COMMENTARY

Bias in the US Environmental Protection Agency's Baseline Health Risk Assessment Supporting the Decision to Require Dredging of PCB-Bearing Sediments from the Hudson River

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The US Environmental Protection Agency's (EPA) baseline Hudson River health risk assessment (HRA) is evaluated and found to be biased toward keeping polychlorinated biphenyls (PCBs) in sediments. The HRA systematically misquantified parameters, underestimating PCB movement from sediments to water and from water to air. The EPA excluded from its analysis all mono- and dichlorinated PCB congeners, which EPA subsequently estimated at one-third of total PCB mass in the river, and excluded dissolved and colloidal PCB. The EPA included silt-adsorbed PCB, but overestimated the rate at which it would settle out of the water column by inappropriately basing the rate on Stokes' Law for more massive spherical particles. Flat clay particles settle more slowly with a longer path length and residence time. The EPA omitted electrostatic charges on clay particles that separate them, preventing agglomeration and maintaining clay in suspension; they also assumed that particles never "reflect" back into the water column after settling, likewise underestimating PCB concentrations in water. Also omitted was PCB codistillation, in which PCBs at low bulk concentrations preferentially distribute to the air-water interface, accelerating PCB transfer from water to air. Indeed, EPA cited empirical data showing more rapid PCB water-to-air transfer, but reduced its effect on the HRA, reducing the transfer coefficient by averaging in lower modeled PCB transfer coefficients that ignored codistillation. Finally, EPA omitted PCB release to the atmosphere from hot water in cooling towers in communities along the Hudson River. Water at cooling tower temperatures may release PCB into the air more than 10 times faster than rates determined from the surface of cold water and multiple orders of magnitude more rapidly than in EPA's models. Together, EPA's procedures reduced airborne PCB concentrations from above to below *de minimis* concentrations. This, in turn, eliminated the requirement for EPA's HRA to quantify inhalation risks posed by airborne PCBs; the HRA, therefore, considered airborne PCBs, but attributed zero health risk to them.

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History and Administrative Procedure

From 1947 to 1977, the General Electric Company (GE) used polychlorinated biphenyls (PCBs; see Figure 1) at Hudson River facilities in Hudson Falls and Fort Edward, directly and indirectly discharging permitted and non-permitted PCBs into the river. These PCBs adhered to river sediments and were transported widely (US Environmental Protection Agency, 2006a). Available records, which were later used to inventory PCBs discharged from GE's two plants during this interval, produced estimates of direct discharges reaching 1,330,000 pounds (6.0×10^5 kg). The actual amount is unknown. Indirect discharges and discharges by other parties and from other sources would be incremental. If the preponderance of disposal was to land, then indirect discharges to the river could have exceeded direct discharges.

PCBs, detected in fish in 1969, were banned from manufacture and commerce in 1974 with passage of the Toxic Substances Control Act. In 1975, the New York State De-

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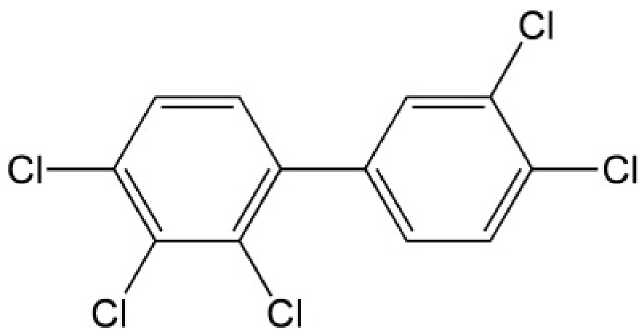

Figure 1. A pentachlorinated PCB congener.

partment of Health issued health advisories to limit consumption of PCB-laden fish, and the New York State Department of Environmental Conservation successfully sued to force GE to study PCB contamination and abatement. Dredging thereby became an administrative issue. In 1984, the US Environmental Protection Agency (EPA) added the Hudson River PCBs Superfund Site to the National Priorities List (NPL), thereby requiring study and possibly remediation under the 1980 Superfund Law.

The 1984 NPL listing decision produced a Record of Decision in which EPA asserted the eventual need to address PCB contamination in the Upper Hudson River. The Record of Decision specified an interim decision, however, to require "No Action" to remediate PCB in sediments, based upon EPA uncertainty about the reliability and effectiveness of available remedial technologies. Accordingly, in 1991 the remediation issue was revisited via a reassessment *Remedial Investigation and Feasibility Study*. Numerous documents support site reassessment, and their full text is available on the Internet (see US Environmental Protection Agency, 2006b). In February 2002, EPA issued a new Record of Decision requiring GE to dredge PCB-contaminated sediments from the Upper Hudson River, beginning with a demonstration project to evaluate the dredging approach.

Purpose, Scope, and Overview

Administrative procedure under Superfund involves interested parties (stakeholders), by design introducing politics into EPA administrative procedure. The present study addresses the question of whether, despite political influence, dredging is justifiable by the science of health risk assessment (HRA). The EPA apparently justified its decision to require dredging based upon a baseline assessment of PCB risks, not an assessment quantifying PCB risks potentially posed under dredging scenarios (US Environmental Protection Agency, 1999, 2000a, 2000b). An HRA should compare potential risks under specific dredging scenarios with baseline risks following completion of the demonstration dredging project. For this comparison process to be valid, baseline risks potentially posed by all relevant exposure routes, including PCB inhalation, should have been estimated in a valid and unbiased manner. The present study addresses this issue.

Selection of Parameters

The issue of bias must be addressed via evaluation of a fair, rather than a biased, selection of EPA's parameters. A *random* selection of parameters is neither required nor appropriate; we focus narrowly upon *mis-estimated* parameters. Accordingly, our procedure was to evaluate EPA's analysis and systematically ignore all parameters whose use by EPA was technically justified. Parameters of interest to us are not those of greatest *a priori* concern (quantitatively most important in determining risk). In our investigation, parameters that were accurately estimated were dropped from concern, no matter how important they might have been quantitatively in determining risk. We identified nine parameters whose evaluation by EPA was found to be technically deficient. In short, we did not "cherry-pick" parameters to bias our analysis in a particular direction. Our analysis, of course, is verifiable against cited EPA documents.

The Criterion of Bias

The bias issue is addressed qualitatively, as well as supported and augmented quantitatively (statistically). Both approaches rely on the simple premise that the direction of errors in analyses of independent (non-covariant) parameters approaches randomness as the number of parameters increases. Randomness of error direction, therefore, is the null hypothesis. Its rejection is justified technically if a low-probability pattern of error directions is observed, such as mis-estimation of a large number of independent parameters in a consistent direction, either permissive to dredging or contraindicating dredging. Observing such a low-probability distribution of error directions, whether or not based upon quantitative (statistical) analysis, would support the conclusion of bias, although not necessarily of intentional bias.

The Public Policy Issue

Under a consent decree, GE would pay the lion's share of Hudson River restoration costs. The costs, measured in hundreds of millions of dollars initially and probably over a billion dollars cumulatively for limited PCB "hotspot" dredging, make the Hudson River a sediment "megasite." Projected remedial costs far exceed median costs for sediment sites and far exceed costs ranging from $19,000 to $812,000 per project paid for achieving the various goals of 37,099 river restoration projects listed in the National River Restoration Science Synthesis database (Bernhardt et al., 2005). For example, median costs for instream habitat improvement projects were reported to be $20,000; for water quality management, $19,000; and for channel reconfiguration, $120,000. These costs impart urgency to the task of revealing any bias, or resolving any appearance of bias, in the scientific analyses informing the dredging decision.

The Public Health Issue

Adding to the urgency of evaluating possible bias, PCBs have been associated with numerous adverse human health effects (Agency for Toxic Substances and Disease Registry, 2000; Buckley and Tofflemire, 1983; Carpenter, 1998; Carpenter, 2005; Carpenter et al., 2003; Chase et al., 1982; Choi et al., 2003; Hennig et al., 2002; Lucier, 1991; Slim et al., 1999; Stehr-Green et al., 1989; Taylor, Stelma, and Lawrence, 1989). Effects include higher incidence of low-birth-weight infants among residents of zip codes of PCB disposal sites (Baibergenova et al., 2003) and, more recently, higher hospitalization rates for coronary heart disease in zip codes with PCB contamination (Carpenter, 2005). PCBs are animal carcinogens and probable human carcinogens (Agency for Toxic Substances and Disease Registry, 2000).

Confounding Issues

Dredging has become confounded with equity—essentially, how much GE should pay for damaging the Hudson River and environs. A proper separation of the equity issue from other dredging issues is essential to unbiased, objective, and otherwise competent scientific decision making. We omit consideration of equity issues.[1] Indeed, any penalty or finding of liability assessed against GE can be applied toward dredging and/or used for other purposes. Thus, the amount of any penalty that might be assessed against GE should be unaffected by this article.

The Opportunity to Decide Issues

The EPA now has postponed dredging to 2009, affording an opportunity to consider whether dredging constitutes the best use of resources. For example, could possible adverse PCB health effects be offset more effectively via less expensive but more health-enhancing strategies, such as health club memberships for families residing along the Hudson River? More germane to PCBs, could greater health benefits be derived by using GE funds to establish a research institute focusing on local epidemiological issues? Resolution of these issues is outside our scope. We focus narrowly on evaluating the possible role of bias in EPA scientific analyses to decide whether or not Hudson River PCBs might pose unacceptable risks under a dredging and/or non-dredging ("baseline") scenario.

Methods

This investigation adopts the methods of health risk assessment (HRA) and health impact assessment (HIA) to identify parameters used by EPA to assess baseline (non-dredging) health risks potentially posed by PCBs in the Hudson River and, essentially, peer review their quantification based upon EPA documentation. Two criteria were used to determine whether effective insulation of science from politics was attained: (1) whether parameter values were estimated accurately, and (2) with respect to any parameters evaluated inaccurately, whether the direction of estimation error was mixed or whether it consistently overestimated or underestimated potential PCB transfer from Hudson River water to air. Overestimating the risk of transferring PCBs from sediments to water and water to air in the vicinity of Hudson River communities could contraindicate dredging, whereas the reverse error would be conducive to dredging.

The null hypothesis is absence of bias. This corresponds to finding a random distribution of errors, not to finding an absence of errors. Any finding of significant *systematic* error in either direction constitutes evidence of bias, justifying rejection of the null hypothesis.

Statistical Analysis

We determined whether each parameter examined was estimated correctly. If EPA's evaluation of a parameter was grossly inaccurate, we included it among parameters to be examined statistically to determine whether the distribution of the directions of mis-estimation was non-random. Each parameter that is estimated inaccurately must be overestimated or underestimated (otherwise, it is accurate). If these outcomes can be assumed to be equally probable, then occurrence of each is associated with an equal expected probability of 0.5 (50%, or "fifty-fifty"). If the parameters also are independent (mis-estimating one parameter does not affect estimation of another), then any two randomly selected parameters that are mis-estimated would have a 0.25 probability ($P = 0.5 \times 0.5 = 0.25$) of being mis-estimated in a direction more permissive to dredging and, likewise, 0.25 would be the probability of the same two parameters being mis-estimated in a direction less permissive to dredging.

In general, the probability of mis-estimating all of *n* parameters consistently in a particular direction by chance alone is 0.5^n where, for example, the probability of mis-estimating five out of five parameters in a direction permissive to dredging would be 0.03 ($P = 0.5^5 = 0.03$). When probabilities reach such low values, below the usual 0.05 criterion of scientific uncertainty, the null hypothesis of randomness is rejected. Speaking qualitatively, bias in the outcome of EPA's analysis (possibly unintentional) would be inferred.

Secondary Methods

Secondary methods also were applied. They are not *a priori* methods and they are not described in detail here. Rather, they are the diverse methods typical of peer review, which most essentially consists of considering the scientific merit with which numerous methods were selected for use and applied in the original analyses supporting the dredging decision. Readers can judge for themselves whether or not we applied the methods of HRA, HIA, and peer review objectively.

Findings

EPA Identification of Parameters Used in Assessing Potential Risks Posed by PCBs

The number of parameters describing the dynamics of PCBs entering the water column from sediments and entering the air from the water column are diverse and numerous, numbering in the hundreds or thousands. The number visible in any scientific explication of this issue depends upon the degree of detail with which the analysis is conducted. The parameters include initial concentrations of all 209 PCB congeners (from monochlorinated to decachlorinated biphenyls) in each medium, bulk amounts, areas involved, and depths of water and sediments, as well as parameters describing the physical, chemical, and environmental degradation (such as half life), transformation (such as dechlorination), and other environmental dynamics (such as solubility, boiling point, volatilization, and vapor density) of these numerous congeners. The safety issue also encompasses toxicological parameters of each PCB congener. The full list of such parameters is too long to elucidate in detail here.

Fortunately, the present analysis requires no such highly detailed elucidation. The parameters that are of greatest concern here are those that are most susceptible to being overestimated or underestimated, especially if by a wide margin, or overlooked entirely. These are the parameters (unlike, say, molecular weights, which are known to a high degree of accuracy) whose estimated values substantially may depend upon who is doing the estimating. Quantification of these parameters can vary from liberal to conservative, depending upon whether the estimator has an (conscious or unconscious) agenda other than to conduct a purely scientific analysis . . . in short, a bias. Nine such estimated, determinative parameters that were (or should have been) used for technical analysis in the baseline HRA supporting the dredging decision were identified in the current study, as follows:

1. *Mobilization of sediment-borne PCBs in dredging*. Sediment-borne PCBs will become mobilized by dredging. The amount mobilized depends upon the dredging method. Mobilization must be considered in assessing the potential public health significance of PCB dredging;
2. *PCB congeners to be included in the analysis*. All 209 PCB congeners should be included;
3. *Phases of PCBs to be included in the analysis*. All phases should be included, most notably PCBs that are adsorbed onto particles, molecular PCBs that are dissolved, and particulate PCBs that are colloidal;
4. *Precipitation of PCB-bearing sediment particles from the water column*. Precipitation rates should be quantified realistically, because this parameter is important in determining the rate of PCB removal (to sediments) and the resulting PCB concentration in the water column;
5. *Electrostatic charges on PCB-bearing sediment particles in the water column*. Clay sediment particles resuspended in water (as by dredging) tend to exhibit negative surface charges. Such particles are maintained in suspension by electrostatic interaction of the negative surface charges with cations (positive ions) in the water. This electrostatic charge configuration inhibits agglomeration. It should be accounted for because of its potential importance in inhibiting settling of clay particles and removal of adsorbed PCB from the water column;

6. *Reflection coefficient of precipitating PCB-bearing sediment particles*. The reflection coefficient quantifies the tendency of particles, once settled out of the water column, to return to the water column as a result of "bouncing." The reflection coefficient should be quantified and is especially important for particles of low mass or likely to be affected by currents, as in the Hudson River;

7. *PCB codistillation*. Codistillation is a chemical process well documented for PCBs. It results from molecular attraction to surfaces. For PCBs, these surfaces include the air-water interface in lakes and rivers. Entry of PCBs into air from water is significantly faster and more extensive in a given interval than would be the case if the same mass of waterborne PCBs were assumed to be distributed evenly throughout the water column (as quantified by the "bulk concentration"). Accurate estimation of waterborne PCB entry into the air that people will breathe requires quantification of PCB codistillation;

8. *Empirical measurement of airborne PCBs over PCB-contaminated waters*. Empirical measurements, to the extent available, should be used for validating modeled relationships, such as models of PCB entry into the air from Hudson River water;

9. *Warm water sources of Hudson River PCB entry into the atmosphere*. Warm water occurs at near-shore locations where cooling water is discharged from industrial facilities and, before discharge, in cooling towers supplied by Hudson River water. These sources of potential entry of PCBs into the atmosphere near population centers must be accounted for when assessing potential public health significance of PCBs and the possibly increased significance to public health if PCB dredging is undertaken.

The technical merit of EPA quantification of each parameter described above is evaluated sequentially in the following subsections.

Mobilization of Sediment-Borne PCBs in Dredging

PCB mobilization must be considered in assessing the potential public health significance of PCB dredging. Its consideration by EPA, however, was inadequate. PCB mobilization exacerbated by dredging depends upon three types of causes:

1. sediment disruption, as by extreme weather events or barge sinkings;
2. the method of dredging; and
3. accounting in full, rather than in part, for PCBs that might be mobilized.

Sediment Disruption by Extreme Weather Events

Research undertaken by Joel Baker and colleagues at the Chesapeake Biological Laboratory in Maryland simulating Hudson River PCB dredging (Baker et al., 2001) revealed that EPA modeling lacked spatial resolution high enough to predict PCB mobilization reliably. They concluded that errors, which could have gone in either direction, probably had in fact underestimated sediment and PCB mobilization from extreme weather events. The authors used this finding to argue in favor of dredging, fearing that harmful PCBs would be mobilized in future years if dredging did not remove them sooner; however, removal by dredging presumably also could exert a nearer-term effect episodically.

The Method of Dredging

The EPA's assessment regarding the Hudson River PCB site was prepared in 1999 and 2000, when GE planned to dredge hydraulically via the "suction" method. Indeed, a television commercial campaign by GE impugned the "clamshell" or "bucket" method of dredging as being too dirty. Since preparation of the HRA, however, GE's proposal has reverted to use of the clamshell method.

Accounting in Full for PCBs That Might Be Mobilized

The mass of PCB that will be mobilized may be expressed as a fraction of the inventory of PCB in Hudson River sediments. If the inventory is underestimated, mobilization will be underestimated commensurately. This source of underestimation is addressed with respect to other parameters, below.

In short, EPA's modeled estimate of PCB mobilization from sediments to the water column and from the water column to the air, together contributing to potential PCB inhalation risks, failed to include important potential sources of PCBs and therefore is unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots actually is undertaken.

PCB Congeners to be Included in the Analysis

All PCB congeners should be included in the inventory of PCBs in Hudson River sediments (Figure 1). Mono- and dichlorinated PCBs, however, were excluded from the inventory of PCBs in Hudson River water, thereby underestimating waterborne PCBs subject to becoming airborne. Several figures in the revised Hudson River HRA (US Environmental Protection Agency, 1999, 2000a, 2000b) depict a precipitous falloff of "total tri+ PCB congener water column concentrations" within approximately 10 meters of the dredge site. PCB congeners can bind from one to ten chlorine atoms. If each number of chlorines were represented equally, exclusion of the monochlorinated and dichlorinated PCBs would represent two of ten (20%). The actual fraction (weight-percent) excluded is unclear because commercial PCBs were sold as Aroclors (for example, Aroclor 1254 with 54 weight-percent chlorine), such that each Aroclor product sold had a distinctive distribution of mono- to decachlorinated PCB congeners (hence the ability to "fingerprint" PCB sources). In addition, PCB degradation in sediments results in gradual dechlorination, which tends to deplete the high-chlorine congeners and enrich the low-chlorine congeners . . . precisely the congeners that were excluded from the figures and which apparently were excluded from consideration in quantifying PCB release from river water to air. The fraction of total PCBs represented by the monochlorinated and dichlorinated PCBs would appear to be about one-third, as suggested by an EPA estimate described below.

The plan to dredge Hudson River sediments selected one option from among several remediation options. The option favored by environmentalists, "Alternative no. 5," would remove 155,000 pounds of PCBs, compared with 1.3 million pounds (650 tons, or approximately 600,000 kg); the latter is the amount reported to have been deposited into the Hudson River by GE from its two upriver capacitor plants before PCBs were banned from US commerce by the Toxic Substances Control Act of 1976. Responding to criticism of the plan to dredge only 100,000 pounds of PCBs under a less ambitious option, GE provided "new data" to the EPA that showed that the actual amount of PCBs that would be dredged from the river bottom under Alternative no. 5 would be 150,000 pounds, almost identical to the amount preferred by environmental groups (Cappiello, 2001):

> The US EPA says it can dredge 50 percent more PCBs from the Hudson River without increasing the volume of sediment removed. (Cappiello, 2001)

By way of explanation, EPA indicated that it simply had refined its PCB estimate of a year earlier; they did this by including previously-excluded monochlorinated and dichlorinated PCBs, on the rationale (according to TAMS Consultants) that "fish principally absorb [higher chlorinated] PCBs." The EPA apparently assumed that the monochlorinated and dichlorinated PCBs constituted one-third of the total PCBs (50,000 pounds out of 150,000 pounds of the total PCBs). Clearly, EPA's HRA of 1999 (US Environmental Protection Agency, 1999) and 2000 (US Environmental Protection Agency, 2000a, 2000b) for Hudson River dredging therefore excluded approximately one-third of the total PCBs from the PCB inventory. This was done notwithstanding that the scope of the Hudson River HRA included the airborne risks, not just fish consumption risks, that might be posed by PCBs resuspended and mobilized by dredging. This exclusion, however, did not stop EPA from taking credit for the extra 50,000 pounds of PCBs assumed to be accounted for by the monochlorinated and dichlorinated PCBs to augment the acceptability of its dredging plan in the face of criticism in 2001.

The EPA actions described above highlight three issues relating to potential bias in the scientific analysis:

1. whether EPA accurately inventoried the amount of PCBs that might pose risks to health;
2. whether EPA accurately assessed risks potentially posed by PCBs in its PCB inventory (addressed in greater detail later); and
3. whether the PCB risks quantified in the HRA corresponded to the PCB amounts that would be dredged and subject to mobilization, with the potential to pose health risks.

The findings indicate that EPA based its risk estimates on a smaller pool of PCBs; they indicate further that this was done in part by excluding monochlorinated and dichlorinated PCB congeners from the HRA. The EPA did this, notwithstanding that the excluded congeners would necessarily be included in sediments that would be dredged and therefore would contribute to airborne PCB concentrations and health risks that might be posed to people situated near the river. In short, EPA's modeled estimate of PCB residue load contributing to potential PCB inhalation risks failed to include important potential sources of PCBs and therefore is unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Phases of PCBs to be Included in the Analysis

All phases should be included, most notably PCBs that are adsorbed onto particles, molecular PCBs that are dissolved, and particulate PCBs that are colloidal. All PCBs in the HRA, however, were assumed to settle under Stokes'

Law for spherical silt particles. This assumption constitutes a continuous process of removal of PCBs from the water column, notwithstanding that molecular and dissolved PCB phases would remain, because they do not settle. That is, these waterborne PCBs are subject to becoming airborne, but this is not accounted for in EPA's HRA.

The mechanical action of dredging hotspots will cause PCBs that are adsorbed to silt particles to enter the water column. Whereas much, if not most, of the PCB in the water column will remain adsorbed to silt, a significant, possibly majority fraction will enter the water column in a dissolved (molecular) or a colloidal phase (consisting of microscopic PCB droplets). Exclusion of PCBs in these dissolved and colloidal phases from the revised Hudson River HRA is reported in Appendix E, Section 5.2, titled "TSS Plume Estimates." In that section, only silt particles were used to estimate settling rates:

> Since data on settling rates were not available, a median value for settling velocity of 1.9×10^{-4} M/sec [16.5 M/d] was used in the transport calculations. (US Environmental Protection Agency, 2000b)

The above description of settling velocity as a "median value" suggests misleadingly that settling was calculated for a heterogeneous distribution of particles whose median settling velocity is 1.9×10^{-4} M/sec [16.5 M/d]. In fact, only the "median" value was used. This uniform settling velocity, corresponding to a 20-micron (uM) sphere, excludes dissolved and colloidal PCBs, which are smaller. Dissolved PCBs (bound to water) and colloidal PCBs (subject to Brownian motion and water turbulence) never settle. This unstated simplification overestimates the rate of PCB removal from the modeled water column by assuming that all waterborne PCBs are adsorbed to particles that settle at the assumed velocity. Actually, a significant, if not predominant, fraction of total waterborne (resuspended) PCBs will consist of free PCBs present in dissolved and colloidal phases.

Inasmuch as silt has a specific gravity of about 2.5, the assumed "median" settling velocity corresponds to (spherical) particles of diameter exceeding 20 uM, whereas Stokes' Law ceases to apply when the settling particles are fines that are less than about 50 uM. The EPA's implicitly assumed particle size therefore, also implicitly, assumes that the vastly more numerous PCB molecules in dissolved and colloidal phases will settle at the median rate. Colloidal PCBs are commonly recognized as being 1 uM and smaller and, of course, individual PCB molecules are smaller still. These PCB molecules and colloids also would suspend in the water phase even beyond the dredge site perimeter of perhaps 20 M. Molecular and colloidal PCBs can remain in the water, suspended as globules of pure PCBs that are smaller than 20 uM, without being captured by silt curtains and without settling at all:

> PCB in colloidal form constitutes the most mobile form of PCB in water, being affected only minimally by settling, physical retention or adsorption. Concentrations of PCB-like compounds in water can be much higher in colloidal form than in suspended solids or in dissolved form, and can be much more difficult to intercept through physico-chemical means. (Paquin, 2001, p. 2)

Indeed, molecular and colloidal phases of PCBs together reasonably may be expected to constitute a significant, possibly the predominant, fraction of total PCBs in the water column, as illustrated by Table 1. Table 1 shows a site at which dissolved and colloidal PCBs together amounted to 54% of the total waterborne PCBs.

An EPA review of experience of dredging PCBs shows that dredging hotspots can disperse waterborne PCBs beyond a 20-meter envelope ("silt curtain") around a dredge site, with observed concentrations of 0.1 to 0.2 ppm (100 to 200 ug/L, or 100,000 to 200,000 ng/L). This is approximately 3,000 to 6,000 times the PCB concentration assumed under a non-dredging scenario in the HRA prepared in support of another project (specifically, the PSEG Power New York proposal to site the Bethlehem Energy Center gas-fired power plant on the Hudson River at Bethlehem, New York; see Oko and Oko, 2001; PSEG Power New York, 2001). In this higher waterborne PCB concentration range, resulting airborne PCB concentrations were reported to have exceeded safe concentrations. Indeed, EPA's HRA Appendix E states the following:

Table 1. Breakdown of forms under which PCB contamination is associated in groundwater at a Smithville, Ontario, Canada, site during the period 1994 to 2001; data compiled from 55 sampling campaigns

	Concentration of PCBs in groundwater (ug/L)		
Form present	**Range**	**Average**	**Proportion (%)**
suspended	0–119	7.7	46
colloidal	0.4–19	6.0	36
dissolved	0.2–8	3.0	18
Total	1–129	16.8	100

Source: Paquin, 2001.

> While these estimates of total tri+ PCB congener concentrations represent cumulative concentrations, dissolved or particulate tri+ PCB congener concentrations may be of even greater interest. *In particular, the dissolved water column concentrations tend to be of greater concern because of their increased bioavailability*. (US Environmental Protection Agency, 2000b, p. 59; emphasis added)

In short, EPA's modeled estimate of PCB residue load contributing to potential PCB inhalation risks failed to include important sources of PCBs in water and therefore is unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Precipitation of PCB-Bearing Sediment Particles from the Water Column

Precipitation rates should be quantified realistically, because they in turn quantify the rate of removal from the water column of PCBs that have been resuspended and mobilized by dredging. Instead, the residence time of flat, PCB-bearing clay particles in river water was quantified unrealistically, based upon the more rapid precipitation of spherically shaped particles acting in accordance with Stokes' Law (Figure 2). This procedure underestimated waterborne PCBs and thereby also underestimated the amount of PCBs that would become airborne.

Mathematical treatment is simplified when a spherical shape for fine particulates is assumed, which is the case in Stokes' Law. This assumption, however, predicts faster than natural settling rates because, in nature, spherical particles are rare. Disks, rod shapes, and irregular random shapes are more common and these shapes settle more slowly than spheres. Mathematical predictions of settling rates that do not account for irregular shapes can predict a 100% faster settling rate at the >20-uM particle size range and more than 1,000% faster at the <10-uM size range.

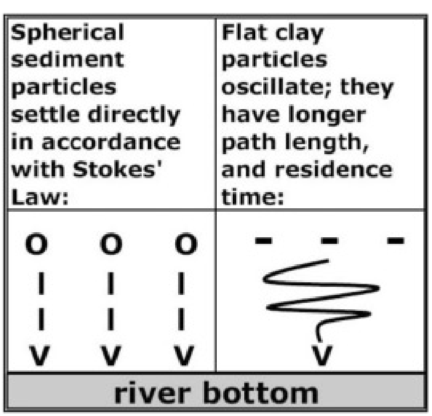

Figure 2. Settlement of waterborne particles to a river bottom: path length and settling rate of spherical versus flat particles.

Clay is abundant in the Hudson River region and would constitute a significant, if not the preponderant, fraction of PCB-contaminated sediment particles that will be resuspended and mobilized during dredging. Flat clay particles settle via a side-to-side oscillation during descent, greatly increasing their path length and residence time in the water column; that is why they settle more slowly than as predicted by Stokes' Law. Such delay in exiting the water column reasonably would be expected to increase the concentration of PCB-laden particles in the water column markedly, much as delays at highway exits markedly increase traffic on the highway. In short, EPA's modeled estimate of the suspended silt cleansing rate failed to include important properties of PCBs bound to sediments and therefore is unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Electrostatic Charges on PCB-Bearing Sediment Particles in the Water Column

Clay sediment particles resuspended in water (as by dredging) tend to exhibit negative surface charges. Such particles are maintained in suspension by electrostatic interaction of the negative surface charges with cations (positive ions) in the water column. This electrostatic charge configuration inhibits agglomeration of fine silt particles resuspended by dredging. Electrostatic charges should be accounted for because of their potential importance in inhibiting settling of clay particles and removal of adsorbed PCBs from the water column of the Hudson River at dredging sites.

Electrostatic charges should be modeled, but instead they were ignored. By this omission, EPA fails to account for prolonged suspension in the water column of charge-separated PCB-bearing clay particles; it thereby also underestimates waterborne PCBs subject to becoming airborne. Most fine particles, in part because of their high surface-area-to-volume ratio, tend to become electrostatically charged in water (Figure 3). Again, clay sediment particles resuspended in water tend to exhibit negative surface charges. The similar charges cause the particles bearing them to repel one another. The space between charge-separated negatively charged particles then is filled with cations (positive ions) already present in the water column. This configuration of charge separation increases particle residence

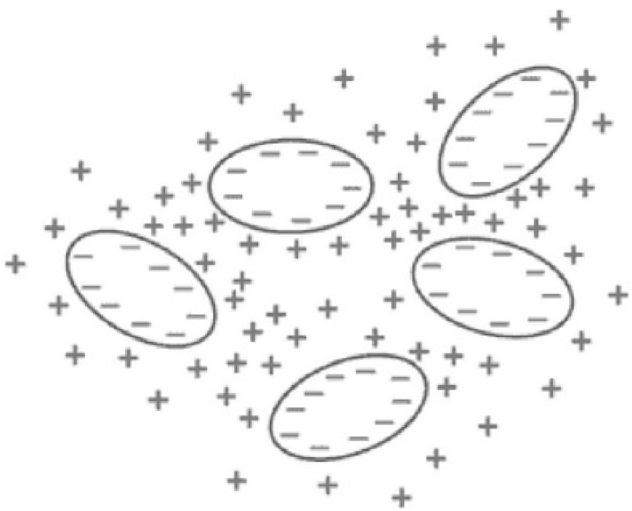

Figure 3. Charge separation of particles suspended in water. (Source: Historically Black Colleges & Universities/Minority Institutions, 2007.)

times in the water column. Some charge-separated particles will not settle at all. Electrostatically separated PCB-bearing particles that do not settle remain in the water column, from which they are more available than settling particles to enter the atmosphere, where they may pose airborne risks.

By excluding this potentially significant factor from the analysis of settling of suspended particles in the Hudson River water column, EPA overestimates the settling velocity of PCB-laden particles to the river bottom and thereby underestimates the likely concentration of PCBs in the water. In short, EPA's modeled estimate of suspended silt cleansing rate failed to include important properties of clay particles bearing PCBs and is therefore unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Reflection Coefficient of Precipitating PCB-Bearing Sediment Particles

The reflection coefficient should be quantified, because it constitutes a potentially significant source of return to the water column of PCB-bearing silt particles of relatively low mass. If 20% of low-mass particles encountering the substrate are swept by currents back into the water column, then EPA's underestimation of the suspended particle population in the water column, arising from omitting a reflection coefficient, would be 20%. We don't know what (if any) single value of the reflection coefficient should be assumed for the Hudson River or what multiple values might be assumed at each location in the river, under varying flow conditions. Clearly, however, EPA incorporated no reflection coefficient at all (or, equivalently, a reflection coefficient of zero was incorporated) in calculating PCB removal rates from the water column. This procedure thereby underestimated waterborne PCBs subject to becoming airborne.

The rate of free settling in water of silt particles influenced by earth's gravity can be predicted from particle size and the specific gravity of discrete particles. At the bottom of settling columns where the particles compact, however, other mechanisms take over. One of these processes is reflection (Shavit, Moltchanov, and Agnon, 2003), which refers to the fact that particles of low mass may bounce off the substrate on which they land. The mass of particles that might be swept back into the water column after settling to the substrate would be expected to be greater in flowing waters, such as in the Hudson River and in laboratory wave chambers (Shavit, Moltchanov, and Agnon, 2003).

Similarly, colloids may remain in suspension indefinitely as a result of bouncing off water molecules with which they collide (a well-documented phenomenon termed Brownian motion). The phenomena of reflection and bounce occur in a zone of activity termed the "hindered zone" of settling. Failure to incorporate a reflection coefficient when calculating settling of PCB-laden particles in the Hudson River water column tends to underestimate particle and PCB concentrations in the water, just as traffic could be underestimated on a highway if the model used fails to count a high fraction of exiting vehicles that immediately reenter the highway. In short, EPA's modeled estimate of suspended silt cleansing rate failed to incorporate a reflection coefficient and is therefore unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

PCB Codistillation

Empirical measurements should be used to validate model assumptions made in quantifying PCB entry into the air. Instead, available empirical measurements were diluted with modeled values (see below), thereby underestimating the water-to-air transfer coefficient. Accurate estimation of waterborne PCB entry into the air requires quantification via accounting for PCB codistillation. By ignoring PCB codistillation in quantifying the water-to-air PCB transfer coefficient, EPA underestimated waterborne PCBs subject to becoming airborne. A recent news item (Anonymous, 2001) based upon research conducted by the Integrated Atmospheric Deposition Network (2000) reveals that codistillation has transferred nearly two tons of PCBs from Lake Ontario to the atmosphere between 1992 and 1996. According to a news report describing this startling finding,

> The Great Lakes have begun to "exhale"significant quantities of chemicals, including . . . PCBs . . . , releasing them into the atmosphere. . . . Researchers say . . . the lakes begin *naturally cleansing themselves* through the volatilization process (i.e., evaporating pollution off the water surface). The latest figures from the Integrated Atmospheric Deposition Network (IADN) *show a net release from Lake Ontario alone of almost two tons of PCBs into the air* . . . from 1992 through 1996. . . . (Anonymous, 2001, p. 9; emphasis added)

That's a half ton (nearly 500 kg) of PCBs *each year* codistilling from the surface of a cold lake. Codistillation, however, also is temperature dependent. Thus it would occur at a greater rate, and to a greater degree, in warm water, such as in Hudson River water heated during industrial use as a cooling fluid, then itself cooled in cooling towers before return to the river. The EPA's failure to account for codistillation might be explained by unfamiliarity with the phenomenon, as well as by an unwillingness to give appropriate credence to empirical data arising from credible reports. In short, EPA's modeled estimate of assumed water-to-air PCB transfer rate failed to include consideration of codistillation and is therefore unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Empirical Measurement of Airborne PCBs over PCB-Contaminated Waters

The degree to which EPA was familiar with PCB codistillation cannot be inferred with certainty. Such familiarity, however, should have been unnecessary for enabling EPA to quantify accurately PCB water-to-air transfer coefficients, inasmuch as empirical measurements cited by EPA had been made to quantify them. Indeed, the revised Hudson River HRA (US Environmental Protection Agency, 2000a, 2000b), Appendix B, cites nine empirical measurements of airborne PCB concentrations (Buckley and Tofflemire, 1983) contributing toward estimating the transfer coefficient of PCBs from water to air (US Environmental Protection Agency, 2000b; see EPA's Table B-1). These and possibly other measurements were used by EPA to produce PCB water-to-air transfer coefficients (as summarized in this article's Table 2; also see EPA's Table B-2 and the original data source, Harza Engineering Co., 1992):

> These data can be used to estimate an empirical water to air transfer coefficient, representing the ratio of the PCB concentration in air divided by the PCB concentration in water. Using the detected PCB concentrations in air and water summarized in Table B-2, empirical air-water transfer coefficients range from 0.02 to 0.4 ug/M^3 per ug/L, with a median value of 0.09, and an average value of 0.15 (ug/M^3 per ug/L). (US Environmental Protection Agency 2000a, p. 18)

The EPA expressed surprise about the magnitude of these measured values, however, possibly because EPA was unfamiliar with codistillation. In that case, EPA would have expected the transfer coefficients to be lower than those

Table 2. The US Environmental Protection Agency's Health Risk Assessment: modeled versus measured airborne PCB concentrations

Measured airborne PCB concentrations at 1-meter altitude		Empirical water-to-air transfer coefficient			
range		range		median	mean
from	to	from	to		
(ug/M^3)		(ug/M^3 per ug/L)			
0.033	0.53	0.02	0.4	0.09	0.15
Airborne PCB concentrations resulting from water-to-air transfer					
measured range		modeled range		measured/modeled	
from	to	from	to	from	to
(ug/M^3)		(ug/M^3)		…	…
0.033	0.53	0.00012	0.00021	157	4,417
		(assumes PCB flux = 13 ug/s)			

Source: US Environmental Protection Agency, 2000a, 2000b.

suggested by the measurements. Further investigation could have elucidated the explanation for the higher-than-expected PCB water-to-air transfer coefficients, but further investigation apparently was not undertaken.

Instead, the measured values described above were assigned a low weighting. This EPA accomplished via adulteration of the nine empirically derived transfer coefficients with two lower transfer coefficients derived via two modeling approaches (Table 2). The two modeling approaches ignore codistillation, instead producing transfer coefficients consistent with Henry's Law acting on bulk PCB concentrations, that is, assuming even distribution of PCBs throughout water. Model results expressed in units of ng/M^2 sec per ng/L could not be compared directly with the empirical values expressed in ug/M^3 per ug/L. The units were brought into line, and the comparison made, via use of the average PCB concentration in the river (24 ng/L = 0.024 *ug/L*; US Environmental Protection Agency, 2000a, p. 18). The EPA used this concentration to produce a flux (13 ug/sec; US Environmental Protection Agency, 2000a, p. 19) which, using the median empirical transfer coefficient (0.09), generated a modeled airborne concentration of 0.00012 to 0.00021 ug/M^3 (US Environmental Protection Agency, 2000a, p. 20), compared with 0.033 to 0.53 ug/M^3 detected empirically (US Environmental Protection Agency, 2000a, p. 20). This corresponds to a factor of a 157 to 4,400 difference between the modeled versus empirical data (0.53/0.00012 = 4,417; 0.033/0.00021 = 157). That is, the modeled water-to-air transport factors downwardly biased the estimated transfer of PCBs from Hudson River water to the atmosphere by a factor ranging from as little as 1/4,400th to 1/157th of the empirically determined values.

The EPA's preference for modeled transfer coefficient values biased the expected concentration of airborne PCBs over the river surface in a direction favorable to EPA's dredging proposal and, in this sense, this action was self-serving. It was sufficiently self-serving to reduce airborne PCB estimates to below levels of concern to EPA and below levels of concern to the New York State Department of Environmental Conservation. Specifically, EPA's weighting procedure diminished assumed airborne PCB concentrations from above published *de minimis* levels, requiring quantitative risk assessment, to concentrations below *de minimis* levels, not requiring quantitative assessment of risks potentially posed by inhalation of mobilized PCBs that might become airborne as a result of dredging (Table 3). Contrary to EPA's routine procedure of validating its air models against reality via use of dyes or other markers, in this case EPA effectively invalidated empirical data based upon real-world data failing to conform to EPA's air model. In short, EPA's modeled estimate of the water-to-air PCB transfer rate failed to incorporate empirical evidence about water-to-air transfer of PCBs and is therefore unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Warm Water Sources of Hudson River PCB Entry into the Atmosphere

Potential warm water sources of Hudson River PCB entry into the atmosphere, such as cooling towers, must be accounted for in assessing the potential public health significance of airborne PCBs under any dredging scenario. Instead, PCB concentrations resulting from water-to-air transfer were estimated based upon unheated (relatively cold) river water. According to the revised HRA for the Upper Hudson and Mid-Hudson River (US Environmental Protection Agency, 2000a):

> The concentrations of PCBs in air were calculated from a combination of historical monitoring data and modeled emissions *from the river*. . . . (US Environmental Protection Agency, 2000a, p. ES-4; emphasis added)

Table 3. Regulatory effect of adjusting PCB concentrations measured in air via incorporation of lower, modeled concentrations

Measured PCB range		New York State Department of Environmental Conservation DAR-1* *de minimis* concentration for PCB	Modeled PCB range	
from	to		from	to
(ug/M^3)		(ug/M^3)	(ug/M^3)	
0.033	0.53	0.1	0.00012	0.00021

*Source: New York State Department of Environmental Conservation, 1997.

The water temperature in cooling towers may be elevated to approximately 100° F (56° C) above that of the ambient river water source.

For every 10° C rise in temperature, the rate of a physical reaction, such as the rate of PCB codistillation, may be expected roughly to double. The rate of PCB transfer from water to air occurring with a 40° C water temperature increase, accordingly, would be expected to undergo four doublings. Thus, the rate at which PCBs in cooling tower water might be expected to escape to the air from water at a temperature of, say, 45° C (113° F) in a cooling tower would be approximately 16 times greater than that in a source of Hudson River water at a temperature of 5° C (41° F).

If dissolved and/or colloidal PCBs rise to 10 ug/L (parts per billion by weight) during dredging, the weight of PCBs entering the cooling tower under one project proposal (the Bethlehem Energy Center power plant; see Oko and Oko, 2001; see PSEG Power New York, 2001), based on a 4,500 gallon/minute uptake, would be 0.25 kg/d (approximately 0.1 tons/year). Examination of studies forming the basis for the passage quoted above pertaining to transfer of PCBs from river water to air, however, reveal no studies addressing PCB release from warm water in cooling towers. In short, EPA's modeled estimate of water-to-air PCB transfer rate failed to incorporate consideration of transfer from heated water and is therefore unreliable for predicting dynamics in the Hudson River if dredging of PCB-bearing sediments at hotspots is indeed undertaken.

Summary of EPA Quantification of Parameters Used in Dredging Decision Making

As documented above, EPA evaluation of the nine subject parameters addressed in this study systematically has underestimated concentrations of PCBs that could, and presumably would, become airborne under non-dredging and dredging scenarios. Adoption of simplifying assumptions in modeling river flow, precipitation of suspended particles, and PCB dynamics can result in omission and/or unreliable quantification of important parameters contributing to overall PCB-associated risk. That this indeed has occurred is hinted at in Section 5 ("Assessment of Water Quality Impacts") of Appendix E of EPA's revised HRA for the Hudson River (US Environmental Protection Agency, 2000b):

> A complete evaluation of water quality impacts requires integrating a calibrated hydrodynamic model of the system with a water quality model capable of predicting changes due to *advection, turbulent diffusion, and settling of the suspended particles. Such a model is beyond the scope of this evaluation.* (US Environmental Protection Agency, 2000b, Section 5, p. 12; emphasis added)

Discussion and Conclusions

Statistical Significance

A parameter that is estimated inaccurately must be overestimated or underestimated; otherwise it is estimated accurately. If these two alternative directions of misestimation are equally probable, as they should be, then occurrence of each is associated with an expected probability of 0.5 (50%, or "fifty-fifty"). If the parameters also are independent (under- or overestimating one does not cause mis-estimation of another), then any two randomly selected parameters that are mis-estimated would have a 0.25 probability of being mis-estimated in a direction more permissive to dredging and, likewise, 0.25 would be the probability of the same two parameters being mis-estimated in a direction less permissive to dredging; 0.50 [1.0 − (0.25 + 0.25)] would be the probability of one mis-estimation being in the dredging-permissive direction and the other in the dredging-prohibitive direction. The confluence of fully nine parameters linked in a single direction, as reported above in the "Findings" section, would be associated with a vanishingly small probability of occurring by chance alone—0.5^9, which is 0.002. Qualitatively speaking, a low probability (for example, below the usual 0.05 scientific confidence level) supports the conclusion that bias (possibly unintentional), rather than chance alone, influenced EPA's analysis consistently in the direction of underestimating PCB risks in the baseline HRA for the Hudson River.

Significance for Health Risk Assessment

The findings reported above suggest that potential inhalation risks that should have been quantified in the EPA's HRA were not quantified. The EPA's HRA states the following:

> Risks and hazards through inhalation of volatilized PCBs were not assessed in the Mid-Hudson HHRA because calculated risks for this pathway were shown to be *de minimis* (insignificant) in the Human Health Risk Assessment for the Upper Hudson River. Given that concentrations of PCBs found in the sediment and river water in the Mid-Hudson are lower than concentrations in the Upper Hudson, the risks from volatilization also would be expected to be insignificant (and

lower) in the Mid-Hudson. (US Environmental Protection Agency, 1999, p. ES-2)

This means that EPA's estimate of airborne PCB concentrations is below the New York State Department of Environmental Conservation *de minimis* Annual Guideline Concentration (New York State Department of Environmental Conservation, 1997, 2003) which, if exceeded, would trigger a requirement to quantify inhalation risks potentially posed by airborne PCBs under a reasonable worst-case scenario. Accordingly, although the HRA "considered" airborne PCBs, risks to public health potentially posed by transfer of PCBs from Hudson River water to the air effectively were assessed as zero. Risks posed by PCBs entering the air from cooling towers (with or without dredging) were neither quantified nor considered. Other sources of airborne PCB risks that also were unquantified, according to EPA's HRA, were "the contribution of PCBs in air from contaminated sediment and floodplain soil" (US Environmental Protection Agency, 1999, Section 2.3.4, p. 20).

Regulatory Significance

If EPA had accepted empirical measurements of PCB transfer from water to air, potential risks to people inhaling PCBs would have been required to be included in its HRA (Table 3). Even the lowest of the five empirical measurements of airborne PCB concentration generated by PCBs at specified concentrations in water (0.03 ug/M^3) exceeded the New York State Department of Environmental Conservation's published Annual Guideline Concentration value for airborne PCBs of 0.002 ug/M^3 by a factor of 15-fold. The EPA's use of the mean (0.15 ug/M^3) or the median (0.09 ug/M^3) of all five empirically measured airborne PCB concentrations would, of course, exceed these critical benchmarks even more dramatically. Most notably, the measured range of airborne PCB concentrations (0.033 to 0.53 ug/M^3) reported by EPA exceeded by a factor of five-fold the New York State Department of Environmental Conservation's *de minimis* value of 0.1 ug/M^3 that would have triggered inclusion of PCB inhalation as an exposure pathway to be quantified in the HRA. The EPA's procedures, therefore, undermined public health protection by eroding safety and/or the margin of safety that should be built into EPA standards of public health protection.

The EPA understatement of PCB release to air affects other projects besides the Hudson River dredging project. The New York State Department of Environmental Conservation, for example, need not account for PCB emissions from cooling towers in approving permit applications for projects (such as power plants), even if those projects will use cooling towers. Indeed, citizen criticism of EPA's Environmental Impact Statement value in the New York State Department of Environmental Conservation's permit review of project proposals has been rejected, not on technical grounds, but because the EPA values previously had undergone peer review. As a result, HRAs prepared by project applicants may 'account' for public health risks potentially posed by waterborne PCBs becoming airborne simply by quantifying them as zero, based upon the erroneous and apparently unreviewable assumption that PCB emissions from water to air will be *de minimis*. The potential significance is exemplified by the permit proceedings for the Bethlehem Energy Center gas-fired power plant on the Hudson River (Oko and Oko, 2001; PSEG Power New York, 2001), in which the applicant was exempted from quantifying risks potentially posed by airborne PCBs on the authority of the EPA's HRA for the Mid-Hudson River (US Environmental Protection Agency, 1999, 2000a, 2000b).

Significance to Hudson River Communities

The most valuable reward for doing river restoration projects is that a river is in some sense "fixed." Although this reward would have to be especially large for the Hudson River to justify the enormous price of "fixing" it, the reality seems different. Whereas sediments and water should be cleaned, EPA's dredging program cleans only PCB hotspots, leaving PCBs in sediments, biota, and water elsewhere in the river, and also leaving virtually all non-PCB contaminants in sediments, biota, and water, even after dredging is completed. Indeed, EPA's dredging proposal addresses 150,000 pounds (68,000 kg) of sediment-borne PCBs compared with 1.3 million pounds (591,000 kg) that GE concedes it discharged into the Hudson from two capacitor plants. That amounts to less than 12% of known PCBs and an even smaller fraction of the total PCBs discharged into the Hudson River.

Whereas sport fisheries should be uncontaminated and game fish caught in the river safe to consume, in fact the fish cannot become edible in the reasonably foreseeable future. Even if every PCB molecule could be removed from the river, all other Hudson River pollutants will survive PCB hotspot dredging, including persistent chlorinated hydrocarbon pesticides, polycyclic aromatic hydrocarbons (PAHs), and heavy metals such as cadmium, copper, lead, mercury, and zinc (New York State Department of Environmental Conservation, 2000). Whereas air pollution arising from river water should become *de minimis*, in fact, mobilization of PCBs by dredging will increase PCB release to the air for years, and other pollutants also will become airborne after dredging is completed. Whereas the incidence of adverse health effects that might be caused by airborne PCBs should become *de minimis*, in fact, such health effects (if really caused by PCBs) might increase for years before they begin to diminish after dredging.

With or without dredging, purging PCBs from Hudson River sediments will require decades (Baker et al., 2001). At one extreme, the remaining PCBs might amount to only the 150,000 pounds to be dredged. In that case, about 90% already has been eliminated without dredging, and the river has cleansed itself of a major fraction of PCBs via processes that are ongoing; further self-cleansing would be expected. Realistically, cleansing has eliminated less than 90%, and multiples of 150,000 pounds must remain. In that case, if dredging occurs, a preponderance of PCBs still would remain after 150,000 pounds is removed. Ultimately, the Hudson River must cleanse itself, with or without dredging.

Some people see light at the end of the tunnel, when dredging will reduce PCBs in sediment, biota, water, and air, and reduce PCB-associated human disease to *de minimis* incidence. Others see light at the end of a different, longer tunnel, when continued natural burial by sediment loading from runoff into the river likewise will sever the connection of sediment-borne PCBs to the water, biota, and air, reducing PCB-associated human disease to *de minimis* incidence. Continued natural dechlorination of buried PCBs and further degradation via physical, chemical, and biological processes acting beneath the sediments eventually will finish the job, with or without dredging.

The dredging argument has focused narrowly on the two tunnels described above leading to *de minimis* PCB levels and whether shortening one via dredging is justified despite near-term environmental disruption. Even objective scientists cannot resolve subjective issues associated with deciding which tunnel constitutes the better route to essentially the same destination. Objective science, however, remains essential. Given the evident biases identified in this article's "Findings," objective consideration of at least three issue areas is needed:

1. Are PCBs harming health and, if so, are effects sufficiently serious, and risks sufficiently high, to justify urgent PCB removal?
2. If PCBs are harming human health in Hudson River communities, will dredging exacerbate harm by further mobilizing sediment-borne PCBs? If PCB-mediated health effects are unacceptable now, will their prolonged exacerbation by dredging be more unacceptable? Additional measures to protect populations would have to be contemplated—short of evacuation, but expensive. Conversely, if PCB health risks are acceptable, why dredge to remove PCBs when natural processes eventually will remove them anyway?
3. If the benefits of eliminating PCBs from hotspots are deemed worth the enormous price in a hypothetical, otherwise clean Hudson River, are they also worth the price in the actual Hudson River, which has pollutants other than PCBs, and PCBs in places other than in the hotspots where dredging will occur? Lost in the dredging debate seems to be the big picture: a dredged river polluted as before, but with at best a 12% decrease in PCB in its sediments. Is narrowly focusing on dredging hotspot PCB justified, if the river will remain toxic with other pollutants and with non-hotspot PCBs?

In light of these questions, the near-term price of dredging must include potential ecological and public health impacts. The findings and considerations addressed above justify three specific conclusions and one general conclusion. First, risks to public health potentially posed by inhalation of PCBs were not modeled correctly (effectively quantified as zero) and therefore would be ignored in a dredging-specific HRA if only the baseline HRA exposure routes and pathways are included for comparison. Second, even if all PCBs could be removed from the river or from hotspots, all other Hudson River pollutants would remain. Their continued presence after dredging would continue to limit recreational and commercial river use for many decades; for example, they still would limit consumption of fish, especially in pregnant women, young children, and other sensitive subpopulations. Third, PCB inhalation risks and their acceptability were unassessed and remain unknown, as is the degree to which dredging would exacerbate them and for how long. Finally, EPA's ultimate decision to dredge or not dredge will depend upon subjective issues whose resolution must be informed by objective science to answer the above questions, and others, credibly.

Note

1. One of us (Michaels) previously consulted to GE under the auspices of RAM TRAC Corporation, but neither Michaels nor RAM TRAC has done

so for over five years. Neither author nor corporation has a business relationship with GE or financial interest in the dredging issue.

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