Usel Monath To Find Undriked (or, 1) Meial PCB (unc us time (unc us time (usitus)

# CONTAMINATION OF THE HUDSON RIVER The Sediment Record

Richard F. Bopp and H. James Simpson Lamont-Doherty Geological Obervatory of Columbia University

# ABSTRACT

Measurements of natural and man-made radionuclides have been used to trace fine-grained sediment accumulation throughout the Hudson River system. The results, when combined with measurements of particle-associated pollutants, such as PCBs, chlorinated hydrocarbon pesticides, and trace metals, provide information on the sources, transport, distribution, history, and fate of these contaminants. This technique has proven quite useful for monitoring contaminant levels in natural water systems and assessing the effect of various remedial actions, particularly the "no-action" alternative.

### INTRODUCTION

For over a decade, geochemists have studied the history of contamination of natural water systems with particle-reactive pollutants by using radioactive tracers to establish a time scale of sediment accumulation. Early practitioners of this technique have investigated polychlorinated biphenyl (PCB) and DDE accumulation in the Santa Barbara Basin (Hom et al., 1974); the accumulation of fallout radionuclides in Lake Michigan sediments (Robbins and Edgington, 1975); trace metal pollution in Narragansett Bay, Chesapeake Bay, and the Savannah River Estuary (Goldberg et al., 1977, 1978, 1979), and kepone contamination of the James River (Cutshall et al., 1981).

Our work on contaminated Hudson River sediments has relied primarily on measurements of a few naturally occurring and man-made radionuclides that have a high affinity for fine-grained particles and thus serve as tracers for both resent sediment and sediment-associated pollutant accumulation. Cesium-137 (Cs-137) and Plutonium-289,240 (Pu-239,240) are both derived from global fallout resulting from atmospheric testing of nuclear weapons. Measurable fallout began in about 1954 and peaked in 1963 (Hardy et al., 1973). An additional source of Cs-137 to the lower 60 mi of the Hudson system is effluent from the Indian Point nuclear reactors (Figure 1), which began operation in the mid 1960s and had a maximum release in 1971 (Booth, 1975). This source also contributes measurable amounts of Cobalt-60 (Co-60) to the sys-

A particularly useful natural radionuclide is Beryllium-7 (Be-7),

FIGURE 1 A map of the Hudson River with sediment core locations designated by mile point (mp).



which is produced in the atmosphere via cosmic ray-induced spallation of oxygen and nitrogen. It reaches the surface of the earth primarily via precipitation and has a half-life of about 53 days. Because of this relatively short half-life, measurable Be-7 is generally confined to near-surface sediments deposited within about a year prior to analysis.

The particle-associated pollutants we have analyzed in Hudson sediment samples include PCBs, chlorinated hydrocarbon pesticides, and trace metals. A major source of PCBs to the system was discharges from two General Electric (G.E.) company capacitor manufacturing facilities in the upper part of the drainage basin (Figure 1) over the period between about 1950 and 1976. Another significant source of PCBs to the system is wastewater discharges, which are dominated by inputs from the New York metropolitan area (Mueller et al., 1982; Figure 1). Chlorinated hydrocarbons analyzed include DDT-derived compounds and chlordane, while trace metal analyses focused on copper (Cu), lead (Pb), and zinc (Zn). For both classes of compounds, a strong New York metropolitan area source is indicated by the sediment data.

Detailed descriptions of the sampling and analytical procedures used in the work described below can be found in Bopp (1979), Olsen (1979), and Williams et al. (1978). Sediment cores were sectioned at 2- to 4-cm intervals with 0 cm defined at the sediment-water interface. Control Number (CN) designations unambiguously identify a particular core and are reported in all publications from this laboratory. Locations on the Hudson River are given in mile points that correspond to

11.0702

the number of statute miles upstream of the southern tip of Manhattan measured along the axis of the channel (Figure 1). All contaminant concentrations and radionuclide activities in sediment samples are reported on a dry weight basis.

#### RADIONUCLIDES IN HUDSON RIVER SEDIMENTS

The advantage of combining sediment contaminant analyses with measurements of independent indicators of the time of deposition results from the heterogeneity of net sediment accumulation rates observed over short distances in natural water systems. Net sedimentation rates in the Hudson River range from less than 1 mm per year in much of the natural channel to more than 10 cm per year in some dredged areas of New York Harbor (Olsen, 1979; Bopp, 1979). Coarse resolution "dating," where the presence of Cs-137 in a sediment sample indicates a significant component of post-1954 deposition, has proven quite useful for establishing first order budgets for sediments and associated contaminants in the Hudson. It has been applied to fine particles (Olsen et al., 1984-85), trace metals (Williams et al., 1978; Bower et al., 1978), and PCBs (Bopp et al., 1981). Occasionally, cores were collected that could be dated in more detail. Most often, such cores exhibited interpretable Cs-137 profiles, penetrating to the first appearance of that radionuclide (1954) and reaching a midcore maximum Cs-137 level (1963) which then decreases toward the sediment-water interface (the date of coring).

The interpretation of such sediment profiles can often be supported by data on other radionuclides, such as measurements of fallout Pu-239,240 that yield a similar distribution with depth in the core, Be-7 determinations to provide a constraint on very recent rates of sediment accumulation, and, when downstream of mp 60, detection of a second Cs-137 maximum that can be associated with the 1971 release from the Indian Point nuclear reactors (Figure 1, Table 1). This second maximum can be unambiguously identified by the presence of reactor-derived Co-60, an excellent marker for post-1971 sediment deposition in the lower Hudson (Simpson et al., 1976; Olsen et al., 1978; Bopp et al., 1982). Ideal cores with continuous records of sediment deposition over the past few decades are relatively rare as a result of both natural disturbances, including large storms and other resuspension events, and human intervention, particularly dredging. Fortunately, when such cores are collected they have large enough net sediment accumulation rates (on the order of 1 cm per year or more) to prevent biological or tidal current mixing in the Hudson from significantly altering the sediment-associated radionuclide and contaminant profiles (Olsen et al., 1981).

From our collection of over 200 Hudson River sediment cores, we have found about 20, spanning the system, with radionuclide profiles that indicate a continuous record of sediment accumulation. Several examples are given in Table 1, and a few others were discussed by Bopp et al. (1982). More recent sediment core data is shown in Figure 2. The core at mp 188.5 (CN 1852) was taken about 10 mi downstream of the

Vatel Sel Rute

, dotata

TABLE 1 The Bases for Establishing the Timescale of Sediment Accumulation in Selected Hudson River Cores

.04

Location (mp)	Date of collection	Principal time indicators	Reference
188.5 CN 1852	July 1983	Fallout Cs-137 (1954, 1963)	Figure 2
143.4 CN 1298	July 1977	dredge boundary (1972)	Bopp et al., 1982
91.8 CN 1329	July 1977	Fallout Cs-137 and Pu-239,240 (1954, 1963)	Bopp et al., 1982
88.6 CN 1984	July 1986	Fallout Cs-137 (1954, 1963); Be-7	Figure 2
53.8 CN 1240	January 1977	Fallout Cs-137 and Pu- 239,240 (1954-1963) and reactor Cs-137 and Co-60 (post-1971)	Bopp et al., 1982
3.0 CN 1380	September 1975	Fallout Cs-137 and Pu-239,240 (1954, 1963); reactor Cs- 137 and Co-60 (post-1971)	Bopp et al., 1982
-1.7 CN 1472	September 1979	Fallout Cs-137 and Pu-239,240 (1954, 1963); reactor Cs-137 and Co-60 (post-1971)	Figure 2
-1.65 CN 1923	July 1984	Be-7; reactor Co-60 (post-1971)	Figure 2

PCB inputs from the G.E. capacitor plants. This reach of the Hudson is characterized by a series of dams, the southernmost being the Federal Dam at mp 154. Downstream of this dam, the Hudson is a tidal system. The core at mp 88.6 (CN 1984) was collected in 1986 and was used to complement contaminant chronologies developed from a mp 91.8 core (CN 1329) collected in 1977 (Bopp et al., 1982). The core at mp -1.7 contained measurable Co-60 in the top five samples, confirming the assignment of the upper Cs-137 maximum to releases from the Indian Point nuclear reactors. The 8-cm penetration of Be-7 in the mp -1.65 core indicates very rapid sediment accumulation (several cm per year) confirmed by the detection of reactor-derived Co-60 to a depth of at least 50 cm. These two cores were used to develop contaminant chronologies FIGURE 2 Profiles of radionuclide activity versus depth in some Hudson River sediment cores.



for New York Harbor sediments from the mid 1950s to 1984.

The radionuclide tracers in such cores can be used to determine levels of sediment contamination as a function of time at various locations on the river (Bopp et al., 1982). We estimate the uncertainty on the time of deposition for any given sample at approximately +2 years to account for possible changes in sediment accumulation rates in short time scales and the possibility of gaps in the depositional record between the individual radionuclide-based stratigraphic markers.

# POLYCHLORINATED BIPHENYLS

Commercially used PCBs are mixtures of up to several dozen distinct congeners that vary in degree of chlorination and the arrangement of chlorine atoms on the molecules. An individual PCB congener may contain between one and ten chlorine atoms per molecule, but the particular mixtures most used at the G.E. capacitor plants on the upper Hudson River (NYSDEC, 1975), designated Aroclor 1242 and Aroclor 1016) are dominated by di, tri, and tetrachlorobiphenyls with Aroclor 1242 also containing about 10 percent penta and hexachlorobiphenyls (Webb and McCall, 1973).

Throughout the Hudson River system, dated sediment cores show a maximum in total PCB concentration in the early to mid 1970s. This feature, shown in Figure 3 and for some additional cores in Bopp et al. (1982) has been attributed to the removal of a dam in 1973 that had provided the first impoundment of water downstream of the G.E. discharges (Figure 1). The dam removal destabilized large amounts of highly contaminated sediments that were transported downstream in the fall of 1973 and with the unusually high runoff the following spring (Hetling,

\* Purpse Typer FIGURE 3 Total PCB concentrations in Hudson River sediment cores versus time of deposition. For all cores except mp 188.5, PCB concentrations were based on measurements of 22 components resolved by packedcolumn gas chromatography (Webb and McCall, 1973). For samples from mp 188.5, quantification was based on three PCB congeners that were observed to be highly persistent (i.e., resistant to dechlorination) in another core from the same cove (core 18-6, Brown et al., 1984). This second core had a similar profile of total PCB concentrations as determined by quantification of all major congeners present (Brown et al., 1984; Bopp et al., 1985).

Graps OF P(b); in sol

78-110

Jod brath



et al., 1978). The maximum observed PCB concentration in sediments decreases with distance downstream from the former dam, reaching over 1,000 ppm in the upper Hudson. In the tidal Hudson, maximum observed concentrations range from about 100 ppm a few miles downstream of the Federal Dam to about 8 ppm in New York Harbor sediments.

# PCB Composition

With the exception of the core at mp 188.5, the composition of sediment-associated PCBs observed near this maximum closely resembles that of Aroclors (1242) and 1016) The composition of PCBs in sediments at mp 188.5 is shifted dramatically toward lower chlorinated biphenyls. This has been attributed to bacterially mediated anaerobic dechlorination of PCBs (Brown et al., 1984) and has been observed in other highly contaminated sediments upstream of the Federal Dam (Brown et al., 1984; Bopp et al., 1984). While anaerobic dechlorination may occur in sediments of the tidal Hudson, it is certainly much less significant than in the more highly contaminated sediments of the upper Hudson. Based on PCB component analysis in dated sediment cores of the tidal Hudson, Bopp et al. (1984) found no evidence of significant compositional changes in PCBs during 20 years of anaerobic burial. Such observations could significantly influence management decisions related to systems with PCB contaminated sediments. Since dechlorination generally lowers the persistence of PCBs in organisms and thus decreases their chronic toxicity

(Hansen, 1979), the occurrence of significant in situ dechlorination would be one factor supporting a no-action alternative, while a lack of significant dechlorination would argue in favor of dredging or other remedial action. Furthermore, bacterially mediated dechlorination shows considerable promise as a hazardous waste treatment technology (Roberts, 1987).

In the upper Hudson River, between the former dam site and the Federal Dam, several surface sediment samples and each of the 10 suspended matter samples collected in 1983 and 1984 had PCB compositions that closely resembled Aroclors 1242 and 1016 (Bopp et al., 1985). This maintains the connection between G.E. discharges and PCB contamination throughout the system, but implies significant isolation of the highly contaminated sediments of the upper Hudson that exhibit gross dechlorination of PCBs.

In the tidal Hudson, the composition of PCBs observed in the sediments is most affected by suspended matter-water partitioning, water to air transport, and inputs from the New York metropolitan area (Bopp, 1979, 1983; Bopp et al., 1981). All of these factors tend to increase the average degree of chlorination of sediment-associated PCB components; however, even in New York Harbor sediments, the PCB composition closely resembles Aroclor 1242 (Bopp et al., 1981).

### Sources of PCBs to New York Harbor Sediments

Figure 4 shows the importance of New York metropolitan area inputs of the highly chlorinated PCB congeners. Since about 1970, levels of hepta, octa, and decachlorobiphenyls have been much higher in New York Harbor sediments (mp -1.65 and -1.7) than in upstream tidal Hudson sediments (mp 88.6 and 91.8), despite the fact that during the 1970s the upstream cores had total PCB levels about twice those of the harbor cores. Although these highly chlorinated congeners generally comprise less than 10 percent of the total PCBs in Hudson River sediment samples, their toxicological significance is magnified by the fact that they are most persistent in higher organisms and tend to increase in relative abundance along a food chain (Hansen, 1979).

The major problem in quantifying New York metropolitan area inputs of PCBs to the Hudson River lies in the limited number of analyses performed on sewage effluent and urban runoff. Simple mass balances and PCB component ratio analysis (Bopp et al., 1981) indicates that between 1971 and 1976 approximately 75 percent of the total PCBs deposited in New York Harber sediments were derived from downstream transport and about 25 percent from local metropolitan area inputs. Detailed analysis of the cores at mp -1.65 and 88.6 indicates that by the mid 1980s, the relative importance of local sources had increased significantly. In 1984, both cores recorded total PCB levels of about 1.3 ppm and by 1986, the level in the mp 88.6 core had dropped to 0.8 ppm)(Figure 5).

Since at peak levels the harbor core had about half the total PCB concentration of the upstream core, local New York metropolitan area inputs now appear to at least equal the downstream supply of total PCBs to New York Harbor sediments.

FIGURE 4 Hepta + octachlorbiphenyl and decachlorobiphenyl concentrations in upstream tidal Hudson (mp 88.6 and 91.8) and New York Harbor (mp -1.65 and -1.7) sediment cores versus time of deposition. Quantification of hepta + octachlorobiphenyls are based on seven PCB components resolved by packed-column gas chromatography and the composition of Aroclor 1260 (Webb and McCall, 1973). Decachlorobiphenyl quantifications are based on standards prepared from the pure compound.

「日本のない」のである



PPD HEPTA + OCTACHLOROBIPHENYLS

#### Response Time To Pollution Events

We believe that this situation is due primarily to the recovery of the system from the major pulse of PCBs associated with the dam removal in 1973 discussed above.

Figure 5 shows details of the decrease in total PCB levels. At mp 88.6 concentrations over the last decade can be modelled rather well by a simple exponential decrease toward zero with a half-time of 3.5 years (Figure 4). At mp -1.65, applying a similar time constant produces a curve that decreases asymptotically toward a value of about 0.5 to 0.7 ppm total PCBs. We interpret this "residual level" as resulting from local New York metropolitan area PCB inputs. This type of analysis was first employed by Bopp et al. (1982), who described the response of the system to two distinct types of pollution events involving sedimentassociated contaminants. For pollutant inputs to the drainage basin, such as with fallout radionuclides or local DDT applications, a halfresponse time for Hudson sediments of about six to eight years was found. As would be expected, for pollutant inputs directly to the river, such as the pulse of PCBs associated with the 1973 dam removal, a much shorter half-response time was determined. Analysis of five sediment cores throughout the system gave half-response times of 1.3 to 3.8 years for PCB concentrations. This is in good agreement with the data presented in Figure 5, which is much more detailed than the earlier analysis and tracks the recovery for several additional years.

FIGURE 5 Detailed recent chronologies of total PCB concenations in sediments from an upstream tidal Hudson core (mp 88.6) and a New York Harbor core (mp -1.65).



The natural cleansing of the river as indicated by decreasing sediment contaminant levels results both from burial of the most contaminated sediments and the removal of pollutants from the system with river discharge and associated suspended particle transport.

209

# PCB Budgets

The PCB burden in sediments upstream of the Federal Dam and possible remedial action in this reach of the river has been discussed in detail elsewhere (Sanders, this volume; Carcich and Tofflemire, 1982). Although no PCB-directed remedial action has been planned for sediments of the tidal Hudson, we have identified two extensive depositional areas where such action is feasible. The first is New York Harbor. Based on average PCB concentrations and Cs-137 penetration depths in 16 sediment cores, Bopp (1979) estimated that about 23,000 kg of PCBs were associated with in situ sediments of New York Harbor. It was also estimated that an additional 37,000 kg of PCBs had been removed from the harbor as part of normal maintenance dredging and deposited on the shelf at the dredge spoil dump site about 11 mi from the mouth of the Hudson River. These estimates were considered accurate to about a factor of two. The only other reach of the river identified as having significant recent sediment accumulation in the channel was near mp 90, where the river both widens and turns. From the only six cores available at the time, an estimate of 12,000 kg of sediment-associated PCBs was obtained for the area from mp 85 to 93. Additional core collection in 1986 produced the coverage shown in Figure 6. Significant spatial heterogeneity of net sediment accumulation rates is indicated by the Cs-137 penetration depths given in centimeters by the numbers in parentheses. From these data and the average recent sediment PCB concentration of about 7 ppm observed in this region, our best (factor of two) present estimate is that about 21,000 kg of PCBs are associated with sediments of this reach.

#### CHLORINATED HYDROCARBON PESTICIDES

Chlorinated hydrocarbons, including DDT and chlordane, formed the

47 47 17 88.60-0.87 FIGURE 6 A map of the Hudson River from mp 86 to 93. Sediment core locations are marked with x's and labelled by mile point. Numbers in parentheses indicate the depth of penetration of Cs-137 in centimeters.

basis of our insect control strategy in the 1950s and 1960s. They are now well-known for their persistence and ubiquity in the environment. A DDT-derived compound found in recent sediments throughout the Hudson is pp'-DDD produced via anaerobic dechlorination of pp'-DDT carried out by bacteria. Pollution chronologies for this compound in Hudson sediments (Bopp et al., 1982; Figure 7) are characterized by maximum values in the 1960s and early 1970s that decline significantly toward the present. This indicates the effectiveness of the ban on DDT use in the United States imposed by the U.S. Environmental Protection Agency (EPA) Sediments from New York Harbor (mp -1.65 and -1.7) show much in 1972. higher levels of pp'-DDD than sediments from mp 91.8 at comparable time horizons (Figure 7), however, other upstream cores (e.g., mp 53.8) have been found that reach peak levels of almost 100 ppb pp'-DDD (Bopp et al., 1982). This suggests that both downstream transport, resulting from DDT applications in the drainage basin, and local New York metropolitan area inputs are significant contributors to the pp'-DDD contamination observed in New York Harbor sediments.

Chlordane in New York Harbor sediments shows a similar profile. Peak levels of a major chlordane component,  $\gamma$ -chlordane, were found in the 1960s and early 1970s. The mp -1.65 and -1.7 cores peak at about 48 ppb (Figure 7). By the mid 1980s levels had decreased by more than 50 percent, to about 16 ppb in the above mentioned cores. This decrease is consistent with the banning of chlordane for most uses by the EPA in 1975.

For chlordane, the dominance of New York metropolitan area inputs is most pronounced. Tidal Hudson sediments upstream of New York Harbor were always found to contain less than 5 ppb  $\gamma$ -chlordane with mid 1980s levels typically less than 2 ppb. Further discussion of chlorinated hydrocarbon pesticide chronologies in the Hudson River can be found in Bopp et al. (1982).

82 JE (4)

-91.8 (36) 91.7 (32)

¥@

IN(14)

(II)

60

88.6*(59*)

87.5*(2)* 87.1*(2*(

10)16

86.5*(8))* 

(20)

90.3/32)

KINGSTON

T EWEN

IN

FIGURE 7 Chronologies of pp'-DDD concentrations in sediments from an upstream tidal Hudson core (mp 91.8) and pp'-DDD and  $\gamma$ -chlordane concentration in sediments from New York Harbor cores (mp -1.65 and -1.7). The most recent data point on the upstream (mp 91.8) pp'-DDD chronology is from the 0-2 cm sample of a core at mp 88.6 collected in 1986. This sample contained significant Be-7, indicating that it was deposited within about a year prior to coring.



### TRACE METALS

A characteristic of our industrial society is elevated levels of trace metals such as copper, lead, and zinc in sediments of natural water systems. Williams et al. (1978) described tidal Hudson sediment levels of these trace metals in terms of three end members: "old" (preindustrial) sediment with average shale levels, recent (i.e., Cs-137 bearing) sediments upstream of New York Harbor, and recent New York Harbor sediments. Over the past two years, several of the cores in Table 1 have been analyzed to provide chronological data on the trace metal content of recent Hudson sediments. The results, shown for Cu and Pb in Figure 8, confirm the observations of Williams et al. (1978), that New York metropolitan area inputs dominate the sources of these metals to New York Harbor sediments. Average harbor sediment levels of Cu and Pb are more than twice as large as levels observed in upstream sediments of the tidal Hudson at comparable time horizons (Figure 8).

The other outstanding feature of this data is the recent decline in trace metal levels seen in sediments of the upstream tidal Hudson core (mp 88.6). The drop of about 50 percent in Cu and Pb levels over the past decade could indicate recent decreases in the substantial industrial discharges of trace metals to the upper Hudson (Rohmann et al., 1985) or it could be related to the recent implementation of secondary treatment for sewage of the city of Albany, whose discharge is to the FIGURE 8 Chronologies of copper and lead concentrations in sediments from upstream tidal Hudson cores (mp 88.6 and 91.8) and New York Harbor cores (mp -1.65 and -1.7). Results of replicate analyses of separate aliquots of sediment are shown for several sections of the mp -1.7 core.



11-372

Hudson a few miles downstream of the Federal Dam. Similar trace metal results have been reported for a core at mp 46 (Peller and Bopp, 1985). This core also penetrated to pre-industrial sediment with Cu and Pb levels of about 25 ppm.

Most curious is the lack of any substantial improvement in Cu and Pb levels in New York Harbor sediments over the past decade, as indicated by the data from cores at mp -1.65 and 1.7. This is particularly puzzling in the case of Pb. Mueller et al. (1982) report that wastewater, urban runoff, and downstream transport are the dominant sources of this metal to the lower Hudson. Improvements in sewage treatment between the early 1970s and 1982 (Mueller et al., 1982) should have decreased wastewater loading of Pb. The switch from leaded to unleaded gasoline, which produced a two-thirds decrease in atmospheric Pb deposition in New York City between 1970 and 1980 (Freely et al., 1976; Toonkel et al., 1980) should also have significantly decreased the urban runoff of Pb, and--as discussed above--our best estimate for the downstream transport of Pb would be a decrease of 50 percent over the past decade. Despite these indications of decreases in loading, New York Harbor sediments show little or no recent improvement in Pb levels (Figure 8). This apparent contradiction indicates the need for further research into the sources and behavior of trace metals in the lower Hudson and suggests that additional attention be paid to regulation of these important environmental contaminants.

413

# CONCLUSIONS AND RECOMMENDATIONS

The case study of sediment contamination in the Hudson River demonstrates that the measurement of radionuclide time indicators is crucial to the interpretation of pollutant levels in sediments. We recommend that this technique be universally applied to particle-associated contaminant monitoring and the assessment of related problems. We are continuing this practice in detailed studies of adjacent systems, including Raritan Bay, Newark Bay, Jamaica Bay, and the nearshore coastal environment.

Pollutant chronologies that can be developed from this technique are useful indicators of contaminant sources and can provide a detailed assessment of what is commonly called the "no-action" alternative. In the case of PCBs in the Hudson River, levels on particles transported downstream in the mid 1980s are several times lower than in the mid 1970s, despite continued postponement of the removal of the most highly contaminated sediments from the upper Hudson (i.e., no action). Assessment of our general nationwide efforts to limit pollution is also possible. There is evidence that New York Metropolitan area inputs of PCBs to the Hudson have decreased recently, probably in response to EPA restrictions on the manufacture and use of PCBs in the United States in the late 1970s. Hepta, octa, and decachlorobiphenyl levels in New York Harbor sediments have declined by about a factor of two over the past decade (Figure 4), while the New York metropolitan area contribution to total PCBs in New York Harbor sediments was estimated at 0.8 ppm in the mid 1970s (Bopp, 1979) and 0.5 to 0.7 ppm in the mid 1980s (Figure 5). Restrictions on chlorinated hydrocarbon pesticide use in the United States promulgated by the EPA in the 1970s are most likely responsible for the recent decline in levels of pp'-DDD and chlordane in Hudson sediments (Figure 7). Finally, with respect to trace metals, New York Harbor sediment chronologies indicate little or no recent improvement (Figure 8) despite recent upgrading of sewage treatment and restrictions on lead in gasoline. This is a most direct recommendation for further study of the sources and fate of these contaminants, not only in the Hudson River, but in other major natural water systems as well.

### ACKNOWLEDGMENTS

We would first like to thank our scientific and technical collaborators, Bruce Deck, Curt Olsen, Nadia Kostyk, Dave Robinson, Kathleen Ledyard, Charles Lester, Ellen Kalb, Yu-Pin Chin, Robert Trier, Sue Williams, Peter Kay and Linda Hubbard. Financial support for our present work on the Hudson is provided by the Hudson River Foundation. Past research efforts have been funded by the New York State Department of Environmental Conservation, the National Science Foundation, the National Oceanic and Atmospheric Administration, and the U.S. Environmental Protection Agency. This is LDGO contribution number 4342.

**41**4

#### REFERENCES

Booth, R. S. 1975. A compendium of radionuclides found in liquid effluents of nuclear power stations. ORNL-TM-3801. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Bopp, R. F. 1979. The Geochemistry of Polychlorinated Biphenyls in the Hudson River. Ph.D. Thesis, Columbia University, New York.

- Bopp, R. F., H. J. Simpson, C. R. Olsen, and N. Kostyk. 1981. Polychlorinated biphenyls in sediments of the tidal Hudson River, New York. Environ. Sci. Technol. 15:210-216.
- Bopp, R. F., H. J. Simpson, C. R. Olsen, R. M. Trier, and N. Kostyk. 1982. Chlorinated hydrocarbons and radionuclide chronologies in sediments of the Hudson River and estuary, New York. Environ. Sci. Technol. 16:666-676.
- Bopp, R. F. 1983. Revised parameters for modeling the transport of PCB components across an air water interface. J. Geophys. Res. 88:2521-2529.
- Bopp, R. F., H. J. Simpson, B. L. Deck, and N. Kostyk. 1984. The persistence of PCB components in sediments of the lower Hudson. Northeastern Env. Sci. 3:180-184.
- Bopp, R. F., H. J. Simpson, and B. L. Deck. 1985. Release of Polychlorinated Biphenyls from Contaminated Hudson River Sediments, NYS C00708 Final Report. New York State Department of Environmental Conservation.
- Bower, P. M., H. J. Simpson, S. C. Williams, and Y.-H. Li. 1978. Heavy metals in the sediments of Foundry Cove, Cold Springs, New York. Environ. Sci. Technol. 12:683-687.
- Brown, J. F., R. E. Wagner, D. L. Bedard, M. J. Brennan, J. C. Carnahan, R. J. May, and T. J. Tofflemire. 1984. PCB transformations in upper Hudson sediments. Northeastern Env. Sci. 3: 166-178.
- Carcich, I. G. and T. J. Tofflemire. 1982. Distribution and concentration of PCB in the Hudson River and associated management problems. Environ. Internat. 7:73-85.
- Cutshall, N. H., I. L. Larsen, and M. M. Nichols. 1981. Man-made radionuclides confirm rapid burial of kepone in James River sediments. Science 213:440-442.
- Feely, H. W., H. L. Volchok, and T. N. Toonkel. 1976. Trace Metals in Atmospheric Deposition. EML-308. Washington, D.C: Department of Energy.
- Goldberg, E. D., E. Gamble, J. J. Griffin, and M. Kiode. 1977. Pollution history of Narragansett Bay as recorded in its sediments. Estuar. Coast. Mar. Sci. 5:549-561.

Goldberg, E. D., V. Hodge, M. Kiode, J. Griffin, E. Gamble, O. P.

Bricker, G. Matisoff, G. R. Holdren, and R. Braun. 1978. A pollution history of Chesapeake Bay. Geochim. Cosmochim. Acta 42:1413-1425.

- Goldberg, E. D., J. J. Griffin, V. Hodge, M. Kiode, and H. Windom. 1979. Pollution history of the Savannah River estuary. Environ. Sci. Technol. 13:588-594.
- Hansen, L. G. 1979. Selective accumulation and depletion of polychlorinated biphenyl components: Food animal implications. Ann. N.Y. Acad. Sci. 320:238-246.
- Hardy, E. P., P. W. Krey, and H. L. Volchok. 1973. Global inventory and distribution of fallout plutonium. Nature 241:444-445.
- Hetling, L., E. Horn, and T. J. Tofflemire. 1978. Summary of Hudson River PCB Results. Technical Paper No. 51. New York State Department of Environmental Conservation.
- Hom, W., R. W. Risebrough, A. Soutar, and D. R. Young. 1974. Deposition of DDE and PCB in dated sediments of the Santa Barbara Basin. Science 184:1197-1199.
- Mueller, J. A., T. A. Gerrish, and M. C. Casey. 1982. Contaminant inputs to the Hudson-Raritan estuary. Chapter VI, Wastewater inputs. Technical Memorandum OMPA-21. Rockville, Md.: NOAA.
- NYSDEC. 1975. NYS Department of Environmental Conservation, in the Matter of Alleged Violations of Sections 17-0501, 17-0511, and 11-0503 of the Environmental Conservation Law of the State of New York by General Electric Co., Interim Opinion and Order, File No. 2833.
- Olsen, C. R., H. J. Simpson, R. F. Bopp, S. C. Williams, T.-H. Peng, and B. L. Deck. 1978. Geochemical analysis of the sediments and sedimentation in the Hudson estuary. J. Sediment. Petrol. 48: 401-418.
- Olsen, C. R. 1979. Radionuclides, Sedimentation and the Accumulation of Pollutants in the Hudson Estuary. Ph.D. Thesis, Columbia University, New York.
- Olsen, C. R., H. J. Simpson, T.-H. Peng, R. F. Bopp, and R. M. Trier. 1981. Sediment mixing and accumulation rate effects on radionuclide depth profiles in Hudson estuary sediments. J. Geophys. Res. 86: 11020-11028.
- Olsen, C. R., N. H. Cutshall, I. L. Larsen, H. J. Simpson, R. M. Trier, and R. F. Bopp. 1984-5. An estuarine fine-particle budget determined from radionuclide tracers. Geo-Marine Letters 4:157-160.
- Peller, P. and R. F. Bopp. 1985. Recent sediment and pollutant accumulation in the Hudson River National Estuarine Sanctuary. <u>In</u> Polgar Fellowship Reports of the Hudson River National Estuarine Sanctuary Program, 1985, Jon C. Cooper ed. New York: Hudson River Foundation.

Robbins, J. A. and D. N. Edgington. 1975. Determination of recent sedimentation rates in Lake Michigan using PB-210 and Cs-137. Geochim. Cosmochim. Acta 39:285-304.

- Roberts, L. 1987. Discovering microbes with a taste for PCBs. Science 237:975-977.
- Rohmann, S. O., N. Lilienthal, R. L. Miller, R. M. Szwed, and W. R. Muir. 1987. Tracing a River's Toxic Pollution, A Case Study of the Hudson, Phase II. New York: Inform.

Simpson, H. J., C. R. Olsen, S. C. Williams, and R. M. Trier. 1976.

Man-made radionuclides and sedimentation in the Hudson River - estuary. Science 194:179-183.

Toonkel, L. T., H. W. Feely, and R. J. Larsen. 1980. The Chemical Composition of Atmospheric Deposition. EML-381. Washington, D.C.: Department of Energy.

Webb, R. G. and A. C. McCall. 1973. Quantitative PCB standards for electron capture gas chromatogspahy. J. Chromatogr. Sci. 11:366-373.

Williams, S. C., H. J. Simpson, C. R. Olsen, and R. F. Bopp. 1978. Sources of heavy metals in sediments of the Hudson River estuary. Mar. Chem. 6:195-213.