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Excessive PCBs in the Hudson River: Attributable to Incompleteness of Dredging, or to Seven Years of Dredging?

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ABSTRACT
GE recently completed a seven-year US EPA-mandated clamshell dredging project to remediate PCB contamination of the Hudson River. Post-project PCB levels in water and fish, however, are higher than anticipated, suggesting to some the need to extend the project to remove more PCB-bearing sediments. Our investigation of the effectiveness of the dredging project revealed that a previously unconsidered physical process must mobilize sediments as a result of dredge bucket closure. We also used computerized dredging data ('bucket files') to estimate the fraction of dredged sediments returned to the river instead of being deposited into waiting barges. We conclude that excessive post-project PCBs in the Hudson River predominantly are attributable to sediment mobilization by clamshell dredges. We predict that proposed extension of the dredging project would prolong mobilization processes, allowing PCBs to spread widely and enter ecosystems that include people, endangered fish such as sturgeon, and endangered birds such as bald eagles.

Introduction

GE (the General Electric Company) recently completed a seven-year US EPA-mandated clamshell dredging project to remediate PCB (polychlorinated biphenyl) contamination of the Hudson River. Post-project PCB levels in water and fish, however, are higher than anticipated, for example in 2016 requiring the New York State Department of Health (NYS DOH 2016) to recommend further restriction of fish consumption. NYS DOH issued a "Don't Eat" fish consumption advisory for walleye fish taken from the Hudson River downriver, between the Rip Van Winkle Bridge at Catskill and the Tappan Zee Bridge. This advisory is more stringent than the previous advisory, which recommended limiting intake of walleye to one meal per month. The current advisory was based upon new data showing elevated levels of PCBs in these fish.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/becj.

In 2007 the U.S. Environmental Protection Agency (US EPA) required GE to remediate the Hudson River PCB Superfund Site via dredging. Also in 2007, we reported pro-dredging bias in the form of errors in US EPA's baseline health risk assessment (HRA) for Hudson River PCBs; indeed, all nine identified errors were made in the dredging-friendly direction rather than randomly (Michaels and Oko 2007). Permissive HRA findings that resulted from these errors constituted a necessary condition for US EPA to conclude that dredging could be accomplished within acceptable health and environmental risk parameters, and to require GE to employ dredging for remediation of the site. The original purpose of site remediation via clamshell dredging was *to reduce safely and substantially the long-term downstream transport of PCBs* (Peer Review Panel 2010; US EPA 2002).

In 2010 we evaluated dredging Phase 1, consisting of a one-year attempt, in 2009, to demonstrate the feasibility of *clamshell* dredging as a multiyear remedy for the Hudson River PCB Superfund Site (Michaels and Oko 2010). The 2010 paper reported failure (of GE) to complete a significant fraction of the planned Phase 1 area within the allotted dredging season, and failure (of US EPA) to demonstrate the feasibility of implementing Phase 2 within acceptable environmental and health risk parameters. Similar conclusions were drawn by US EPA's peer review panel for Hudson River PCB dredging (Peer Review Panel 2010). Others more generally have characterized conventional clamshells as more typically used for navigational rather than for environmental dredging (for example, Bridges et al. 2008; Palermo et al. 2008):

> Although *conventional dredges normally used for navigation dredging* (e.g., conventional clamshells or cutterheads) can be effective for environmental dredging, evolving technologies for dredge and dredgehead designs (e.g., enclosed buckets, articulated fixed-arm mechanical, swinging ladder cutterheads, and articulated ladder cutterheads) may offer better performance for environmental dredging. (Palermo et al. 2008, 257; emphasis added)

Accordingly, we recommended consideration of hydraulic dredging as originally proposed, or other alternatives to conventional *clamshells* (Michaels and Oko 2010). Indeed, US EPA specification of clamshell dredging in the Hudson River is unusual, as most PCB dredging from U.S. waters has relied upon hydraulic dredges, which were used, for example, in the New Bedford Harbor in Massachusetts, the Cumberland Bay in Plattsburgh, New York, and the Fox River in Green Bay, Wisconsin.

Notwithstanding the above, US EPA required GE to initiate Phase 2 in 2011, after a one-year hiatus in 2010 for project evaluation, culminating in our paper (Michaels and Oko 2010) and the peer review panel's adverse report (Peer Review Panel 2010). The scope of Year 1 of Phase 2, in 2011, included completion of the undredged Phase 1 area. As we reported, Phase 1 not only failed but, more fundamentally, it lacked the potential to succeed in demonstrating the feasibility of Phase 2, because Phase 2 posed two problems not posed in Phase 1: (1) dredging in faster-moving water, and (2) confining dredge-disturbed PCB-contaminated sediments to within isolated 'hot spots,' despite river currents capable of carrying mobilized PCB liquids, dissolved molecules, colloids, and suspended particulates downstream to areas in which future dredging was not planned.

Phase 1 differed from Phase 2 in being conducted largely at one side (the east side) of Rogers Island, where sediment transport was slowed by a nearby stone dam and sediment curtain. Phase 1 also predominantly involved bank-to-bank dredging. Phase 2 involved widely separated PCB hot spots and faster moving open river water. Redeposition of mobilized PCB-containing sediments in the Phase 1 area was followed generally by redredging, thereby minimizing the impact of dredge-disturbed sediment flow and mobilization beyond the dredging zone. Thus, US EPA's authorization to conduct Phase 2 based upon Phase 1 constituted a non sequitur.

Failure of Phase 1 to meet engineering performance standards (EPSs) and health risk criteria (Peer Review Panel 2010) was ominous for Phase 2 (Michaels and Oko 2007, 2010; Peer Review Panel 2010). Implementation of Phase 2 for two years, in 2011 and 2012, and its continuation in 2013 and for years thereafter until completion, together raised five emerging and unique issues that we evaluate here, including the following:

1. *Sediment mobilization*: US EPA accuracy in estimating PCB-contaminated sediment mobilized by dredging;
2. *PCB mobilization*: Possible PCB loss by desorption from resuspended sediment particles;
3. *Storms*: Possibly changing frequency of sediment-mobilizing high-flow events;
4. *Endangered species: Endangered species* classification of Hudson River sturgeon and bald eagles; and
5. *Autism*: Progress of research into possible PCB causation of autism.

Methods

Our investigation included reviewing literature, making site visits, attending meetings, and evaluating several exposure and toxicology issues. We conducted three site visits to observe and photograph dredging, each time visiting US EPA's field office in Fort Edward, interviewing US EPA and GE personnel and contractors, analyzing dredging data, attending public meetings, and examining scientific and regulatory documents (for example, Harza 1992; NYS DEC 2000, 2003; PSEG NY 2001; Shavit, et al. 2003; UN EP 2003, and other sources in References). Our analysis adopts methods of health risk assessment (HRA), critical evaluation of project-related scientific information sources (for example, GE 2009, 2010a, 2010b, n.d.; US EPA 1999, 2000a, 2000b, 2001, 2006, 2010a, 2010b, 2010c, 2010d, 2010e, 2012, n.d.a, n.d.b), and objective scientific peer review. The latter are not a priori methods, and they are not described in detail here. Rather, they consist of diverse methods that are generally typical of peer review by scientists seeking to remain objective. Most essentially, these methods consist of our own disciplined, critical evaluation of the scientific merit with which numerous methods were selected for use and applied prior to dredging, during dredging Phase 1, and during Phase 2.

The scope of our assessment therefore includes our own peer review of GE and US EPA methods, findings, and conclusions, such as those reported orally in public meetings, and in written public communications on GE (n.d.) and US EPA (n.d.a, n.d.b) Web sites for Hudson River dredging, and more formally in GE (2009, 2010a, 2010b, app. GE (2009, 2010a, 2010b) and US EPA (1999, 2000a, 2000b, 2001, 2006, 2010a, 2010b, 2010c, 2010d, 2010e, 2012) draft and final reports published for consideration by the public, specific interested parties, and members of the Hudson River dredging project peer review panel (Peer Review Panel 2010). Members of the public and other readers of our assessment can judge for themselves whether and to what degree we succeeded in applying the methods of HRA and of peer review objectively. We hope that we have done so completely.

Findings

General

Mobilization of dredge-disturbed sediment was ≥ 100 times higher than measured by US EPA's engineering performance standard (EPS) for resuspension, and no EPS exists to detect, quantify, or reduce downstream sediment redeposition. Much PCB adsorbed to dredge-disturbed sediment desorbs within minutes of mixing into river water. This fugitive molecular and colloidal PCB is transported downstream, but missed in routine resuspension monitoring. Complicating matters, the frequency and intensity of storms is increasing. Invisible to EPSs, storms may scour fugitive PCB-contaminated sediment, and transport it downstream gradually and episodically, over years or decades. Long-term downstream transport of PCB poses risks to endangered species, possibly including extirpation of sensitive sturgeon from the Hudson River. Finally, recent animal research links PCBs to developmental processes that, in humans, are thought to underlie autism causation, but US EPA has failed to address potential autism risks.

Issue 1, sediment mobilization: US EPA accuracy in estimating PCB-contaminated sediment mobilized by dredging

Sediment mobilization by dredge jaw closing. Sediment resuspension arising from bucket (clamshell) dredging is reported to "result from the impact, penetration, and removal [of the dredge bucket] from the bottom sediments; leakage while raising it through and out of the water column; and washing during movement through the water column" (Zappi and Hayes 1991, citing Barnard 1978). Resulting "suspended solids in the area of influence of the bucket dredge, without hopper barge overflow, can range from 20 to 1,100 mg/L" (Zappi and Hayes 1991, citing McLellan et al. 1989). A process contributing to sediment mobilization that apparently has been neither addressed nor described previously is generation of a suction force behind closing dredge jaws.

Specifically, the sediment fraction mobilized has been calculated previously relative to a full dredge bucket, but that parameter fails to account for the mobilizing effects of closing dredge jaws on sediment that is situated outside of the bucket. Dredge bucket jaws are constructed of rigid walls of steel that are suspended beneath

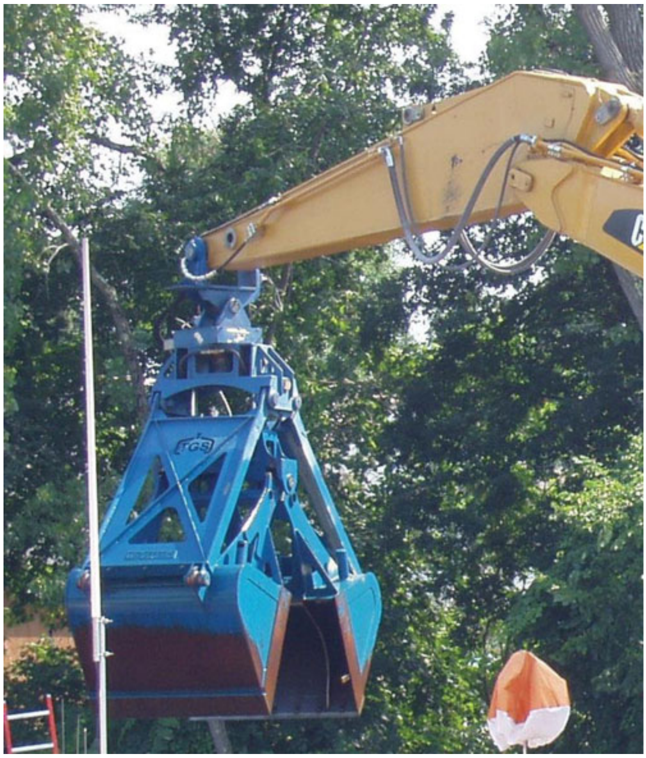

Figure 1. Hudson River dredge showing bucket suspended beneath superstructure.

a rigid nonsolid steel superstructure (Fig. 1). The jaws of a typical 5-cubic-yard (3.85-cubic-meter) bucket used in the Hudson River each have an open cross-sectional area of 88 square feet (9.8 square meters) measuring 7.1 feet (2.2 meters) in width and approximately 4.4 feet (1.3 meters) in height, producing a solid cross-sectional area of $>$30 square feet (3 square meters). The superstructure adds another 6 feet (1.8 meters) of height, producing a total of over 10 feet (3 meters).

The total cross-sectional area that moves through river water during closing of each dredge jaw therefore is approximately 50 square feet (4.6 square meters), most of it above river sediment grade (typical dredge jaw penetration depth is up to 1.5 feet (0.5 meter), visible as the abraded area at the bottom of the bucket depicted in Fig. 1). The angle of attack changes (becomes more vertical) as the bucket closes and, of course, the velocity of jaw movement through the water is greatest toward the bottom, which also is the solid portion of the dredge bucket.

As the bucket jaws close, physics requires that they create three strong currents. One current results from compression of water and sediment situated between the closing bucket jaws. It forces water and sediment out of the dredge bucket. The other two currents result from suction of water and sediment situated in the reduced-pressure zone behind each dredge jaw. These latter two currents exert a force that drags water and sediment, causing them to follow behind moving dredge jaws as they close. All three forces create turbulence. The compressive force, especially because it drives water and sediment upward through the open top of dredge jaws, produces turbulent eddies of sediment typically extending to the river surface, readily visible and varying from gray to black, depending upon location in the river.

The inward-directed suction force exerted in the reduced-pressure zone behind the dredge jaws acts on water much as a moving vehicle acts on air. This force is manifested (for example) by race cars drafting close behind another car to accelerate by using the powerful suction force created by the lead car's evacuation of air behind it. The suction force also is made visible as opaque diesel exhausts flow over the tops of moving trucks and are sucked turbulently downward in the trailing low-pressure zone. Physics demands that loose or uncompacted sediment situated outside each opposing jaw of dredge buckets likewise must be sucked off the river bottom during bucket closure. The swirling sediment then is left in the river as the dredge buckets are lifted to the surface and beyond.

Sediment mobilization is quantified by comparison of sediment volumes placed in barges with sediment volumes dredged in each bucket closure. Bucket closures are recorded automatically via computers on board dredge platforms, and published as the 'bucket files' (GE 2010b; Michaels and Oko 2010; US EPA 2010a). Sediment that is mobilized behind closing dredge jaws, however, is routinely not quantified in the bucket files, because such sediment is not dredged and not placed in barges. For example, consider a typical five-cubic-yard dredge bucket that penetrates to a sediment depth designed to fill it to 80 percent of full capacity. Its field capacity would be four cubic yards (0.8×5 cubic yards). If only two of the four cubic yards are barged, by subtraction the inferred mobilization also is two cubic yards, or 50 percent of field capacity.

The mobilization fraction calculated as above excludes turbulent sediment mobilization due to suction generated by each closing dredge jaw. Accordingly, the actual mobilization fraction is higher by the amount disrupted outside each dredge bucket jaw. Physics demands that the compressive force exerted to the interior of dredge bucket walls equal the suction force exerted outside. A reasonable approximation, therefore, is that uncounted sediment mobilization outside dredge buckets roughly equals the amount of sediment that is mobilized within buckets. This approximation also is conservative, inasmuch as the sediment that can be mobilized includes that situated behind each of two dredge jaws. This added mobilization factor gives rise to the possibility of the sediment mobilization fraction exceeding 100 percent of the dredge bucket field capacity. That is, dredge buckets cannot mobilize more sediment than they contain, unless (as described above) they also mobilize sediment that they do not contain.

Estimation of sediment mobilization fraction. We previously made two independent quantitative estimates of the fraction of sediment mobilized when a dredge bucket descends to the river bottom, closes, lifts its load, and transfers its load to a waiting barge (Michaels and Oko 2010). One estimate, based upon the difference between sediment volume enclosed by an open versus a closed dredge bucket, was a mobilization fraction of approximately 80 percent. The other, based upon analysis of published bucket files versus published barged-sediment data, was approximately

75 percent during Phase 1, Year 1. These values exclude consideration of the new factor described above, i.e., suction creating turbulence behind closing dredge jaws.

A related factor, likewise unquantified (in Michaels and Oko 2010, and also herein), is failure of bucket closure, that is, turbulent mobilization of sediments by descending dredge jaws that cannot close when they encounter obstacles on the river bottom (such as bicycles, automobile tires, logs, boards, rocks, concrete blocks, rebar, and other construction debris). When dredge buckets fail to close, the onboard computer does not record the data in the bucket files. Indeed, for this reason, the fraction of bucket descents that result in nonclosure is unknown, notwithstanding that these bucket descents mobilize sediment in the river. Most essentially, notwithstanding our inability to quantify some parameters precisely, the factors described above, along with bucket geometry and computerized bucket data, indicate that dredge buckets dumped more material back into the river than into waiting barges. That material remains mobile via physical processes or, if taken up by biota, through ecosystem dynamics.

The two factors described above, though we cannot quantify them exactly, at the least add conservatism to our previously published estimates of 75–80 percent sediment mobilization per bucket closure. This fraction was applicable to dredge buckets, but was significantly (but likewise to an unquantified degree) reduced when considering overall sediment mobilization in Phase 1, because of bank-to-bank dredging. Such redredging in Phase 1, however, is not a feature of Phase 2 (except in its first year, 2011, which included bank-to-bank dredging of the uncompleted Phase 1 area), because Phase 2 addresses widely spaced PCB hot spots. Sediments that are resuspended and carried downstream beyond a PCB hot spot may redeposit on a portion of the river bottom that will never be dredged (or redredged). Phase 2 hot spot dredging comprises the preponderance of the forty-mile (sixty-four-kilometer) stretch of the Upper Hudson River that is included in the dredging project, making the per-bucket mobilization fraction highly relevant for Phase 2. Given the preponderant scope of Phase 2, the per-bucket mobilization fraction is relevant in evaluating the Hudson River dredging project in its entirety.

Issue 2, PCB mobilization: Possible PCB loss by desorption from resuspended sediment particles

Estimation of PCB mobilization fraction. Apart from the *sediment* mobilization fraction addressed above is the related issue of the possibly different *PCB* mobilization fraction. PCB might be mobilized by desorption from dredge-disturbed sediment as particle surfaces encounter relatively PCB-free river water. To the degree that this occurs, PCB may be mobilized from dredge-disturbed sediment as it falls back to the river bottom or remains suspended (resuspended) in the water column. Such desorption produces free PCBs in the molecular and colloidal phase, which are transported downstream with river water. Free PCB in river water no longer is adsorbed to clay or silt particles. Sampling of clay or silt particles in routine resuspension monitoring would not capture free PCBs in dissolved or colloidal form.

"PCB in colloidal form constitutes the most mobile form of PCB in water, being affected only minimally by settling, physical retention or adsorption" (Paquin 2001).

To develop a more realistic picture of resuspension, we estimate, roughly but quantitatively, the amount of fugitive free PCB that clamshell dredging might have created in Phase 2. Fugitive PCB originates, and primarily is carried by, fine particles of silt, clay, and sand that, together, give rise to free PCB via desorption. Accordingly, we used data on hydraulic dredging to derive information on the size distribution and resuspension of such sediment in moving water like the Hudson River. Available literature (Nau-Ritter et al. 1982) indicates that approximately 30 percent of PCB adsorbed to resuspended sediment particles desorbs and enters river water in dissolved or colloidal form within minutes of resuspension. Further, most fine particles ('fines') remain resuspended for hours to weeks before settling, during which they slowly release most if not all of the remaining 70 percent of adsorbed PCB (Schneider 2005). We assume that much or most of the 70 percent is captured by routine resuspension monitoring. The 30 percent that quickly enters the aqueous phase, however, would not be captured in routine particle monitoring for verification of compliance with US EPA's EPS for resuspension.

The *mass* of PCB corresponding to loss of 30 percent desorbed from particles of dredge-disturbed sediment to the aqueous phase is missed in monitoring PCB *concentration* in water, due to river flow variation. We approximate it as follows. We do not know the exact size distribution of resuspended particles, but laboratory development of a dredging elutriate test (DiGiano et al. 1995) revealed that turbulence mixes a wide range of particle sizes into the water column, but denser particles settle preferentially, leaving behind an elutriate (supernatant) of less dense resuspended particles, of which 90 percent were ≤ 10-μm (micrometer, or micron) diameter. The most common size class was 4 μm. Accordingly, we similarly assume spherical particles of diameter 4 μm. Although the particles are resuspended, we assume a heavier-than-water specific gravity of 1.8, which, as they are small, can be maintained in suspension by turbulence in river water. This specific gravity is somewhat lower than 2.6 previously reported for Hudson River sediments (Gruendell 1966; Michaels and Oko 2010), as we also assume here that relatively lighter resuspended particles are enriched in relatively less dense organic matter.

Our 4-μm spherical particle model is only a rough guide. Fine particles resuspended after dredge disturbance actually are nonspherical, and some are more porous than others, whereas we assume hard spheres. Both properties increase surface area. For example, clay, an important constituent of silt, is both porous and nonspherical, with particle surface areas of 200–600 m^2/g (square meters/gram). Our hard-sphere model therefore is conservative, because porous-nonspherical particles have more surface area, can adsorb more PCB, and thus can desorb more PCB to river water.

The high surface area of small sediment particles such as clay disproportionately carries resuspended PCB (DiGiano et al. 1995; Anchor Environmental 2003; Michaels and Oko 2010). We assume that each resuspended hard-spherical particle is coated initially with a monolayer of PCB molecules. We also assume an average

Table 1. PCB desorption from resuspended sediment in ten-acre Phase-1 Year-1 Hudson River dredging area.*

Mass of PCB rapidly desorbed from a resuspended spherical sediment particle of diameter four microns		
radius of 4-micron (µm) diameter spherical particle	2	µm
surface area of spherical particle of 4-µm diameter: $4\pi r^2$	50.3	sq. µm
area occupied by one molecule of (decachlorinated) PCB	300	sq. angstroms
area occupied by one molecule of (decachlorinated) PCB	3.00 E-06	sq. µm
PCB molecules in monolayer on one 4-µm-diameter particle	1.68 E+07	PCB molecules
molecular weight (MW) of the PCB molecule	240	g/mole
number of PCB molecules per mole (Avogadro's number)	6.02 E+23	PCB molecules
moles of PCB monolayer adsorbed to 4-µm diameter particle	2.78 E-17	moles
mass of PCB molecules on one 4-µm diameter particle	6.68 E-15	g
fraction of PCB rapidly desorbed and entering river in aqueous Phase	0.3	…
mass of PCB rapidly desorbed to water, per 4-µm diameter particle	2.00 E-15	g/0.04-µm particle
Mass of a resuspended spherical sediment particle of diameter 4 microns		
volume of spherical particle of 4-µm diameter: $4/3\,\pi r^3$	3.35 E+01	cu. µm
conversion, cubic µm to liter (= 1,000 cu. cm)	1.00 E-15	cu. µm/liter
volume of spherical particle of 4-µm diameter: $4/3\,\pi r^3$	3.35 E-14	liters
specific gravity of 4-µm diameter spherical particle	1.8	g/mL = kg/liter
conversion, g/mL to g/cu. m	1.00 E-06	(g/cu. m)/(g/mL)
specific gravity of 4-µm diameter spherical particle	1.80 E+06	g/cu. m
mass of spherical particle of 4-µm diameter	6.03 E-14	kg/0.04-µm particle
mass of spherical particle of 4-µm diameter	6.03 E-11	g/0.04-µm particle
Number of spherical sediment particles of diameter four microns fitting into a five-cubic yard dredge bucket		
conversion, cubic yards to cubic meters	7.65 E-01	cu. m/cu. yd.
volume of 5-cubic yard dredge bucket	3.82 E+00	cu. m
field capacity if filled to 80 percent of full capacity	3.06 E+00	cu. m
volume of spherical sediment particle of 4-µm diameter	3.35 E+01	cu. µm
conversion, cubic µm to cubic m	1.00 E-18	cu. m/cu. µm
volume of spherical sediment particle of 4-µm diameter	3.35 E-17	cu. m
no. of 4-µm spherical sediment particles per 5-cubic yard bucket	9.13 E+16	particles/bucket
Allowable resuspension in ten-acre Phase-1 Year-1 dredging area, under US EPA's 2 percent-EPS		
mass of sediment particles per 5-cubic yard dredge bucket	5.50 E+03	kg
US EPA engineering performance standard (EPS) for resuspension	2	percent
allowable resuspended particle mass, in accordance with EPS	110.1	kg/5-cu. yd. bucket
bucket closures in ten-acre area dredged in Phase 1 Year 1	221,521	closures/10 acres
allowable resuspended particle mass, in ten-acre Phase-1 Year-1 area	2.44 E+07	kg/10 acres
Mass of PCB rapidly desorbed to water from resuspended particles in ten-acre Phase-1 Year-1 area		
4-µm diameter spherical particles per gram	1.66 E+10	particles/gram
4-µm particles resuspended in ten-acre Phase-1 Year-1 area	4.04 E+20	particles
mass of PCB adsorbed as monolayer on resuspended particles	2.70 E+03	kg of PCB adsorbed
mass of PCB rapidly desorbed from resuspended particles	8.10 E+02	kg of PCB desorbed

*Scientific notation: $1.00 \times 10^{+01}$ tabulated as 1.00 E+01.

PCB molecular weight of 240 grams/mole. Table 1 (above) shows the following calculated parameter values:

1. the mass of a monolayer of PCB on a 4-µm spherical particle is 2.00×10^{-15} g;
2. the mass of a particle of 4-µm diameter and specific gravity 1.8 is 6.03×10^{-11} g;
3. an 80 percent-full 5-cu. yd. dredge bucket can contain 9.13×10^{16} 4-µm particles;

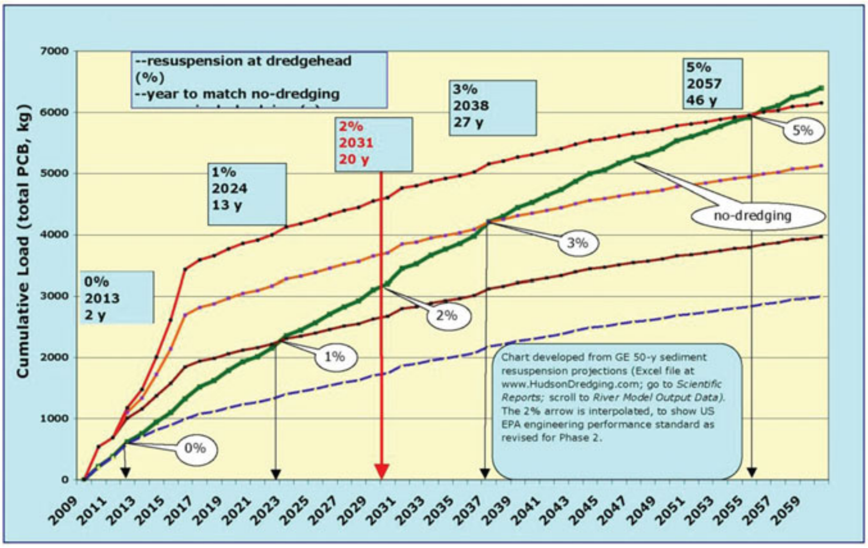

Figure 2. At Waterford: GE projected years needed to match no-dredging, assuming zero dredge mobilization of PCB other than 'resuspension'.

4. US EPA's 2 percent-EPS allows resuspension of 2.44×10^7 kg in the ten-acre Phase 1, Year 1 dredging area; and
5. the estimated mass of PCB desorbed to the river in aqueous phase is 810 kg.

GE estimates show that the break-even point, at which dredging will have reduced PCB mobilization as much as it has increased it during the dredging project, would be twenty years, assuming compliance with US EPA's 2 percent-EPS for resuspension. This would bring the break-even year to 2032 (Fig. 2). Under GE's highest mobilization assumption, 5 percent of sediment is released back to the river "at the dredgehead," in which case dredging will require forty-six years to match the effectiveness of the no-action remediation alternative. *That is, no benefit can be expected until the year 2057 at the earliest, optimistically assuming no delays and, critically (see* Discussion), *no mobilization of PCB sediments other than 'resuspension'*.

Issue 3, storms: Possibly changing frequency of sediment-mobilizing high flow events

After the first season of dredging, GE reported (Carson 1962; DiGiano et al. 1995; Gardiner et al. 1996) that sediment samples outside the dredged area "show that dredging caused wide-spread redistribution of PCB-containing sediments on the surface of the river bottom." High-flow events already have driven some of this dredge-mobilized sediment downstream (see, e.g., Islam et al. 2012, 24). Indeed, recent years have evinced a trend toward increasing frequency and intensity of storms (Matonse and Frei 2012, 25), including extreme events such as Hurricane Katrina in 2005, Irene in 2011, and Sandy in 2012, all attaining extraordinary energy, largely from warmer ocean water in their path (see, e.g., Trenberth 2007).

Evident global climate change (whatever may be the less-well-known contribution of civilization to it) has been manifest in a concomitant trend toward more frequent high-flow events in rivers and streams, resulting from rainfall, tidal surges, and flooding. Indeed, Matonse and Frei (2012) investigated whether the hydrological impacts of Hurricane Irene and Tropical Storm Lee continue a historical trend toward increasing frequency of extreme hydrological events in New York State's Catskill Mountains and Hudson River Valley region. They found

> a marked increase in the frequency of extreme hydrologic events during the last one to two decades. This increasing trend is more evident during the late summer and early fall, the season of the most extreme precipitation events.

This trend, therefore, can be extrapolated to the future, and incorporated into Superfund remediation project assumptions, including assumptions for Hudson River PCB dredging.

Tropical Storms Irene and Lee caused 100-year and 500-year flooding, in which the Mohawk River carved new channels up to forty-five-feet deep. The storms exerted comparable impacts on the Hudson River. For example, the storms delivered an extraordinary amount of fresh water to the Hudson River watershed, along with a U.S. Geological Survey (USGS) estimate of nearly three million tons (2.7×10^6 kg) of sediment (Wall and Hoffman 2012, 18).

Potential effects of swift river flow include scouring of PCB-laden sediment exposed by dredging to downstream areas, washing away of plantings designed to stabilize the river bottom and reestablish ecosystems, disruption of caps placed over residual PCB-containing sediments, flooding, and depositing PCB sediment on the shore as 'flood mud.' Islam et al. (2012, 17), investigating the impact of Tropical Storm Irene-associated precipitation on the Hudson River and estuary ecosystem, reported the following:

> Continuous monitoring data at the PCB superfund site at Fort Edward, NY …showed significant and coincident increases in sediment flux (22 metric ton/hr to 2400 metric ton/hr) and stream flow (85 m^3/s to 480 m^3/s) following Irene. In addition, in-situ particle size measurements suggest that significant amounts of small particles (<70 µm diameter) were transported during the flood event.
> Moreover, the contribution of these extreme storm effects to the overall loading is comparable to that of long-term sediment transport under ordinary conditions. This suggests that effects of episodic events should be considered as part of ecosystem management during activities such as navigational channel dredging, remediation projects, and long-term water usage and discharge control.

Issue 4, endangered species: Endangered species classification of Hudson River sturgeon

US EPA reported that PCB concentrations in fish tissue in the Upper Hudson River increased fivefold after the first year of dredging (US EPA 2010a, 2010e, 2012, n.d.a, n.d.b). US EPA reported more recently that PCB concentrations in fish tissue in the Upper Hudson River sampling area have returned to normal, presumably due to a combination of contaminated sediment removal and downstream transport of residuals (*Id*. 2010e, 2012, n.d.a, n.d.b). Indeed, US EPA's Hudson field office director David King acknowledged orally at a conference at Marist College (January 16, 2013) that twenty to thirty years might be required for PCB levels in fish tissue to decline again to levels safe for human consumption. Resuspended PCB transported downstream is assumed (by us and by US EPA) eventually to reach the Lower Hudson River, which is the principal habitat of two species of sturgeon (Shepherd 2006; USDOC 2012). Indeed, such transport is more than theoretical, but has been documented empirically. Hudson River Natural Resource Trustees reported (NYS et al. 2013) that PCB transport (mostly prior to dredging) already has resulted in PCB contamination of the Lower Hudson River:

> The Hudson River Natural Resource Trustees are conducting a natural resource damage assessment (NRDA) to investigate natural resource injuries that may have occurred due to the release of polychlorinated biphenyls (PCBs) from General Electric (GE) facilities at Hudson Falls and Fort Edward, NY. This report summarizes available information on PCB contamination in the Hudson River ecosystem, including historic information, but focusing particularly on data collected and analyzed between 2002 and 2008 as part of ongoing NRDA activities. **The Hudson River, for greater than 200 miles below Hudson Falls, NY, is extensively contaminated with PCBs**. Surface waters, sediments, floodplain soils, fish, birds, wildlife, and other biota are all contaminated with PCBs. (NYS et al. 2013, 1; emphasis added)

The shortnose sturgeon (*Acipenser brevirostrum*) was listed as endangered in 1967, though (in 2006; Shepherd 2006) it appeared to be recovering inasmuch as it has not been a target of fishing since 1967. The U.S. Department of Commerce, on February 6, 2012, added the Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) to the *Endangered Species List* (US DOC 2012). The Commerce Department must protect sturgeon habitat—principally the Hudson River (Shepherd 2006)—as required by the federal Endangered Species Act. Loss of habitat is a big part of the problem of loss of sturgeon, inasmuch as the principle alternative loss factor, fishing for either species of sturgeon, has been prohibited for well over a decade, since a moratorium on harvesting wild Atlantic sturgeon was imposed in 1998 after decades of overfishing. Commercial landings of Atlantic sturgeon crashed before the moratorium was imposed (Fig. 3; Shepherd 2006). The Lower Hudson River, below the Federal Dam at Troy, evidently will be impacted by PCBs for years or decades as contaminated dredge-mobilized sediments are scoured and transported downstream from an increasing area of river bottom in the Upper Hudson River, at Fort Edward and to the south.

Early life stages of sturgeon including larvae and eggs—*caviar*—are particularly susceptible to PCB contamination (US EPA 2010c). According to US EPA (previous to the official *Endangered Species* classification of the Atlantic sturgeon): "Fragile populations of threatened and endangered species in the Lower Hudson River, represented by the bald eagle and shortnose sturgeon, are particularly susceptible to adverse effects from future PCB exposure."

By "future PCB exposure" US EPA (2010c) meant future exposure if dredging does not occur, but dredging did occur. PCB levels in Lower Hudson River water presumably will vary over space and time as they increase gradually to an

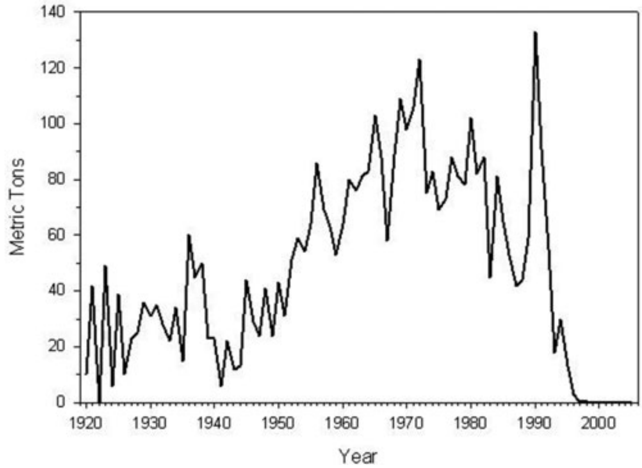

Figure 3. Total commercial landings of Atlantic sturgeon in the United States historically.
Source: G. Shepherd. 2006. Status of fishery resources off the northeastern United States. Atlantic and shortnose sturgeons: Atlantic *(Acipenser oxyrhynchus)*, shortnose *(Acipenser brevirostrum*. National Oceanic and Atmospheric Administration (NOAA), Northeast Fisheries Science Center (NEFSC), Resource Evaluation and Assessment Division, http://www.nefsc.noaa.gov/sos/spsyn/af/sturgeon/

undetermined maximum over a period of years or decades, during which annual sturgeon reproductive cycles will be stressed. The degree of stress, and ability of already-stressed sturgeon populations to withstand it, both remain unknown.

Modeling of the dynamics of three million tons of sediment loading into the Hudson River following Tropical Storms Irene and Lee, undertaken by Ralston, Geyer, and Warner (2012, 11), revealed the following:

> The simulated sediment transport showed surprisingly little sediment export—most of the sediment delivered by the storms was trapped in the tidal river north of West Point, according to the model.

Similar dynamics may be expected from PCB-bearing sediments mobilized by dredging. That is, estuaries can trap sediments and the toxins that they harbor, to the detriment of ecosystems including Hudson River sturgeon occurring below the Federal Dam at Troy.

Issue 5, autism: Research into possible PCB causation of autism

PCBs are known neurotoxicants (ATSDR 2000). Moreover, PCBs have been implicated in causation of Parkinson's disease (Goldman et al. 2016), ADHD (Keil and Lein 2016), and autism ((Keil and Lein 2016; Landrigan et al. 2012; Wayman et al. 2012a, 2012b). PCBs also are known developmental neurotoxicants *at environmental levels of exposure* (ATSDR 2000). Based upon prospective epidemiology studies, maternal exposure to PCBs during pregnancy has been linked to dyslexia, attention deficit hyperactivity disorder (ADHD), and loss of cognition (reduced IQ; Winneke 2011). More recent (animal) studies now link PCBs to DNA methylation (Keil and Lein 2016) and to specific developmental processes that, in humans, are thought to

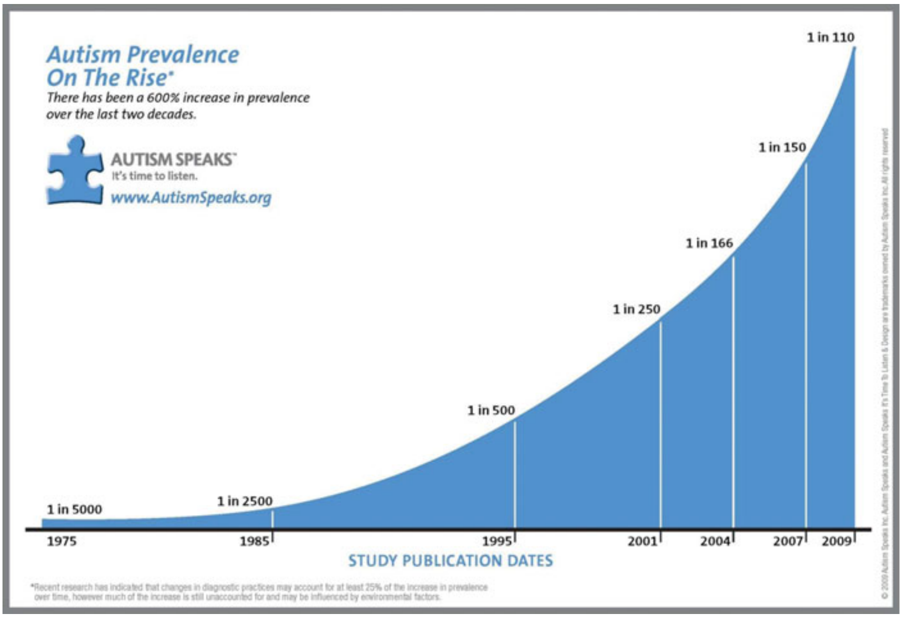

Figure 4. Autism prevalence trend.

underlie causation of autism (Landrigan et al. 2012; Wayman et al. 2012a, 2012b), most notably the following:

1. stimulation of calcium signaling in the brain that alters nerve cell dendrite branching;
2. increased dendrite growth and branching; and
3. alteration of synapse formation in developing brains (in animal bioassays).

The prevalence of autism has been increasing dramatically in recent decades (Fig. 4; Autism Speaks n.d.), and today affects 1.13 percent of children (one of eighty-eight; Autism Speaks n.d.; Landrigan et al. 2012; USDOH 2012) and nearly one of fifty-four boys (Autism Speaks n.d.). A substantial portion of the increase in autism prevalence evidently is attributable to environmental factors. Boys are nearly five times more likely than girls to have autism (Autism Speaks n.d.), suggesting sex-linked inheritance of susceptibility factors, as boys have just a single (maternal) X chromosome that, if damaged, lacks potential compensation from genes in a counterpart (paternal) X chromosome as is the case in girls, who inherit an X chromosome from each parent.

Discussion, conclusions, and recommendations

Issue 1, sediment mobilization: US EPA accuracy in estimating PCB-contaminated sediment mobilized by dredging

US EPA's engineering performance standard (EPS) pointedly refers to "resuspension," not "mobilization." These terms might seem intuitively synonymous but, in US EPA parlance, *resuspension* denotes just a miniscule fraction of dredge-mobilization of sediment. A significant *sediment mobilization discrepancy* therefore exists between sediment that is mobilized by dredging versus the much smaller amount of sediment that is measured and reported by GE, and used to document compliance with the US EPA resuspension EPS. The discrepancy arises from the fact that the preponderance of dredge-resuspended sediment falls back to the riverbed, and remains on the river bottom, still mobile, but unrecorded by GE or US EPA because its resuspension typically is episodic over years to decades and, in the main, has not yet occurred.

US EPA (2010d, 2010e, n.d.a) EPSs limit dredge mobilization of sediments to a maximum of 2 percent "at the dredgehead." Results of US EPA modeling using HUDTOX, however, clearly indicated that the 2-percent EPS, even for resuspension alone, could not be attained at the dredgehead; indeed, it was redefined upward simply by changing (at least doubling) the estimated mass of PCB to be dredged (and also the allowable resuspension fraction), and therefore the amount (mass) of allowable PCB resuspension:

> [The Record of Decision] originally estimated the PCB mass to be removed as approximately 70,000 kg, and the total project cumulative load standard was set at just below 1 percent of this total, or 650 kg. Based on the Phase 1 experience and additional sampling results, the estimated PCB mass for the entire project has been revised to the range 140,000 to 200,000 kg. (US EPA 2010d, 4–2).

The sediment mobilization problem also was highlighted by US EPA's Hudson River Dredging Peer Review Panel. The panel's initial draft report (Peer Review Panel 2010), published to elicit comments, made an interesting error that was followed by a more interesting response by US EPA. The panel's comment no. 6 stated the following:

> [EPA's] incomplete analysis done for the 2004 EPS does not consider near-field and far-field PCB deposition rates on the sediment bed surface.

Thus, according to the peer review panel, US EPA failed to consider sediment mobilization at the dredgehead ("near field"), where dredged sediments are mobilized. US EPA's response to Hudson River Dredging Peer Review Panel comment no. 6 is highly informative regarding this issue, and exemplifies US EPA's worst practice in handling data that might interfere with Agency plans:

> EPA did simulate near-field suspended matter transport and settling in its near-field modeling analysis. The HUDTOX model runs did not reflect the near-field settled solids but *did incorporate* an estimate of dredging-related suspended solids transport 1,000 meters downstream of the dredge. This analysis was the basis for the EPA forecasts of dredging-related *resuspension*. (US EPA 2010b; emphasis added)

Thus, US EPA apparently could not meet the 2-percent (originally 1-percent) EPS limit at the dredgehead, so it declined to apply its HUDTOX modeling results at the dredgehead to forecast dredging-related resuspension quantitatively. Instead, US EPA applied results obtained from HUDTOX at a cleaner place in the river, 1,000 meters downstream of dredging. Inasmuch as nearly all dredge-disturbed sediment (orally reported by US EPA at roughly 99 percent) falls back to the river bottom near the dredgehead, the use of HUDTOX results from 1,000 meters downstream ignores roughly 99 percent of resuspension occurring at the dredgehead. This is at best misleading and, indeed, the expert peer review panel was misled as indicated by its incorrect criticism (quoted above) that US EPA had failed to model resuspension at the dredgehead (in the "near field"). The Agency did do the modeling, but (as US EPA stated) declined to use the results.

As explained, sediment mobilization via dredging includes resuspension (at the dredgehead or wherever estimated) as well as the preponderance of dredge-disturbed sediment that falls back to the riverbed and is not barged (which we approximated conservatively at 75–80 percent of the amount initially excavated). This sediment drops back to the river bottom, still mobile, but it is excluded from US EPA's resuspension parameter. US EPA's statement quoted above therefore shows that the Agency justified dredging by ignoring gradual erosion from the river bottom of dredge-mobilized PCB-bearing sediments, which reasonably would be expected to occur over a period of years to decades. The Agency thereby also ignored inevitable, though gradual, entry of PCBs from these sediments into downstream water, ecosystems, and air. Thus, in fifty years US EPA conceivably might find the river to be in much the same condition from GE dredging up sediments today as it was found to be fifty years ago from GE disposal of PCB into the river.

The modeling and data handling issues raised above presumably would have come under scrutiny by US EPA's Hudson River PCB Dredging Peer Review Panel, but US EPA explicitly prohibited the panel from opining whether dredging should continue, or whether Phase 2, if undertaken, could meet project health goals. Nonetheless, the Peer Review Panel (2010) rejected US EPA's response, quoted above, concluding in its final report:

> Phase 1 showed that the 2004 EPS [engineering performance standards] for Resuspension, Residuals, and Productivity were not met individually or simultaneously during Phase 1 and cannot be met under Phase 2 without substantive changes. EPA and GE proposed changes to the EPS, but the Panel finds that the new proposed standards from either party would not contribute to the successful execution of Phase 2. (*Id.*, 84)

The *sediment mobilization discrepancy* discussed above represents more than merely a difference between a predicted versus a measured parameter value. It represents a fundamental inconsistency in US EPA's past justification of the need to dredge versus US EPA's current characterization of the performance of the dredging project. The need for dredging was justified by the observed, persistent mobility of PCB sediments requiring, according to US EPA, their removal via dredging. In contrast, in the new context of actual dredging, US EPA dramatically has altered its concept of mobility. *Mobility* in the dredging project is newly quantified by the miniscule fraction of mobilized (resuspended) PCB that is detected at significant distance downstream. Thus, US EPA has ignored nearly all sediment and PCB mobilization in evaluating compliance with the engineering performance standard *for resuspension*. In ignoring mobility of PCB-containing dredge-mobilized sediments for gauging compliance with the resuspension EPS, US EPA has ignored a much larger degree of PCB sediment mobility than that which constituted US EPA's most essential basis for requiring, in 2007, remediation of the Hudson River PCB Superfund Site via dredging.

Failure of US EPA to use HUDTOX modeling results at the dredgehead is not the only example of misleading use of modeling or monitoring data by US EPA, and should be viewed in this broader context. One example will suffice. In seeking to justify dredging, US EPA had prepared a baseline health risk assessment (HRA; US EPA 1999, 2000a, 2000b) that excluded all mono- and di-chlorinated PCB congeners based upon a misleading premise, specifically, that these congeners do not bioaccumulate in fish tissue, which contributes to human exposure to PCBs (Michaels and Oko 2007). The mono- and di-chlorinated congeners, even if they bioconcentrate less dramatically than the higher-chlorinated congeners, still are present in fish tissue. They should have been present in the HRA.

In the 1960s, Rachel Carson's *Silent Spring* (1962) famously raised awareness of environmental risks posed by DDT, which is a nearly identical twin of PCBs (Michaels and Oko 2010). Both DDT and PCBs contribute to human health risk by entering air, water, and ecosystems that include food chains terminating in consumption of fish and birds by people. Higher-chlorinated PCBs degrade via dechlorination, resulting in build-up of the mono- and di-chlorinated congeners. Their omission from US EPA's HRA, therefore, contributed significantly to obtaining its dredging-permissive results. Indeed, when US EPA came under attack by environmental groups for favoring a dredging plan that would remove only one hundred thousand pounds of PCB, US EPA responded by adding back the mono- and di-chlorinated PCB congeners that initially had been excluded when assessing potential health risks. US EPA thereby claimed that the actual amount of PCBs that would be dredged under its "revised" plan would be one hundred fifty thousand pounds, indicating that, in US EPA's own view, the mono- and di-chlorinated congeners that were omitted from the baseline HRA would contribute 50 percent more than the one hundred thousand pounds of PCB actually included in the inventory on which the HRA was based (Michaels and Oko 2007).

We conclude that US EPA estimation of mobilization of dredge-disturbed PCB-contaminated sediment has been grossly inaccurate. Sediment resuspension has been mismeasured and evidently not limited to within the applicable EPS of 2 percent of the amount of PCB dredged at the dredgehead. Environmental performance standards that address the broader issues of sediment mobilization and spreading to new areas of the river bottom remain nonexistent, notwithstanding peer review panel findings that such EPSs are needed. We also conclude, therefore, that any extension of the dredging project as demanded recently by many in the environmental community should be predicated upon agency remediation of these deficiencies.

Issue 2, PCB mobilization: Possible PCB loss by desorption from resuspended sediment particles

Comparison with US EPA mobilization assumptions. US EPA engineering performance standards (EPSs; US EPA 2010d, 2010e) limit dredge mobilization of PCB in sediments to ≤ 2 percent "at the dredgehead," which roughly is at the dredging platform. A 2010 US EPA (2010e) factsheet explicating *Technical Requirements for Phase 2 of Hudson River Dredging* states, for example:

> The amount of PCBs allowed to travel down the river will not be allowed to exceed 2% of the amount of PCBs actually excavated from the river bottom, as measured at designated locations downstream of where the dredging is taking place.

As shown in Table 1 (in *Findings*), this limit routinely has been exceeded substantially, in part because measurement at downstream locations does not reflect the amount of PCB excavated at the dredgehead, and that eventually will flow down the river. Even if the 2-percent limit were not exceeded at all, however, GE estimates (Fig. 2, in *Findings*) shows that the break-even point, at which dredging will have reduced PCB mobilization as much as it has increased it during the dredging project, would be forty-six years. That is, no benefit can be expected until the year 2057 at the earliest, optimistically assuming no delays and, critically, no mobilization of PCB sediments other than resuspension.

Issue 3, storms: Possibly changing frequency of sediment-mobilizing high-flow events

The documented trend toward more frequent and more intense storms and resulting sediment mobilization (see *Findings)* can be and should be extrapolated to the future, and incorporated into Superfund remediation project assumptions, including assumptions for Hudson River PCB dredging. US EPA reported in 2011 that high river-flow caused by Tropical Storms Irene and Lee did not elevate concentrations of resuspended sediment above acceptable guidelines specified in the EPS for resuspension. However, the EPS, as already shown, dramatically underestimates PCB mobilization, and therefore constitutes a poor measure of that parameter.

When storms greatly increase river flow, uncompacted PCB sediments disturbed by dredging are scoured from the river bottom. They enter the swiftly moving water column, and are transported downstream. This downstream transport may be invisible to US EPA's EPS for resuspension because the increased river flow simultaneously dilutes the scoured sediments. This dilution reduces PCB concentrations that can be measured in river water, thereby masking the increased scouring of sediment and elevation of the rate of its downstream transport.

Swift river flow events increase downstream transport of PCB sediments to a greater degree if dredging is not suspended during their occurrence. Such episodes presumably would increase the pace of downstream contamination of water, ecosystems, and air. US EPA's EPS for resuspension fails to measure these effects, and no EPS exists to measure the resulting increase in the area of newly contaminated river bottom. Future high-flow events, over years to decades, will continue to transport dredge-mobilized PCB sediments episodically downstream, where they will enter water, ecosystems, and air. Indeed, with sufficient dilution from increased river flow, virtually all dredge-disturbed PCB sediment conceivably could be driven downstream by storms and other high-flow events without contravening US EPA's EPS for resuspension. Thus, any extension of dredging should be predicated upon adoption of EPSs that effectively quantify and limit *long-term* scouring of dredge-disturbed sediments and resulting increases in the area of newly contaminated river bottom.

Issue 4, endangered species: Endangered species classification of Hudson River sturgeon

In 1999, more than a decade prior to addition of the Atlantic sturgeon to the Endangered Species List, US EPA issued an addendum to its baseline ecological risk assessment for the Lower Hudson River (49). The addendum, updated in 2010, evaluated future risks posed up to the year 2018 by PCB transport from the Upper Hudson River to ecosystems in the Lower Hudson River, between the Federal Dam at Troy and the Battery in New York City. As a baseline assessment, it assumes no dredging; indeed, it assumes "the absence of remediation." Its major conclusions (US EPA 2010c, 6) include the following:

> — Fish in the Lower Hudson River are at risk from future exposure to PCBs. Fish that eat other fish (i.e., which are higher on the food chain), such as the largemouth bass and striped bass, are especially at risk. PCBs may adversely affect fish survival, growth, and reproduction;
>
> — Fragile populations of threatened and endangered species in the Lower Hudson River, represented by the **bald eagle** and **shortnose sturgeon**, are particularly susceptible to adverse effects from future PCB exposure [emphasis added];
>
> — The future risks to fish and wildlife are greatest in the upper reaches of the Lower Hudson River and decrease in relation to decreasing PCB concentrations down river. Based on modeled PCB concentrations, many species are expected to be at risk through 2018 (the entire forecast period).

Dredging will continue to increase transport of PCBs from the Upper Hudson River to the Lower Hudson River to a degree exceeding the no-action alternative for the full forecast period. The conclusions of the *Ecological Risk Assessment Addendum*, therefore, reflect consistency of US EPA's (2010c) conclusion of record with our own: that endangered sturgeon, endangered bald eagles, and other species are at risk from continued dredging and PCB mobilization, and therefore with the general principle that environmental health is crucial for food chains and the safety of the human food supply (Hulme 2013).

Our conclusion also is consistent with that of US EPA's Hudson River PCB Dredging Peer Review Panel (2010). The panel concluded in 2010 that US EPA had failed to set an allowable sediment-loading limit, failed to gather data needed do this, and failed to develop models to predict transport of dredge-mobilized sediment and PCB bioaccumulation based upon Hudson River hydrodynamics. Thus, US EPA sampling of resuspended PCB was insufficient, because US EPA failed to sample or model the vastly larger quantity of dredge-mobilized PCB resting on the river bottom. US EPA, therefore, cannot assure the public that transport of sediment already mobilized by dredging will not increase downstream PCB loads gradually and episodically for decades, threatening ecosystems in the Lower Hudson River. It cannot assure the public and the U.S. Department of Commerce that endangered sturgeon and bald eagles can survive decades of increased PCB transport to the Lower Hudson River. Continued dredging therefore should be predicated upon development of appropriate EPSs and compliance with them, which together might enable US EPA to make such assurances credibly.

Issue 5, autism: Research into possible PCB causation of autism

Treatment of children severely impaired by autism is palliative rather than curative; that is, children with autism typically become adults with autism (Landrigan et al. 2012). Impacts on families of children with autism may be devastating physically, psychologically, and financially. Economic impacts to society likewise are enormous (Landrigan et al. 2012; Autism Speaks n.d.), and may be exacerbated since the American Psychiatric Association in 2013 changed its diagnostic mental illness definitions, combining people with severe autism and others with milder forms (such as those with Asperger's Syndrome) into a single autism spectrum disorder (ASD) category (Jabr 2012).

The issue of whether the officially completed GE Hudson River dredging project should be extended to remediate remnant PCBs must be viewed in the context of US EPA's longstanding special mandate regarding children's health, embodied by US EPA's (2001) *Children's Health Risk Initiative*. In 1997 the Office of Children's Health Protection was instituted within US EPA. Its mission was and remains "to make children's health protection a fundamental goal of public health and environmental protection …[by] ensuring strong standards that protect children's health."

Long-term remediation projects undertaken under the federal Superfund Act or its state equivalents are subject to five-year reviews. As dredging Hudson River PCBs was mandated in 2007, the first five-year review of the project was undertaken as required in 2012 (US EPA 2012). Accordingly, one of us (Michaels) informed US EPA of the emerging link between PCBs and possible causation of autism and, in a public comment, suggested that the scheduled five-year review address this issue relative to numerous river communities alongside the path of the dredging project. The five-year review (US EPA 2012), however, neither addressed this issue substantively, nor alluded to it. Indeed, the word *autism* was absent from the eighty-two-page report. Given the high and increasing prevalence of autism (Fig. 4; Autism Speaks n.d.), and its seriousness, cost, and apparent linkage to environmental agents that may include maternal exposure to PCBs during pregnancy, extending the dredging project should be predicated upon satisfactory consideration of this emerging public health issue. The next five-year review of the dredging project is underway, for release in 2017.

Will further clamshell dredging fulfill the purpose of dredging?

Clamshell dredging has failed to meet US EPA's EPS goal of limiting short-term resuspension to ≤2% of the amount excavated. Consider a numerical illustration based upon the parameters quantified (at least approximately) earlier: 1,000 kg of PCB-contaminated sediment is excavated at the dredgehead. The EPS for resuspension is ≤ 2 percent, which is ≤ 20 kg. If 25 percent (≤ 250 kg) is barged, then 75 percent (≤ 750 kg) is mobilized, drastically contravening the 20-kg EPS. If, as reported orally by US EPA, 99 percent (750 kg x 0.99 = 742.5 kg) falls back to the river bottom near the dredgehead, then just 1 percent (7.5 kg) remains in the water column. If US EPA measured resuspension at the dredgehead, all of this resuspension would be captured in the measurement (742.5 + 7.5 = 750 kg).

A downstream measurement that is made *after* separation of the 1 percent remaining in the water column from the 99 percent falling back to the river bottom near the dredgehead would capture only the 7.5 kg remaining in the water column. The location of such a measurement, according to US EPA HUDTOX modeling, appears to be ≥ 1,000 m downstream. The resuspension value obtained at this location (7.5 kg in the example) complies with the EPS for resuspension (20 kg for every 1,000 kg excavated). Measuring or modeling resuspension 1,000 m downstream of dredging, therefore, in this example drastically contravenes the EPS for resuspension by overlooking 742 kg of dredge-disturbed sediment that has fallen back to the river bottom, but is still mobile (no longer buried in the riverbed).

The above numerical example also illustrates that clamshell dredging has failed to fulfill US EPA's main, original purpose of dredging: to reduce safely and substantially the long-term downstream transport of dredge-disturbed PCB sediments. The 742 kg of sediment that has fallen back to the river bottom in the above example still is mobile, in the sense that it can be and (if not redredged) eventually will be transported downstream via episodic high-flow events over years to decades. This redeposited mobile PCB sediment, as illustrated earlier, is invisible to the EPS for resuspension. The EPS, in turn, therefore is blind to long-term health and environmental risks potentially posed to downstream ecosystems.

Conclusion

Any long-term project, especially if unusually expensive, must be evaluated periodically to assess the degree to which it is fulfilling its purpose. If it is not fulfilling its purpose, it must be redesigned or terminated. Clamshell dredging was and remains a bad idea for the Hudson River, and has been shown incapable of fulfilling its original purpose of reducing safely and substantially the long-term downstream transport of PCBs. Our overall conclusion, therefore, is that excessive post-project PCBs in the Hudson River predominantly are attributable to sediment mobilization by clamshell dredges. We predict that proposed extension of the dredging project would prolong mobilization processes, allowing PCBs to spread widely and enter ecosystems that include people, endangered fish such as sturgeon, and endangered birds such as bald eagles.

Recommendations. We recommend that the design of any extended or future PCB dredging be improved to comply with US EPA's EPS limiting *short-term* resuspension to ≤ 2 percent of PCB in sediment excavated, and adopt EPSs also limiting *long-term* downstream deposition of residual sediments outside of dredge zones. Increasing storm frequency and intensity must be incorporated into prediction of dredging-associated sediment transport. EPSs must limit transport to within levels shown sustainable for survival and reproduction of sturgeon, eagles, and other endangered species in the long-term, well beyond several years needed for completion of dredging. US EPA likewise must address the potential of dredging to increase the incidence of autism in affected river communities and, if necessary, adopt health protective EPSs. Finally, hydraulic dredging, originally proposed, should be considered as an alternative to conventional clamshells for extending and completing remediation of the Hudson River PCB Superfund Site.

About the authors

Robert A. Michaels is president of Schenectady-based RAM TRAC Corporation, and a toxicologist specializing in assessment and management of risks to public health potentially posed by environmental contaminants. He has served numerous corporate clients, the U.S. Congressional Office of Technology Assessment, and public interest organizations such as the Natural Resources Defense Council (NRDC). Dr. Michaels chaired the State of Maine Scientific Advisory Panel, and for twenty years chaired the Certification Review Board of the Academy of Board Certified Environmental Professionals (ABCEP); he now serves as an ABCEP trustee. Michaels has been secretary of the National Fire Protection Association (NFPA) Committee on Classification and Properties of Hazardous Chemicals, board member of the National Association of Environmental Professionals, and member of the Editorial Advisory Boards of Springer-Verlag and Cambridge University Press journals. In 2004 he was awarded ABCEP's Kramer Medal recognizing his professional contributions. Uriel M. Oko is an independent consulting engineer in Albany, New York. He specializes in environmental remediation, cathodic protection for prevention of corrosion and material failures. At the Missouri University of Science and Technology he investigated surface behavior of mine tailings water that had been contaminated with heavy metal ions: zinc, lead, copper and mercury. He has designed remediation systems for pollution abatement of aquifers, stripping systems for the removal of MTBE (methyl-tert-butyl ether) and other volatile organic compounds from water, and cathodic protection systems for underground pipelines and storage tanks. Dr. Oko has served as an expert witness in litigation of industrial accidents. Prominent cases have involved metallurgical examination of collapsed bridge sections, fugitive chlorine gas from a water treatment plant, and collapsed scaffolds, cranes, and ladders.

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