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Cost-Effective Reduction of PCB Contamination in the Hudson River and Estuary

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1. Introduction

Polychlorinated biphenyls (PCBs) are a class of chlorinated hydrocarbon compounds that may result in adverse health effects on humans and wildlife. In New York's Hudson River and Estuary, significant quantities of PCBs are present in river and estuary sediments and in the biota. At least two salient characteristics of the Hudson River's PCB pollution make decisions about cleaning up the river problematic. First, PCB flows are complex, resulting in sediment concentrations of PCBs that are not uniformly distributed and PCB levels that are highly variable in the flesh of commercial and recreationally important fish. Second, there are multiple sources of PCB inputs into the river system. Thus, from an economic standpoint, it is important to identify the right combinations of sources to target for reduction and also to estimate the extent to which each source should be reduced. Further, the choice of source reduction ought to be tied to a model of PCB transport and fate.

A physical model developed by researchers at Manhattan College links the levels of PCB inputs into the lower Hudson River system to the concentrations of PCBs in sediments and fish (Farley *et al.* 1999). The model divides the lower Hudson River and Estuary into zones that are located in series from the Federal Dam at Troy to the mouth of the estuary downstream (some of the zones at the mouth of the estuary are located in parallel). In the physical model, PCBs flow at varying rates from zone to zone. Some of these PCBs are taken up in "sinks" in each zone.

PCBs enter any zone from an upstream or upcurrent zone, a wastewater treatment works point source, a combined sewer overflow point source, a tributary to the Hudson, or via atmospheric deposition. PCBs may exit a zone through chemical breakdown (aerobic biodegradation or anaerobic dechlorination), resuspenion from the sediments and subsequent downstream river flow, volatilization, the migration of fish out of the zone, or because of remediation efforts, such as dredging.

Using the physical model, reductions of sources of PCBs can be linked to lower concentrations of PCBs in the sinks. Any source of PCBs into any particular zone can be reduced at a cost. Thus the cost of achieving a lower concentration of PCBs in a sink can be deduced.

If we assume that a particular concentration of PCBs in a sink (*e.g.*, sediments, water column, fish flesh) has been established as a legal standard, an important public policy question is: *How much does it cost to reduce the concentration of PCBs in the sink to the legal standard?* In reality, this question is made more complex by at least four important issues:

- *It may not be technologically feasible to reduce PCB inputs from some sources* (*e.g.*, atmospheric deposition). This issue can be dealt with by assuming that there will be a background contribution of PCBs into a zone from those sources for which there is no feasible technological pollution control.

- *There may be more than one kind of pollution abatement technology for any particular source*. This issue requires a comparison, for any particular source type, of the costs of PCB reductions from that source in order to identify the cheapest or most cost-effective technology.

- *There are multiple sources of PCBs into any particular zone.* This issue requires a comparison of technologies across sources (or possibly across combinations of sources) to determine what source (or combination of sources) can be reduced at the least expense in order to achieve the legal standard.

- *The need to abate PCB inputs from specific sources may depend upon the choice of environmental standard and the pattern of transport of PCBs from those sources.* If the environmental standard applies to resources in a specific location, such as the PCB concentration in striped bass in the mid-estuary, reductions of PCB inputs from sources downstream of the mid-estuary, such as wastewater treatment plants, combined sewer overflows, or tributaries, may be less important or unnecessary.

We report here on the results of a research project directed at answering this important policy question. At the outset of the project, we had planned to integrate the physical model with an economic model to assess the cost-effectiveness of possible pollution control measures for the Hudson River and Estuary. We have successfully developed an economic model, but we have not been able to integrate it fully with the physical model due to the lack of usable simulation results from the latter. (The physical model has been developed and implemented under separate sponsorship.)

Even without useful physical model simulation results, we demonstrate how scientific and engineering information, incorporated into an economic optimization framework, can provide a valuable decision tool for environmental management. The next logical step is to incorporate simulation results from the physical model into the economic model to demonstrate the latter's ability to identify cost-effective PCB clean-up alternatives.

The remainder of this report is made up of eight additional sections. In Section 2, we summarize briefly the historical background of PCB pollution and policy responses in the Hudson River case. The history of the case includes an extensive political background involving negotiations among a large multinational corporation, one of the largest U.S. states, and the federal government. The political context of the clean-up of PCBs in the Hudson is extraordinarily complex and interesting, with potentially billions of dollars in clean-up costs at stake. Further, actions taken to clean up the Hudson are likely to set an important precedent that may affect the clean-up of PCBs on other river systems elsewhere in the country. Because we are not privy to the internal politics, we present only the public expression of this negotiation process in Section 2.

In Section 3, we describe the physical model of the lower Hudson and other efforts to model PCB transport and fate in both the upper and lower Hudson. This description of the model is based upon published reports (Farley *et al.* 1999; Farley and Thomann 1997).

In Section 4, we describe the economic damages associated with PCBs in the Hudson, and we review the very small literature that evaluates these damages. This section has been provided to help in understanding the policy background. Our preferred modeling approach involves the estimation of neither the economic damages associated with PCB contamination nor the explicit benefits of remediation efforts.

In Section 5, we describe the different types of environmental standards that exist to protect the health of humans and the Hudson ecosystem. The most relevant standard is the FDA standard of 2 parts per million (ppm) in commercial fish and shellfish. The adequacy of this standard to protect human health is in dispute, however. The fact that striped bass in the lower Hudson below Poughkeepsie now have levels of PCB concentrations below the FDA standard may have important implications for the choice of the economically rational clean-up strategy.

In Section 6, we present estimates of the costs of alternative technological solutions to clean up the PCBs in the Hudson. These costs are obtained primarily from a review of the technical literature. We focus on dredging and associated dredged material disposal costs and wastewater treatment costs. Reductions of PCBs from other sources (tributaries, the atmosphere) are not currently feasible.

In Section 7, we develop a suite of theoretical economic models that might be employed to determine the most appropriate course of action in cleaning up the Hudson. This theoretical section is followed by Section 8, where we conduct simulations of the cost-effectiveness model, suggesting how the economic model might make use of the results of the physical model to determine clean-up alternatives. Finally, in Section 9, we summarize the results of the research.

2. Policy Background

2.1 Health Effects of PCBs

Polychlorinated biphenyls (PCBs) are a class of chlorinated hydrocarbon compounds that may result in adverse health effects on humans and wildlife.[1] The long-term human health effects of exposure to PCBs are unknown. Suspected effects on human health are based upon studies of the effects on laboratory animals.[2] These potential effects include compromised immune systems, low birth weights, and learning impairments. PCBs also are a probable carcinogen. Humans are exposed to PCBs mainly through the ingestion of fish.[3] PCBs bioaccumulate in fish of higher trophic levels, which are those most likely to be eaten by humans. These species include striped and largemouth bass, white and yellow perch, and the American eel, among others (Table 2.1).

2.2 PCB Sources, Transport, and Fate

Beginning in the 1950s, PCBs were released into the environment as a component of some types of industrial wastewater effluent, before it was realized that they might harm human health. Although PCBs can become less harmful over time through processes of degradation known as

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[1] PCBs are also known as "Aroclors." There are 209 known PCB congeners. Some congeners closely resemble dioxins.

[2] http://www.epa.gov/region02/superfnd/hudson/humanhealth.htm.

[3] Low concentrations of PCBs in water or air are not thought to pose significant public health issues.

Table 2.1: Primary Species Consumed by Humans and Consumption Advisories* for the Hudson River

(N = no consumption advised; N* = no consumption advised for infants, children under the age of 15 years and women of childbearing age.)

Species	Upper Hudson	Mid-Hudson	Mid- to Lower Hudson
Alewife	--	1 meal/mo	
American eel	--	N	1 meal/mo†
Atlantic needlefish	--	N	1 meal/mo
Blueback Herring	--	1 meal/mo	
Blue crab	--	N	≤6 crabs/wk; No tamalley
Bluefish	--	N	1 meal/mo
Carp	N	N	1 meal/mo
Goldfish	N	N	1 meal/mo
Largemouth bass	N	N	1 meal/mo
Lobster	--	--	No tamalley
Merganser (diving duck)	N	N	N
Rainbow smelt	N	N	1 meal/mo
Rock bass	N	1 meal/mo	--
Shad	--	1 meal/wk	N*
Smallmouth bass	N	N	1 meal/mo
Snapping turtle	N	Trim fat, liver; discard eggs; N*	Trim fat, liver; discard eggs; N*
Striped bass	N	N	1 meal/mo; N*
Walleye	N	N	1 meal/mo
Waterfowl (various)	N	2 meals/mo; Trim fat, liver	2 meals/mo; Trim fat, liver
White catfish	N	N	1 meal/mo
White perch	N	N	1 meal/mo
Yellow perch	N	1 meal/mo	--

*Advisories are for fish containing PCBs or PCBs and cadmium.

†N from Dobbs Ferry to Greystone (south of Poughkeepsie)

Source: New York State Department of Health (1999) aerobic biodegradation or anaerobic "dechlorination," it is now known that degradation processes in the Hudson are slow and incomplete.[4] Therefore, PCBs can be described as one of several types of "persistent" organic pollutants (POPs). PCBs move from one location to another primarily through methods of sediment transport, including large-scale movements associated with storm events or modifications of river flow, say, through the removal of a dam. Minor amounts of PCBs move from the sediments into the water column. PCBs also may be washed up onto river banks during periods of high stormwater flow.

PCBs tend to adhere to fine-grained sediments. Consequently, the removal of PCBs from a riverine or estuarine environment often requires a program of dredging. Where PCBs are widespread, dredging can be very costly. Further, there may be additional costs associated with the disposal of dredged PCB-laden sediments as a hazardous material (Dávila *et al.* 1993; Carpenter 1986). Because of these costs, the presence of PCBs in riverine environments now has become one of the nation's most significant aquatic pollution problems. Recently, an *ad hoc* committee of the National Academy of Sciences has been convened to study the remediation of PCB-laden riverine sediments.[5]

2.3 Restrictrions on Human Consumption of Fish

In lieu of remediating sediments, the most common method of reducing potential health effects is to limit the consumption of fish. Fish consumption can be limited through an outright ban on commercial harvest or through "consumption advisories," which typically advise individuals as to the number of fish that can be safely consumed during a period of time (Table 2.1). Bans and advisories are based upon the estimated content of PCBs in fish sampled from the environment. Sampled PCB content is compared to a human consumption standard such as the one developed by the U.S. Food and Drug Administration (FDA) of 2 ppm. Other types of standards are described in Section 5 below.

2.4 History of PCB Pollution in the Hudson and Policy Responses

In New York's Hudson River and Estuary, significant quantities of PCBs are present in river and estuary sediments, in the water column, and in the biota. The history of salient events related to PCB pollution and subsequent attempts to remediate the pollution is summarized in Table 2.2. PCBs in the Hudson originated mainly from two electrical capacitor-manufacturing plants owned and operated by the General Electric Company (GE) at Hudson Falls and Fort Edward (Figure 2.1). Purposeful discharges and subsequent leakages have resulted in the release of approximately 550 tons of PCBs into the upper Hudson River.[6] The intentional release of PCBs was banned by the U.S.

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[4] Recent research on the dechlorination of PCBs in Hudson River sediments has shown that the rate of dechlorination is a function of the concentration of PCBs. Note also that PCB concentrations can be diminished through dilution with clean sediments, and they may exit a riverine system through volatilization.

[5] http://www4.nas.edu/cp.nsf/Projects+_by+_PIN/BEST-K-98-07-A?OpenDocument

[6] EPA estimates that between 105 and 650 tons of PCBs were released, with 550 tons as the most likely level.

Table 2.2: Hudson PCB Pollution Timeline

Date	Event
1947	General Electric Company (GE) begins discharging PCBs into the upper Hudson River as a waste product from an electrical capacitor manufacturing plant located at Fort Edward
1952	GE begins discharging PCBs into the upper Hudson as a waste product from an electrical capacitor manufacturing plant located at Hudson Falls
1973	Dam at Fort Edward is removed, resulting in the large-scale movement of PCBs downstream and the formation of 40 PCB "hot spots" in the upper Hudson above the Federal Dam at Troy (Figure 2.2)
1976	New York State Department of Environmental Conservation (NYSDEC) bans human consumption of striped bass caught in the Hudson
1977	GE discontinues purposeful discharges of PCBs from the electrical capacitor manufacturing plants on the upper Hudson
1977-78	The navigation channel near Fort Edward in the upper Hudson is dredged, removing 180,000 cubic yards of sediments, including 14,000 cubic yards of highly contaminated sediments containing an estimated 80 tons of PCBs; these sediments are placed in a clay-lined containment cell; 36 hot spots remain in the upper Hudson
1979	EPA bans environmental releases of PCBs
1981	EPA lists the "Hudson PCBs Site," a 200-mile length of the river, on the Superfund National Priorities List
1983	The Hudson PCBs Site is designated officially as a federal Superfund site
1984	EPA publishes a Record of Decision (ROD) on the Hudson River PCBs site; the ROD includes requirements for in-place capping, containment, and monitoring of remnant deposits near the GE plants and a study to evaluate the effectiveness of the Waterford Treatment Plant in removing PCBs from Hudson River water; the ROD includes an interim "No Action" decision on the clean-up of PCBs from the Hudson FDA lowers the safety standard for the level of PCBs in seafood from 5 parts per million (ppm) to 2 ppm
1987	EPA designates the NJ-NY Harbor Estuary as a "national estuary" under the federal Clean Water Act New York State Legislature passes the Hudson River Estuary Management Act, designating the lower Hudson as an "estuarine district"

Table 2.2: Hudson PCB Pollution Timeline

Date	Event
1989	NYSDEC initiates a *Hudson River Project Action Plan* in which it recommends the dredging of sediments from several of the upper Hudson PCB hot spots
	NYSDEC issues a request to EPA to reassess its 1984 No Action clean-up decision
1990	EPA initiates a *Reassessment Remedial Investigation/Feasibility Study* (RI/FS) of PCB-contaminated sediments in the upper Hudson
1991	GE completes bank stabilization of shoreline remnant PCB deposits according to a consent decree negotiated with EPA
	GE, EPA, and NYSDEC discover a previously unidentified subterranean source of PCBs near the Hudson Falls plant (at Baker's Falls)
	GE initiates remedial measures to prevent additional leakages of PCBs from the Hudson Falls plant
	EPA completes RI/FS Phase 1, involving the compilation and analysis of existing data. Further, it includes preliminary ecological and human health risk assessments.
1992	NYSDEC publishes proposed dredging locations for PCB hot spots in the upper Hudson (Thompson River Pool)
1993	Studies conducted at Hudson Falls reveal PCB-contaminated groundwater and seeps
1995	NYSDEC reopens the upper Hudson to recreational fishing on a catch-and-release basis only
1996	NYSDEC publishes the *Hudson River Estuary Management Plan* in which it describes the need to expedite the federal RI/FS process
	The Policy Committee of the NJ-NY Harbor Estuary Program publishes its *Final Comprehensive Conservation and Managment Plan* in which it backs EPA's RI/FS process
1997	EPA issues a *Data Evaluation and Interpretation Report* (DEIR) indicating that sediment inventories of PCBs in the upper Hudson are unlikely to be remediated "naturally" through dechlorination

Table 2.2: Hudson PCB Pollution Timeline

Date	Event
1997	NYSDEC samples striped bass in the lower Hudson to determine PCB content
	The Hudson River Natural Resource Trustee Council (Trustee Council) is established with the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish & Wildlife Service (FWS) and NYSDEC as trustees
	The Trustee Council conducts a preassessment screen (PAS) for a natural resource damage assessment; the PAS indicates a "reasonable probability" of making a successful claim for damages
1998	EPA issues a *Low Resolution Sediment Coring Report* indicating that declines in PCB inventories in the hot spots are due mainly to the remobilization of PCBs into the water column; these PCBs are being redistributed elsewhere in the Hudson River system
	EPA decides against taking an interim remediation action prior to the completion of the RI/FS
	The Trustee Council publishes a draft "scope" for a natural resources damage assessment plan; the Council indicates that a confidential "preliminary estimate" of damages has been made
1999	NYSDEC announces a plan to open a portion of the lower Hudson (south of Poughkeepsie) to commercial fishing of striped bass in two years (2001)
	Five Manhattan fish wholesalers charged under the federal Lacey Act with selling striped bass caught in the lower Hudson during 1995-98
	EPA publishes ecological and human health risk assessments for both the upper and lower Hudsons
	GE criticizes the risk assessments as "fundamentally flawed" and calls for an independent review
	NY Governor Pataki requires GE to clean up contaminated sediments at Hudson Falls
	NY Attorney General Spitzer sues GE for economic damages (lost commercial shipping and other transportation uses) associated with PCB-contaminated sediments
2000	EPA to subject the two risk assessments to peer review
	EPA to make a preliminary decision on dredging the upper Hudson PCB hot spots
	The Trustee Council expects to release a draft damage assessment plan for public review in the spring
2001	EPA to make a final decision on dredging the upper Hudson PCB hot spots

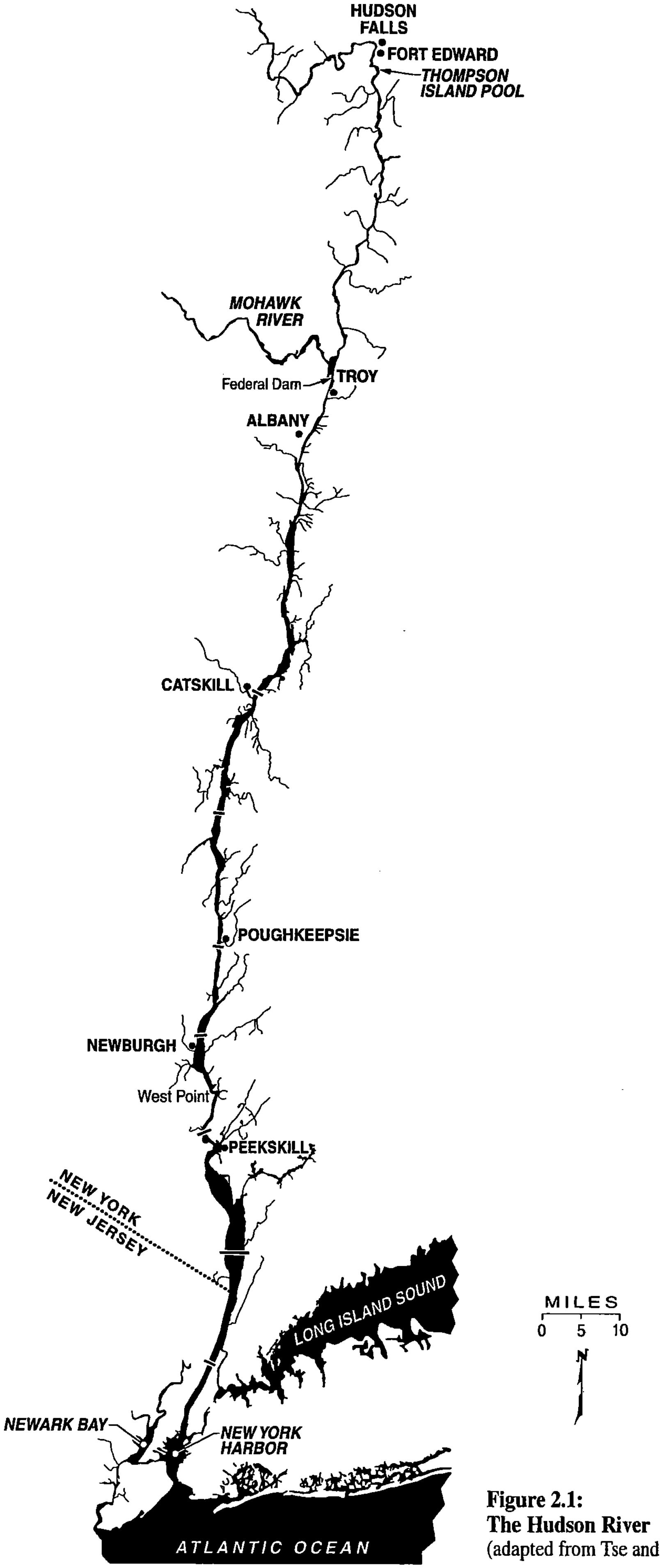

Figure 2.1:
The Hudson River
(adapted from Tse and Williams 1996.)

Environmental Protection Agency (EPA) in 1974. During 1977-78, approximately 80 tons of PCBs were removed from the upper Hudson when the channel near Fort Edward was dredged for navigation purposes (NYSDEC 1996). A program of sediment sampling sponsored by the New York State Department of Environmental Conservation (NYSDEC) identified 40 locations ("hot spots") where PCB concentrations in the sediments of the Upper Hudson exceed 50 ppm (EPA 1998a; Figure 2.2). It is now estimated that at least 68 tons remain in the sediments north of the Federal Dam at Troy, and approximately one-fifth of a ton washes over the dam each year (about one pound per day).[7] In 1983, EPA listed the "Hudson River PCBs site" as a Superfund site.[8] As an interim measure at that time, EPA decided to take no action on the further remediation of PCBs in the sediments of the upper Hudson River.

It is useful to divide the river into the upper and lower Hudson, separated by the Federal Dam at Troy.[9] (Indeed, as described in Section 3, separate physical models of PCB sources, transport, and fate have been developed for the upper and lower Hudson.) The upper Hudson's hot spots are one of the main sources of PCBs into the lower Hudson, but they are not the only source. Approximately one-tenth of a ton of PCBs enters the lower Hudson each year (about 0.55 pounds per day) from wastewater treatment plants (Chen 1995). These plants receive PCBs from combined sewers or industrial discharges. In many cases, the ultimate source of PCBs received by wastewater treatment plants is difficult to identify. Other sources of PCBs into both the upper and lower Hudson include atmospheric deposition, nonpoint rainfall runoff, and unidentified sources located on tributaries.

2.5 Restriction on Uses of the Hudson

The result of PCB pollution has been to restrict human use of the river. The main restriction has been on the commercial harvest of striped bass in the lower Hudson and the issuance of consumption advisories for striped bass and other fish in both the upper and lower Hudson. In 1976, NYSDEC banned the consumption of wild harvest striped bass caught from the lower Hudson[10] and shut down the recreational fishery for striped bass in the upper Hudson. Twenty years later, in 1995, NYSDEC opened the upper Hudson for sportfishing on a catch-and-release basis only. Due to decreasing concentrations of PCBs in striped bass sampled from the lower Hudson in 1997, NYSDEC plans to reopen the lower Hudson (from Poughkeepsie south) to commercial fishing in 2001.

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[7] The flow over the dam varies during the year and as a function of weather conditions. Rivlin (1998) suggests that as much as one-quarter of a ton (1.5 pounds per day) washes over the dam each year. Clearly, higher levels of PCBs flow over the dam during the spring freshet. In heavy stormwater flow years, as much as 3.5 tons may wash over the dam.

[8] This site stretches 200 miles from Hudson Falls south to the Battery in New York Harbor.

[9] The New York State Department of Health divides the Hudson into the upper (north of the Federal Dam at Troy); mid-Hudson (from the Federal Dam to the bridge at Catskill, NY); and lower Hudson (the bridge at Catskill to the Battery). EPA has followed this designation in conducting its human health risk assessments.

[10] This has not eliminated the fishing for and consumption of striped bass from the lower Hudson. For example, in 1999, five Manhattan fish wholesalers were charged under the federal Lacey Act (governing the sale or interstate transport of species regulated by a state) with selling striped bass caught in the lower Hudson during 1995-98.

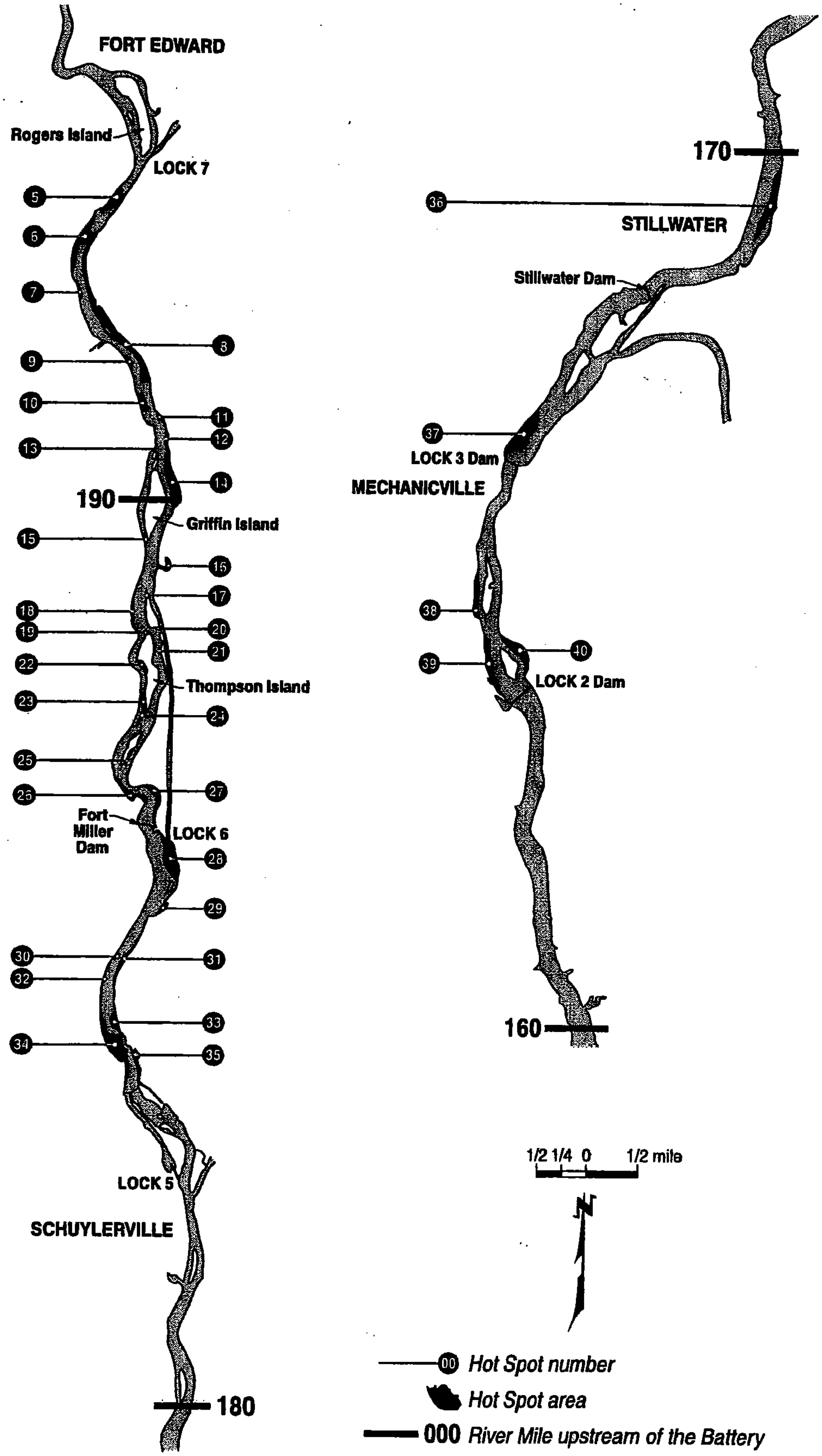

Figure 2.2: Locations of 36 PCB Hot Spots in the Upper Hudson River (adapted from EPA 1997)

As a result of EPA's human health risk assessments, physical contact with Hudson River water is not thought to be dangerous (EPA 1999b, 1999c). Further, the levels of PCBs in water withdrawn from the Hudson by municipalities for drinking purposes are far below the EPA standards for safe drinking water (EPA 1999c).

Another potential restriction on the use of the Hudson due to PCBs concerns commercial shipping. Before 1970, maintenance dredging of shipping channels in Newark Bay resulted in dredge spoils that were deposited in part at upland sites adjacent to the bay (Suszkowski 1978) and in part at a dumpsite 10 miles off the New Jersey coast. After 1970, dredge spoils were dumped only at the 10-mile site (Bopp *et al.* 1991). In 1994, the Army Corps of Engineers (ACoE) and EPA revised the testing requirements for ocean disposal of dredged material. As a result of these revisions, much of the material to be dredged from the Newark Bay shipping channels was considered either unacceptable for ocean disposal (so-called "Category 3" sediments) or acceptable only if capped after disposal (so-called "Category 2" sediments).

Farley *et al.* (1999) argue that the reason that these sediments cannot be classified as "Category 1" (acceptable for ocean disposal) is due solely to the historical inputs of dioxins (from the Diamond-Shamrock plant at 80 Lister Avenue in Newark, NJ). Farley *et al.* (1999) argue that neither current inputs of dioxins, historical inputs of PCBs or PAHs, nor current inputs of PCBs or PAHs are responsible for the sediments not meeting the standard.

From 1994 until early 1999, the new sediment standards delayed a planned deepening to 50 feet of four approaches into the New York-New Jersey port system. With the threatened withdrawal of the Maersk and SeaLand shipping companies, this impasse dissolved. The ACoE's plan now is to mix dioxin-laden sediments with fly ash to dilute the concentration of the pollutant. The sediments are then either to be placed in submerged borrow pits at the entrance to the harbor and capped or transported and deposited into defunct coal mines in Pennsylvania.

2.6 EPA's Reassessment Process

Acting on a request from New York State in 1989 to reexamine its decision to take no action on the upper Hudson PCB hot spots, EPA initiated a "reassessment" process in 1990 (Tomchuk, p.c., 1998). The reassessment is being conducted in several phases. As of December 1999, EPA had concluded an evaluation and interpretation of historical data (EPA 1997); an assessment of the inventory of PCBs in the sediments of the upper Hudson (EPA 1998a); baseline modeling of the transport, fate, and bioaccumulation of PCBs in the upper Hudson (EPA 1999a); and ecological risk assessments (EPA 1999e, 1999c) and human health risk assessments (EPA 1999d; 1999b). Risk assessments were conducted separately in both the upper and lower Hudson.[11]

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[11] The human health risk assessment was conducted on the "mid-Hudson" from the Federal Dam at Troy down to Poughkeepsie (EPA 1999d).

EPA has now initiated a peer review process for the risk assessments. EPA plans to make a preliminary decision on remediation of the sediments in the upper Hudson by the end of 2000. A final decision on remediation is expected by the end of 2001.

2.7 Damage Assessment

Along a separate path, a Hudson River Natural Resource Trustee Council (Trustee Council) was established in September of 1997, comprising the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish and Wildlife Service (FWS), and the New York State Department of Environmental Conservation (NYSDEC). The Trustee Council decided in October 1997 to move forward with a natural resources damage assessment. A "preassessment screen" was carried out to document the need for a full-scale damage assessment. In September of 1998, a draft scoping document was produced, outlining the steps for conducting a full-scale damage assessment (Trustee Council 1998). A plan for conducting the damage assessment is to be published during the spring of 2000 (Sanford, p.c., 2000). The assessment will result in estimates of the economic damages associated with natural resource injuries resulting from the PCB pollution. These calculations will be used to determine compensation to the public for the loss of natural resource services. In lieu of compensation from those parties responsible for the pollution to the public, some natural resources may be restored to their original pre-pollution state.

2.8 Cleaning Up the Hudson

At least two salient characteristics of the Hudson's PCB pollution make decisions about cleaning up the river problematic. First, PCB flows are complex, resulting in sediment concentrations of PCBs that are not uniformly distributed and PCB levels that are highly variable in the flesh of commercially and recreationally important fish. Second, there exist multiple sources of PCB inputs into the system.

From an economic perspective, it is important to identify the right combinations of sources to reduce and also to estimate the extent to which each source should be reduced. In order to determine the economically optimal course of action, therefore, the choice of source reduction ought to be tied to a model of PCB transport and fate.

3. Physical Model of the Lower Hudson

3.1 Physical Model of Transport, Fate, and Bioaccumulation of PCBs

Scientists at Manhattan College have developed a model of the transport, fate, and bioaccumulation of PCBs in the lower Hudson and estuary (Farley and Thomann 1997). The model tracks PCB (and PAH and dioxin) flows and concentrations in the water column and in upper sediment layers. It also models the food chain and provides biota-sediment-accumulation factors to calculate PCB concentrations in phytoplankton, zooplankton, small fish, perch, and striped bass, plus

PCB, PAH, and dioxin accumulation in dredged material indicator species (*Nereis virens* and *Macoma nasuta*) (Farley *et al.* 1999).

The physical model is based on a mass-balance approach and consists of separate components for hydrodynamic transport, sediment transport, dissolved organic carbon, and bioaccumulation. Geographically, the model extends from the Federal Dam at Troy into New York Bight and Long Island Sound, using a total of 30 horizontal water column segments (15 within the river and 15 in the estuary). Underlying each water column segment are 2 to 14 sediment segments (for a total of 120) ranging in thickness from 0.5 to 2.5 cm.

3.2 Physical Model Scenario Simulations

This physical model can be run to demonstrate the effects of reductions in PCB inputs from the main sources into the lower Hudson and the estuary. Farley *et al.* (1999) provide some limited simulation results. The following scenarios were modeled (pp. 92ff):

- Baseline PCB loading from upper Hudson hot spots and from all other sources. This will result in maximum PCB concentrations (low environmental quality) and low-end (zero) remediation costs.
- Elimination of PCB loading from the upper Hudson hot spots but no reduction from the wastewater plants or other sources. This option incurs dredging and dredge spoil disposal costs. This will result in reduced levels of PCB concentrations in the lower Hudson.
- Elimination of all PCB loading from the upper Hudson hot spots and all other sources (the Mohawk River, all New Jersey tributaries, wastewater treatment plants, combined sewer overflows, storm water outflows, and atmospheric deposition). This results in maximum environmental quality and assumes extensive (quite possibly technically infeasible) investment in source reduction.

In each case, the model begins with PCB concentrations found in Hudson River sediments in 1987 and evaluates resulting concentrations in sediments and fish in 1992, 1997, and 2001.

Lower Hudson total sediment PCB concentrations in 1987 are estimated to have been highest just south of the Federal Dam at Troy (1.2 mg C/L; Farley *et al.* 1999:165[12]). The concentration dropped to 0.7 mg C/L in the region south of Kingston and decreased further to 0.3 mg C/L around the New York-New Jersey border. In the New York-New Jersey Harbor, concentrations were higher (1.1 mg C/L). In New York Bight and Long Island Sound, 1987 concentrations were estimated at less than 0.1 mg C/L.

Table 3.1 illustrates the model results for the three scenarios. (Note: these numbers are approximations read from graphs in Farley *et al.* (1999:93 and 97). The average total PCB

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[12] The notation C/L indicates total chemical concentration, i.e., freely dissolved plus dissolved organic carbon (DOC)-bound plus particulate concentration (Farley *et al.* 1999:169).

Table 3.1: Physical Model Simulation Results

		Scenario 1 (all PCB loads)	Scenario 2 (no hot spot loads)	Scenario 3 (no PCB loads)
Total surface sediment PCB	1992	1.8	0.15	0
concentration (μg/g dry)	1997	0.5	0.15	0
Below Troy Dam	2001	0.4	0.15	0
Total surface sediment PCB	1992	0.3	0.3	0.25
concentration (μg/g dry)	1997	0.25	0.2	0.15
NY/NJ Harbor	2001	0.2	0.2	0.05
Total surface sediment PCB	1992	0.15	0.15	0.1
concentration (μg/g dry)	1997	0.1	0.1	0
NY Bight/Long Island Sound	2001	0.1	0.1	0
Average total PCB concentration	1992	4.5	3.7	3.5
μg/g wet weight) in perch	1997	3.2	1.4	1.0
	2001	2.2	0.8	0.5
Average total PCB concentration	1992	2.1	1.9	1.7
(μg/g wet weight) in 2-5 year old	1997	1.7	0.8	0.6
striped bass	2001	1.1	0.5	0.3
Average total PCB concentration	1992	3.2	2.7	2.6
(μg/g wet weight) in 6-15 year old	1997	2.3	1.6	1.2
striped bass	2001	1.8	0.8	0.5

Source: Farley *et al.* (1999)

concentrations in striped bass are below the 2 ppm FDA standard (expressed as 2 μg/g wet weight in Farley *et al.* 1999 and in Table 3.1) in many of the data points shown in the table. However, 95th percentile PCB concentrations exceed the standard for all data points in scenario 1, for all but the 2001 2-5 year old value in scenario 2, and for all but the 2001 and the 1999 2-5 year old values in scenario 3.

3.3 Upper Hudson Component Models

Ideally, we would like to include data on the upper Hudson in our analysis, but a model of PCB flows in the upper part of the river has been developed only recently. Nevertheless, our model is readily adaptable to include the upper Hudson when suitable data for the upper part of the river become available. The Environmental Protection Agency (EPA) is in the process of building a model of the upper Hudson.[13]

To date, the following component models have been developed for the upper Hudson:

- Upper Hudson River Toxic Chemical Model (HUDTOX): transport and fate model covering the Hudson River from Fort Edward to Troy; mass balances for water, sediment, and PCBs.
- Depth of Scour Model (DOSM): two-dimensional, GIS-based sediment erosion model applied to the Thompson Island Pool to provide spatially refined information on sediment erodibility in response to high-flow events such as a 100-year flood.
- Bivariate Bioaccumulation Factor (BAF) Analysis: compares sediment and summer average water-column PCB concentrations to measured PCB levels in fish tissue.
- Empirical Probabilistic Food Chain Model: uses feeding relationships to link fish body burdens to PCB exposure concentrations in water and sediments.
- Gobas Mechanistic Time-Varying Model (FISHPATH and FISHRAND): time-varying, mechanistic models to evaluate the potential for PCB uptake into fish tissue; describes the uptake, absorption, and elimination of PCBs in fish over time.

These models have been run for a forecast period of 21 years beginning January 1, 1998. Forecast simulations were run for two different assumptions for PCB loadings at the upstream boundary at Fort Edward: first, water column PCB concentrations were held constant at a level equal to the annual average PCB concentration observed in 1997 (9.9 ng/L); and second, water column PCB concentrations were held constant at zero. It was assumed that during the forecasts, PCB migration from the GE Hudson Falls Plant site would not increase and that there would not be any type of event similar to the releases that occurred with the alleged partial failure of the Allen Mill gate structure in 1991.

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[13] The material in this section is drawn from information at: http://www.epa.gov/region02/superfnd/hudson/bmr-exsum.htm.

The principal conclusions drawn from modeling of the upper Hudson to date are as follows:

- It appears that the river is currently on the tail of a long PCB washout curve controlled largely by the rate at which PCBs are being reduced in the upper mixed sediment layer. Consequently, forecasts of system responses depend on an accurate representation of processes controlling solids dynamics and PCB interactions across the sediment-water interface.

- The forecasting results suggest that the water column and sediments of the upper Hudson River will not have reached steady-state by 2018 (the end of the forecast period). At that time, even with constant upstream PCB loads, water concentrations still show a declining trend, suggesting that the sediments continue to be a source of PCBs to the system.

The model results to date provide predictions under baseline conditions, that is, without remediation. The outputs from the models (baseline sediment, water, and fish PCB concentrations) are used as inputs in human health and ecological risk assessments. Subsequently, the models will also be used in a feasibility study to evaluate and compare the impacts of various remedial scenarios.

3.4 Integration of Physical Model with Economic Model

Our cost-effectiveness model has been designed to incorporate outputs from the Farley-Thomann "physical model" for the lower Hudson with economic analysis to characterize the most cost-effective source reduction of PCBs in the Hudson River. Given one or more regulatory standards, such as PCB concentrations in fish flesh or in sediments, an integrated physical/economic model allows decision makers to choose the least-cost method of achieving the relevant standards. Further, the analysis permits an understanding of the spatial and temporal distributions of PCB reductions and the cost of modifying these distributions. The integrated model is described in Section 7.

4. Benefits of PCB Remediation

The primary model we develop in Section 7 of this study has been designed to determine the least-cost method of lowering PCB stocks and flows into the lower Hudson River in order to achieve a specific environmental standard. In most cases, the selection of a standard is based upon a characterization of the human health or ecological risks created by the pollutant of concern. In some cases, the standard may be a compromise that emerges from a political process. Human health or environmental standards are not usually selected *directly* on the basis of the economic analysis of benefits and costs.

4.1 Cost-Benefit Analysis

In the absence of an environmental standard, an economically rational way of determining the most appropriate reduction of PCB stocks and flows is to compare the costs of remediation with the benefits of lower levels of PCBs in the Hudson. In a typical pollution case, remediation costs increase at an increasing rate as more remediation takes place. The benefits of remediation (which may be measured as reduced levels of pollution damage) also increase with remediation efforts, but these benefits increase at a decreasing rate. Only in very unusual cases does the complete removal of a pollutant from the environment make economic sense, because the costs are too high and the additional benefits too low. From an economic perspective, the efficient level of remediation is understood to be the point where one additional dollar of remediation costs results in one additional dollar of reduced damages. This approach is known as a cost-benefit analysis.

4.2 Cost-Effectiveness Analysis

With a standard in place, the calculation of reduced levels of economic damages with increased levels of remediation becomes unnecessary. In this situation, the economically rational way of determining the most appropriate reduction of PCB stocks and flows is to select the combination of remediation technologies that minimizes the costs of reaching the standard. This approach is known as cost-effectiveness analysis, and it is the approach taken in this study.

Because the benefits of PCB reductions are ignored in cost-effectiveness analysis, it is possible that the standard might be set at a level that is inefficient from the standpoint of cost-benefit analysis. Nevertheless, cost-effectiveness analysis clearly is appropriate in cases where standards already exist as a matter of law or policy or where benefits are thought to be significant but may also be uncertain and difficult to measure.

4.3 Damage Assessment

For future work, it may be useful to estimate the economic benefits of PCB reductions in the lower Hudson River. Work along these lines is likely to be sponsored by the Trustee Council as they proceed on their damage assessment for the Hudson River. Indeed, the Trustee Council already has completed a preliminary estimate of damages, although they have indicated their intention to keep the preliminary estimate confidential until the damage assessment is complete (Trustee Council 1998).[14] One of the trustees, NOAA, has indicated that the lower Hudson is the major trust habitat of concern.[15] In this section, we outline the kinds of economic benefits that are likely to be considered, and we review the limited relevant literature.

4.4 Direct Human Use Benefits

Economic benefits fall into two general classes: direct (and indirect) human use benefits and non-use values. With respect to the first class, human uses that have been curtailed or terminated due

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[14] Notably, the scale of the preliminary estimate is such that the Trustee Council has decided to undertake the more comprehensive "Type B" damage assessment (Trustee Council 1998).

[15] http://www.darp.noaa.gov/neregion/hudsonr.htm#anchor407080.