content and other geochemical properties of sediments affect the partitioning between the solid particles and the bioavailable freely dissolved phase (Fadaei and others, 2015). Remediation practices that focus on the reduction in total mass of PCBs (such as dredging) do not necessarily constitute a reduction in bioavailability within a given watershed. For example, extensive dredging of the Hudson River, N.Y. from 2009 to 2015 cost $1.7 billion and removed an estimated 2.65 million cubic yards of contaminated sediment (EPA, 2017). Yet fish tissue concentrations of PCBs in the Hudson River have not decreased substantially (Field, Kern, and Rosman, 2016) despite this significant PCB mass removal from the sediment, resulting in ongoing risk to human health (Kvasnicka and others, 2019). Caution should be exercised in assessing co-benefits of BMPs to capture sediment-bound PCBs without considering the bioavailable fraction of PCBs that are affecting bioaccumulation in fish.

Investigation methods and remediation efforts with a focus on the reduction of PCB bioavailability have been developed and successfully implemented. As part of the Anacostia River Sediment Project, one of several Superfund sediment mega-sites with oversight from federal regulators, a two-year monitoring program (2016–2018) was conducted to support the Remedial Investigation and Feasibility Study for PCBs in tributaries to the Anacostia River (Ghosh and others, 2020). The study focused on measuring and quantifying loads associated with water column, sediment porewater, and air deposition of the main branch and tributaries of the river. Equilibrium concentrations for PCBs in mussels and fish were calculated based on measured water column concentrations and measured accumulation of PCBs in caged mussels co-deployed with passive samplers. Results of the study indicated that although 75 percent of the total PCB load entering the Anacostia River was associated with storm events, the concentration of PCBs in stormwater sediment were lower than the concentrations in bed sediments within the main channel of the river. Targeting PCBs in stormwater sediment would result in the largest reduction of PCBs; however, this would not reduce bioaccumulation by fish. The results of this investigation highlight an important distinction in addressing PCB loads to a watershed, namely that the concentration and bioavailability of PCBs entering a waterbody is as important as total mass in efforts to improve water quality.

Human health risk from consumption of fish is the primary driver for developing TMDLs for PCBs. The freely dissolved concentrations in the water column and porewater typically incorporated into a bioaccumulation factor provide the basis for PCB bioaccumulation models, including those used to set the mandated reductions in TMDLs (Arnot and Gobas, 2006; Gobas and Arnot, 2010; Fadaei and others, 2015). The freely dissolved concentration of hydrophobic contaminants like PCBs are primarily driven by partitioning between solid and aqueous phases. Targeting PCB loads by mass alone may meet load reduction goals but fails to meet subsequent reductions in fish tissue concentrations. Additional study is needed to assess the benefits of BMPs to reduce both the mass and bioavailability of PCBs such as in situ remediation approaches.

In situ remediation technologies such as reactive capping reduce the bioavailability of hydrophobic contaminants (like PCBs and organochlorine pesticides) (Ghosh and others, 2011). Black carbon in the form of biochar or activated carbon is a powerful sorbent for PCBs and has been adopted for use in EPA Superfund Remediation Sites (EPA, 2013). This technology was successfully implemented in a 5-acre lake contaminated with PCBs in Dover, Del. (Patmont and others, 2020). Sediment was treated with 4.3 percent activated carbon, and additional ecological restoration was conducted, consisting of removal of invasive plant species and installation of an intertidal wetland. The restoration resulted in 60–80 percent reduction in surface water and sediment porewater PCB concentrations with 50 percent reduction in tissues of non-migratory fish species from the lake. These reductions were accomplished without a reduction in the total mass of PCBs present in the sediment. Biochar and activated carbon can also be incorporated as amendments to existing stormwater BMP technologies for PCB reduction (Imhoff, Culver, and Chiu, 2019; Kjellerup, 2019; Tian and others, 2019). These types of amendments may also improve capture and reduction of hydrophilic contaminants (like pesticides and perfluoroalkyl substances) also found in urban stormwater (Spahr and others, 2020).

The use of in situ remediation technology provides additional benefits for BMP practitioners. Physical removal and disposal of contaminated sediments from a BMP can increase liability and disposal expenses for the responsible management agencies. Recent studies on long-term efficacy of activated carbon found these treatments continue to remain effective 6–10 years after application in a river and tidal wetland (Bridges and others, 2020). To further enhance efficacy and reduce total PCB concentrations in sediment, microbial bioremediation has also been evaluated with carbon material amendments. The combination of PCB-degrading bacteria with a strong sorptive material reduces both the bioavailable fraction of PCBs as well as the bulk concentration in sediments. Payne and others (2019) conducted a pilot test of bio-amended activated carbon in a contaminated wet pond in Quantico, Va. Treatment consisted of a surface application of an activated carbon pellet (Sedimite, Sediment Solutions, Ellicott City, Md.) coated with PCB-degrading bacteria. Total

PCB concentration in the sediment was reduced by 52 percent, and the porewater concentration was reduced by 95 percent in 409 days after application (Payne and others, 2019). As bioremediation with activated carbon continues to develop, this may provide a cost-effective way to target both the bioavailability and mass of PCBs in sediments captured by BMP structures such as retention ponds.

Future Application

This report identifies three approaches to reduce PCBs to impacted watersheds to assist responsible jurisdictions and agencies in selecting a remediation strategy. First, gray infrastructure improvement can reduce legacy PCB deposits within urban landscapes and can be incorporated into operation and maintenance activities. Second, communication between responsible parties can identify unknown source areas through better integration of watershed and landscape sources. Third, remediation efforts that solely focus on reducing the load, or total mass, of PCBs to a watershed may not effectively reduce human exposure if the bioavailability of PCBs within the watershed is not addressed. This report focuses on published studies with quantifiable PCB reduction and acknowledges that additional approaches may be selected that are not discussed.

Summary

Polychlorinated biphenyl (PCB) contaminated stormwater continues to contribute to the impairment of watersheds with potential adverse effects to human health. Established best management practices (BMPs) for nutrients and sediments may have co-benefits for PCB reduction when PCBs are present in the associated drainage area of the BMP. Few quantifiable studies exist demonstrating PCB removal and capture efficiencies to inform managers on PCB load reductions. Older urban landscapes likely contain large deposits of PCB materials that contribute to elevated stormwater loads. Source identification and removal has been demonstrated to be an effective method to reduce PCB loads but requires a well-developed conceptual model of PCB transport. Assessing bioavailability and transport of PCBs within a waterbody is an important consideration when developing a PCB reduction strategy.

Modeling PCB fate and transport at a watershed-scale is difficult. For a watershed-scale annual model, as opposed to a site-specific or storm event driven model, CAST, VELMA, or SLAMM could be used. All these models require additional information or modifications to estimate PCB loads. A simplified model that assumes uniform distribution of PCBs in stormwater sediment could be developed; however, PCB delivery is episodic and not driven by storm events or baseflow. A hydrologic model will not predict pollutants that are not reliably mobilized by water. Developing a unique model or demonstrating a connection between land use and PCB discharge in stormwater would require extensive sampling and model validation. Using track-down studies is more likely to result in accurate source identification and opportunities for management to target current unknown sources of PCBs within a watershed.

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Publishing support provided by the Baltimore Publishing
Service Center.

Needham and others—**Best Management Practices for the Reduction of Polychlorinated Biphenyls**—SIR 2023–5074

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20235074