PCB BIOACCUMULATION FACTORS IN POTOMAC ESTUARY FISH

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ABSTRACT

Species-specific bioaccumulation factors for polychlorinated biphenyls (PCBs) were developed for fish in the interstate Potomac River estuary, including tidal fresh waters. Bioaccumulation factors relating fish to water column (total BAFs) and sediment (SedBAFs) were calculated from recent PCB data collected by or for Virginia, Maryland and the District of Columbia agencies. Resident species exhibiting the strongest tendency to accumulate PCBs, as indicated by the high total BAFs and SedBAFs, were channel catfish, gizzard shad, pre-migratory striped bass, and common carp. When total BAFs and SedBAFs are normalized to fish lipid content and freely-dissolved water column PCBs or sediment organic carbon content, the species most susceptible (sensitive) to accumulating PCBs from their environment include pre-migratory striped bass, largemouth bass, and channel catfish, and possibly white catfish, bluegill sunfish, and pumpkinseed sunfish. PCB gradients occur in the different media with the highest PCB concentrations in the Washington metropolitan area. PCB concentrations in fish tissue, water column, and sediment appear to be approaching, or at, steady state in the tidal system. Virginia, Maryland and the District selected target species and used their BAFs (adjusted to a common condition) to establish water and sediment target concentrations for the tidal Potomac TMDL. The water quality standard for PCBs is about equal to the BAF-based water column PCB target in the District, but is 1.5 times higher in Maryland and 26.6 times higher in Virginia. Hence, fish failing the fish tissue threshold are found in waters that pass the water quality standard.

INTRODUCTION

Water column and surface sediment targets for PCB concentrations can be derived by dividing a jurisdiction's fish tissue screening threshold by some factor that represents the fish's ability to absorb and retain PCBs. US Environmental Protection Agency guidelines (EPA 2003) recommend developing a bioaccumulation factor (BAF) for persistent hydrophobic chemicals such as PCBs. This factor, called a "total" BAF, is the ratio of the PCB concentration in an organism's wet tissue to its concentration measured in waters where both the organism and its food and environment are exposed to PCBs. Another factor, the SedBAF, relates fish PCB concentration to sediments rather than water. Bioaccumulation factors depend on an assumption that PCBs in fish tissue, water, and sediments are relatively stable over months or years. Total BAFs and SedBAFs were developed and used to establish water column and sediment PCB targets for the tidal Potomac PCB Total Maximum Daily Load (TMDL) study (Haywood and Buchanan 2007). A fate and transport model (LimnoTech 2007) was run to determine PCB loading rates that result in the targets being achieved everywhere in the estuary. This paper summarizes how the BAFs were developed and further examines the results.

METHODS

Total BAFs and SedBAFs were calculated for 23 and 21 species, respectively, from the available fish tissue (2000-2005), water column (2002-2006), and surface sediment (2000-2005) PCB data for the Potomac estuary. Samples were collected by or for the Virginia Department of Environmental Quality, Maryland Department of the Environment, and the District of Columbia Department of the Environment, and analyzed for PCBs by Chesapeake Biological Laboratory, Virginia Institute of Marine Science, or the US Fish & Wildlife Service (ICPRB 2007). Only fish samples collected in tidal waters were used in the analysis. Each fish sample (n = 204) was assigned a trophic level of predator (primarily piscivorous), planktivore (consumes primarily phyto- and/or zooplankton), or benthivore-generalist (opportunistic foragers consuming stream "drift" and/or benthic invertebrates), and a home range radius of 2, 5, or 10 miles, depending on species characteristics. Striped bass less than 560 mm were included because they have typically not begun to migrate (Setzler-Hamilton and Hall 1991).

Each fish sample was associated with all water column and sediment PCB data in the area within a radius equal to the home range radius of the species. Median values of water and sediment data collected in each Potomac PCB model segment were calculated; then the means of all values for model segments wholly or partly inside each home range radius were calculated. This approach weighs the available data more evenly across the home range than a grand average. Due to the hydrophobic nature and high partition coefficients of PCBs, EPA (2003) recommends using the average of multiple water or sediment samples taken in the fish's habitat over sufficiently long time periods. Individual fish samples in the 2000-2005 period could be associated with as many as 46 water column or 81 sediment samples in the frequently sampled Washington DC metropolitan area. However, the median number of ambient water column and sediment samples available to calculate the factors was 2.5 and 2, respectively, for species with 2 mile home range radiuses, 6 and 3 for species with 5 mile home range radiuses, and 13 and 6 for species with 10 mile home range radiuses.

Total PCB (tPCB) concentrations in fish were used as reported. Significant inter-laboratory differences in recovery of PCB homologs 1 and 2 prevented the used of water and sediment tPCBs concentrations as reported. To use all available homolog 3-10 (PCB3+) data, water column and sediment tPCB concentrations were derived by dividing the reported PCB3+ concentrations by 0.92 (water column) or 0.90 (sediments).

Total BAFs were calculated for each fish sample using Equation 2-2 in EPA (2003):

$$\text{Total BAF} = \frac{[\text{tPCB}]_{\text{tissue}}}{[\text{tPCB}]_{\text{water}}} \tag{1}$$

where $[\text{tPCB}]_{\text{tissue}}$ is tPCB concentration in fish wet tissue (ng/kg) and $[\text{tPCB}]_{\text{water}}$ is the water column tPCB concentration in the fish's home range area (ng/liter). Total BAFs for PCBs vary depending on the individual lipid concentrations of each fish and the water column concentration of freely-dissolved PCBs in the home range area. Total BAFs were normalized to each sample's fish lipid content and the freely-dissolved PCB concentration, and the resulting baseline BAFs were used to quantify each species' sensitivity to PCB bioaccumulation. The baseline BAF is calculated using Equation 2-3 in EPA (2003):

$$\text{Baseline BAF} = \frac{[\text{PCB}]_{\text{tissue}} / \%\text{lipid}}{[\text{PCB}]_{\text{water}} \cdot \%\text{fd}} = \left[\frac{\text{totalBAF}}{\%\text{fd}} - 1\right] \cdot \frac{1}{\%\text{lipid}} \qquad (2)$$

where %fd is the fraction of the total PCB concentration that is freely-dissolved in the water column in the fish's home range area, and %lipid is the fraction of tissue that is lipid in the fish sample. The fraction of freely-dissolved PCB is related to dissolved and particulate organic carbon concentrations in the water column, and was calculated with equation 4-6 in EPA 2003. Ambient values ranged from 9% - 50% in water column samples associated with the tidal fish tissue samples, with a median value of 29.2%. For the purpose of comparing species across different environmental conditions, the median of each species' baseline BAFs was normalized to a common condition, i.e., the median lipid content of the species and a freely-dissolved PCB concentration representative of the ecosystem:

$$\text{Adjusted total BAF} = ((\text{median baseline BAF} \cdot \text{median }\%\text{lipid}) + 1) \cdot 0.292 \qquad (3)$$

The resulting adjusted total BAF for each species has no variability due to individual differences in lipid content or to spatial or temporal differences in freely-dissolved PCB concentrations.

The SedBAF, or sediment BAF, relates fish tissue and surface sediment PCBs and, like the total BAF, it reflects the fish's exposure to all relevant exposure routes. SedBAFs can be used to confirm the total BAF results or to predict total BAFs when water column concentrations of PCBs are low or variable and hence difficult to measure (EPA 2003). The SedBAF is calculated by dividing the fish tissue PCB concentration (ng/g wet weight) by the sediment PCB concentration (ng/g sediment dry weight). SedBAFs vary depending on individual lipid concentrations and the sediment fraction of organic carbon (%SOC) in the home range area. SedBAFs were normalized to each sample's fish lipid content and the area's %SOC (Equation 2-14 in EPA 2003). The resulting biota-sediment bioaccumulation factors, or BSAFs, serve as a second measure of each species' sensitivity to PCB bioaccumulation. An adjusted SedBAF for each species was derived by normalizing the median of the species' BSAFs to the median lipid content of the species and a %SOC of 2.85%, representing the ecosystem:

$$\text{Adjusted SedBAF} = \text{median BSAF} \cdot (\text{median }\%\text{lipid} / 0.0285) \qquad (4)$$

RESULTS

Species-specific total BAFs, baseline BAFs, and adjusted total BAFs are presented in Table 1 and SedBAFs, biota-sediment BAFS (BSAFs), and adjusted SedBAFs are presented in Table 2. Total BAFs for fish species inhabiting tidal waters of the Potomac River are variable, with values in an individual species ranging as much as 40-fold (Figure 1). Species median values in liter per kg tissue wet weight range 34-fold from 16,200 (brown bullhead catfish) to 548,000 (gizzard shad). The baseline BAF values indicate pre-migratory striped bass, largemouth bass, and channel catfish, and possibly white catfish and the bluegill and pumpkinseed sunfishes are most sensitive to PCB bioaccumulation, or most readily absorb and maintain PCBs from their environment. The latter three species are less certain because sample sizes are small.

SedBAF values within each species vary proportionally as much as the total BAF values.

Sediment PCB concentrations are generally believed to be less changeable over time than water column PCB concentrations, so the SedBAF variability is likely related to the spatial gradients apparent in sediment PCB concentrations. For example, the Anacostia sediments have distinct local hot spots adjacent to the Washington Navy Yard and below Watts Branch (Haywood and Buchanan 2007). Median SedBAF values, in g sediment dry weight per g wet weight tissue, ranged 32-fold from 0.22 (black crappie) to 7.08 (channel catfish). BSAFs indicate pre-migratory striped bass, largemouth bass, channel catfish, and common carp and possibly white catfish and bluegill sunfish most sensitive to PCB bioaccumulation (Table 2).

DISCUSSION

The variability evident in the individual total BAFs (Figure 1) and SedBAFs is expected for several reasons. Fish tissue PCB concentrations, the numerator in the BAF equation, vary depending on the lipid content and food habits of each individual fish. Benthic food pathways typically expose fish to higher PCBs than planktonic pathways. Seasonal changes in fish lipid contents and food habits will affect tissue concentrations. Concentrations of water and sediment PCBs, the denominators in the BAF equation, vary spatially in the Potomac estuary due to uneven external loadings. The highest concentrations are found in tidal freshwater around and just downstream of the Washington DC metropolitan area (Haywood and Buchanan 2007). Fish moving in their home ranges may experience different levels of PCBs depending on their geographic location. Small numbers of water and sediment samples used in calculating the denominator also adds to uncertainty in the BAF estimates. The non-normal distributions of the BAFs and SedBAFs suggest the median is a better measure of central tendency than the arithmetic mean. Until more samples are collected, most confidence should be placed in species BAFs and SedBAFs derived with larger sample numbers: channel catfish, white perch, largemouth bass, common carp, pre-migratory striped bass, and gizzard shad.

Bioaccumulation that approximates a steady state condition, where fish tissue and ambient PCB concentrations are relatively constant over the life time of the fish, increases the predictive value of the BAFs (EPA 2003). Steady states can occur before equilibrium is reached between external loads and ambient conditions, a process that will take an estimated 50+ years in the tidal Potomac (LimnoTech 2007). The tidal Potomac system may be close to, or at, steady state conditions. When PCB tissue concentrations for the six most sampled species (above) are grouped into three relatively homogenous regions, there are no consistent differences and few significant differences between 2000-2002 and 2003-2005 (Figure 2). The three regions are the Anacostia River, the tidal fresh (upper) Potomac and tributaries, and the oligohaline-mesohaline (middle-lower) Potomac and tributaries. Similarly, no consistent differences in sediment concentration are seen at the few river locations where 2000 data overlap 2003 and 2005 data. Finally, values of another indicator of steady state, the sediment-water quotient (Π_{socw}) to *n*-octanol water partition coefficient (K_{ow}) ratio (EPA 2003), support the assertion of steady state conditions. Medians of the ratios computed for the Anacostia, upper Potomac and middle-lower Potomac regions all fell between 2 and 10, values that indicate a steady state.

The baseline BAF which references water column PCBs and the BSAF which references sediment PCBs both characterize the sensitivity of a fish to PCB exposure from all pathways. The correlation coefficient between 181 paired values of baseline BAFs and BSAFs from all

Table 1. Species-specific total BAFs (Eqn. 1), baseline BAFs (Eqn. 2), and adjusted total BAFs (baseline BAF normalized to each species median lipid fraction and a single, representative freely-dissolved PCBs fraction of 29.2%). * Species with highest baseline BAFs.

Trophic Level	Species	n	Total BAF (median)	Baseline BAF (median)	Lipid fraction (median)	Adjusted total BAF
			liter/ kg wet wt	liter/kg lipid		liter/ kg wet wt
planktivore	Gizzard Shad	12	548,000	9,790,000	0.296	845,000
benth/gen	Channel Catfish	37	306,000	* 20,000,000	0.058	341,000
predator	Striped Bass (Pre-Mig)	13	259,000	* 38,000,000	0.024	268,000
benth/gen	Common Carp	17	240,000	8,940,000	0.055	144,000
benth/gen	Pumpkinseed Sunfish	5	53,800	* 26,800,000	0.013	103,000
predator	White Perch	26	65,500	10,500,000	0.027	82,000
benth/gen	Yellow Perch	2	69,000	11,900,000	0.022	77,700
benth/gen	Mummichog	3	50,900	3,600,000	0.062	65,700
predator	Atlantic Croaker	4	51,500	843,000	0.266	65,500
predator	Largemouth Bass	19	91,300	* 26,200,000	0.008	61,500
benth/gen	White Catfish	3	112,000	* 26,100,000	0.008	58,700
planktivore	Bluegill Sunfish	3	38,600	* 27,900,000	0.007	57,100
predator	Black Crappie	1	98,900	5,750,000	0.032	54,000
predator	American Eel	9	66,600	1,540,000	0.090	40,400
predator	Blue Catfish	3	38,700	5,400,000	0.025	38,800
benth/gen	Brown Bullhead Catfish	5	16,200	5,940,000	0.022	38,500
planktivore	American Shad	3	54,700	1,250,000	0.104	38,100
benth/gen	Spot	9	23,500	814,000	0.138	32,700
predator	Bluefish	8	24,900	1,880,000	0.051	28,100
benth/gen	Green Sunfish	1	47,900	380,000	0.190	21,000
predator	Grey Trout (Weakfish)	1	18,400	370,000	0.186	20,100
benth/gen	Yellow Bullhead Catfish	2	22,500	2,680,000	0.024	18,500

Table 2. Species-specific SedBAFs (Eqn. 3), BSAFs (Eqn. 4), and adjusted SedBAFs (BSAF normalized to each species median lipid fraction and a single, representative sediment organic fraction of 2.85%). * Species with highest BSAFs.

Trophic Level	Species	n	SedBAF (median)	BSAF (median)	Lipid fraction (median)	Adjusted SedBAF
			g sed dry wt/ g wet wt	g SOC/ g lipid		g sed dry wt / g wet wt
benth/gen	Channel Catfish	39	7.08	* 3.68	0.058	7.52
benth/gen	Common Carp	13	4.44	* 3.04	0.055	5.87
predator	Striped Bass (Pre-Mig)	13	4.77	* 4.84	0.032	5.40
planktivore	Gizzard Shad	9	6.27	0.404	0.296	4.19
predator	American Eel	9	2.57	1.10	0.090	3.46
predator	White Perch	26	1.47	1.91	0.027	1.79
predator	Grey Trout (Weakfish)	1	1.64	0.254	0.186	1.66
planktivore	Bluegill Sunfish	2	1.34	* 5.36	0.007	1.32
predator	Largemouth Bass	17	1.59	* 4.57	0.008	1.29
predator	Blue Catfish	3	1.37	1.47	0.025	1.27
predator	Atlantic Croaker	4	1.36	0.124	0.266	1.16
benth/gen	Pumpkinseed Sunfish	5	1.37	* 2.30	0.013	1.06
predator	White Catfish	3	2.09	* 3.88	0.008	1.05
benth/gen	Brown Bullhead Catfish	4	0.846	1.28	0.022	1.00
benth/gen	Spot	9	0.675	0.172	0.138	0.830
benth/gen	Yellow Perch	2	0.683	1.02	0.022	0.801
planktivore	American Shad	3	1.07	0.204	0.104	0.747
benth/gen	Yellow Bullhead Catfish	2	0.560	0.864	0.024	0.716
predator	Bluefish	8	0.869	0.333	0.051	0.597
benth/gen	Mummichog	2	0.655	0.237	0.062	0.519
predator	Black Crappie	1	0.222	0.180	0.032	0.203

locations in the estuary was 0.67 ($p << 0.01$). This good agreement indicates BSAFs in the tidal Potomac could be used to predict total BAFs, as suggested by EPA (2003), when the distribution of PCBs in sediment and water is known. When species baseline BAFs and BSAFs are ranked and the ranks averaged, the most sensitive of the well sampled ($n>10$) species in tidal waters is pre-migratory striped bass followed by largemouth bass, channel catfish, and common carp. Although less well sampled, bluegill sunfish, white catfish, and pumpkinseed appear to be sensitive species also. There is some evidence of biomagnification in the baseline BAF and BSAF results: three of the seven most sensitive species are predators.

Four of the seven sensitive species—largemouth bass, white catfish, and bluegill and pumpkin sunfish—do not have high total BAF or SedBAF values (Tables 1 and 2). These species, all commonly found in tidal fresh and nontidal waters in the Potomac basin, have low lipid fractions ($\leq$1.3%) and will exhibit low PCB contamination on a wet weight basis. Conversely, gizzard shad with a moderate sensitivity to PCB accumulation but very high lipid content has the highest total BAF and second highest SedBAF. Common carp, channel catfish, and pre-migratory striped bass also have high BAFs. These latter species stand out as ones exhibiting the strongest responses to PCBs, a consequence of their particular combinations of lipid content, PCB exposure pathways, and sensitivity to PCB bioaccumulation.

Species comparisons across the variety of Potomac tidal waters are improved when total BAFs and SedBAFs are adjusted to a single condition with respect to water column freely-dissolved PCB concentration and sediment organic carbon content. This removes variability caused by different water-sediment PCB distributions. The noticeable differences between the adjusted and unadjusted BAFs of some species (Tables 1 and 2) are the result of dissimilar sediment-water PCB distributions at the tidal Potomac fish sampling sites. In the urban Anacostia River, PCB concentrations normalized to units of particulate organic carbon are about 2.9 times higher in the sediments than the water column. In the upper, tidal fresh Potomac River, carbon-normalized PCB concentrations in the water column and sediments are about equal. In the middle-lower tidal Potomac, water column PCBs are slightly higher than sediment PCBs and both decline with distance downstream. Adjusting the BAFs changes the rankings of the species, but the four species with the highest total BAFs and SedBAFs, i.e., channel catfish, gizzard shad, pre-migratory striped bass and common carp, retain the highest ranks.

The Virginia, Maryland, and District of Columbia agencies developing the tidal Potomac TMDL each selected a target fish species and used the species' adjusted total BAF and adjusted SedBAF to calculate target PCB concentrations for the water column and sediments, respectively, in their jurisdictional waters (Table 3). The target species were those sampled by the jurisdiction with the highest total BAF or SedBAF values. Maryland and the District did not select gizzard shad as the target species for their total BAFs because they currently do not measure PCBs in that species. PCB TMDL loads that lead to attainment of these PCB target concentrations will be protective of the target species and all species with lower BAFs. The current water quality standard for PCBs is about equal to the BAF-based water column PCB target in the District and 2.5 times higher in Maryland however it is 26.6 times higher in Virginia. As a result of this difference, approximately 53% of the Virginia tidal Potomac fish samples that violated the state's fish tissue threshold were found in waters that did not violate the state's current water quality standard.

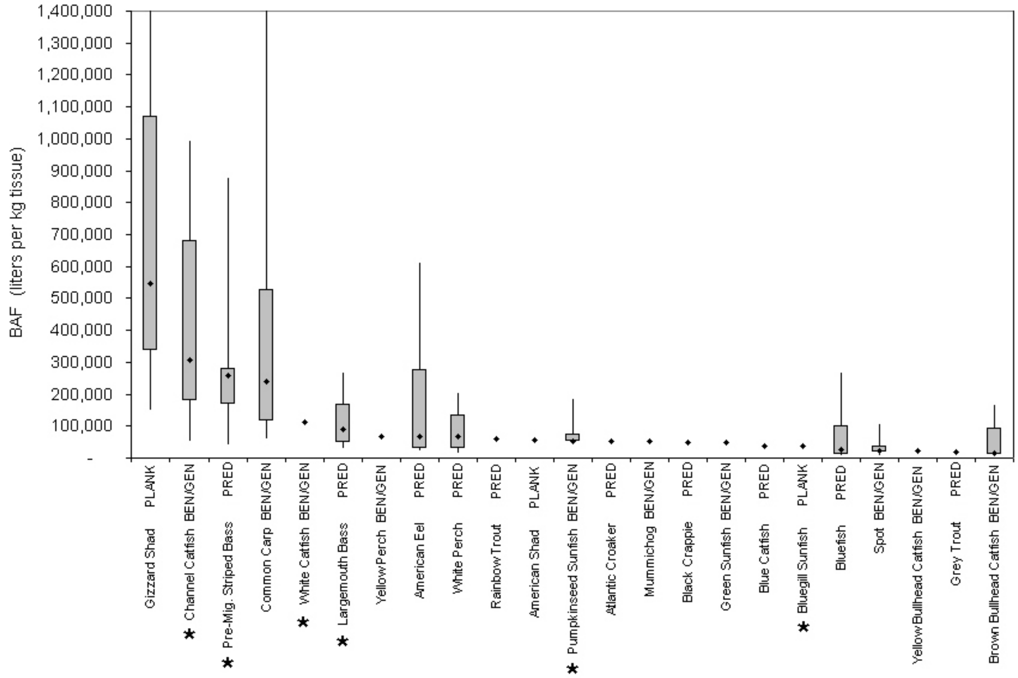

Figure 1. Total BAFs. Lines, 5th% - 95th%; boxes, 25th% - 75th%; dot, median.
*** Species with highest *baseline* BAFs are most sensitive PCB accumulation.**

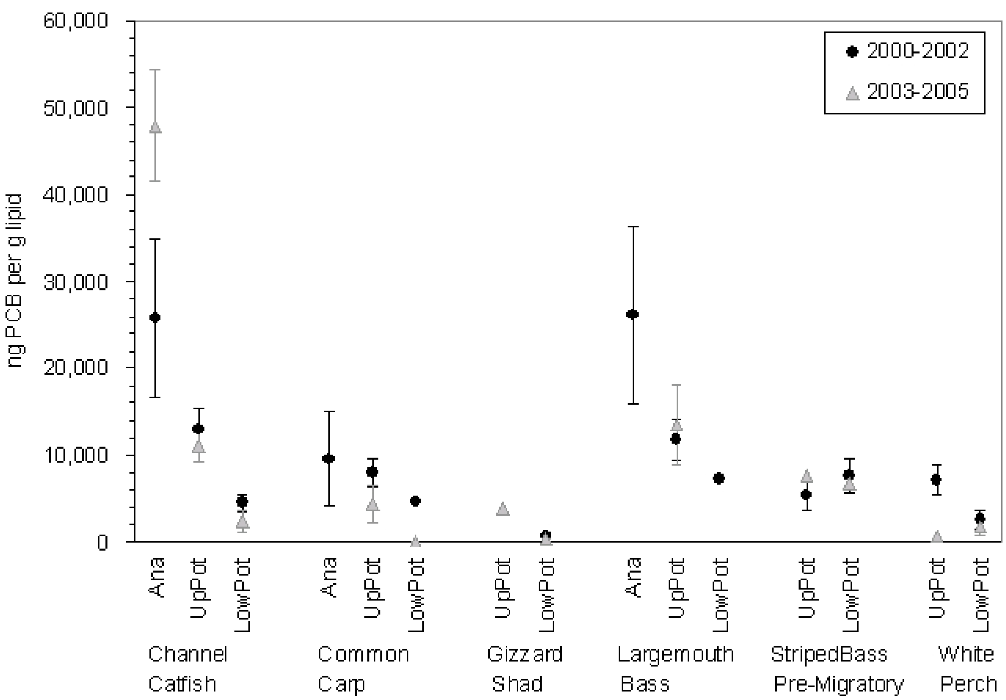

Figure 2. Comparison of 2000-2002 and 2003-2005 average PCB concentrations normalized to units of lipid for the six most frequently collected fish species in the tidal Anacostia R (Ana), the upper tidal Potomac R mainstem & tributaries (UpPot), and the middle and lower tidal Potomac R mainstem & tributaries (LowPot). Standard error is shown for sample n > 2.

Table 3. Jurisdiction current fish tissue thresholds and water quality standard criteria for PCBs, and BAF-based water column and sediment PCB targets.

Juris.	Current Fish Tissue Threshold, ng/g wet wt	Current Water Quality Standard Criteria, ng/liter	Calculated Water Column Target, ng/liter (Target Species)	Calculated Sediment Target, ng/g sed dry wt (Target Species)
DC	20	0.064	0.059 (channel catfish)	2.7 (channel catfish)
MD	88	0.64	0.26 (channel catfish)	12 (channel catfish)
VA	54	1.7	0.064 (gizzard shad)	7.2 (channel catfish)

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