Pollution Minimization Plan Technical Resource Guide

Developed for the

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by

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Source Identification and PCB Contribution

PCBs

Polychlorinated biphenyls, or PCBs, are industrial chemicals that do not occur naturally in the environment. PCBs were previously used in transformers, motor oils, electrical equipment, cable insulation, plastics, adhesives, caulking, oil-based paint, carbonless copy paper, and other products. In 1979, the US banned the manufacture of PCBs (US EPA Basic Information). PCBs previously entered the environment during their manufacture in the US, and they continue to be released today from poorly maintained hazardous waste sites, leaking transformers, illegal or improper dumping of PCB wastes, and burning of wastes in municipal or industrial incinerators. In addition, over 200 different manufacturing processes, such as paint production, can inadvertently produce PCBs (Washington State 2014). PCB concentrations of 50 parts per million and under are allowed during these manufacturing processes under EPA regulation (Washington State 2014). After PCBs enter the environment, they do not readily break down and cycle among air, water, soil, plants, and animals (US EPA Basic Information). PCBs are comprised of up to 209 chlorinated biphenyls, each with different chemical and physical characteristics. The type of congeners present influences the PCB's biodegradability, thus affecting how the PCB reacts in the environment and to remedial methods. For example, high-chlorinated biphenyls are less volatile and less water-soluble than low-chlorinated ones (US EPA 2013).

Because PCBs accumulate in animal fats, they can bioaccumulate up the food chain. PCBs have the ability to bind with sediments, and microorganisms that live in sediment can consume the contaminant. Predators at the top of the food chain, especially fish-eating birds, have the highest levels of PCBs in their tissues, often many times higher than those found in their environment. In wildlife, PCBs can cause developmental impairments, reproductive failures, and mortality, leading to population declines (US EPA Basic Information).

Contaminated fish consumption poses the greatest risk to humans from exposure to PCBs. Other exposure pathways occur in contaminated air and sediments. In humans, PCBs can cause cancer, alter hormone levels, alter the condition of the liver, skin, and cardiovascular system, and impair the development of the brain and neurological system (US EPA Basic Information).

Many of Virginia's waterways have been found to contain PCBs, including the James, New, Potomac, Rappahannock, Roanoke and York Rivers, as well as some of their tributaries. In fact, all of these rivers' basins are included in PCB fish consumption advisories (VDH 2015). PCBs often make their way into rivers via effluent from industrial, wastewater, and stormwater sources. Industrial effluent, which is wastewater generated by industrial activity, must undergo treatment before being discharged. However, typical treatment methods do not effectively remove PCBs present in the waste stream. For household wastewater, current municipal wastewater treatment plants are unable to sufficiently remove micropollutants like PCBs, bisphenols, and medications. These contaminants are released back into the environment once the treated water is discharged from the wastewater treatment plants. Stormwater runoff, particularly in urban areas, can contain numerous contaminants capable of adversely affecting the water quality of surrounding waterbodies. Occurrences of PCBs in urban stormwater are common, though generally at low concentrations. Virginia water quality criteria stipulate that state waters will be free from substances interfering with the six designated uses of recreation, public water supply, fish consumption, aquatic life, wildlife, and shellfishing. Water quality standards (WQS) establish the numeric criteria that define the water quality necessary to support these designated uses. A waterbody will be considered "impaired" if it does not support one or more of these uses. Fish consumption, public water supply, and wildlife are most commonly affected by PCB contamination.

In Virginia, there are 8,849 river miles, 79,940 lake acres, and 2,052 estuary square miles of impaired or threatened waters in need of TMDLs. PCB contamination of fish tissue is a significant cause of designated use impairment in Virginia rivers (7%), lakes (79%), and estuaries (96%) (VDEQ et al 2014).

EPA Methods for Testing PCBs

Several different methods exist to determine the concentrations of individual PCB congeners present in a sample. These methods help to properly identify PCB sources and to choose the appropriate PCB remediation technology. PCB congeners may also help determine the source of PCBs at a site through PCB fingerprinting (Battelle Memorial Institute et al 2012). Accurately identifying the chlorinated biphenyl congeners present within impaired watersheds can help determine the source(s) of PCBs present and ensure that the best remediation method is chosen. However, not all of these methods can be used for every environmental sample, and they may only be accurate enough to be used for a screening concentration vs. a more accurate end-of-pipe PCB concentration.

EPA Method 1668 determines individual PCB congener concentrations at environmentally relevant concentrations. The Method was developed for use in soil, sediment, surface water, wastewater, biosolids, and tissue matrices. Method 1668 determines chlorinated biphenyl congeners in environmental samples through isotope dilution and internal standard high resolution gas chromatography/high resolution mass spectrometry (HRGC/HRMS) (US EPA 2008).The ultra-low level Method creates a more accurate assessment of the chlorinated biphenyl congeners present in samples by basing detection limits and quantitation levels on the level of interferences and laboratory background levels instead of the previous method of basing them on instrumental limitations (US EPA Office of Water 2010).

Total Maximum Daily Load

Total Maximum Daily Loads (TMDLs) aim to identify a loading capacity, or the maximum pollutant load a waterbody can receive and still be in compliance with water quality standards. In fact, TMDLs are used to reduce the risk contaminants pose to humans as well as remove waters from the impaired waters list. Load allocations (LAs) for nonpoint sources and waste load allocations (WLA) for point sources are designed to reach compliance with a loading capacity identified in a TMDL. In order to develop PCB load limits through LAs and WLAs, it is important to know the amount of PCBs entering, leaving, and trapped within an environmental system.

A mass balance is a valuable tool used to design cost-effective strategies for minimizing contaminant loads and reducing human and ecosystem health risks. A mass balance is based on the principle of ‘conservation of mass’, which states that the amount of a pollutant entering a system should equal the amount trapped in, leaving, or chemically changed in the system. Thus, it is used to identify the amount of pollutants entering, leaving, and trapped within an environmental system. Once PCB concentrations in water, sediment, fish tissue, and any other applicable mediums are identified, PCB loading can be estimated using mass balance equations. This involves collecting environmental samples and then using mathematical models to determine links between the samples (US EPA 2015). It is important to note that samples taken at different times of year will vary in terms of pollutant concentration, and that loading estimations for different times of year will have to be extrapolated from the available samples. Using mass balance models for a waterbody would allow scientists to establish current PCB loadings and then create new PCB loading goals for the TMDL.

Identifying the Sources of PCBs

TMDLs help to provide a linkage among various PCB sources. They also show the strengths and weaknesses of an analytical approach, the factors within a waterbody or watershed that affect PCB loadings, and the results of any modeling to reach the numeric PCB target. Analytical approaches, such as non-modeling, mass balance, and modeling approaches, can be used to calculate PCB contributions. Non-modeling approaches include using a bioconcentration factor to calculate water column value and assuming a proportional one-to-one relationship between fish tissue and PCB loadings (US EPA Office of Wetlands 2011).

PCBs come from a wide variety of point and nonpoint sources and are found throughout the state. To reduce PCB loadings into the environment, it is very important to be able to pinpoint sources.

Point Source Loadings

Point sources for PCBs can include combined sewer overflows (CSO), wastewater treatment plants, rail yards, landfills, municipal separate storm sewer systems (MS4), industrial effluent, inadvertent production sources such as paint manufacturing, and other sources in locations where PCB-laden products have been used. The EPA encourages states to develop estimates of PCB loadings applicable to each category of sources where facility or category-specific PCB discharge data are available. This method is preferable over calculating a single average for all dischargers. States are encouraged to create representative estimates for loadings of each land use or source category if source-specific data is not available. Point source estimates should also include any contributions from National Pollutant Discharge Elimination System (NPDES)-permitted sources, such as municipal wastewater treatments plants (WWTPs), applicable industrial sites, and MS4s (US EPA Office of Wetlands 2011).

Nonpoint Source Loadings

TMDLs should include estimates of nonpoint source loadings, such as runoff from contaminated sites, atmospheric deposition, contaminated sediment, and groundwater. Runoff models can be used to estimate PCB loadings to a waterbody from the watershed. Load allocations for contaminated sites are included in the nonpoint source loading portion of the TMDL (US EPA Office of Wetlands 2011).

Examples of Management Strategies Implemented by Other States to Address Water Quality Impairments (Includes Pollution Minimization Plans)

Pollution Minimization Plans, or PMPs, are used to reduce or prevent releases of contaminants into a waterbody in order to achieve effluent quality at or below water quality based effluent standards. Regulatory agencies have developed PMP guidance manuals to assure that point source facilities are informed of requirements and understand steps needed to prove that a strategy is being implemented. Monitoring and reporting are vital steps used to ensure the PMP is progressing towards compliance with its goals (NYS DEC 2004).

State agencies across the US have developed PMPs for specific pollutants entering water basins. The following states have established PCB PMPs: California, Delaware, Michigan, New Jersey, New York, Ohio, Oregon, Texas, and Washington. These PMPs can be used to offer insight in developing minimization plans to address PCB consumption advisories in Virginia's waterways.

California: San Francisco Bay PCB TMDL

San Francisco Bay has a PCB TMDL that is recommended to be used during site investigation and cleanups throughout the Bay Region. The goal of the San Francisco Bay's TMDL wasteload allocations is to achieve a ten-fold decrease in PCB sources to the Bay. The TMDL's numeric target is based on fish tissue PCB concentration protective of human health. A fish tissue screening level of 10 ng/g (ppb) is used in the TMDL to represent a ten-fold reduction in fish tissue PCB concentration. Surface sediment PCB concentrations in the Bay must be decreased to an average of 1 µg/kg (ppb) in order to achieve this number (San Francisco Bay Regional Water Quality Control Board 2013).

Out of all of the PCB sources to the Bay, stormwater runoff is the greatest contributor. Therefore, a wasteload allocation of 2 kg/year total PCBs for stormwater is established in the PCB TMDL. This represents a ten-fold decrease over the estimated current load. Remedial actions in areas where street sediments contain PCBs in the 1 mg/kg (ppm) range prior to any remedial action are being pilot-tested by Bay Area municipalities (San Francisco Bay Regional Water Quality Control Board 2013).

Contributions from stormwater runoff at sites with residual PCBs in soils after state- and federal-ordered cleanup must be eliminated in order to reach the TMDL target. On-land source control measures must be implemented for these cleanup sites to ensure that on-land sources of PCBs do not further contaminate Bay sediments (San Francisco Bay Regional Water Quality Control Board 2013).

In order to confirm that TMDL PCB targets are achieved, sampling and analysis are needed. The following analytical methods are recommended by the San Francisco Bay Regional Water Quality Control Board for use at cleanup sites: EPA Method 8270D, EPA Method 1668A or 1668C, and PCB analysis requirements under the authority of EPA's Toxic Substances Control Act. Other analytical methods are not recommended because they often do not measure the total amount of PCBs present in an environmental sample (San Francisco Bay Regional Water Quality Control Board 2013).

Delaware: Delaware River PMP and TMDL

The Delaware River Basin Commission (DRBC) has the lead in developing and implementing TMDLs and PMPs for the Delaware River Estuary (Fikslin 2012). The PMP requires the control and abatement of PCB releases into the Delaware River (DRBC 2013). The TMDL allows 379.96 mg total PCBs/day, which is equivalent to 139 kg/year. Most of this is allocated to nonpoint sources, with 38.86 mg/day being allocated to point sources including municipal and industrial discharges (Panero et al 2005). The DRBC has developed a two stage approach consistent with EPA TMDL guidelines for establishing and allocating PCB TMDLs. The staged approach allowed for adaptive implementation. In Stage 1, TMDLs and individual Wasteload Allocations (WLAs) were developed for each river zone. In Stage 2, individual WLAs and Load Allocations were finalized and replaced Stage 1 WLAs and LAs. Stage 2 TMDLs were based upon the summation of PCB homolog groups (DRBC 2003).

Below are the PMP elements included in the plan:

- Good faith commitment
- Discharger contract
- Description and maps of facility
- Description and map of known sources
- List of potential sources
- Strategy for identifying unknown sources of the pollutant (trackdown)
- Previous, ongoing, or planned minimization activities undertaken voluntarily or required by other regulatory programs
- For municipal wastewater treatment plants (WWTPs) only, recommendations for action under other regulatory programs
- Pollutant minimization measures
- Source prioritization
- Key dates
- Measurement of progress
- Sampling and analytical methods (DRBC 2013)

The DRBC requires that dischargers submit an annual report to the Commission. The 2013 Water Quality Regulations state that the report does the following:

1. Describes any material modification to the facility's operations, site boundary, service area, or waste streams in the course of the preceding year that might affect releases of the pollutant, along with appropriate revisions made to the PMP.
2. Outlines the measures under way and completed to achieve maximum practicable reduction of pollutant releases since the last report and since initiation of the PMP.
3. Reports incremental and cumulative changes from the pollutant loading baseline established.
4. Describes progress toward achieving maximum practicable reduction of the pollutant.

Two of the major nonpoint sources of PCB pollution for the Delaware River come from the previous Exxon Mobil site in Paulsboro, NJ and the Metal Bank site in Philadelphia, PA. The DRBC determined that soil PCB cleanup by itself is beneficial in reducing PCB concentrations, while managing soil erosion is useful in reducing off-site migration of PCBs. Applying one of these strategies alone will most likely not achieve TMDL allocations. The following are benefits that come from combining the two strategies:

1. Can achieve lower PCB loads at the site with higher PCB cleanup targets for soil (e.g., by reducing off site migration, soil clean-up levels can be 10 ppm vs 1 ppm)
2. There is site-specific flexibility to achieve a given load.
3. If soil management is applied across-the-board, fewer sites need to remove soil to meet the TMDLs (Bierman et al 2007).

Strategies for identifying potential sources from industrial dischargers included investigations of the following: industrial processes or equipment similar to those known to have generated the pollutant elsewhere; historic activities at the site; and possible soil or stormwater management system contamination as a result of historic or ongoing activities. For the prioritization of known sources, factors to be considered included available information on pollutant mass or volume, and the likelihood of release into Basin waters (DRBC 2006).

The PMP outlined the following actions known to minimize probable sources of PCBs:

- Removal of PCB contaminated material including residuals stored on-site
- Engineering controls (caps and containment dikes)
- Fluid change-out
- Modifications to industrial processes that include or result in PCBs
- Substitutions of or modifications to raw or finished materials
- Modifications to material handling

- Discharge stream separation so as to isolate a stream containing PCBs
- Discharge minimization aimed at overall PCB mass load reduction
- Add/enhance/modify pre-treatment
- Remedial activities for spills/leaks (current/legacy)
- Piping system cleanout
- Routinely inspect facility, especially during storm events where stormwater is a major contributor of PCBs to ensure implementation of BMPs (DRBC 2006)

The main strategy used to determine the success of the PMP was the measurement of reduced PCB loads over time. Direct effluent sampling using EPA Method 1668 was required once every two years (DRBC 2006). As of June 2012, the DRBC found that the top ten dischargers that contributed 90% of the point source PCB loading had reduced their loadings by 46% since 2005 (Fikslin 2012).

Michigan: Statewide PCB TMDL

Michigan's statewide PCB TMDL was established for inland water bodies impacted by atmospheric deposition and other sources of PCBs. The following considerations were used to prioritize the TMDL's development:

- The existing TMDL schedule for the number of TMDLs currently scheduled each year for the state,
- Michigan's five-year rotating watershed monitoring cycle,
- Available monetary resources and staff to complete TMDLs,
- Supporting information and data on quality and quantity of the pollutant causing the impairment,
- Severity of the pollution and complexity of the problem,
- EPA's recommendation to develop TMDLs within 13 years of listing (LimnoTech 2013).

Since fish consumption by humans and wildlife is the most significant route for human PCB exposure in Michigan, a fish tissue residue value was recommended as the target for the PCB TMDL. A water concentration based on the 0.023 mg/kg (ppm) fish tissue residue value was made to confirm that a fish tissue residue value would be consistent with the water quality standard (WQS) for PCBs (LimnoTech 2013).

It is impractical to base TMDL reductions on the requirement that every fish be in compliance with the fish tissue residue value of 0.023 mg/kg, as the TMDL is applied statewide and considers a wide range of fish tissue concentrations. Therefore, it is recommended that reductions in PCB concentrations in fish tissue be based on an appropriate level of protection. For Michigan inland waters, the 90th percentile provides an appropriate level of protection for the PCB TMDL because 90% of the state's waters would have a lower proportionality constant than the threshold value. Ninety percent of Michigan’s waters containing a top predator species with high bioaccumulation potential would likely attain WQS once the TMDL is implemented (LimnoTech 2013).

Lake trout was chosen to establish PCB load reductions and resulting TMDL compliance since they have the second highest concentration of PCBs, are a native species, and are a preferred sport fish species in the state. Lake trout were also chosen since the majority of fish consumed by humans are from trophic level four fish (LimnoTech 2013). Trophic levels are used to determine an organism’s position in a food chain and can be numbered successively depending on how far an organism is along in that food chain. A trophic level four is indicative of tertiary consumers, or carnivores that eat other carnivores.

The statewide TMDL can be used as a single statewide average loading reduction, or it can be divided into geographic regions to produce separate loading reductions for each region. The Michigan Department of Environmental Quality and the EPA decided to calculate one, statewide average required reduction percentage for PCBs. This decision was primarily based on the fact that a consistent pattern between air concentration and fish tissue of PCBs was lacking throughout the state. Post-TMDL monitoring will be used to address any regions or waters across the state that still do not meet WQS as a result of the TMDL. Site-specific TMDLs can be developed in the future if needed (LimnoTech 2013).

The overall reduction percentage mandated to reach TMDL targets for Michigan inland waters were determined via the following: calculating the average atmospheric PCB concentration in the state, combining the atmospheric PCB concentration with the threshold proportionality constant to calculate expected fish tissue concentrations for existing conditions, and determining the percentage by which existing fish tissue concentration would need to be reduced to attain the 0.023 mg/kg (ppm) fish tissue target statewide (LimnoTech 2013).

New Jersey: PCB Pilot Source Trackdown Study

As part of a PCB TMDL for the Delaware River in New Jersey, a PCB Pilot Source trackdown study was performed in the sewer collection system of Camden Municipal Utility Authority (CCMUA). The goals of the trackdown study were to identify potential upland sources of PCBs and to evaluate the most appropriate sampling and analytical techniques for tracing PCB contamination to the Municipal Utility Authority (MUA) collection system. In addition, the project was designed to assist MUAs with combined sewer overflows (CSOs) in performing TMDL required PCB PMPs through documentation of PCBs on city streets. Researchers also examined the way in which regulatory programs inform the PMP process. Scientists evaluated the following field and analytical methods:

- PCB analytical EPA Method 1668
- The quantification of over 124 separate PCB congeners as a means to identify unique source signatures through pattern recognition
- The use of a passive in-situ continuous extraction sampler (PISCES) for sample integration over protracted time periods (14 days)
- The use of electronic data collection systems interfaced with a GIS (Belton et al. 2008).

PCBs were found in all the sewer locations sampled (urban and suburban) and in all sampling media. Metal reclamation operations (smelters, junkyards, etc.) were found to be one of the prime PCB sources in central Camden due to fugitive dust emissions. Other sources included contaminated sites, transportation, gas plant (pipeline), and paper and pulping operations (Belton et al. 2008).

New York: PMP for Wastewater Treatment Plants and Lake Ontario TMDL

New York State developed a PMP for wastewater treatment facilities in 2004. The PMP was for both point source dischargers and industrial users discharging to publicly owned treatment facilities. The PMP requirements for a broad range of contaminants, including PCBs and heavy metals, were as follows:

1. Annual review and semi-annual monitoring of potential sources of the pollutant
2. Quarterly monitoring for the pollutant in the influent of the wastewater treatment system
3. Submittal of a control strategy designed to proceed toward the goal of maintaining the effluent below the water-quality-based-effluent limit (WQBEL)
4. Implementation of appropriate, cost-effective control measures consistent with the control strategy
5. An annual status report that shall be sent to the permitting authority including all minimization program monitoring results for the previous year, a list of potential sources of the pollutant, and a summary of all action undertaken pursuant to the control strategy
6. Any info generated as a result of Procedure 8.D can be used to support a request for subsequent permit modifications, including revisions to or removal of the requirements of Procedure 8.D consistent with 40 CFR 122.44, 122.62, and 122.63 (NYS DEC 2004). Procedure 8 allows the permit authority to monitor and limit

parameters at internal locations when solely controlling them at final outfall is not practical or feasible (Mirabile and Mitchell 2015).

Also in New York State, a TMDL was developed for PCBs in Lake Ontario. Loading capacity was calculated using the LOTOX2 model. The Wasteload Allocation included New York point sources and the Load Allocation included the Niagara River, other New York tributaries, Canadian tributaries, and atmospheric deposition. EPA Method 1668C was used to determine chlorinated biphenyl congeners in samples via isotope dilution and internal standard high resolution gas chromatography and high resolution mass spectrometry (LimnoTech 2011).

Ohio: Lake Erie Basin PMP

For the Ohio Lake Erie Basin, PMPs are required for all pollutants with a permit limit less than the analytical quantification level. This includes a broad range of pollutants, such as PCBs and mercury. Maintaining the effluent at or below the water-quality-based-effluent limit (WQBEL) is the primary goal of the PMP. The following three elements are required:

1. A plan-of-study/control strategy for locating, identifying, and where cost-effective,
2. Reducing the sources of the pollutant contributing to discharge levels;
3. Tracking the progress of the PMP through monitoring;
4. Results of the PMP presented in an annual report (Ohio EPA 1998).

A control strategy is a method used to control or monitor identified sources of pollutants, whereas a plan-of-study is used to investigate and locate sources of the pollutant subject to PMPs. Controls must be cost-effective for the industrial sources and permittees. A plan-of-study can be used to recognize sources of data to be reviewed and points to be sampled during the initial stages of the PMP. “Source” is not defined intentionally to allow flexibility in monitoring requirements and to ensure all potential inputs are considered. Typical sources include stormwater and groundwater inputs, atmospheric deposition, raw materials, and wastestreams to the treatment plant (Ohio EPA 1998).

The Ohio Environmental Protection Agency (Ohio EPA) may comment on control strategies or plans-of-study before they are implemented, but they do not usually approve them until after implementation. This is done to encourage dischargers to begin PMP efforts prior to permit renewal as well as to recognize the individuality of control strategies (Ohio EPA 1998).

Treatment plant effluent is required to be monitored at least once per quarter, and potential sources must be monitored at least twice a year. Known sources should be sampled more often. Annual PMP reports must include a list of potential sources of the pollutant, monitoring results for the previous year, and a summary of all actions taken to meet the WQBEL (Ohio EPA 1998).

For Bioaccumulative Chemicals of Concern (BCC), such as PCBs, permittees can use fish tissue data to track the progress of the PMP. Ohio EPA has the authority to require fish tissue sampling; however, implementation of fish tissue studies is left to the permittee's discretion in most PMPs. Since BCCs typically accumulate in stream sediments, ambient fish tissue studies also need to measure the sediment contaminant levels where fish are caught (Ohio EPA 1998).

A PMP is not required as long as the permittee can demonstrate that the discharge is realistically expected to be in compliance with the WQBEL. A permittee could use mass-balance calculations, treatment modeling, or fish tissue data to do this. There must also be other valid demonstrations of WQBEL compliance (Ohio EPA 1998).

Oregon: Department of Environmental Quality's TMDL Process

Oregon TMDLs describe what needs to happen, but they do not set out a schedule for implementation. Therefore, once a TMDL has been established, an implementation plan is necessary to explain the actions needed to improve water quality and to set up a schedule for implementing these actions. An implementation plan includes: a list of pollutants of concern and their source, proposed treatment approaches, a timeline for implementation activities, and proposed methods for tracking the effectiveness of implementation activities (Oregon DEQ 2007).

The TMDL Water Quality Management Plan (WQMP) section identifies certain designated management agencies (DMAs) required to create and implement plans if their responsibilities are not addressed through a permit requiring a prescribed approach. DMAs are local, state, or federal governmental agencies with legal authority over a source or sector contributing pollutants. TMDL implementation plans can be required from non-governmental entities if their actions contribute significantly to water quality problems. Since the Oregon Department of Agriculture and Forestry activities are regulated under other state rules and statutes, these departments are exempt from submitting implementation plans. The State of Oregon Department of Environmental Quality, or DEQ, strives to review all submitted plans within 60 days of receipt (Oregon DEQ 2007).

Many DMAs have plans or strategies already in place to control or prevent water pollution; however, these plans may not cover all TMDL pollutants or relevant sources of pollution. TMDL implementation plans should therefore build upon existing efforts, not duplicate them. DMAs are not expected to know all the solutions or answers when they submit their implementation plan to DEQ. DEQ does expect the following to be included in the implementation plans:

1. Identification of suspected or known sources of each pollutant under the DMA's jurisdiction,
2. Identification of actions the DMA is currently taking or planning to take to address each of those sources, and
3. A description of how the DMA will gauge the effectiveness of control efforts over time.

A timeline for implementation and milestones and methods for monitoring progress/effectiveness should also be provided in the plan (Oregon DEQ 2007).

Texas: Lake Worth PCB TMDL

Lake Worth in Texas established a PCB TMDL after elevated concentrations of PCBs were found in fish tissue. The goal of the TMDL is to reduce fish tissue PCB concentrations to a level establishing an acceptable risk to fish consumers. This reduction in fish tissue PCB concentrations would allow the Texas Department of State Health Services (TDSHS) to remove the consumption advisory. A numeric target of < 0.04 mg/kg (ppm) defines the acceptable fish tissue PCB concentration as the measurement endpoint for the TMDL. This TMDL, which was adopted in 2005, became an update to the state Water Quality Management Plan (TCEQ 2005).

The Lake Worth TMDL consists of the following elements:

1. problem definition;
2. endpoint identification;
3. source assessment;
4. linkage between sources and receiving waters;
5. margin of safety;
6. pollutant load allocation;
7. public participation;
8. implementation and reasonable assurance (TCEQ 2005)

Fish consumption advisories, water quality standards, and risk assessments are used to define any problems within Lake Worth. Endpoint identification is the numeric target defining the PCB concentration in fish tissue that is considered an acceptable risk to human health. EPA guidance and state health department assumptions are used to develop these numeric targets for PCB tissue concentrations resulting in an acceptable risk level. Source assessment is used to determine the primary source(s) of PCBs for a specific area. Multiple factors can alter PCBs or affect PCB uptake and elimination, such as weathering, aerobic microbial degradation, low water flow, and seasonal variability in loading. These factors can make it more difficult to properly identify PCB sources. Therefore, core sediment samples and fish tissue samples can be used to help provide the linkage between source(s) and receiving waters (TCEQ 2005).

A margin of safety is used to account for any uncertainty with the pollutant load and associated water quality. For example, applying the most protective target concentration for PCBs will provide additional assurance that protection from adverse health effects will be achieved. A pollutant load allocation is the maximum load of a pollutant from non-permitted or upstream sources and from regulated point sources allowed to enter a specific waterbody without violating applicable water quality standards. Public and stakeholder participation is encouraged throughout the development of the TMDL. Public meetings and comment periods are scheduled to inform and involve the public throughout the process. An implementation plan details activities determined necessary to restore water quality, such as permit actions, additional sampling and monitoring, and best management practices. These activities provide reasonable assurances that both the regulatory and voluntary activities will achieve the required pollutant reductions (TCEQ 2005).

Washington: Walla Walla River TMDL

A TMDL was established for the Walla Walla River in Washington after the river was listed as being water quality limited for multiple chlorinated pesticides/breakdown products, including Aroclor 1260 in edible fish tissue. The following elements are required for TMDLs by EPA Region 10: scope, applicable water quality standards, loading capacity, numerical targets, margin of safety, wasteload and load allocations, seasonal variation, and monitoring plan (Johnson et al 2004).

Total suspended solids (TSS) and turbidity were not derived specifically for PCBs in the Walla Walla River due to the inherent difficulty in measuring low levels of PCBs in surface waters. Meeting TSS/turbidity targets in the Walla Walla drainage basin will reduce PCB concentrations in the river because PCBs have a strong affinity for soil particles and atmospheric deposition is likely the major source of PCBs to agricultural land (Johnson et al 2004).

Water quality targets are recommended to be implemented in the Walla Walla River at the mouths of all the mainstem tributaries in Washington and at the state line. Monitoring was implemented to determine if land-use changes were effective in decreasing TSS loading to the Walla Walla River and bringing the river into compliance with the standards. Monitoring was suggested to begin with collecting a year’s worth of baseline data on turbidity and TSS at ten sites within the Walla Walla River basin.

Sampling should be conducted at least twice a week, streamflow should be measured, and depth integrating sampling procedures should be used (Johnson et al 2004).

The City of Spokane, WA is working to improve the health of the Spokane River through managing stormwater and wastewater. The Spokane River and Lake Spokane are both on Washington State's 303(d) list of impaired water bodies for a number of contaminants, including PCBs. The City's Integrated Clean Water Plan addresses management processes in place to remove PCBs from both stormwater and wastewater effluent. The approach would remove stormwater from combined and separated stormwater piping to capture PCBs on site; the more water captured before entering the stormwater pipes and sewer, the less there is to require treatment or to flow into the river (CH2MHILL Engineering 2014). The City has also utilized PCB remediation methods and technologies, such as Black Walnut Shell Filtration Systems.

Current Approaches for Managing PCBs Entering Water Bodies in Virginia

Virginia Pollutant Discharge Elimination System

The Virginia Pollutant Discharge Elimination System, known as VPDES, is meant to establish limits on the quantity and concentration of pollutants discharged into Virginia's water bodies. Permittees must monitor the water quality of effluents, report the results to the Virginia Department of Environmental Quality (VDEQ), and ensure that facilities are properly operated and maintained. To ensure proper operation and maintenance of facilities and to confirm self-monitoring information is representative and accurate, the VDEQ conducts facility inspections as the principle form of regulatory compliance surveillance. The VDEQ utilizes a risk-based protocol to identify facilities needing increased or decreased inspection frequency and/or complexity. Permittees may have "special conditions," or additional requirements, that are included in their permits. Examples include pretreatment programs for publicly owned treatment works (POTWs), stormwater pollution prevention plans, and the Toxics Management Program (VDEQ et al 2014). The requirement for a PMP to address PCB TMDL derived Waste Load Allocations (WLAs) would be included in applicable permits as a special condition.

Water Quality Management Plans and TMDLs

Water Quality Management Plans (WQMPs) are required by the Clean Water Act as the link between water quality assessment and water quality based controls. WQMPs recommend control measures for water quality problems. The control measures are implemented through the VPDES permit system for point sources of pollution and through the application of best management practices (BMPs) for nonpoint pollution sources (VDEQ et al 2014).

WQMPs are also used to implement Total Maximum Daily Loads. TMDLs integrate point and nonpoint sources of pollution contributing to impairment of the water body. The overall goal of implementing TMDLs is to restore watersheds to support economic and recreational activities, human health, and to provide healthy habitats for fish, plants, and wildlife. Since 2000, Virginia has completed 68 implementation plans, covering 263 impaired stream segments and addressing 336 impairments across the state (VA WQ Integrated Report 2014).

Completed PCB TMDLs

The following Virginia sites have completed a TMDL:

Potomac River Embayments and Anacostia River PCB TMDL

Refer to the Interstate commission on the Potomac River Basin’s 2007 *Total Maximum Daily Loads of Polychlorinated Biphenyls for Tidal Portions of the Potomac and Anacostia Rivers in the District of Columbia, Maryland, and Virginia* document

Phased Levisa Fork TMDL
Refer to MapTech, Inc.’s 2013 *Phase II Benthic and Total PCB TMDL Development for Levisa Fork, Slate Creek, and Garden Creek*

Shenandoah River
Refer to EPA and VDEQ’s 2001 Final Report: *Development of Shenandoah River PCB TMDL*

Roanoke River Watershed
Refer to Tetra Tech, Inc.’s 2009 *Final Roanoke River PCB TMDL Development (Virginia)*

PCB TMDL 2016-2022 Priorities
The following sites are on DEQ’s list of PCB TMDL priorities to be completed by 2022:

Tidal James and Elizabeth River
Applicable cities and counties included in the Tidal James and Elizabeth Rivers include Charles City, Chesterfield, Dinwiddie, Henrico, Isle of Wight, James City, New Kent, Prince George, Surry, City of Chesapeake, City of Colonial Heights, City of Hampton, City of Hopewell, City of Newport News, City of Norfolk, City of Petersburg, City of Portsmouth, City of Richmond, City of Suffolk, City of Virginia Beach, City of Williamsburg.

New River
Applicable cities and counties included in the New River TMDL include Giles, Montgomery, Pulaski, Wythe, and City of Radford.

Mountain Run
Culpeper is the applicable county included in the Mountain Run TMDL.

Upper James River, Maury River, Hardware River, and Slate River
Applicable cities and counties included in the Upper James River, Maury River, Hardware River, and Slate River TMDL include Albemarle, Amherst, Appomattox, Bedford, Buckingham, Campbell, Cumberland, Fluvanna, Goochland, Henrico, Nelson, Powhatan, Rockbridge, City of Buena Vista, City of Lynchburg, and City of Richmond.

Bluestone River
Tazewell is the applicable county included in the Bluestone River TMDL.

Lewis Creek
Applicable cities and counties included in the Lewis Creek TMDL include Augusta and City of Staunton.

PCB Strategy for the Commonwealth

In 2005, the VDEQ published the PCB Strategy for the Commonwealth. The purpose of this statewide strategy was to provide a framework for implementing the Toxic Source Assessment Policy protocols in PCB-contaminated surface waters and for the application of environmental management programs like the TMDL.

VDEQ uses cleanup levels recommended by the EPA for assessment and cleanup of PCB-contaminated sites. If elevated levels of PCBs are discovered, the VDEQ must notify the US EPA. The US EPA can then determine whether to respond directly or to defer to VDEQ with US EPA oversight. A VDEQ work group recommended site-specific assessment over the use of state-wide screening levels for sediment. During the TMDL development process, the VDEQ expects to increase its quantification of active sources. The PCB Strategy for the Commonwealth states that all upland sources of PCBs must be remediated before in-stream work begins to avoid the potential for sediment recontamination. The Strategy also states that if the Toxic Source Assessment shows that contaminated upland areas have a direct pathway to waterbodies, soil hot spots will be managed via soil removal.

The report lists the following as possible remediation options:
1. Facility-specific removal actions of contaminated soils
2. Removal action, such as dredging of PCB hot spots
3. Restricting the bioavailability and movement of PCBs through the use of capping (reactive capping is a potential new technology)
4. Thermal desorption
5. Natural attenuation

The VDEQ uses screening levels to prioritize contaminated sites requiring further investigation. Appendix G of the PCB Strategy explains the development of screening levels and cleanup levels. Screening levels for soil are based on the EPA Region III Risk-based concentration table. To calculate screening levels, the Biota-Sediment Accumulation Factor (BASF) approach and the Bioaccumulation and Aquatic System Simulator (BASS) model were used. These models calculate screening levels based on bioaccumulation in the human food chain. For sites where use is restricted to commercial/industrial use, the screening level is 1.4 ppm. For residential and unrestricted-use sites, the screening level is 0.32 ppm (VDEQ 2005).

Additional Government-Administered Strategies

In 2007, the Secretary of Natural Resources completed a plan for the cleanup of the Chesapeake Bay and its tributaries. The Chesapeake Bay and Virginia Waters Clean-Up Plan includes strategies for cleanup methods, a timeline for water cleanup, funding sources, and objectives (Interstate Commission on the Potomac River Basin 2007). PCB TMDLs for various water bodies in Virginia are structured to comply with this plan.

There are several other state-led efforts to reduce pollutants in the Chesapeake Bay. The Chesapeake Bay TMDL, administered by the VDEQ, was issued in 2010. The Chesapeake Bay TMDL was developed in response to the Chesapeake Bay and many of its tributaries not meeting water quality standards throughout the 1990s. In addition, the VDEQ's Statewide Fish Tissue and Sediment Monitoring Program assesses and evaluates Virginia water bodies to identify contaminant accumulation with the potential to adversely affect human health. The Virginia Erosion and Sediment Control and the Virginia Stormwater Management Programs help to implement sediment reduction BMPs. These two programs are administered by the Department of Conservation and Recreation. Further studies are needed to more fully address the atmospheric deposition of PCBs within the Commonwealth (Interstate Commission on the Potomac River Basin 2007).

In 2014, the Chesapeake Bay Program (CBP) implemented a Toxic Contaminants Policy and Prevention Management Strategy for the Chesapeake Bay and its rivers. Recognizing that there are many toxic contaminants in the Bay, the CBP decided to start by addressing PCBs and developing a comprehensive strategy for reducing the amount of PCBs that enter the Bay and the watershed. This strategy aims to improve practices and controls that reduce PCBs in the Bay to levels that do not harm humans or aquatic life. This is primarily done by building on existing programs and creating TMDLs to reduce the amount and effects of PCBs in the Chesapeake Bay and its watershed (Chesapeake Bay Program 2015).

PCB Remediation Methods and Technologies

In situ treatments are generally cheaper and cause less community and ecosystem disturbance. However, they are less suited for deep water sediment, woody debris, and multiple contaminants. In comparison, there are more *ex situ* treatment options available, and *ex situ* treatments tend to be more intensive than *in situ* treatments. *Ex situ* treatments allow for more control over environmental conditions, and removal and isolation from the environment reduces recontamination and or dispersal. However, *ex situ* treatments require a processing site and can be more expensive (Williams 2006).

In addition to environmental dredging, several sediment remediation technologies for removing PCBs from sediments and water have been developed, including bioremediation, mobile UV decontamination, and a redeployable polymer blanket.

Below is a list of methods that have been shown to successfully remediate PCBs across different matrices, including an additional section addressing methods used to remediate PCB contamination in effluent and waste streams.

Environmental Dredging

Medium: sediments

Environmental dredging is more precise than navigational dredging, thus ensuring more removal with fewer disturbances to the ecosystem and contaminants. This technology is cheaper than other removal technologies, and it has less of an impact on the surrounding community and wildlife. Mechanical and hydraulic dredging are two examples of environmental dredging. Mechanical dredges use a bucket or clamshell to move contaminated sediment to a barge for transport. Mechanical dredges handle debris well and are better suited for shallow areas and smaller sediment volumes. Hydraulic dredges use a “cutterhead” to break up sediment and a pump and pipe to transport the sediment to a barge or processing site. Hydraulic dredges can handle high sediment volume, work well in deep water, and provide ease of transport for sediment and water. Hydraulic dredges are not well suited for large debris. The effectiveness of environmental dredging depends on the type and size of equipment used and the operating conditions (TAMS and Malcolm Pirnie 2004).

If cleanup levels are achieved, dredging and excavation can result in the least uncertainty regarding future environmental exposure to contaminants, as the contaminants are permanently removed from the ecosystem and disposed of in a contained environment (US EPA Office of Wetlands 2011). Removal also requires less long-term maintenance operations than other methods. While dredging can cause increases in the concentrations of fish tissue contamination, these increases are only temporary (US EPA Region 2 2010). In fact, PCB concentrations after dredging in the Thompson Island section of the Hudson River increased after dredging in the area immediately downstream. While dredging is associated with a moderate, localized increase in PCB concentrations in small fish, there are no discernible effects more than a few miles downstream of dredging operations (Richter et al 2010).

The cleanup of the Hudson River PCB site in New York and New Jersey relied on mechanical dredges with environmental buckets for PCB remediation (US EPA Region 2 2015). Contaminated sediments were scooped up from the river bottom and loaded into hopper barges. Computer software was used to identify where to dig, and depth and location of digging was determined by satellites (US EPA Region 2 2015).

Landfilling

Medium: soils and sediments

Landfilling is one of the most-used methods for dealing with PCB-contaminated soils and sediments. Dredging and soil excavation are necessary precursors to this method of remediation. Dredging causes a fraction of PCBs formerly tied to sediments to be resuspended in water. It also removes organic fine grained sediments and leaves behind coarse inorganics that have a lower affinity to bind with PCBs. This causes PCBs to become temporarily more concentrated in the water column, increasing the chance for bioaccumulation in aquatic wildlife (Mikszewski 2004).

Sequestering liquid PCBs or contaminated soils in a hazardous waste landfill can cause the PCBs to volatilize and escape through surrounding air channels. A further danger of landfilling is that PCBs could infiltrate groundwater if the leachate collection systems fail (Mikszewski 2004).

Dredging alone is an expensive procedure, further adding to the costs of landfilling. For example, excavating and landfilling one acre of soil contaminated to a depth of 50 cm is estimated to cost from $400,000 to $1,700,000 (Khan et al. 2004).

Soil Washing

Medium: soil and sediment

Soil washing is a water-based, multi-step process of remediating sediment *ex situ* to top soil quality by mechanically mixing, washing, and rinsing soil (US EPA 2013). Solvents can be combined with the water during the washing process. Solvents are selected based on their environmental and health effects and their ability to solubilize specific contaminants. Contaminant removal occurs in one of two ways: dissolving/suspending them in the wash water that can be sustained by chemical manipulation of pH or by concentrating them into a smaller volume of soil (US EPA 2013).

Particle size separation, gravity separation, and aeration can be used to concentrate the contaminants into smaller volumes of soil (US EPA 2013). Hydrocarbon contaminants tend to bind to smaller soil particles. Separating the smaller, contaminated soil particles from the larger, clean particles can reduce the overall volume of contamination. The volume of soil containing the smaller soil particles (clays and silts) can then be treated by other methods or be disposed of. The volume of soil containing the larger soil particles is considered to be non-toxic and can be used as backfill. Reducing the volume of material requiring further treatment by another technology makes soil washing a cost-effective technology (Khan et al 2004).

An additional advantage of soil/sediment washing includes the ability to recover metals and clean a wide range of both inorganic and organic contaminants from coarse grain soils. Furthermore, soil washing facilities can be constructed where the sediment is unloaded, eliminating the cost of transporting the sediment elsewhere. Depending on site-specific conditions and the target waste quantity and concentration, the average cost for soil washing technology, including excavation, is approximately $170/ton (Khan et al. 2004).

BioGenesis^{SM}
Medium: soil and sediment

BioGenesis^{SM} sediment washing was patented in December 2001 to decontaminate both coarse-grained and fine-grained particles. This technology is a low-temperature decontamination process, which uses a proprietary blend of chemicals, impact forces from high pressure water, and aeration to decontaminate sediments off-site. It works by isolating individual particles and removing contaminants and naturally occurring material adsorbed to the particles (BioGenesis, 2008). According to a 2008 BioGenesis^{SM} Bench-Scale Treatability Study, processing steps include:

1. Soil/sediment preparation;
2. Attrition scrubbing/aeration (using proprietary washing chemicals in an attrition scrubber to reduce the affinity between contaminants and soil/sediment particles);
3. Removal of naturally occurring organic material;
4. Chemical addition and mixing;
5. Application of collision impact forces;
6. Organic contaminant oxidation

7. Solid/liquid separation
8. Wastewater treatment
9. Disposition of treated solids

The end result of the BioGenesis^{SM} process is treated soil or sediment. Depending on the results achieved and on obtaining any necessary regulatory approvals, the treated soil or sediment can also either be disposed of or potentially used as fill material or as raw material in the production of topsoil or other construction grade products (BioGenesis, 2008). BioGenesis^{SM} offers the advantage of being able to handle large volumes of soil. Additionally, a BioGenesis^{SM} treatment facility can be constructed where the sediment is unloaded, which eliminates the need for and cost of transportation.

In a 2008 Bench-Scale Treatability Study Report using BioGenesis^{SM} on the Housatonic River Rest-of-River site, validation test run results showed that the amount of solids recovered in the treated soil and sediment was related to the grain-size of the untreated soil and sediment. In addition, PCB concentrations decreased with each treatment cycle. For coarse-grained sediment, the total PCB concentration was 35.6 mg/kg prior to treatment and ranged from 4.6 to 21.8 mg/kg after three treatment cycles. For treated fine-grained sediment, the total PCB concentration was 107 mg/kg before treatment and ranged from 11.3 to 18.4 mg/kg after treatment. And for treated floodplain soils, the initial total PCB concentration was 50 mg/kg prior to treatment and ranged from 4.2 to 8.5 mg/kg after the three treatment cycles. This process works to reduce other metals effectively in the process (BioGenesis, 2008).

A full-scale operation using BioGenesis^{SM} was conducted on dredged material from the New York/New Jersey Harbor. As stated in the 2009 BioGenesis final report on the *Demonstration Testing and Full-Scale Operation of the BioGenesis^{SM} Sediment Decontamination Process*, sediment was treated from three different dredged material sites, and analytical tests on the treated sediment showed reductions in PCBs, dioxins, all heavy metals except arsenic. The concentration of total PCBs in decontaminated sediment was below the standard of 490 µg/kg, but still above the 2008 New Jersey Residential Direct Contact Soil Remediation Standard of 200 µg/kg. Many contaminants were readily removed; however, others, such as PAHs, were difficult to remove (BioGenesis, 2009).

Along with PCB remediation, this study sought to determine the cost per unit to treat the contaminated sediment, as well as determine whether such costs are competitive with current prices for the management of contaminated dredged material. In a commercial scale facility (500,000 cubic yards/year), the cost of BioGenesis^{SM} is very competitive at approximately $50-59 per cubic yard (BioGenesis, 2009).

Bioremediation

Medium: soil and sediment.

Bioremediation uses microorganisms to facilitate degradation of contaminants *ex situ*. Remediation is achieved through a biological process in which indigenous microbial populations consume the target contaminant. The process relies on enzymes expressed from microorganisms to break down contaminants into non-toxic, less-complex organic constituents, which are then used for bacterial growth and reproduction (BioTech Restorations*)*.

PCB microbial degradation occurs via two paths: aerobic and anaerobic. Aerobic biodegradation consists of the oxidative degradation of PCBs into chlorobenzoic acid and its further degradation products. Activated carbon has been found to decrease PCB bioavailability without slowing degradation. Anaerobic dechlorination of PCB contaminated sediments involves PCB reduction and replacement of chlorine by hydrogen (Gomes et al 2013).

There are several major advantages of bioremediation. It is a natural process that improves the overall quality of soils, different types of bioremediation technologies are available, and costs are relatively low to moderate. Furthermore, the addition of phosphorous, supplementary carbon sources, nitrogen, oxygen, primers, and analog enrichment can improve efficiency. However, bioremediation requires particular environmental conditions for microbes to grow, and the process is therefore very sensitive to abiotic factors such as temperature and moisture content. Additional disadvantages include the inability to introduce microbes to grow at depths sufficient to reach contaminants, and the slow rate of PCB removal (Gomes et al 2013).

BioPath Solutions

Medium: soil, sediment, groundwater

The company formerly known as BioTech Restorations, Inc. (BTR) pioneered a new method of treating contaminated soil and sediment that employs tilling to prepare for treatment to permit bacterial breakdown. It works on a variety of pollutants, including PCBs and pesticides and can be employed in soil, groundwater, and dredged marine sediments. BioPath Solutions, an environmental remediation company specializing in the cleanup of POPs, is now the sole licensee of this technology. According to a statement from the former BioTech Restorations, Inc.:

> “Years of research have been conducted to the development, testing, and validation of a biological method for the treating of POPs. The research team found that indigenous bacteria’s ability to secrete reductive enzymes is impaired by the presence of POPs. Without being able to produce the reductive enzymes, the indigenous bacteria are unable to degrade the target contaminants. With the addition of BTR’s Factor treatment, microbial enzyme production is restored, thus resulting in enzymatic de-chlorination of the target contaminants and prompt microbial utilization of the residual organic constituents.
>
> A Factor treatment can reduce cleanup costs of a polluted site by 50%. Treatments are designed for on-site cleanup of soil, sediments, or groundwater, eliminating the need for off-site transportation and permitted disposal. Remediation times vary from six weeks for petroleum hydrocarbons to six months for PCBs. BTR is so confident in its process that it is the only remediation company offering a guarantee that a Factor will achieve a site’s mandated cleanup goals (BioTech Restorations).”

A first generation Factor was developed in 1998 to remove toxaphene from soils in the former Hercules pesticide production facility in Brunswick, Georgia. Within 24 weeks, a single Factor application decreased toxaphene from 3500 ppm to non-detect. Since then, BTR and now BioPath Solutions have improved the process, pioneered new applications, increased efficiencies, and lowered costs (BioTech Restorations).

This remediation method was used on PCB-contaminated sediments from the Housatonic River, and the methods and results were recorded in the 2014 Housatonic River BioTech Restorations Remediation Phase I Study: Quality Assurance Project Plan prepared by Environmental Stewardship Concepts, LLC. Sediment assays were used to determine the most effective Factor formulation to use for this site; the incubation time for the sediment assay is 8-10 weeks. The goal of the sediment assay is to select the best performing one or two Factors under the precise soil/bacteria conditions for the site. Over eight formulations with proven efficacy in reducing PCBs and other chlorinated organic chemicals have been developed (Environmental Stewardship Concepts 2014).

According to an interview conducted with Chris Young, creator of the original BTR treatment Factor, the treatment Factor works in soil and has been used with TCE-contaminated pumped water. An estimated volume of about 500 cubic yards of soil is needed at minimum for the treatment to work, and larger volumes work best. A minimum depth of 24 inches is necessary in order to get the equipment in to work on contaminated soil. When working in water, the temperature needs to be greater than or equal to 5º C to 40º C.

Including the Housatonic River site, BTR treatment Factors have been successfully implemented to reduce PCB and other persistent chlorinated organic pollutant concentrations in soils of 17 different laboratory and field investigations including:

- New England Log Home Bench Study- Great Barrington, MA;
- Blue Jay Ct. 2 acres- East Palo Alto, CA;
- Newland Tree Farm 3 acres- Newland, NC;
- Superfund site test- Woolfolk Chemical (Environmental Stewardship Concepts 2014).

This method is less expensive than offsite disposal, but is not appropriate for soil volumes of less than 500 cubic yards. Nutrient control is a critical element of the process, and therefore the method may not be applicable within a river. However, for dredged sediment or in situ soils, BioPath can develop specific "bioblends," treatments that are site specific and account for a particular mix of contaminants. The budgeting for a project using the BioPath method accounts for multiple treatment cycles. After two to four treatment cycles, PCB levels are reduced to non-detect levels, or 99.99% reduction (Chris Young, pers. comm.).

Carbonaceous Materials

Carbonaceous materials are simply carbon-based materials. Some commonly used carbonaceous materials used for PCB-contaminated sediment remediation include activated carbon, biochar and grapheme.

Activated Carbon

Medium: sediment and water

In a 2014 study, Beless et al. compared the efficiency of five different carbonaceous materials for sorbing PCBs from aqueous solutions. The study compared activated carbon, charcoal, carbon nanotubes, grapheme, and grapheme oxide as sorbent materials for 11 PCB congeners. Results showed that activated carbon was the superior sorbent material (Beless et al 2014).

In a 2009 study, scientists mixed activated carbon into contaminated sediment to study the *in situ* stabilization of PCBs in marine sediment (Cho et al. 2009). Mixing activated carbon into the sediment did not cause resuspension of PCBs into the water column, nor did it cause adverse effects for the benthic community. Results showed about a 50% reduction in PCB uptake in sediment treated with activated carbon, and a similar reduction in estimated PCB porewater concentration. In addition, sediment treated with 2% activated carbon was shown to reduce PCB bioaccumulation in marine clams. After 18 months, sediment exposed to the activated carbon retained a capacity to reduce aqueous PCB concentrations by about 90%. A 2008 study showed that the addition of activated carbon at 0.5-fold the native organic carbon level reduced PCB bioaccumulation anywhere from 42% to 85% for different contaminated river sediments (Sun and Ghosh 2008).

A 2012 study by the same group examined PCB levels in contaminated sediment five years after initial treatment (Cho et al. 2012). Results showed that PCB levels in sediment cores post-treatment had remained at the reduced levels first observed five years prior. These results support the long-term effectiveness of *in situ* activated carbon.

Biochar
Medium: soil and sediment

Biochar is the byproduct of thermal decomposition of organic matter. Biochar can be used to reduce the bioavailability and phytoavailability of PCBs in soil, and simultaneously improve soil quality. Denyes et al. conducted a study on biochar as a reductor for PCB levels in plants, and found that adding 2.8% (by weight) of biochar to contaminated soil reduced PCB root concentration in two different plants by 77% and 58%, respectively (Denyes et al 2012). When 11.1% biochar was added to the soil, reduction of 89% and 83% were observed. In addition, Denyes et al. found that biochar amended to PCB-contaminated soils from industrial sites increased the amount of aboveground biomass and worm survival rates (Denyes et al. 2012).

Electroremediation
Medium: soil and sediment

Applying electric potential to contaminated sediment can stimulate the breakdown of PCBs by microorganisms. Voltage applied to contaminated sediment provides electron-donors and/or acceptors to PCB dechlorinating and degrading microorganisms. In a 2013 study by Chun et al., scientists applied voltage to PCB-contaminated sediment from the Fox River Superfund site under *in situ* conditions. Results showed that applying voltage did stimulate oxidative and reductive microbial transformation, with increased voltage enhancing overall degradation. Using electrolytic biostimulation, approximately 62% of weathered Aroclor was removed from sediments within 88 days (Chun et al. 2013).

Electroremediation can provide a more environmentally sustainable remediation method for *in situ* contamination compared to other forms of remediation that require combustion or excessive use of non-renewable natural resources. Electrodialytic remediation is based on the combination of the principle of electrodialysis with the electrokinetic movement of ions in soil. This method has been found to successfully remediate contaminants across different matrices, such as *ex situ* soils, fly ash, mine tailings, freshwater and harbor sediments, and sewage sludge. A study conducted in 2015 using electrodialytic remediation with iron nanoparticles resulted in an 83% PCB removal rate when direct current was used (Gomes 2015b).

Phytoremediation

Medium: upland soil, shallow, and shoreline sediments

Phytoremediation uses plants and their associated microorganisms to sequester, extract, and degrade contaminants from soil or water either *in situ* or *ex situ* (Gomes et al 2013). Plants have also been found to take up various organics and either process them for use in physiological processes or degrade them. Some plants have the ability to store large amounts of metals that do not seem to be utilized by the plant (Cronk and Fennessy 2001).

Phytoremediation is effective in upland and shallow areas as well as shorelines. It can be used alongside bioremediation with dredged sediment. Many investigations have found that the tissues of some plant parts are more efficient at accumulating PCBs than other parts. The majority of the research centered on phytoremediation has shown that the bacteria growing in the rhizosphere does most of the remediation (US EPA 2013).

Rhizoremediation refers to plant enhancement of microbial activity, which takes place in the root zone and improves bioremediation through the release of secondary metabolites. In order to improve the effectiveness of phytoremediation, genetically-modified bacteria or bacterial genes involved in the metabolism of PCBs can be introduced into the phytoremediation process (Gomes et al 2013).

While PCBs are partially retained in plant biomass, phytoremediation provides a noninvasive means of removing/degrading the contaminants. Phytoremediation can be implemented using a variety of plants; canarygrass and switchgrass were found to be particularly effective on soil (Chekol et al., 2004). Other plants, including pine tree, alfalfa, flatpea, willow, deertongue, tall fescue, poplar, tobacco, and mustard, have been tested for their efficiencies to reduce PCBs in contaminated soils (Jha et al 2015).

In a 60-week study, Huesemann et al (2009) used eelgrass to remove PAH- and PCB-contaminated marine sediment *in situ*. PAHs and PCBs were removed to a larger extent from planted sediments than from the unplanted control. After the 60 weeks of treatment, PAHs declined by 73% in the presence of plants but only 25% in the controls. Total PCBs decreased by 60% in the planted sediments while none were removed in the unplanted control. Overall, biodegradation was greatest in the sediment layer containing the majority of the eelgrass roots. The presence of eelgrass likely stimulated the microbial biodegradation of PAHs and PCBs in the rhizosphere by releasing plant enzymes, root exudates, or oxygen (Huesemann et al. 2009).

Liang et al. conducted a study in 2014 using bioaugmentation to enhance PCB removal in a switchgrass rhizosphere. Bioaugmentation is the process of adding active microbial strains to the environment to stimulate the degradation of contaminants. In this experiment, switchgrass-treated soil with the bacterium *Burkholderia xenovorans* LB400 bioaugmentation had the highest total PCB removal. Furthermore, the presence of switchgrass facilitated the LB400 survival in the soil. Overall, the study found that combining phytoremediation and bioaugmentation could be an efficient and sustainable treatment to remediate PCB contaminated soil and recalcitrant PCB congeners (Liang et al. 2014).

Phytoremediation is a solar energy-driven system requiring minimal maintenance and environmental disturbance, creating a low-cost remediation method. Furthermore, phytoremediation garners high public acceptance due to its great aesthetic value (Jha et al 2015). Other advantages to phytoremediation include the following; it is a passive remediation method; organic pollutants can be converted to carbon dioxide or water instead of transferring toxicity; secondary waste is minimal; the uptake of contaminated groundwater can prevent the migration of contamination; and it can be used on a wide range of contaminants (Khan et al. 2004). However, there are a few disadvantages to consider: bioaccumulation is dependent on soil properties (pH, organic carbon content), high contaminant concentrations inhibit plant growth, efficiency is affected by plant stress factors, and plant disposal must be assessed to prevent the transfer of pollution (Gomes et al. 2013).

UV Treatments

UV-Oxidation

Medium: sediment and water

UV-oxidation treatment is a viable technology for treating contaminated groundwater. It uses an oxidant in conjunction with UV light. The two basic forms are UV-peroxide systems and UV-ozone systems. This technology is applicable to all types of petroleum products, PCBs, dioxins, PAHs, and other various forms of organic carbons (Khan et al. 2004). UV-oxidation treatment costs range from $10 to $50 per 1000 gallons of water. Costs are affected by several factors, including the degrees of contaminant destruction required, the type and concentration of the contaminants, the flow rate of the groundwater system, and the requirement for pre- and post- treatment (Khan et al. 2004).

Mobile UV Decontamination
Medium: soil and sediment

A study conducted in 2013 by Kong et al. demonstrated that using UV and visible light is effective in treating PCBs in transformer oil (Kong et al. 2013). Researchers at the University of Calgary developed a mobile PCB remediation unit that builds upon this study showing ultraviolet light's capability of effectively degrading PCBs in transformer oil, soils, and sediment. The project, backed by SAIT Polytechnic and IPAC Services Corp., is a 15 meter long mobile unit that combines UV and visible light technologies to degrade PCBs by as much as 94%, at a fraction of the cost of inicineration while remaining on site (Unviersity of Calgary 2013). This technology is well suited for operation in areas where soil or sediment could be removed and processed nearby. The unit is currently designed to handle smaller areas of contamination but the project group plans to expand the technology to address the needs of larger remediation projects.

Capping
Medium: soil and sediment in stream bottoms

Capping is a way to isolate contaminated soils in upland areas, landfills, sediments, and stream bottoms by applying a clean layer or "cap" on top of the contaminated area (US EPA Office of Wetlands 2011). Caps are typically constructed using clean sand, silt, gravel, or crushed rock (Gomes et al. 2013). While capping often refers to the use of caps in aquatic environments, capping of contaminated upland soils is also common. Remediated soil or soil with very low levels of contamination can be capped with a clean layer of soil and other materials. For highly contaminated upland soils that will not be remediated *in situ* or *ex situ*, asphalt caps can be used. Asphalt caps create an impermeable barrier that prevents direct contact with contamination (Gomes et al 2013). At the General Electric Site in Spokane, WA, an asphalt cap was used to cover PCB contaminated soils in the northwest corner of the Site. Periodic reviews of the site showed that while the asphalt stayed mostly intact over the years following construction, cracks were eventually observed and had to be patched (GE 2008).

In water, capping of contaminated sediments has a number of logistical challenges, not the least of which are natural and vessel scour. Bioturbation is meant to be confined to only the clean cap layer, which, if successful, limits the possibility of resuspension of contaminated sediments. However, sediments can escape through a variety of processes, and caps do sometimes fail.

While traditional capping passively contains a pollutant, reactive capping is an emerging technology that caps the designated area with additives that can absorb and immobilize, increase degradation, or reduce the bioavailability of PCBs. Additives used in this process include activated carbon, biochar, and metals such as zero-valent iron coated palladium (Gomes et al. 2013). In a pilot study at Hunters Point Shipyard in San Francisco, CA, activated carbon added to the capping layer decreased the transfer of PCBs from sediment to the aquatic environment by 73% over the course of five years (Gomes et al 2013). CETCO®, a minerals technologies company, markets the *Reactive Core Mat (RCM)*, a cap which can be tailored to meet the specific needs of a remediation project by augmenting the additives included in the product.

Aquablok® and Aquagate® are two complimentary reactive containment technologies from Aquablok Ltd that can be used to form a “funnel and gate” system in sediment. Aquablock® acts as a low permeability barrier to contain wastes while Aquagate® allows specific treatment materials for bioremediation or phytoremediation to interact with contaminated sediment, thus improving the remediation outcome (AquaBlock 2014)**.**

***In situ* Sediment Ozonation (ISO)**

Medium: soil and sediment

In situ sediment ozonation (ISO) is a new technology developed by the University of Utah in cooperation with the National Oceanic and Atmospheric Administration (NOAA). ISO uses a floating rig equipped with ozone reactors and conveyors to remediate without dredging. Ozone has been shown to react with PCBs by forming more biodegradeable products as well as boosting biological activity in sediment or soil (Gomes et al. 2013). ISO enhances this process using pressure-assisted ozonation, which injects sediment with ozone and rapidly cycled pressure changes to increase the efficacy of the ozone (Hong 2008). The final report on the technology suggests that the materials to build ISO rigs are readily available in current dredging technology. Researchers have reported that contaminated sediment could be treated for as little as $50 per cubic yard using pressure-assisted ozonation compared to $75-$1,000 per cubic yard for other exisiting methods. This technology also naturally enhances biological activity and would be a logical choice to increase remediation efficieny of more passive technologies such as bioremediation or phytoremediation (Hong 2008).

nZVI Dechlorination

Medium: soil, sediment, and water

Nanoscale zero-valent iron remediation (nZVI) is primarily an *ex situ* treatment based on zero-valent iron (ZVI), a technology which has been used to clean up aquifers contaminated with a variety of chemicals. Where PCBs are concerned, ZVI works through dechlorination into less toxic and more biodegradeable constituents (Gomes et al. 2013). ZVI has been tested in the sediment of both the Housatonic River and New Bedford Harbor; however mixed results have prevented ZVI from mainstream implementation. nZVI improves upon ZVI through a reformulation using nanoparticles which exhibits superior reactivity and more consistent removal of PCBs in groundwater and soil (Mikszewski 2004). While nZVI can be used *in situ*, due to limited research on the effects of nanoparticles on the environment, most commercial and academic uses are conducted off-site. However, NASA currently licenses an associated technology, emulsified zero-valent iron (eZVI), and has demonstrated successfully removing a variety of contaminants both *in situ* and *ex situ* (Parrish 2013).

Solvent Extraction

Green PCB Removal from Sediments System

Medium: sediment

NASA scientists have developed a redeployable polymer blanket for *in situ* removal of PCBs in sediment systems. It is patented as the Green PCB Removal from Sediments System (GPRSS). The GPRSS blanket is filled with environmentally safe solvent (e.g. ethanol), which attracts PCBs. The PCBs migrate into the solvent-filled spikes inside the blanket. The blanket is then removed from the sediment, and the PCB-laden solvent is extracted from the blanket and treated *ex situ* using a derivative of the NASA's Activated Metal Treatment System (see section below) to break down the PCBs (Parrish 2013). Components of the GPRSS can be decontaminated and reused. The system can also be scaled up or down for various applications (DeVor et al 2014).

A recent field study showed that the GPRSS is capable of removing an average of 75% of PCBs by mass from contaminated sediments (DeVor et al 2014). Thus far, only laboratory size prototype units have been developed, so cost estimates are not yet available (Dr. Lewis Parrish, pers. comm.).

Activated Metal Treatment System (AMTS)

Medium: construction and paint materials

The Activated Metal Treatment System (AMTS) is a solvent solution developed by NASA to remove PCBs from paint, caulk, concrete, brick, and wooden surfaces (Parrish 2013). The AMTS has been extremely successful during *in situ* remediation of industrial facilities where PCBs were used widely as paints and sealants on storage tanks, buildings, and other structures. The product allows extraction of PCBs without removal of the structures whereupon the contaminants can be treated safely *ex situ*. While AMTS is primarily used for structure remediation, Bio Blend ® Technologies, a company currently licensing AMTS, is testing the technology in a variety of applications including *in situ* extraction of PCBs from soils and sediment (Parrish 2013). In a pilot study in Salem, Massachusetts, AMTS testing indicated that PCB concentrations in concrete decreased by as much as 78% in two weeks (Bio Blend).

Incineration

Medium: soil, sediment, water

Incineration is used to treat organic contaminants in both solids and liquids by exposing them to temperatures greater than 760º C in the presence of oxygen. This causes volatilization, combustion, and destruction of these contaminants (US EPA 2013). Incineration is most commonly used for complete destruction of PCBs. Specialized incinerators burn PCB-contaminated soils or sediments at temperatures up to 1200º C (Mikszewski 2004). EPA approved high efficiency incinerators to destroy PCBs with concentrations over 50 mg/kg (ppm) since 50 mg/kg is the maximum Toxic Substances Control Act allowance for PCBs in products. EPA also requires any incinerators burning PCB-contaminated soil and sediments to achieve the 99.999% Destruction and Removal Efficiency (or less than 1 mg/kg) required for PCBs (US EPA 2013).

In a 2011 study, a life cycle assessment was conducted to compare the environmental impacts of incineration and non-incineration technologies. Infrared High Temperature Incineration (IHTI) and Base Catalyzed Decomposition (BCD) were used to represent incineration and non-incineration, respectively. A midpoint/damage method using SimaPro 7.2 and IMPACTA2002+ methodology was adopted to produce a life cycle impact assessment (LCIA), where midpoint refers to any adverse effects occurring halfway through the remediation process, and end-point includes any adverse effects occurring at the end of the process. The LCIA evaluated human toxicity, ecotoxicity, resource consumption, and climate change impact for both technologies using a midpoint/end-point approach (Hu et al. 2011).

Based on the results, incineration can lead to a range of health and environmental impacts. For example, large volumes of water are required to cool the off-gas and absorbers. Incomplete combustion can lead to the generation of volatile and semivolatile organics (Hu et al. 2011). In a comparison of IHTI to BCD, BCD was found to have a lower environmental impact in the PCB contaminated soil remediation process based on life cycle assessment results. IHTI primary and secondary combustion subsystems were found to contribute more than 50% of midpoint impacts for respiratory inorganics and organics, carcinogens, terrestrial acidification, eutrophication, and ecotoxicity, and global warming. In comparison, the rotary kiln reactor subsystem in the BCD process was found to present the highest contribution to almost all the midpoint impacts including respiratory inorganics, non-carcinogens, terrestrial ecotoxicity, global warming, and renewable energy. Improvements in combustion efficiency could decrease the negative impacts on energy use and human health (Hu et al. 2011).

Incineration is applicable for both PCB-contaminated soils and liquids. In 1992-93, 34,000 tons of PCB-contaminated soil were destroyed using IHTI at the Rose Township Dump Superfund site in Michigan (Hu et al. 2011). However, the applicability of incineration to the remediation of PCB contaminated soils is limited by the concentrations and types of metals present. Incineration causes metals to vaporize and react to form other metal compounds or to remain in the soil residuals. If mismanaged, this can result in potential exposures and adverse health effects (US EPA 2013). When operating conditions do not meet strict temperature requirements, PCBs can be evaporated out (Hu et al. 2011).

Incineration can be costly. High energy consumption is needed in order to treat PCBs. For on-site incineration, no correlation exists between unit cost and quantity of material treated. Unit costs are potentially affected by other factors, including type of incineration, concentration of contaminants, maintenance needs, and soil type and characteristics of the matrix (Hu et al. 2011). A fixed PCB incinerator costs up to $2,300/ton of contaminated material (Mikszewski 2004). According to the Federal Remediation Technology Roundtable’s Remediation Technologies Screening Matrix and Reference Guide Version 4.0, the cost for removing PCBs through incineration varies from $695/cubic yard to $1,171/cubic yard depending on the total volume of waste (Japan International Cooperation Agency and Nippon Koei Co 2014).

Solidification and Stabilization

Medium: soil and sediment

Solidification and stabilization (S/S) involves adding a binding agent to the contaminated soil in order to convert the soil into an insoluble, less mobile, and less toxic form (US EPA Office of Wetlands 2011). S/S can be applied *ex situ* or *in situ* for soil or *ex situ* for sediment. For *ex situ* S/S, the soil is excavated, sorted to remove excess debris, and then mixed and poured with the stabilizer. The resultant slurry can be poured into molds and disposed of in waste management cells, injected into the subsurface environment, or reused as construction material with proper regulations. For the *in situ* process, S/S agents are usually injected into the subsurface environment and mixed with soil using backhoes or augers. While S/S can successfully immobilize PCBs, environmental conditions like extreme temperatures and acid rain can negatively affect the chemical stabilizer during S/S application (US EPA 2013), and degrade the stabilized mass over time, similar to concrete. Costs for *in situ* S/S range from $80 per cubic meter for shallow applications to $300 per cubic meter for deeper applications (Khan et al. 2004).

Thermal Desorption
Medium: sediment, sludge, filter cakes

Thermal desorption is a method that physically separates organic wastes from the solid matrix (sediment, sludge, and filter cakes) using temperatures high enough to volatilize the organic contaminants. Although thermal desorption is both an *ex situ* and *in situ* method, the more common and largest volume applications are on *ex situ* soils. Unlike other methods, thermal desorption is a physical separation process (US EPA 2013). Since this method uses heat to vaporize contaminants, it cannot be used to treat non-volatile contaminants. Applying heat to contaminated soil forces the wastes with low boiling points to turn into vapor, which are then be collected and treated (McCreery and Linden 2015).

There are three primary stages of a typical thermal desorption: materials preparation, desorption, particulate removal, and off-gas treatment. Treatment of off-gas is required for all thermal desorption systems in order to remove particulate and other contaminant emissions and vapors (US EPA 2013). Condensed liquid formed from cooling the off-gas is separated into aqueous and organic fractions. The water is used to cool the treated soils and prevent dusting. The organic fraction is removed from site. Depending on the composition, it is then either destroyed in an incinerator or is recycled as a supplemental fuel (Gomes et al. 2013). Removal of the organic fraction allows the soil to be used for other purposes without fear of contamination instead of having to dispose of the original soil in a landfill and bring in replacement soil (McCreery and Linden 2015).

The thermal screw and the rotary dryer are the two most common thermal desorption designs. Thermal screw units use screw conveyors or hollow augers that are used to transport the contaminated medium through an enclosed trough. Steam or hot oil moves through the auger to indirectly heat the medium. Rotary dryers are comprised of horizontal cylinders that are typically inclined and rotated and can be heated directly or indirectly. Of the two, the thermal screw design requires more waste pretreatment than the rotary dryer design and may be more expensive (US EPA 2013).

Temperature plays a vital role in the thermal desorption process. Thermal desorption processes can be categorized as high temperature thermal desorption (HTTD) and low temperature thermal desorption (LTTD). HTTD tends to reduce contaminants more thoroughly (to less than 5 ppm), although it causes many of the natural soil properties to be altered. LTTD preserves the organic components and physical characteristics of soil, thus allowing the soil to be reused and to support biological activity (McCreery and Linden 2015). However, thermal desorption is not particularly effective at separating inorganics from contaminated medium. This limitation can potentially cause problems at sites where PCBs and heavy metals coexist. High moisture content medium may result in lower contaminant volatilization and an increased need to dry the soil before treatment begins (US EPA 2013). Soils consisting of a majority of fine particles like clays and silts are undesirable for this treatment. Fine particles tend to be emitted as dust, which can clog and destroy the machinery used to collect the vaporized contaminants (McCreery and Linden 2015).

During a cleanup of the former Industrial Latex production site in Wallington, New Jersey, a “triple shell dryer” thermal desorption unit was used to reduce PCB concentrations to 0.16 ppm. A triple shell dyer is an indirect form of heated thermal desorption that uses a rotating cylindrical kiln to supply heat (McCreery and Linden 2015). In another example of indirect thermal desorption, scientists working on an assessment in China used a transportable indirect thermal dryer unit to remediate PCB-contaminated soils. This unit was successful in reducing total PCBs in soils from 163-770 µg/g to 0.08-0.15 µg/g, representing a removal efficiency of greater than 99.9%. Atmospheric emissions from the unit were in compliance with current PCB regulations. This method appears to be highly efficient and environmentally sound (Yang et al. 2014).

In a South West England case study, LTTD was found to be the most effective and commercially viable solution for field application. Thermal desorption was used to treat Aroclor 1254 contaminated soil at a telecommunications manufacturing facility. Thermal desorption led to a 48-70% decomposition of PCBs in sediments. However, it also led to the formation of polychlorinated dibenzofurans (PCDFs) (Gomes et al. 2013). Furans are similar to dioxin; they have similar chemical structure and health effects. One study found that children born to mothers specifically exposed to PCDFs had retarded growth and dysmorphic physical features, and during development they displayed delayed cognitive development and more behavioral problems than unexposed children (Guo et al. 2004).

Landfarming

Medium: soil, sediment, sludges

Landfarming is an *ex situ* biological treatment process that can be applied to contaminated soils, sediments, or sludges. A pilot-scale land treatment study used approximately one cubic meter of sludge and sediment materials of industrial waste containing PCBs. Results indicated that complete biostabilization can be achieved when reversibly sorbed PCB and PAH are biodegraded. Irreversibly sequestrated PCB and PAH remain immobile in soil particles. The study also showed that PCB degradation was caused by a combination of processes, volatilization, photolysis, and biodegradation, instead of just one process (Gomes et al. 2013).

Remediation Methods for Industrial, Wastewater, and Stormwater Effluent

Moving-Bed Biofilm Reactor

Medium: effluent

Biodegradation can be used as an effective method for removing PCBs from contaminated wastewater. A 2012 study assessed the performance of a combined moving-bed biofilm reactor and a membrane filtration system (MBBR-MF) for treating wastewater contaminated with PCBs. The MBBR method has several advantages, including sequential anaerobic-aerobic conditions more suitable for organic biodegradation. The complete mixture of biofilm and PCBs in the reactor makes the PCBs readily available to microorganisms, which enhances PCB degradation (Dong et al. 2012).

To avoid the complexity involved in studying several PCB congeners, PCB77 (3,3',4,4'-tetrachlorobiphenyl) was chosen to be used in a laboratory-stimulation sewage treatment MBBR system to identify possible PCB biodegradation pathways. Results demonstrated a PCB removal efficiency of 83-84% in an anaerobic-aerobic MBBR system. Gas Chromatography-Mass Spectrometry analysis confirmed the efficiency of the process. The removal efficiency was lower than that of the anaerobic or aerobic microbial degradation of PCBs using special microbial species; however, this data proves the ability of the relatively new MBBR process to degrade PCB77. Furthermore, the use of special microbial groups will enhance MBBRs to achieve even higher removal efficiency when treating PCB-contaminated wastewater. MBBR also has many desirable features, such as efficient operation and low energy consumption (Dong et al. 2012).

Membrane Bioreactor System

Medium: effluent

Researchers from the Centre de recherché industrielle du Quebec (CIRQ) and Institut national de recherché scientifique (INRS) were recently granted a U.S. patent for their newly developed wastewater treatment system. This system, known as the membrane bioreactor (MBR) system, removes emerging micropollutants from wastewater treatment effluent. Early studies have demonstrated that this technology is able to remove 99% of bisphenol-A (BPA) and similar compounds in contaminated water. The membrane bioreactor system is also capable of removing medications from effluent (Hays 2016).

A pilot test study used MBR as an enhanced secondary treatment method for the removal of PCBs in industrial and municipal effluent. Several individual congeners were analyzed. Effluent MBR concentrations were between <0.01 ng/L to 0.04 ng/L. Over 90% of PCBs were removed with the use of both a membrane filtration system and a MBR system (HDR 2013).

Natural Media Filtration

Medium: effluent

Sand filtration followed by granular activated carbon treatment is typically employed to remove PCBs and other contaminants from stormwater before it is discharged into receiving waters. However, these systems are less able to remove PCBs adhered to particles (Jaradat 2008).

Natural media filtration (NMF) systems are comprised of surface filters consisting of a natural medium, either live compost material or peat, instead of conventional media. These natural materials have a smaller pore size and larger, more hydrophobic surfaces than traditional counterparts, which may promote adsorption of dissolved PCBs and capture of particle-bound PCBs (Jaradat 2008). NMF can also be used to remove and sequester other hydrophobic organic compounds (HOCs), heavy metals, oils, greases, nutrients, and organics from an assortment of wastestreams (ROUX 2015).

Compost materials used in NMF have high humic content, or natural organic matter, which likely contributes to NMF having a very high capacity for adsorbing PCBs and other HOCs. Once adhered, the humic compounds are stable and insoluble with large molecular weights. Contaminant removal by ion exchange, filtration, biodegradation, adsorption, or by a combination of these processes occurs in the compost layer. The high nutrient content of the compost layer can support and possibly stimulate microbial degradation of PCBs and other HOCs. Therefore, the stimulated bacterial activity in a NMF filter is hypothesized to decrease PCB levels (Jaradat 2008). While biodegradation of less-chlorinated PCB congeners can occur, biodegradation decreases as degree of chlorination increases.

ROUX Associates, Inc. used NMF on a metal fabrication facility in Indiana. During bench scale and pilot scale studies, NMF had an 88% average PCB removal rate. PCB concentrations have been consistently under the 100 ppt analytical detection limit since the full scale NMF system began in 2007. The facility was able to reach an 86% savings in capital cost and 90% in annual operating cost when comparing NMF to conventional treatment alternatives. Benefits of NMF include low maintenance, superiority to traditional treatment methods, and cost-effectiveness (ROUX 2014).

Black Walnut Shell Filtration

Medium: effluent

Black walnut shell filtration was developed as a more suitable method of filtering free oil and suspended solids where sand and multi-media filters were traditionally used. Walnut shell filtration is broadly recognized for polishing oily water in downstream refineries, upstream oilfields, and power plant facilities (Exterran 2010). It can also be used to treat refinery wastewater, cooling water, and oil field water. Black walnut shells have surface characteristics that allow for excellent coalescing and filtration and attrition resilience (Siemens 2015).

Free oil and suspended solids are removed as water passes through the walnut shell media. The Monosep™ filtration system redirects process water 24 hours after filtration into the bottom of the Monosep's vessel to fluidize the media bed. Process gas or air is added to create an airlift pump, which lifts the contaminated media to the top of the vessel. Oil and suspended solids are separated from the walnut shells by the turbulence of the backwash water and gas (Siemens 2015).

Filtra Systems STiR uses a backwashable walnut shell media that is capable of removing both solids and oil and grease. Walnut shells are soft enough to provide a sufficiently complex flow-path for trapping suspended solids and hard and solid enough to be stable and long-lasting. Walnut shell media has a low specific gravity, thus allowing it to be easily fluidized. Since the STiR media is fluidized, approximately 100% of trapped particulates are removed. STiR filters use a mechanical mixer, which agitates the entire filter during the backwash cycle. This results in more efficient backwash operations than other media filters. STiR media has the following benefits over traditional media filters: media regeneration for the life of the product (20 years), ease of handling upset conditions, smallest backwash volume of any competing technology, and consistently high removal efficiency (US DOE 2011).

The U.S. Department of Energy (DOE) Kansas City Plant conducted a pilot study with STiR to see if the technology could potentially replace groundwater treatment systems in the future. Filtra Systems STiR was found to remove suspended solids and oils, thus preparing the water for final treatment of dissolved, volatile organic contaminants (US DOE 2011). During 25 days of operation, STiR frequently removed 100% of suspended solids from the effluent. Except during the “upset” conditions test, iron’s removal rate was greater than 90%. Other inorganics, such as calcium, manganese, and chloride, were not removed during STiR (US DOE 2011).

In some instances, the STiR vendor added a high molecular weight mineral or castor oil to the water stream to certify PCB removal. Because PCBs are hydrophobic, they will quickly separate in the oil as the waste stream moves through STiR. All of the oil is then removed by the walnut shell media during backwash. Numerous installations have found this method to be so effective that granulated activated carbon was not needed for final polishing of a PCB-contaminated waste stream (US DOE 2011).

According to the vendor, STiR has a general holding capacity of approximately 1 lb of suspended solids and 0.5 lbs of grease and oil per cubic feet. Based on this pilot study, a Mode STiR-12V will backwash 1200 gallons daily. Solids volumes will be 5% to 10% of the daily backwash volume. Operational costs based on electricity consumption are approximately $7.50/day or $2,733/year. A 2005 test found Filter Systems STiR to have an estimated $200,000 capital cost and an additional $6,900 worth of annual operating cost, which includes media replacement and related labor every three years, electricity supply, and periodic maintenance-related labor and parts replacement. For the Kansas City Plant, the recommended unit would cost an estimated $208,389 with an installation cost of approximately 15-20%of the capital equipment cost (US DOE 2011).

While the Filtra Systems STiR was used to treat groundwater, black walnut shell filtration systems have the potential to be used on wastewater treatment plant, stormwater, and industrial effluent, as seen in Spokane, WA to improve the health of the Spokane River.

StormwaterRx

Medium: effluent

StormwaterRx LLC offers Stormwater Management solutions for industry by designing, manufacturing, installing, and maintaining stormwater treatment best management practices (BMPs). StormwaterRx currently has two products available to treat PCBs in stormwater: Aquip® and Purus™ (StormwaterRx PCBs).

Aquip® is specifically designed to reduce turbidity, heavy metals, suspended solids, nutrients, and organics, including PCBs. It is a patented, enhanced media filtration system that is typically installed above ground with a single pump station. Aquip® uses passive filtration, so there are no chemicals or backwash, operates unattended, 24/7, and is a gravity flow-through system. Depending on the amount and type of contaminants present, Aquip® is available in several performance levels, each specifically designed to reduce suspended solids, heavy metals, turbidity, organics, and/or nutrients (StormwaterRx Aquip Filter).

URS analyzed collected treatment system influent and effluent water samples at a redacted site in early 2013. The site installed Aquip® in February 2012 to treat PCBs present in stormwater and groundwater seepage entering the basement of a building. An electric sump pump was installed to pump water from Sump A through Aquip® to remove the PCBs. Treated effluent is then plumbed back into an existing line for discharge. The StormwaterRx unit was equipped with effluent and influent sample ports for the collection of water samples (URS 2013).

Purus™ is a stormwater polishing system designed to treat different stormwater contaminants depending on the Purus™ configuration selected. The Purus™ Organic Polishing configuration is capable of treating turbidity and organics, such as PCBs. This system provides the most advanced level of stormwater treatment, so it is ideal for industries with more stringent or watershed specific water quality standards, or where higher concentrations of pollutants are unavoidable. It features flow matched to upstream treatment rates and can include slip-stream treatment configuration. Since Purus™ requires nearly clear influent, it is utilized after the Aquip® filtration system (StormwaterRx Purus Polisher).

Between December 2012 and April 2013, between 36,500 to 70,700 gallons of water flowed through the Purus™ treatment system. During the first sampling event in February 2013, Aroclor 1260 was detected at a concentration of 0.625 µg/L in the influent sample. No Aroclors were detected above the Method Detection Limit (MDL) of 0.0694 µg/L in the effluent sample. The April 2013 sampling event detected the following three Aroclors in the influent sample: 1242 at 0.105 µg/L; 1254 at 0.988 µg/L; and 1260 at 2.20 µg/L. No Aroclors were detected above the MDL of 0.0588 µg/L in the effluent sample. These results indicate that the treatment system is removing PCBs from the influent and producing effluent with non-detectable concentrations (URS 2013).

Chitosan-Enhanced Sand Filtration

Medium: effluent

North Boeing Field (NBF) located in Seattle, WA discharges a portion of its stormwater and base flows to the Slip 4 Early Action Area of the Lower Duwamish Waterway Superfund site. Sediments in Slip 4 are contaminated with PCBs and other pollutants. Boeing was required to address PCBs with short- and long-term stormwater treatment systems (Geosyntec 2011). The Long-Term Stormwater Treatment (LTST) system was designed using a Chitosan-Enhanced Sand Filtration (CESF) system, which removes all suspended solids and associated PCBs. While CESF does not remove PCBs adhered to total suspended solid (TSS) particles and then discharge clean particles back out to the effluent, it does effectively reduce the mass of PCBs and TSS in stormwater (Landau Associates).

Considering the size of the entire NBF drainage basin (303 acres), it was not feasible to treat all stormwater runoff from every storm event. Based on a cost benefit analysis, a sizing design based on 1,500 gallons per minute (gpm) was agreed upon by both Boeing and EPA. Therefore, a 1,500 gpm CESF system was chosen and will operate at full capacity whenever adequate stormwater is present. The Long-Term Stormwater Treatment CESF system is predicted to accomplish a 73% total PCB load reduction annually (approximately 96% in dry weather and 68% in wet weather). The LTST system treatment process will operate similarly to the Short-Term Stormwater Treatment (STST) system. The Short-Term Stormwater Treatment system includes coarse solids settling in aboveground settling tanks, coagulation of solids via chitosan acetate dosage, sand filtration through a bank of sand filter units to remove coagulated solids, and automated sequential backflushing of the sand filter units to maintain treatment capacity and PCB and TSS removal efficiency. This approach was successful for removing PCBs in water by the NBF STST system (Landau Associates).

Conclusion

While additional methods for treating *organic* contaminants exist, they are not suited for successfully remediating *organochlorine* compounds like PCBs and should not be considered. Examples of these technologies include natural attenuation, chemical oxidation, and certain thermal treatments. Natural attenuation is a passive remediation method that requires a large sediment influx to essentially burry contaminants but does not remove the contaminant from the environment (Gomes et al. 2013). Additionally, many chemical oxidation and thermal treatments are better suited for PAHs.

Some contaminated sites may be best suited for a mix of two or more remediation methods making up a “treatment train”. Contaminated materials can be “primed” by one type of remediation method, and then “polished” using another. For example, while chemical oxidation alone is not recommended to remediate PCBs, it can be used as a primer method to enhance subsequent pollutant removal during bioremediation methods. While there is much more scientific literature on individual treatments than combination treatments, recent trends towards adaptive management are gradually increasing the amount of literature on treatment trains (Cummings 2007).

Other sites may contain amounts of contaminated material that are too large to remove but too small to implement any of the above mentioned technologies. In these scenarios, implementation of best management practices (BMPs) could be the preferred remediation option.

Due to the widespread problem of PCB contamination, efficient and cost-effective remediation methods are highly sought after. Therefore, new methods and technologies to treat PCB contamination continue to be developed.

Table 1. Media and Applicable Remediation Technologies

(see attached file)

Table 2. Remediation Technologies Summary

(see attached file)

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Appendices

Appendix A: Previous Projects Addressing PCB Contamination

PCB contamination is a common theme for Superfund sites and other hazardous waste sites. Below we describe the remediation approaches taken at several different hazardous wastes sites across the U.S. where Environmental Stewardship Concepts, LLC has served as a technical advisor or been otherwise involved in cleanup efforts.

Bliss-Ellisville Superfund Site, MO: Contaminated soil at the Bliss-Ellisville site was removed and the area backfilled with clean soil and capped. The area was then reseeded to control erosion. Long-term groundwater monitoring was instituted for the site.

Charles River, MA: Remediation included excavation and off-site soil disposal. construction of a terrace wetland and breakwater structure, and mulching, seeding, and fertilizing along the river, and monitoring.

Clinch River/Poplar Creek, TN: Remediation for the contaminated sediments and biota at this site included the implementation of existing institutional controls to control potential sediment-disturbing activities, fish consumption advisories to reduce human exposure, annual monitoring to detect changes in contaminant levels and mobility, and a survey to confirm the effectiveness of fish consumption advisories.

Commencement Bay, WA: The selected remedy for this site included excavating source area soils and slag, disposal of source area soils and debris, capping of the entire site, demolishing remaining structures, and replacing the entire surface water drainage system. Continued monitoring was implemented, along with restrictions and guidelines to ensure that development activities do not impact the long-term effectiveness of cleanup.

Delaware River TMDL Phase 2 Development: The Delaware River Basin Commission (DRBC) has taken the lead in developing a PCB TMDL for the Delaware Estuary. The DRBC monitors ambient waters, sediments, and fish tissue for PCBs. In 2013, the DRBC updated their water quality criterion to 16 picograms/liter of water for PCBs in the Delaware Estuary. It is expected that the U.S. EPA will adopt new TMDLs to correspond to this new water quality criterion.

Fields Brook Wetlands, OH: The final remedial action selected for this site included the removal of contaminated soils through a combination of excavating with backfilling and landfilling, or covering of the contaminated soils. Institutional controls, access restrictions, and monitoring were also implemented.

Fox River, WI: A combination of dredging, capping, and sand covers was used to reduce fish contamination and the transport of PCBs from the Fox River into Green Bay and Lake Michigan as quickly as possible. Long-term monitoring and natural recovery after remediation were also implemented.

Hudson River, NY: The remediation plan for the Hudson River in New York included dredging, planting of submerged aquatic vegetation and riverine fringing wetland vegetation, and long-term monitoring. Cleanup work on the floodplains has not begun.

Lower Duwamish River, WA: The final cleanup plan for the Duwamish River included a mix of technologies. Dredging, capping, enhanced natural recovery, and monitored natural recovery were all implemented. Source control of upriver and floodplain areas has been underway for some years.

New Bedford, MA: Remediation at this site included the removal of PCB-contaminated sediment into confined disposal facilities (CDFs). The capped CDFs are monitored and will be maintained over the long term. Institutional controls, such as seafood advisories and educational campaigns, had to be instated to protect human health.

New London Submarine Base, CT: The selected remedy for site remediation consisted of excavation of contaminated sediment, restoration of excavated areas to pre-existing elevations, and seeding the restored area to establish native wetland vegetation. After the initial remedial actions, the area was monitored to ensure that the native wetland vegetation had been established, and land use controls were implemented.

Pine River/Velsicol Superfund Site, MI: PCBs, PBBs and other chemicals in the Pine River were initially cleaned up using a combination of dredging, dewatering, and installation of sheet piling. The first remedy was not successful, owing to recontamination from the plant site source. A range of soil and groundwater remedies is planned.

Sangamo Weston/Twelve Mile Creek/Lake Hartwell, SC: The remedy chosen for this site included the excavation/dredging of PCB impacted soils and debris, installation of groundwater recovery and treatment systems, fish consumption advisories, regular flushing of sediments trapped behind the three impoundments, re-establishment of aquatic habitat and native vegetation, bank stabilization, and annual monitoring. A public program to increase awareness of the advisory and methods to prepare and cook fish was also implemented.

Spokane River, WA: PCB-contaminated sediments behind a dam on the Spokane

River were contained using a three-layer cap consisting of coal, sand, and gravel. Contaminated soil from other areas of the Spokane River cleanup was contained in waste repositories. Fish advisories were also implemented to protect human health.

Appendix B: Complete Search Results

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