

SOURCES AND MATERIAL BALANCE OF MERCURY IN THE NEW YORK-NEW JERSEY HARBOR

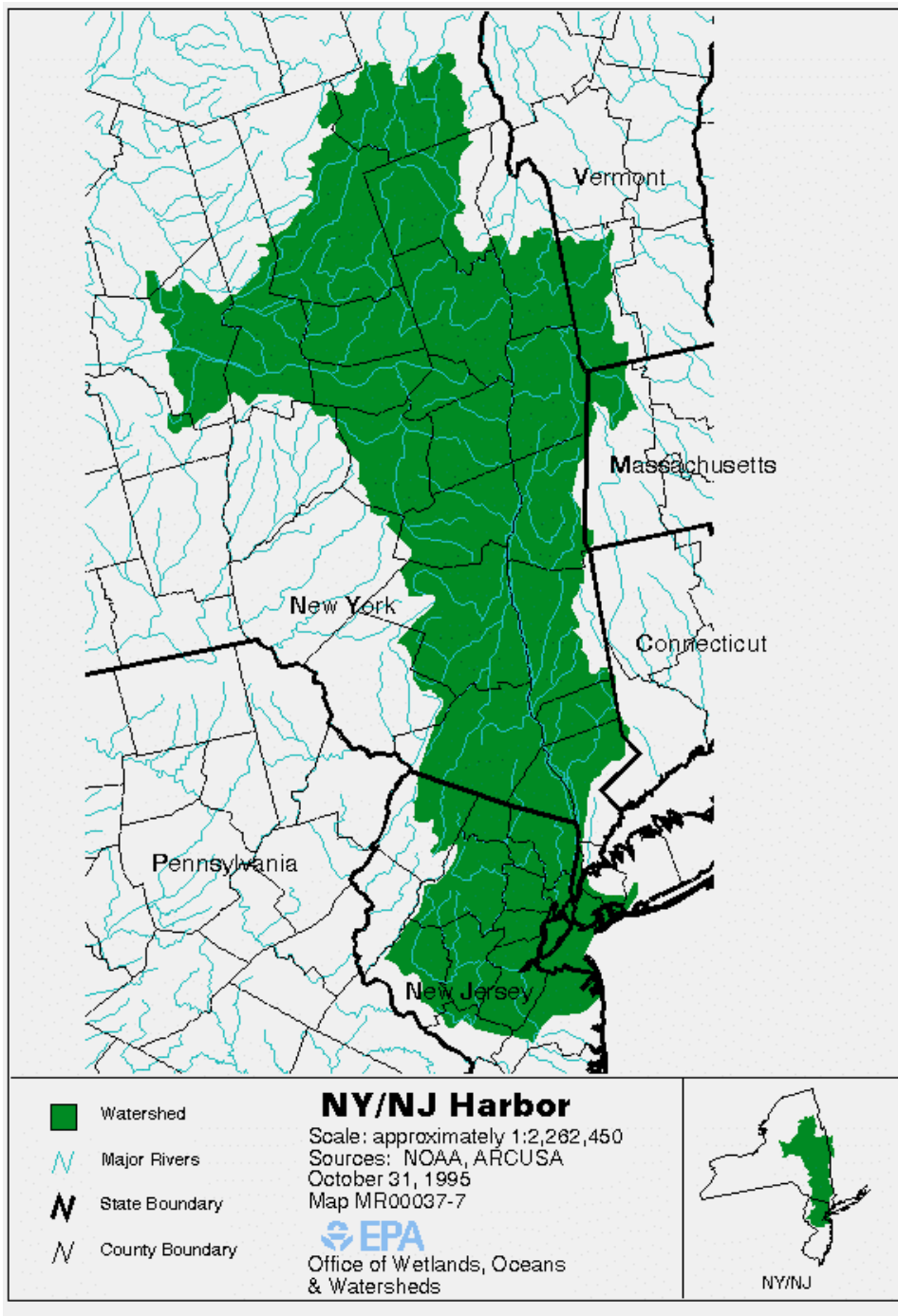
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**INDUSTRIAL ECOLOGY FOR POLLUTION PREVENTION
STUDY OF THE NYAS HARBOR CONSORTIUM**





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EXECUTIVE SUMMARY

This study was part of the project *Industrial Ecology for Pollution Prevention* of the Harbor Consortium of the New York Academy of Sciences. Its objectives were to quantify the sources of past and present emissions of mercury in the Hudson-Raritan basin (HRB), an area of 42,000 square kilometers with a population of fifteen million; to establish an order-of-magnitude material balance of sources and sinks of mercury in the period 1880-2000; and recommend measures that may be taken to decrease mercury contamination in the NY/NJ Harbor. All tonnages are in metric tons unless an exception is noted. Mercury emissions are as reported by companies and environmental agencies. Mercury loads in sediments were estimated on the basis of a limited number of samples and generally accepted sediment flows; their accuracy can be improved by additional sampling over the Harbor area.

Past and present sources of mercury in HRB

Much of the mercury discarded by humans or deposited by the atmosphere on the HRB surface is gradually conveyed by water and sediment flows to the New York-New Jersey Harbor. The study showed that since the mid-eighties, mercury inputs to NY/NJ Harbor have decreased by a factor of ten. For example, the mercury in the effluents of wastewater treatment plants (14.9% of the total "freshwater" flow) decreased from 4,700 kilograms in 1987 to 332 kg in 1998. Also, prior to 1985, the mercury concentration in Hudson river (constituting 72% of the "freshwater" flow) was estimated at 0.1 to 0.6 parts per billion (ppb) of mercury, i.e. 2,000 to 12,000 kg per year. In contrast, multiple samples of the Hudson waters in the Harbor, in 1991, showed an average concentration of 0.021 ppb, i.e. 400 kg per year.

A similar improvement has been noted in sediments, the principal conveyor of mercury into the Harbor: Core samples of sediments that were deposited in the past have shown average mercury concentrations of 5-10 parts per million. In contrast, a 1993 survey of 84 samples of surficial sediments showed an average concentration of only 0.79 ppm. A similar survey in 1994 indicated an average surficial concentration of 0.70 ppm (700 kg/year). These values are approaching the pre-industrial concentrations of mercury in sediments (0.1-0.3 ppm).

The rapid decrease of mercury into the Harbor by the end of the 20th century is partly due to the drastic curtailment of mercury use in the U.S., from a peak of 2,800 tons/year in the sixties to less than 350 tons by 2000. It is also due to the switch from coal-fired to gas-fired plants in the HRB area and the change from the polluting incinerators of the past to modern Waste-to-Energy plants.

At present, the primary sources of atmospheric emissions in HRB

are utility and industrial boilers (873 kilograms of mercury/year), secondary iron and steel plants (644 kg), sewage sludge incinerators (152 kg), and Waste-to-Energy plants (140 kg). An estimated 40% of the HRB stack emissions of mercury (i.e., 724 kilograms per year) are deposited within the HRB (short-range deposition) and 60% are added to the global atmospheric load of mercury. The annual deposition of mercury from the global atmosphere in this region (10 grams per square kilometer) amounts to an additional 420 kg of mercury. Thus, the estimated overall atmospheric deposition of mercury from the atmosphere on the surface of HRB is 1,144 kilograms per year. If all of this mercury were to find its way to the sediments carried by the river flow into the Harbor (1 ± 0.3 million tons per year), the average concentration of mercury in new (i.e., surficial) sediments would be about 1.1 ± 0.3 ppm of mercury. This rough estimate is in line with the 1994 measurements in the Harbor of surficial sediments of 0.7 ppm.

As mercury emissions to the atmosphere and treated wastewater have been reduced, landfills have become the largest depository of used mercury. An estimated 29,000 kilograms of mercury contained in HRB used products are discarded in landfills annually. Mercury is a volatile metal at normal temperatures and pressures. When it is spilled from a device such as switch or thermostat, it will evaporate with time. Also the prevailing conditions in municipal waste landfills (moisture, organic matter, temperature) are favorable for the formation of methyl mercury, a highly toxic compound that is the principal threat to ecosystem and human health (through fish consumption). However, some measurements of mercury gaseous emissions at Florida landfills indicate relatively low mercury fluxes. Additional research is required to quantify the gaseous and also liquid emissions of mercury and methyl mercury from landfills.

Mercury balance in HRB

An order-of-magnitude mercury balance was carried out for the Hudson-Raritan basin for the industrialized period of 1880-2000. The total amount of mercury discarded on land and water or emitted to the atmosphere was estimated at about 13,000 tons. Some of this mercury remains in HRB landfills, soil, and upstream sediments while the rest has been conveyed by water and sediment flow into the Harbor. Also, mercury was conveyed out of the Harbor by two principal means:

- a) Dredging of about 300 million cubic meters of wet sediments during the 20th century has removed an estimated 6,000 tons of mercury;
- b) The “freshwater” flow out of the Harbor has carried out to the ocean about 600 tons of mercury.

On the basis of this order-of-magnitude balance, if all of the mercury emitted in HRB ended up in the Harbor sediments, there are still about 6,500 tons of mercury remaining in sediments. A much better estimate can be made by developing and analyzing a database of existing and new data on sediment concentration profiles at selected locations and depths within the New York-New Jersey Harbor.

Recommended measures

This analysis has shown that the concentration of mercury in the sediments deposited each year in the Harbor has decreased from 10 parts per million or higher, in the past, to 0.7 ppm, in recent years. This latter value is approaching the pre-industrial level of mercury in sediments (0.1-0.3 ppm) but may still be high enough to present an ecological threat. Therefore, it may be necessary to curtail mercury emissions still further. The following measures are recommended in this report:

- a) Removal of mercury switches from discarded automobiles prior to compacting or shredding (estimated cost: \$3,200 per kilogram of mercury).
- b) Collection and recycling of fluorescent lamps (estimated cost: \$33,000+ per kilogram of mercury)
- c) Implementing Activated Carbon Injection in coal-fired power plants and sewage sludge incinerators (cost depending on specific application)
- d) Diverting mercury-containing products from landfills and WTE plants
- e) Requiring that all combustion process plants dispose their flue dusts in monofills.

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1. INTRODUCTION

This study was part of the project *Industrial Ecology for Pollution Prevention* of the Harbor Consortium of the New York Academy of Sciences. Its objectives were to quantify the sources of past and present emissions of mercury in the Hudson-Raritan basin (HRB). Its objectives were to quantify the sources of past and present emissions of mercury in the Hudson-Raritan basin (HRB), an area of 42,000 square kilometers with a population of fifteen million; to establish an order-of-magnitude material balance of sources and sinks of mercury in the period 1880-2000; and recommend measures that may be taken to decrease mercury contamination in the NY/NJ Harbor. All tonnages are in metric tons with noted exceptions. Mercury emissions are as reported by companies and environmental agencies. Mercury loads in sediments were estimated on the basis of a limited number of samples and generally accepted sediment flows; their accuracy can be improved by additional sampling over the Harbor area.

The report is based on a detailed analysis of data of several documents and published technical reports, using industrial ecology methodology. The New Jersey and New York City Departments of Environmental Protection and the Port Authority of NY/NJ provided additional data on current conditions. On the basis of this information, the industrial history of HRB in the period 1880 to 2000 was reconstructed in order to determine patterns of production, consumption and emissions of mercury. The 1980 and 1989 “mileposts” were examined in particular, because of the extensive data provided in two seminal reports on the Hudson-Raritan estuary, by Rod, Ayres, and Small (1989) for Hudson River Foundation and by HydroQual Company (1991) for EPA. The 1995 “milepost” was also useful because of the comprehensive analysis of anthropogenic sources of mercury emissions presented in the EPA Report to Congress (EPA 1997).

2. PAST MERCURY EMISSIONS IN HRB

The principal sources of mercury emissions in the past were: Mercury production, consumption and discarding of used products; coal combustion; and non-ferrous smelting. The emissions from these three sources are discussed in the following section.

2.1 Mobility of mercury

Most of the mercury produced intentionally by industry is used in the manufacture of chemicals (mainly chlorine in chlor-alkali plants) and products that are used by other companies or consumers. All the mercury contained in products, with the exception of those recycled in a way that mercury is captured, eventually ends up in the form of gas, liquid or solid emissions. There is also unintentional generation of mercury by industry in the form of gas, liquid and solid emissions.

At room temperature, mercury is in liquid form. In the normal temperature range of 0-40°C, its vapor pressure increases from 0.001 to 0.007 mm Hg. This is a much lower pressure than water (e.g., the water vapor pressure at 40°C is 5.67 mm Hg). However, the concentration of mercury in the atmosphere of the

northern hemisphere has been estimated (Slemr et al 1991,1996) to be in the range of 1.5-2 nanograms per cubic meter. This concentration is several orders of magnitude lower than the vapor pressure of this metal. Therefore, exposed metallic mercury, e.g. mercury droplets in landfilled solid wastes, will slowly evaporate to the atmosphere.

2.2 The mercury cycle

Mercury emissions, from combustion of fossil fuels or from other chemical processes, are principally in the form of mercury vapor or as oxidized mercury attached to particulate emissions. Emissions can be divided into three categories. Since the crust of the Earth contains 0.05-0.1 parts per million of mercury, there are naturally occurring, or pre-industrial, emissions from land (estimated at about 500 metric tons per year; Bergan et al.1999) and oceans (1400 tons; Bergan et al. 1999). Anthropogenic emissions can be divided into a) new emissions and b) re-emissions of previously mobilized and deposited mercury. An analysis of the available information on global mercury emissions is shown in Table 1 (Themelis 2001).

Table 1. Hypothesis as to rates of global mercury emissions and deposition at assumed atmospheric residence time of 1 year (Themelis 2001)

	Year 1990, tons	Year 1994, tons
Pre-industrial emissions:	1900	1900
Anthropogenic re-emissions	1800	1800
Anthropogenic new emissions	2100	1000
<i>Anthropogenic total</i>	<i>3900</i>	<i>2800</i>
Total emissions to atmosphere	5800	4700
Atmospheric loading	5800	4700
Change in atmospheric loading (annual average for 1990 -1994)		-270
Annual deposition (total emissions – change in atmospheric load)	5800	4970

Bergan et al. (1999) constructed a similar balance (Table 2) where mercury sources were differentiated into mercury vapor (Hg^0) and mercury ions (Hg^{II}).

Table 2. Estimated global mercury emissions
(tons/year, Bergan et al. 1999)

Emission Type	Hg ⁰ (tons/y)	Hg(II) (tons/y)	Total (tons/y)
Natural, land	500	0	500
Natural, sea	1400	0	1400
AG new emissions	1300	850	2150
Re-emissions	2000	0	2000
<i>Total</i>	<i>5200</i>	<i>850</i>	<i>6050</i>

2.3 Mercury production and consumption in the period 1880-2000

This section considers the sources of past accumulation of mercury in the New York-New Jersey Harbor. Since 1880, the U.S. Bureau of Mines has maintained very good records of metal production and consumption; as of 1990, this compilation has been continued by the U.S.G.S. These records are a valuable source for establishing the amounts of mercury produced and consumed in the U.S. in the period of 1880-2000. Mercury production reached a maximum of 2289 tons in 1965 and a minimum of 156 tons in 1950 (Figure 2). By 1999, the U.S. production was only 400 tons, all of it by recycling of used mercury products.

U.S. Mercury Production

after Rod, Ayres, and Small, 1989; Sznoppek and Goonan, 2000

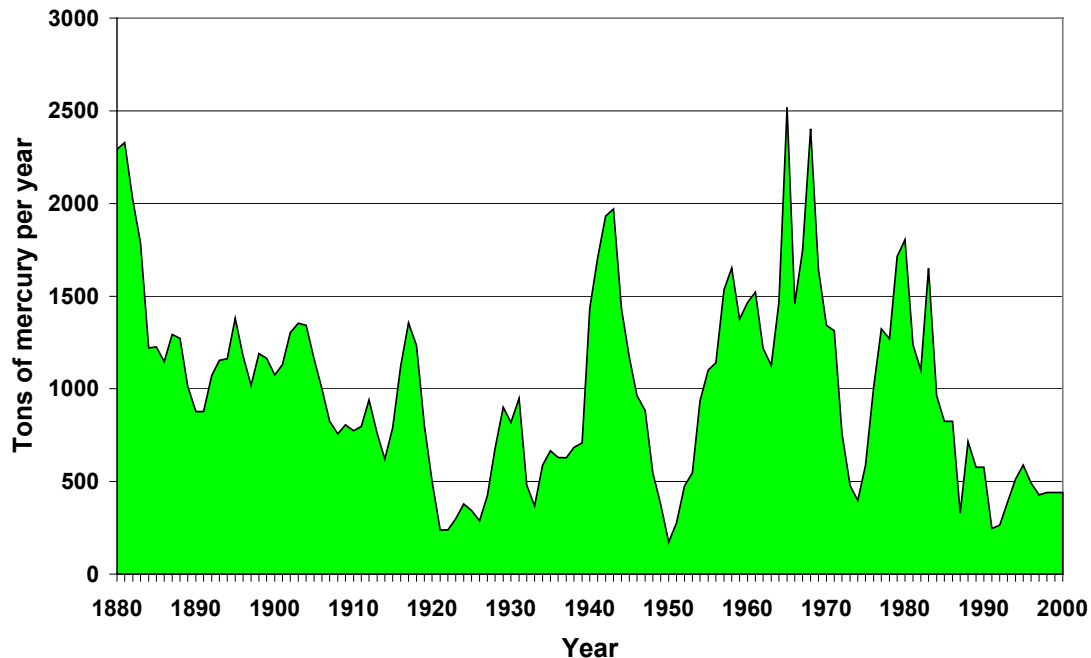


Figure 1. U.S. production of mercury, 1880-2000

Integration of the data in Figure 2 showed that in this 120-year period, a total of about 148,000 tons of mercury were consumed by the U.S. economy. Mercury consumption reached a maximum of 2811 tons in 1964 and a minimum of 346 tons in 1997. The rapid decrease in consumption since 1980 was due to legislation to eliminate mercury from batteries (54% of demand for mercury in 1984 down to 2% by 1992), use as fungicide in paint (16% in 1989 down to zero by 1992) and to market forces away from mercury use in other products (thermometers, thermostats, switches, etc.). In the period of 1993 to 1998, the remaining domestic mines closed and legislation was enacted mandating mercury recycling (Sznoppek and Goonan 2000).

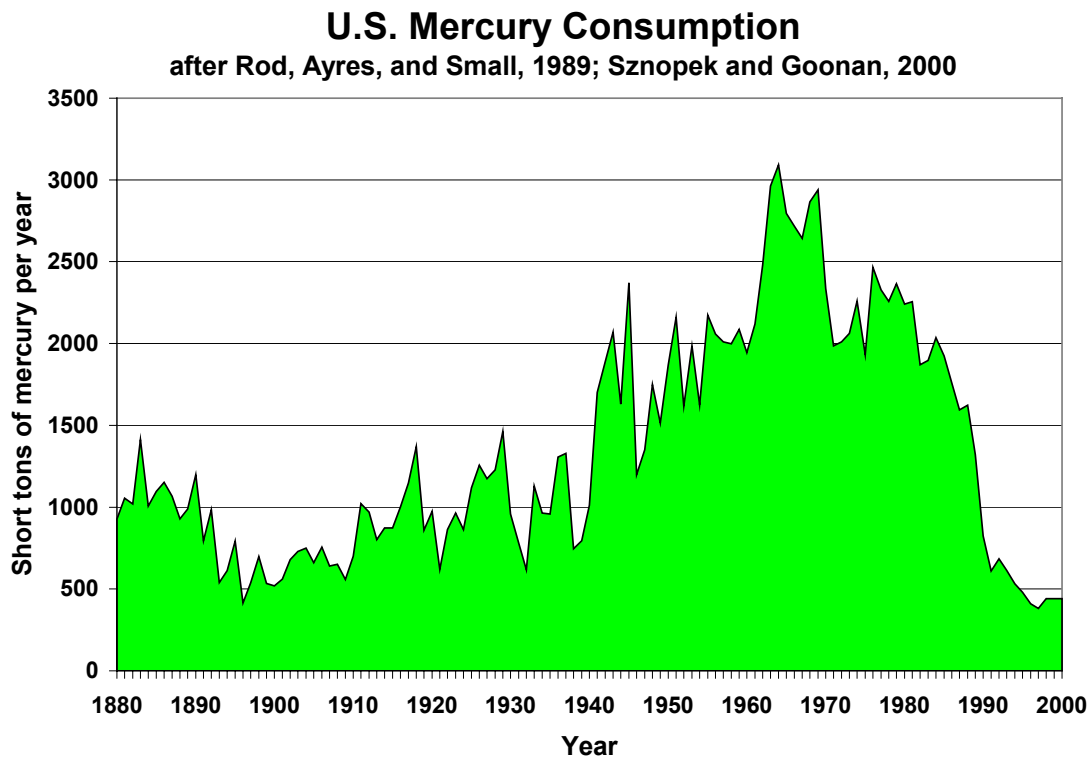


Figure 2. Consumption of mercury in the U.S. economy, 1880-2000 (1 metric ton = 1.1 short tons)

In reconstructing the consumption of mercury in the Hudson-Raritan basin (HRB), the U.S. and HRB population data for the 1880-1980 period were used (Table 3). It can be seen that the fraction of HRB population remained nearly constant, from 7.6% of the US in 1880 to 7.4% in 1980. In the last two decades of the 20th century, HRB did not keep pace with the increase in U.S. population and decreased to 5.6%. Industrial activity in HRB decreased from 17.8% in 1880 to less than 6% of the U.S. by the end of the last century.

By combining the data for U.S. mercury consumption (Figure 2) and assuming the fraction of the HRB population constant at 7.5%, the amount of mercury consumed in HRB over the 120-year period was estimated to be in the

range of 11,000 tons (U.S. total: 148,000 tons). With the exception of any industrial mercury stocks and mercury products still in use, this material has been either deposited in landfills, combusted in incinerators or discarded on land and water. Some of the mercury in sediments has been removed by the continual dredging of the New York Harbor and river estuaries. Some has been carried out of the harbor in the riverine and tidal flow. Finally, some remains in the harbor sediments. An order-of-magnitude mercury balance is presented at the end of this report.

Table 3. U.S. and HRB industry and population data 1880–2000
(Rod et al. 1989; U.S. Bureau of Census)

Year	Industrial workers, (x 1000)		HRB industrial workers as % of US	Population (x1000)		HRB population as % of US
	US	HRB		U.S.	HRB	
1880	2,872	510	17.8	50,189	3,814	7.6
1900	5,101	836	16.4	76,094	5,707	7.5
1930	7,267	1105	15.2	123,076	9,231	7.5
1950	11,780	1463	12.4	152,271	11,420	7.5
1980	14,223	886	6.2	226,546	16,674	7.4
1998				272, 691	15,300	5.6

2.4 Mercury emissions from coal combustion

In order to estimate the amount of mercury emitted from coal combustion in the HRB area, it is necessary to consider the global generation of carbon emissions from the combustion of solid fuels in the past (Figure 3). By integrating the data of Figure 3 over the period 1775-2000, the total amount of carbon emitted from the combustion of solid fuels is 140 billion tons. For an assumed average concentration of 75% carbon (Perry 1999) and 0.15 ppm of mercury in global coal (Hopke 1985, Rod et al 1989, Wang), 28,000 tons of mercury have been emitted from global coal combustion. An estimated 25% of this amount (U.S. economy =25% of the global economy, Themelis 2001), i.e. about 7,000 metric tons, was generated by the U.S. Since the HRB area has represented 7.5% of the U.S. population, the amount of mercury emitted by coal combustion in HRB is estimated to be about 500 tons.

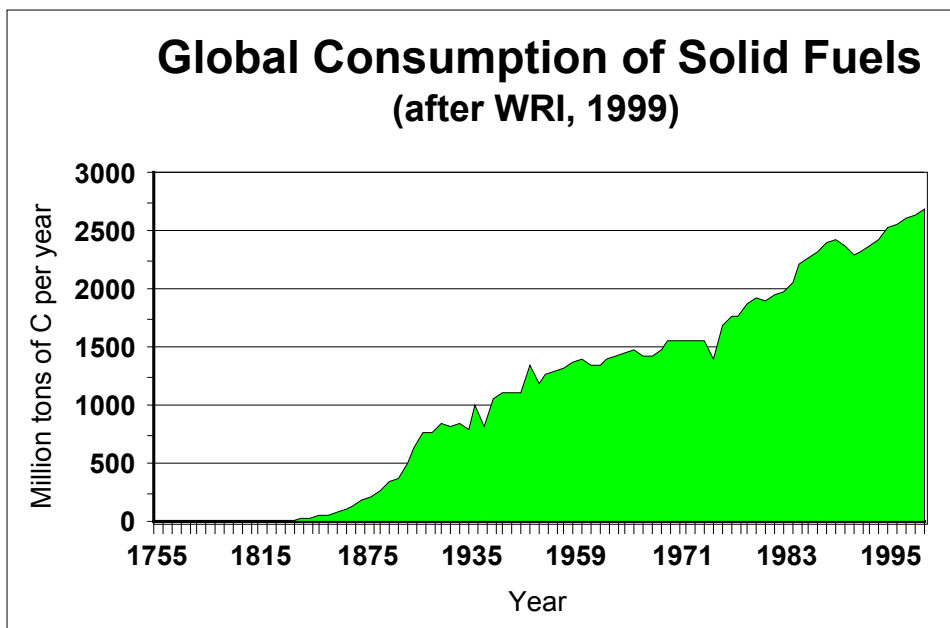


Figure 3. Global consumption of carbon in solid fuels, 1755-2000 (WRI 1999; 1996-2000 data were calculated by assuming same rate of growth as in 1985-1995, i.e., 1.5% per year).

2.5 Mercury emissions from copper smelting

The principal primary metal produced in the HRB area in the 20th century was copper. There are no more copper or other non-ferrous smelters in the HRB area. However, it is of interest to estimate the amount of mercury that has been emitted in this area because of copper smelting. On the basis of data collected by EPA (1997) on U.S. operating copper smelters, copper ores contain from 2 to 12 parts of mercury per million parts of copper. The U.S. copper production increased from 300,000 tons per year in 1900 to a maximum of 1.6 million tons in the early seventies (U.S.G.S. 2001). Copper production in HRB peaked at about 39% of U.S. in 1900 and decreased to about 25% by the seventies. However, by then most of the raw material used in HRB smelters and refiners was not ore but either impure copper, smelted elsewhere, or copper scrap. These materials do not contain mercury.

The total U.S. copper production from copper ores, in the period of 1880-1980, when the HRB smelters stopped operations, amounted to less than 90 million metric tons (U.S.G.S., 2001). For a conservative estimate, it was assumed that 25% of the U.S. primary copper production was produced in HRB, that the copper concentrates contained the maximum of 12 parts mercury per million parts of copper, and that none of this mercury was captured in the smelters' gas control systems. The corresponding amount of mercury emitted in HRB is calculated to be less than 300 metric tons.

2.6 Summary of past mercury emissions in HRB

The above findings on past mercury emissions in HRB can be summarized as follows:

- Assuming that all mercury used in HRB was discarded in the environment:	11,000 metric tons
- Emissions from coal combustion	500
- Emissions from copper smelting	300
- Assumed industrial losses during operation (10% of all production)	1,100
Total:	12,900 metric tons

3. GLOBAL, REGIONAL, AND SHORT-RANGE DEPOSITION OF ATMOSPHERIC MERCURY

3.1 Global and regional deposition

The residence time of emitted molecules of mercury in the atmosphere has been estimated by various researchers to range from 0.5 to 2 years, with 1 year being the most likely value (Bergan 1999; Brunke 2000). At an assumed residence time of one year, the amount of mercury re-deposited in 1994 on the land and water was estimated at about 4970 tons per year (Table 1).

While mercury is in the atmosphere mostly in the form of metal vapor, most of the deposition on land and water is in the form of “wet” deposition, as oxide, chloride or other compounds. The annual rate of wet precipitation of mercury has been measured at various locations in North America (Table 4) and was found to range from 10 to 35 grams/km². It is interesting to note that if the 4970 tons of mercury (Table 1) were to be distributed uniformly over the surface of the Earth, the expected rate of deposition would be about 10 grams/km² per year (Themelis 2001).

3.2 Regional and short range deposition of mercury on HRB

Table 4 shows that wet deposition of mercury in northern NY state was 10 grams/km² per year. For the HRB surface area of 42,000 km², the corresponding amount of mercury deposited is 420 kilograms per year. However, HRB includes densely populated areas. Therefore, it would be expected that the combustion and smelting sources within HRB result in an additional amount of “short-range” deposition. This amount is calculated in Section 4.4 of this report to be 724 kilograms per year. Therefore, the recent total mercury deposition in HRB is estimated at 420+724 = 1144 kilograms per year. On a surface area basis, this number corresponds to nearly 27 g/km² per year. This value is in the range of values reported in Table 4 for other densely populated areas.

Some of the mercury deposited on land is dissolved in surface and near-surface waters that eventually end up in riverine flows. Mercury also deposits on fine mineral particles that are entrained in water flow and eventually settle to the river bottom in the form of sediments. For these reasons, the HRB surface acts

as a giant funnel that catches mercury emissions both from point and area sources. By means of riverine and sediment flow, a large part of these emissions is eventually transported to the New York-New Jersey Harbor.

Table 4 – Measured rates of wet deposition of mercury
in grams per square kilometer
(data from Bergan et al. 1999; Weinstein et al. 2000)

Location	Observation (Range)	Reference
Scandinavia		
Northern Norway	(3-5)	Iverfeldt (1991)
Northern Sweden	10	Iverfeldt (1991)
SW Sweden 1985-1989	27	Iverfeldt (1991)
SW Sweden 1990-1992	10	Iverfeldt et al. (1995)
USA		
Northern NY State 1993	10	Burke et al. (1995)
Little Rock Lake, WI	8.7	Fitzgerald et al. 1991
Wisconsin	9 (5 – 13)	Benoit et al (1994)
NE Minnesota 1988-1989	15 (6 – 20)	Glass et al. (1991)
Upper Midwest	7.4	Glass and Sorensen 1999
Florida 1992-1993	(15 – 23)	Guentzel et al. (1995)
Lake Michigan	8.3	Hoyer et al. 1995
Chesapeake Bay	21.0	Mason et al. 1994
Baltimore, MD	35.0	Mason et al. 1994
Lake Champlain, NY	7.9	Rea and Keller 1996
Japan		
Kobe	40	Lindberg et al. (1992)
Oceans		
Tropical Pacific	3	Fitzgerald et al. (1983)
NW Atlantic	11	Fitzgerald (1989)
NE Pacific	10	Fitzgerald (1989)
Enewetak (11N, 165E)	4.2	Fitzgerald (1989)
Samoa (13S, 170W)	7.0	Fitzgerald (1989)
Tasman Sea (35S, 170E)	3.8	Fitzgerald (1989)

4. CURRENT COMBUSTION AND SMELTING EMISSIONS IN HRB

Table 4 showed that the wet mercury deposition varies only by a factor of three between heavily populated and remote areas. This indicates that in contrast to some other gases, e.g. sulfur dioxide, mercury travels long distances and affects the global atmosphere, much as carbon dioxide. The following sections discuss the various sources of mercury emissions to the atmosphere.

4.1 Mercury emissions from fossil fuel combustion

Most coals contain 0.1-0.3 parts per million of Hg (EPA 1997). Hopke (1985) and Rod et al (1989) estimated the representative concentration of

mercury in global coal to be 0.15 ppm. The oil residues from petroleum refining contain about the same amount of mercury while refined oil and natural gas contain much less. Fossil fuels are used in utility boilers to produce electricity, in industrial and commercial boilers to produce electricity or steam, and in residential boilers to produce heat. The reported 1998 emissions of mercury from all U.S. coal-fired utilities amounted to 42.7 tons (EWG 2000). This number is about 10% lower than the 1995 emissions of 47.2 tons reported in the EPA Report to Congress (1997). The same report (EPA 1997) catalogued by state the 1994 emissions of mercury from these three types of boilers. New Jersey was shown to have total boiler emissions of 644 kilograms and New York State of 3101 kilograms of mercury (Table 5). The 1998 data on utility emissions in Table 5 were obtained from the EPA detailed compilation of mercury emissions from all U.S. utility boilers (EPA 2001). Total New Jersey combustion emissions were provided by the New Jersey Department of Environmental Protection (NJ DEP 2001). In summary, mercury emissions from New York and New Jersey boilers decreased by 60% between 1994 and 1998, principally because of the substitution of coal by fuel oil at some power plants.

Table 5. Mercury emissions from utility, industrial and residential boilers (kg/y)

	New Jersey		New York		Basis of 1998 numbers
	1994 (EPA)	1998	1994 (EPA)	1998	
Utility: Coal	173	NA	1208	NA	EPA 2001
Gas	0	NA	0	NA	
Oil	5	NA	57	NA	
<i>Total</i>	<i>178</i>	<i>186</i>	<i>1265</i>	<i>487</i>	
Industrial-commercial	230	79	1310	500	NJ: total - utilities. NY: 60% decrease Since 1995, same as NJ.
Residential	236	80	526	200	NJ: Total - utilities. NY: 60% decrease Since 1995, same as NJ.
Total NJ, NY fossil fuel	644	345	3101	1187	NJ from NJ DEP, 2001 NY by addition of all boilers.
Total HRB emissions from fossil fuel combustion [Population of HRB=57% of NY+NJ populations]:					
<ul style="list-style-type: none"> • 1994: $(644 + 3101) \times (0.57) = 2135$ kg • 1998: $(345+1187) \times (0.57) = 873$ kg 					

4.2 Mercury emissions from secondary iron and steel production

Mercury emissions from Electric Arc Furnace plants (secondary steel production) and cupolas (secondary iron production) was a source of mercury emissions that was not included in the 1997 USEPA report. One third of the U.S. cars in operation are equipped with one or more light, anti-lock braking systems,

or “active ride control” switches, containing from 1-3 grams of mercury each (Gregory 2001). If these switches are not removed prior to compacting or shredding a car, when the scrap metal is smelted much of the contained mercury is emitted to the atmosphere. Table 6 was constructed from NJ plant data provided by M. Aucott (NJ DEP 2001) and NY plant data provided by NYS DEC (2001). It shows that an estimated 644 kg of mercury are emitted annually. Table 6 also shows that there is much variation in the emissions of mercury per ton of steel produced. This may be due to the mix of the feed scrap, or to differences in gas control technology. Generally, it would be expected that plants equipped with dry scrubbers and bag filters have higher mercury collection efficiency than electrostatic precipitators. Also, plants that employ activated carbon injection are expected to capture a higher fraction of the mercury in the gas stream (see Section 10).

Table 6. Mercury emissions from iron and steel production (NJDEP 2001)

Facility	Plant capacity, In short tons/y	Date of NJ DEP Test	Measured mercury emissions, lb/h	Mercury emissions, kg/year**
Atlantic States IP Co.	234,000	Nov. 1999	0.03	108
Hoeganaes Corp	119,028	Nov. 1999	No data	13 (estimate)
Co-Steel Sayreville	800,000	June 2000	0.0058	21
Co-Steel Raritan	1,160,320	Aug. 1999	0.0286	103
Griffin Pipe Products	182,000	Sept. 1997	0.038	141
U.S. Pipe and Foundry	262,964	Sep 1997	0.024	86
NJ subtotal	2,758,312			472 kg
Auburn Steel* Co. Inc.	NA		0.029	114
A.T. Specialty Steel Corp.*	NA		0.008	32
Allegheny Technologies*	NA		0.0032	13
Crucible Materials Corp.*	NA		0.0032	13
NY subtotal	NA			172 kg
NY and NJ total				644 kg

* NY Facility Data Source: *Toxic in Vehicles: Mercury*. January, 2001 **At 90% plant availability

4.3 Mercury emissions from Waste-to-Energy (WTE) plants

At one time there were in New York City nearly 17,000 apartment/house and 32 municipal incinerators burning municipal solid wastes (MSW) (Walsh et al 2000). Between 1908 and 1990, an estimated 100 million metric tons of MSW

were incinerated in incinerators that were provided with little or no emission controls. Collectively, they emitted one million tons, i.e. 1 % of the MSW weight, of soot particles to the atmosphere (Walsh et al 2000). Many people are not aware of the enormous difference between the polluting incinerators of the past and the modern Waste-to-Energy plants that are used in many communities in NY, NJ, and elsewhere to combust solid wastes, recover metal values, and generate electricity. For example, the modern Waste-to-Energy plant of SEMASS at Rochester, MA has replaced many landfills in southern Massachusetts. It processes 0.9 million tons of MSW per year in three combustion chambers and has a particulate emission rate of 0.003%, that is 300 times lower than the emissions of the NYC incinerators of the past (Themelis et al 2000).

Mercury emissions from WTE plants are due to mercury contained in the MSW that vaporizes during combustion. Mercury-containing products include electric switches, lamps, paint residues, and thermometers (EPA 1997). The mercury content of MSW can be reduced by better collecting/sorting methods, for example by recycling fluorescent tubes. By the late nineties, nearly all U.S. WTE plants were equipped with electrostatic precipitators or fabric filters, activated carbon injection, and other gas control devices. For example, the mercury emissions from the SEMASS, MA plant discussed earlier, amount to only 34 kilograms of mercury per year. The measured concentration of mercury in the collected flue dust (69,000 tons per year) is 18 parts per million, i.e. 1350 kg/year. Therefore, 97% of the input mercury in the MSW (estimated to be about 1.5 ppm in the feed MSW to the SEMASS plant) is captured in the form of flue dust (Themelis et al 2000).

With respect to HRB, New Jersey regulations mandated that by the end of 1995 all municipal waste combustors (MWCs) be retrofitted with activated carbon injection (ACI). Table 7 (NJ DEP 2001) shows that the mercury emissions of the NJ WTE plants decreased by a factor of ten in the years between 1993 and 1999. This has been attributed to two principal factors:

- The decreased usage of mercury in consumer products and therefore in the MSW stream. As mentioned earlier, U.S. consumption of mercury has decreased from about 2000 short tons in the eighties to the present level of about 400 short tons per year.
- Improved gas controls, such as activated carbon injection.

Table 7. Decrease in mercury emissions from New Jersey Waste-to-Energy plants, 1991-1999 (NJ DEP, 2001)

Facility	WTE capacity, short tons/day	1991,'92,'93	1996	1997	1998	1999
		Pounds of mercury per year				
Camden	1,050	1,084	431	350	144	113
Essex	2,275	1,771	216	323	115	162
Gloucester	575	149	32	51	25	15
Union	1,440	844	84	42	24	32
Warren	400	562	4	4	3	4
Total	5,740	4,410	767	770	311	326

(all units left as reported by NJ DEP; 1 ton =1.1 short tons; 1kg = 2.2 pounds)

Table 8 compares the 1999 mercury emissions of the five New Jersey plants with the SEMASS plant referred to earlier and also with the Onondaga, NY, Waste-to-Energy plant. The last column of Table 8 brings all the data into a common metric: kilograms of mercury emitted per million metric tons of MSW combusted. Obviously, the lowest figure in this column is the most environmentally desirable. It should be stressed that the better results shown for some of the MSW plants in Table 8, reflect both better gas control systems and also the ability of some communities to divert mercury-containing objects from the MSW stream. For example, an aggressive campaign in Warren County, NJ reduced the amount of mercury in the MSW stream from 3 parts per million to less than 1 ppm (NJ DEP 2001). This may explain the fact that the Warren County WTE emitted only 10 kilograms of mercury per million tons of MSW processed (Table 8).

Fitzgerald and O'Connor (2001) estimated that the total MSW stream in the HRB area was 17 million tons (18.76 million short tons). Of this amount, 1.95 million tons (2.15 million short tons, or 11.4% of total MSW) were combusted. The estimated mercury emission was 140 kg. This emission corresponds to 72 kilograms of mercury per million metric tons of MSW processed. This number is greater than the emission ratings (in kilograms per ton) of several of the WTE plants shown in Table 8. Therefore, it can be surmised that WTE mercury emissions in HRB can be reduced further, by making a greater community effort to remove mercury containing objects from the MSW stream, or by further improvements in the gas control systems of some plants.

To appreciate the reduction in mercury emissions caused by MSW combustion in the last decade of the 20th century, it should be noted that a study by the National Renewable Energy Laboratory (NREL 1993) reported that the 1989 emissions of all U.S. incinerator plants amounted to 81,800 kilograms of mercury. A few years later, the EPA Report to the Congress (EPA 1997) showed that the 1995 emissions from all U.S. Waste-to-Energy plants amounted to 26,900 kg of mercury. Finally, if we apply the metric of 72 kilogram/million tons of HRB to the 33 million of tons currently combusted in WTE plants (Berenyi, 1998), the corresponding mercury emissions from all U.S. WTE plants (about 105 plants) amount to 2,380 kg/year, i.e. ten times lower than the EPA 1995 estimate and forty times lower than the NREL 1989 estimate.

Table 8. 1999 Mercury emissions from Waste-to-Energy plants

Facility	Gas control system (all use carbon injection)	MSW combusted, Short tons per year	Annual average Micrograms of mercury per dry standard cubic meter	Mercury emissions Kg/y	Kilograms of mercury per million metric tons of MSW
Camden, NJ	ESP	451,000	25.1	51.3	125
Essex, NJ	ESP	985,000	31.8	73.5	82
Gloucester, NJ	Filter bags	210,000	38.0	6.8	36
Union, NJ	Filter bags	562,000	2.2	14.5	28
Warren, NJ	Filter bags	160,000	2.4	1.8	12
NJ Total		2,368,000		148	69
Onondaga, NY*	Filter bags	326,000		15.4*	52
SEMASS, MA	Filter bags	986,000	5.1	33.0	37

*reported by OCRRA, Onondaga, NY

4.4 Mercury emissions from sewage sludge incinerators

New Jersey and several other states incinerate the sludge generated in the process of treating sewage in Waste Water Treatment Plants. A very recent communication from NJDEP (May 2001) provides a very detailed tabulation of the estimated mercury emissions from the New Jersey sewage sludge incinerators (SSI, Table 9). In 2000, the total NJ SSI emissions amounted to 152 kilograms. The New York City sludge is dewatered, pelletized and used as soil conditioner (NYC DEP, 2001).

Table 9. 2000 mercury emissions from New Jersey sewage sludge incinerators
(NJ DEP May 2001)

Sewage sludge incinerator	Mercury emissions (kg/y)
Atlantic County	5
Bayshore	6
Camden	48
Gloucester	2
Northwest Bergen	11
Parsippany-Troy Hills	8
Pequanock	15
Somerset Raritan	13
Stony Brook	41
Wayne Twp	4
Total	152

4.5 Mercury emissions from medical waste incinerators (MWI)

The EPA Report to Congress (EPA 1997) reported that in 1995 there were about 2400 Medical Waste Incinerators (MWI) in the U.S., ranging in capacity from 1 to 54 tons per day. Sixty-one of these were in New Jersey and eighteen in New York. The 1995 mercury emission rates from all U.S. MWI were estimated at 14,600 kg of mercury. For the HRB population (5.6% of U.S), the corresponding emissions in 1995, would be 818 kg. However, a very recent and detailed communication from NJ DEP (Table 10, May 2001) shows that the total NJ emissions from MWIs in 2000 were only 0.9 kg/year. On the basis of this estimate, the MWI mercury emissions are negligible.

Table 10. 2000 mercury emissions from New Jersey medical waste incinerators
(NJ DEP 2001)

Medical waste incinerator	Mercury emissions (kg/y)
Elizabeth General Medical Center	0.003
Helene Fuld Medical Center	0.09
Monmouth Medical Center	0.11
Morristown Memorial Hospital	0.20
Passaic Valley Hospital	0.02
Rahway Hospital	0.03
Shore Memorial Hospital	0.01
St. Joseph's Hospital and Medical Center	0.45
Total	0.91

4.6 Summary of combustion and smelting emissions in HRB

The above findings on current combustion and smelting sources of mercury emissions in HRB for 1999-2000 can be summarized as follows:

- Utility, industrial, and residential boilers: 873 kilograms/y
- Emissions from iron and steel smelting: 644
- Emissions from Waste-to-Energy plants: 140
- Emissions from sewage sludge incinerators: 152

Total: 1,809 kg/y

EPA (1997) assumed that about 60% of the mercury emitted from combustion sources is in elemental form and contributes to the global mercury load in the atmosphere; 40% is in reactive form and tends to deposit locally. On the basis of this distribution, the HRB mercury emissions that were deposited in HRB are $1809 \times 0.4 = 724$ kg/y. This “short-range” deposition is in addition to the regional deposition of atmospheric mercury, estimated to be 420 kg/y for HRB (See Section 3.2). On this basis, the total atmospheric deposition of mercury in HRB is estimated at 1144 kilograms per year.

5. WATER AND SEDIMENT FLOWS TO NEW YORK HARBOR

This section presents estimates of the mass flows of water and of sediments into the greater New York Harbor.

5.1 Water flows

Table 11 shows an estimate of the surface areas of the drainage sub-basins within the Hudson-Raritan basin and two estimates of the average flows of rivers entering the NY/NJ Harbor. Olson et al (1984) estimated that Hudson represented 86% of the total riverine flow and Hydroqual (1992) 90%. Both estimates are close to the 87% estimate by Mueller et al (1982). The seasonal variation from the average value is enormous: The 7-day, 10-year “low flow” for Hudson has been measured at only 82 m³/s, while the 100-year “flood flow” was 5,760 m³/s (NOAA 1985). In comparison to the average river flow, the daily tidal flow is an order of magnitude higher; average values at the southern tip of Manhattan range from 8,000-11,000 m³/s (Abood 1974; Chillrud 1996).

Table 11. Surface area and water drainage in Hudson-Raritan Basin

River	Drainage basin, km ² Olson et al 1984	Average annual discharge of freshwater, m ³ per second	
		Olson et al 1984	Hydroqual 1991
Hudson	35,600	550	546
Passaic	2,400	41	32
Hackensack	525	6	3
Raritan	2,800	45	24

All other			19
Total	41,325	642	605

Table 12 shows the sources of “freshwater” flow into the NY/NJ Harbor as of 1989. Water discharges from municipal wastewater treatment plants (WWTPs) were fifty times larger than the direct industrial discharges. The distribution of WWTP and industrial effluent flows in the NY/NJ rivers, as of 1989, is shown in Table 13.

Table 12. 1989 sources of “freshwater” water flow into the NY/NJ Harbor
(HydroQual 1991)

Water Source	Total flow (765 m ³ /s)
Tributaries	80.7%
Municipal point sources	14.9%
Stormwater	3.7%
Combined sewer overflows (CSOs)	1.3%
Direct Industrial Discharges	0.3%

Table 13. 1989 distribution of municipal and industrial effluent flows
(HydroQual 1991)

Waterway	WWTP effluents	Industrial effluents
	Total: 114 cubic meters per second (2500 mill. gall. per day)	Total: 2.4 cubic meters per second (52 mill. gall. per day)
Hudson	15%	6%
East River	42%	-
Upper NY Bay	15%	2%
Jamaica Bay	12%	-
Lower NY Bay	5%	-
Arthur Kill	4%	77%
Kill van Kull	2%	-
Raritan River	1%	4%
Hackensack River	4%	8%
Passaic River	-	2%

5.2 Sediment flow

The upper Hudson River collects water from an area of about 12000 square kilometers. The annual sediment load into the upper Hudson River was estimated at about 0.35 million metric tons by U.S.G.S. In contrast, the Mohawk River drains an area of only 9000 km² and discharges an additional 0.75 million metric tons of sediment into Hudson (USGS 1977).

Mueller (1982) reviewed USGS data for the period 1979-1980 and estimated the tributary sediment discharge in the Hudson-Raritan riverine flow to be 1.3 million tons per year. The Olsen et al report to NOAA (1984) summarized all earlier findings and concluded that the best estimate for the annual fine-grained sediment from Hudson River sources to the New York-New Jersey Harbor was

1±0.3 million tons. The same report estimated that 80% of the fine-grained sediments settled in the inner New York Harbor, 11% in Newark Bay, and 4% in Raritan Bay.

The sediment accumulation requires periodic dredging of the harbor to keep navigation channels and ship berths open. The accumulation rate of fine-grain sediments ranges from 0.1-0.3 centimeters per year in low accumulation areas to 9 cm/y in the dredged areas (Olsen et al. 1984-85; Myerson, 1988). This is due to the fact that dredged areas act as giant settling tanks where water velocity decreases and sediments have time to precipitate (Bokuniewicz 1987). Port Authority of NY-NJ has estimated that, for maintenance purposes, it is necessary to dredge about 3 million cubic meters of wet sediments (60-65% water) from the NY-NJ Harbor. Figure 7 (Section 8.1) shows the volumes of wet sediments that were dredged during the period 1930-2000 (Wakeman and Themelis, 2001). In total, nearly three hundred million cubic meters of sediments were dredged during the twentieth century, i.e. an average of 3 million cubic meters per year.

The fine grain sediments depositing in the Harbor consist of about 70% riverborne particles, 20% marine-origin, and 10% particulate matter carried in WWTP, stormwater and combined stormwater and sewer overflow (Olsen et al. 1984-85; Myerson 1988). The dredged material contains both fine grain sediments and also sand brought into the Harbor by the tidal flow; Chillrud (1996) estimated that it consisted of nearly equal parts of fine-grained sediments and sand. Adams et al (1998) estimated the water content of wet sediments to be about 40% and the specific density of the dry particles 2.65. Thus, the wet bulk density of sediments "in-situ" was estimated at 2 tons per cubic meter.

Metals have a tendency to partition between sediments and water. In most cases, sediment metal concentrations exceed water concentrations by at least 1000 times (Rohmann et al. 1985; NOAA 1987). In the case of mercury, the partition or distribution coefficient between sediments and water column (i.e. the concentration ratio) was reported to be as high as 400,000 (Fitzgerald 2001).

6. MERCURY FLOWS INTO NEW YORK HARBOR

6.1 Mercury dissolved in riverine flow

The Hydroqual (1991) study included a table of water quality analysis data taken in Hudson river near Green Island, NY, between 1981-1988. Concentrations of 0.1 to 0.6 parts per billion of mercury were recorded prior to 1985 (1 ppb is nearly equal to 1 microgram per liter of water). For an assumed average concentration of 0.2 ppb and riverine flow of 642 m³/s (Table 11), the annual riverine input of mercury at that time would amount to about 4,000 kilograms. However, since 1985, the recorded mercury concentration in all HRB rivers has decreased below the detection limit (<0.1 ppb) of the environmental agency that measures riverine water quality. Also, forty three samples of the water column taken in the tributary and channel flow of New York Harbor in January 1991 (Brosnan and O'Shea 1992) showed an average concentration of 0.0179 ppb of mercury; the 12 samples taken along the Hudson had an average concentration of 0.015 ppm. Assuming that the total river flow to the Harbor

contained on the average 0.02 ppm, the mercury carried in the river flow in 1991 was 400 kilograms, i.e. ten times lower than prior to 1985.

6.2 Mercury in riverborn sediments

As noted in Section 5.2, the sediment flow into the Harbor has been estimated at 1 ± 0.3 million tons per year. If it is assumed that the estimated deposition of mercury in HRB (1144 kg/y, Section 4.6) finds its way into the riverborn sediments, the corresponding mercury concentration in one million tons of sediments would be 1.1 ± 0.3 ppm. The high range of this value is close to the average sediment concentration of 1.27 ppm reported by Brosnan and O'Shea (1992) for twenty samples obtained. Adams et al (1998) reported that a harbor-wide survey of surficial sediments (84 samples) in 1993 indicated an average concentration of 0.79 ppm of mercury. The same number of samples taken in 1994 yielded 0.697 ppm. These concentrations are approaching the pre-industrial levels of mercury in sediments (0.1-0.3 ppm; Hopke 1985, Rod et al 1989, Chillrud 1996).

6.3 Mercury in effluent streams of Wastewater Treatment Plants

In 1989 (HydroQual, 1991), municipal wastewater treatment plants (WWTP) discharged about 15 percent of the average $765 \text{ m}^3/\text{s}$ "freshwater" flow into the NY/NJ Harbor (Table 12). Table 13 shows that 42% of the total NYC WWTP flow is discharged into East River. Hudson River and Upper NY Bay received 15% of the effluent discharge. Arthur Kill, on the west side of the Fresh Kills landfill on Staten Island, received 4% of the municipal and 77% of the total industrial effluent.

Figure 4 shows that the mercury concentration in WWTP effluents decreased dramatically from 1987 to 2000: In 1987, the NYC WWTPs discharged 3500 kg/y into the Harbor. In 2000, the same plants discharged a total of only 120 kg/y. Current WWTP current effluent rate and mercury concentration data were obtained from the NYC (NYC 2001) and the NJ (NJ DEP 2001) departments of environmental protection. The 1987-1989 data were obtained from the HydroQual report to EPA (HydroQual, 1991).

Figure 5 also shows a drastic reduction in mercury contamination from the NJ WWTPs: The municipal facilities discharged nearly 1200 kilograms of mercury in 1989 and only 176 kg/yr in 1998. However, the complete tabulation of all NJ treatment plants (i.e. municipal, industrial and all others) showed a total of 372 kg (NJ DEP 2001). The corresponding amount for the New Jersey HRB population (57% of NJ) amounts to 212 kg/y. Thus, the total HRB mercury from wastewater treatment plants is estimated at $120+212= 332$ kg/y.

In summary, the mercury in all municipal NJ and NYC WWTP effluent flows into the NY/NJ Harbor has decreased from 4700 kg in 1987-1989 to 332 kg in 1998. This improvement is probably due to the curtailed use of mercury, both by industry and consumers, during the last decade of the twentieth century.

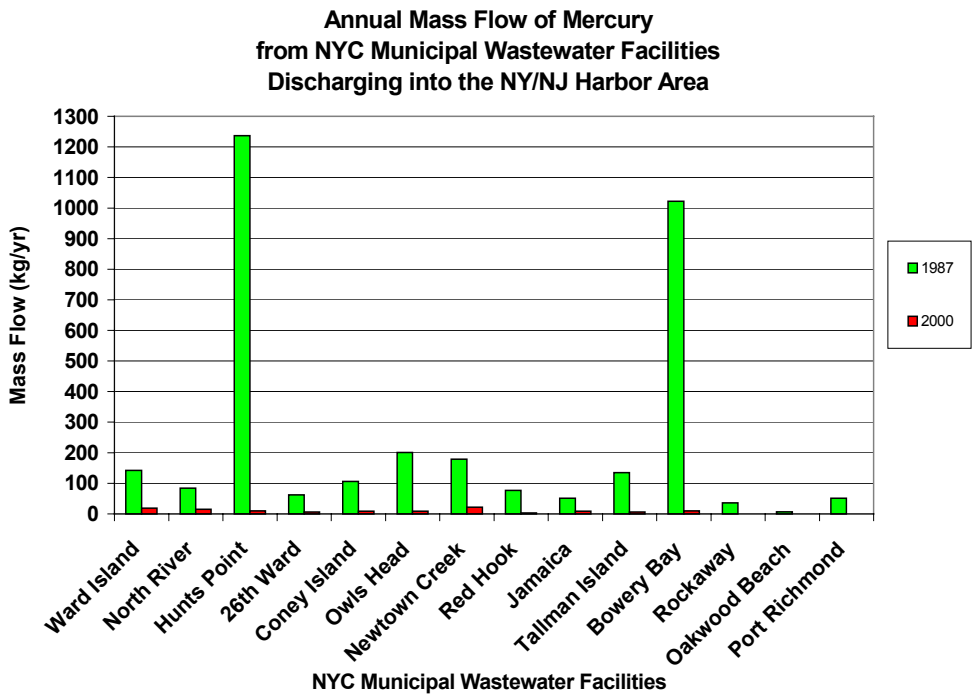


Figure 4. Reduction in mercury content of NYC WWTP effluents, 1987 to 1998
(Hydroqual, 1991; NYC DEP, 2001)

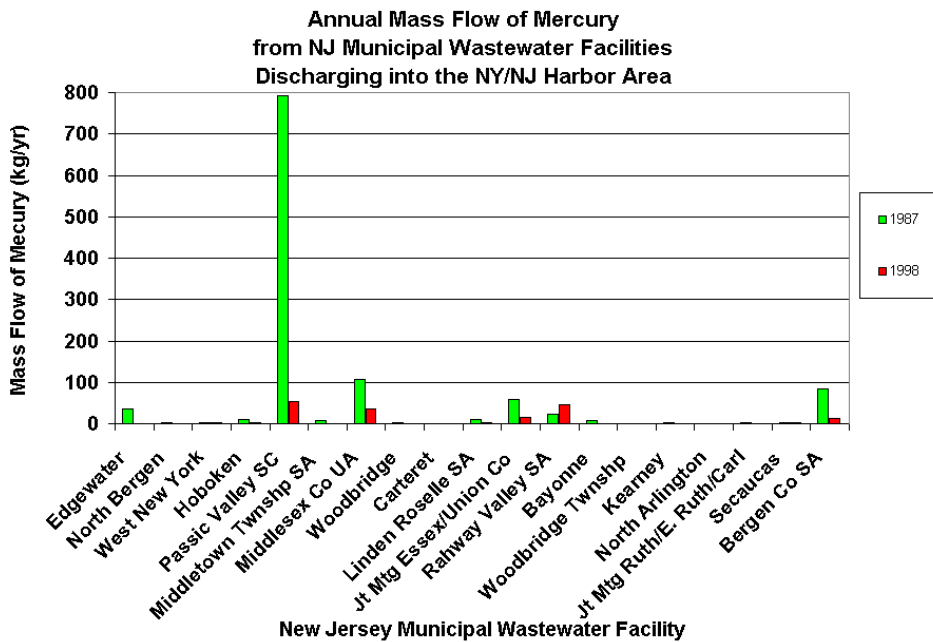


Figure 5. Reduction in mercury content of NJ WWTP effluents, 1987 to 1998
(Hydroqual 1992; NJ DEP, 2001)

6.4 Recovery of mercury in Sewage Sludge Incinerators

In Section 4.4, it was noted that the mercury emissions from NJ sewage sludge incinerators in 2000 were 152 kg; there may be additional mercury retained in the “bottom” and “flue” ash of NJ sludge incinerators. It is interesting to compare this number with the amount of mercury recovered from wastewater in the sludge of WWTPs. Unfortunately, the only data available to us on WWTP in

fluents were not from NJ but from NYC WWTPs. Figure 6 shows the reported mercury in NYC WWTP influent, effluent and amount retained in the sewage sludge (obtained by material balance), for the year 2000. It can be seen that the calculated amount of mercury recovered in sewage sludge was 351 kilograms, or 75% of the input to the WWTPs. If it is assumed that the % recovery of mercury in the sludge of the NJ WWTPs is also 75%, the amount of mercury in the NJ influent sewage would be 704 kg (4×176) and in the sewage sludge 528 kilograms (3×176). On the other hand, at an assumed 50% recovery, the NJ influent would be 352 kilograms and the mercury recovered in the sludge 176 kilograms, i.e. about the same as the reported amount emitted from NJ sludge incinerators (152 kg, Section 4.4). This indicates that one area to cut down mercury emissions is by introducing activated carbon injection, as used in WTE plants, at least for the larger sewage sludge incinerators, like Camden, NJ (emissions of 48 kg Hg per year) and Stony Brook, NJ (41 kg/y).

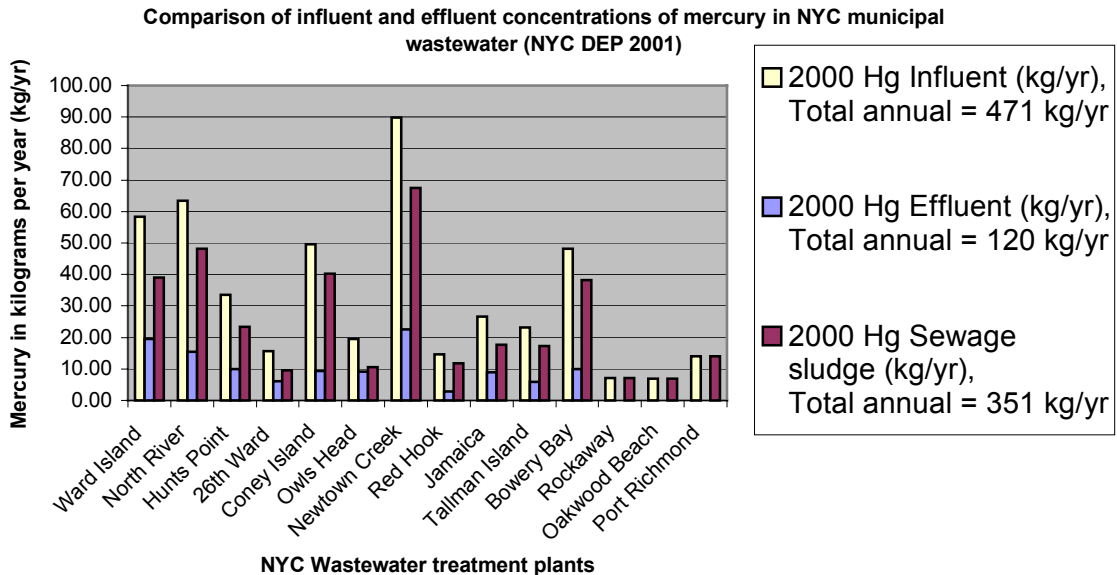


Figure 6. Mercury recovery in sludge of NYC wastewater treatment plants (NYC DEP, 2001)

7. MERCURY EMISSIONS FROM LANDFILLS

Mercury in landfills is due to three principal sources: a) Mercury in used products contained in the MSW stream, b) mercury in flue ash from coal-fired power plants, and c) mercury in flue ash from WTE plants.

As noted earlier, Fitzgerald and O'Connor (2001) estimated that of the total MSW stream in the HRB area, 1.95 million tons were combusted and 17 million tons were landfilled. By assuming a current average of 1.5 ppm mercury in the MSW stream (calculated from material balance at SEMASS, MA WTE), it is estimated that 29,000 kilograms of mercury in the HRB waste end up annually in landfills. Mercury-containing objects include fluorescent lights, batteries, electric switches, thermometers, paints and other waste. Primary pathways of mercury vapor releases to the atmosphere at municipal landfills include landfill gas (LFG) releases from passive and active vent systems, passive emissions from landfill surface covers of different ages, and emissions from daily activities at a working face.

The Lindberg and Price (1999) investigation of Florida landfills concluded that mercury emission rates over aged landfill covers ranged from 1 to 20 nanograms per square meter per hour. The atmospheric mercury emissions from municipal landfill operations in Florida were estimated to be 10 kg/y. Lindberg and Price also estimated that the mercury concentration in MSW decreased from 4 ppm in 1985 to 1-1.4 ppm in 1995. The last figure is in agreement with the estimate of 1.5 ppm made in this study for the SEMASS WTE at Rochester, Mass. They also reported that some areas of the landfill, identified from patches of vegetation that were damaged by exposure to high levels of CH₄, were characterized with the highest fluxes of mercury (18 to 22 ng m⁻² hr⁻¹).

Fresh Kills is the largest landfill in the world. It is located on the west side of Staten Island along Arthur Kill and has an area of 12 km² and a maximum height of 46-m. During the period 1945-1999, at least 10,000 tons of municipal solid wastes per working day were deposited at Fresh Kills. At an assumed average concentration of 4 ppm in the landfilled MSW, 735 tons of mercury are buried in Fresh Kills. However, applying the 20 nanograms per m² per hour of Lindberg and Price (1999) to the entire land surface of Fresh Kills (12 km²) yields an annual atmospheric emission of only 2.2 kilograms of mercury. According to this estimate, landfills are not a major source of gaseous emissions of mercury. However, the most bioactive and dangerous compound of mercury, both to ecosystems and humans, is methyl mercury (Benoit et al 1999). The organic matter and moisture within landfills create favorable conditions for the reduction of inorganic mercury compounds and the formation of methyl mercury. Therefore, more research is required to determine how much of the landfilled mercury is mobilized in leachate solutions during the life and after closure of a landfill.

One obvious way for reducing mercury emissions from landfills is to reduce the mercury content of manufactured products that at the end of their life may end up in landfills. This is already being done with such products as fluorescent lighting; the 1999 average mercury content of 4-ft fluorescent lamps was 11.6 mg vs. the 1985 average of 48.2 mg (Gregory 2001). Another way is to increase the diversion of used products from landfills: e.g., presently only 10% of

the spent fluorescent lights are recycled in NYC. However, contrary to popular belief, diverting materials from landfills for recycling is not economic and must be subsidized by society for the sake of the environment. For example, recycling of 83,000 fluorescent lamps (at 12 mg average mercury content, Gregory 2001) would produce one kilogram of mercury of value of less than \$3. However, the collection cost of the lamps would cost at least \$33,000 per kilogram of mercury (Gregory 2001).

Table 14. Estimated amounts of HRB mercury disposed annually in state and out-of-state landfills

Source of mercury	Mercury content		Basis of estimates
	kg/y	Percent of total	
MSW landfilled	29,000	89.2%	16.6 million short tons of MSW landfilled; (Fitzgerald and O'Connor 2001); ave. mercury content (SEMASS data): 1.5 ppm.
Flue ash from NY/NJ coal-fired utilities	430	1.3%	EPA, DOE reports of mercury in flue ash of NJ, NY plants (EWG 2001)
Flue ash from WTE plants	3,100	9.5%	2.15 million tons of MSW combusted in HRB (F & O'C); 1.5 ppm of mercury in MSW (3225 kg) minus WTE emissions (140 kg)
Total to landfills	32,530	100%	

Table 14 shows that a substantial amount of mercury is collected in the flue ash (or flue dust) of Waste-to-Energy and coal-fired power plants. If this ash is disposed along with MSW in a landfill, its mercury content is subject to the methylation reaction, same as the MSW mercury. However, modern WTE plants like the SEMASS plant, dispose of their flue ash in a "monofill" landfill that does not contain organic matter. This method of flue dust, or flue ash, disposal should be required of all operations involving combustion of mercury-containing materials.

8. AN ORDER-OF-MAGNITUDE MERCURY BALANCE IN NY-NJ HARBOR

As described earlier, water and sediment flow to the ocean transports a large part of the mercury discarded or deposited on the surface of HRB to the New York-New Jersey Harbor. Mercury that is dissolved in water eventually flows out to the ocean. However, mercury attached to sediments can stay in the Harbor for a long time, unless it is moved out by dredging or is gradually mobilized by chemical or bacterial reaction to form methyl mercury that is absorbed by organisms. Since the concentration of mercury in the sediments is of the order of parts per million, and in water of parts per trillion, mercury in sediments can

continue to contaminate the Harbor waters for a long time after the sources of contamination have ceased to exist.

An order-of-magnitude mercury balance was carried out for the Hudson-Raritan basin for the industrialization period of 1880-2000. As discussed in Section 2.3, the total amount of mercury discarded on land and water or emitted to the atmosphere was estimated at about 12,900 tons. Some of this mercury remains in HRB landfills, soil, and upstream sediments while the rest has been conveyed by water and sediment flow into the Harbor. Also, mercury was conveyed out of the Harbor by dredging and by the freshwater flow to the ocean.

8.1 Removal of mercury by dredging operations

Three to four million cubic meters of sediments must be dredged annually to clear navigation channels, berths, and marinas in the New York/new Jersey Harbor. Figure 7 (Wakeman and Themelis 2001) shows the amounts of sediments dredged annually during the period 1930-2000. An estimated 300 million cubic meters of wet sediments were dredged between 1900 and 2000. Most of this material was disposed at a designated ocean site in the New York Bight. Adams et al (1998) estimated that the “porosity” of sediments “in- situ” was about 40% (i.e. 60% solids content) and the average specific density of the sediment particles 2.65. Accordingly, the concentration of sediments is calculated to be 2 tons per cubic meter of dredged material. Assuming an average concentration of 10 ppm of mercury in the 300 million cubic meters of dredged sediments yields the value of 6000 tons of mercury removed from the Harbor by dredging.

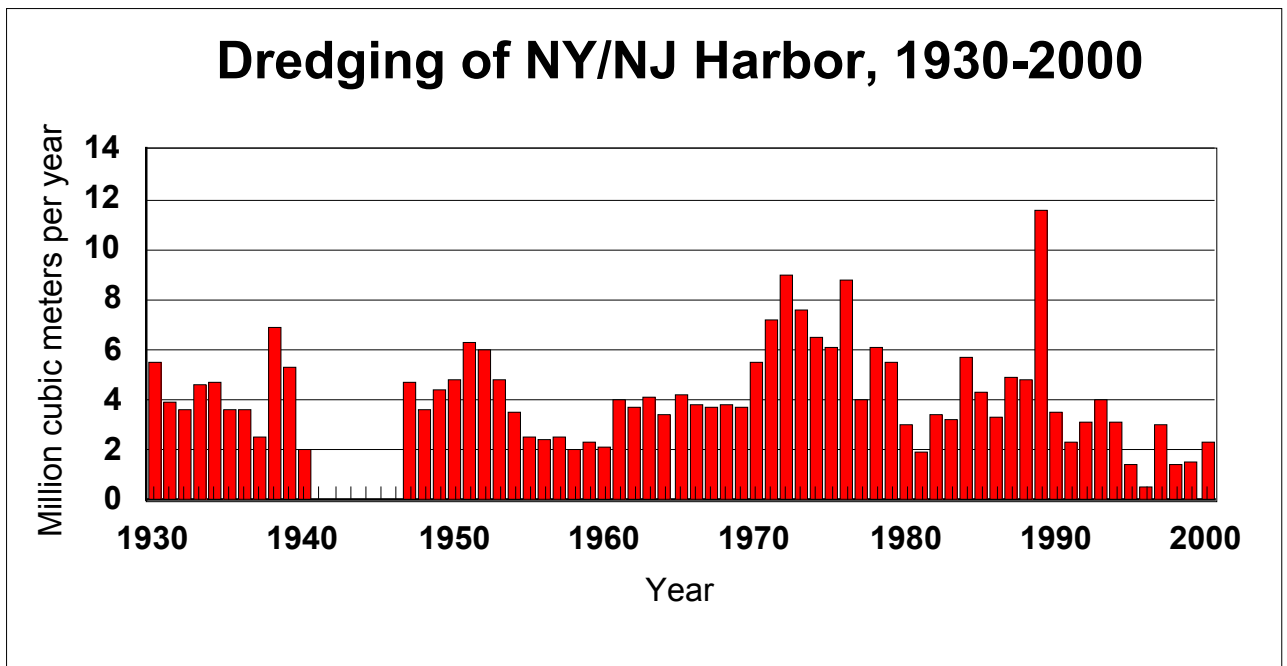


Figure 7. Record of dredging operations in NY/NJ Harbor

(1930-1976: Data by Dayal et al. 1981; 1976-1995: US EPA EIS 1997; 1995-2000: Wakeman et al. 2000)

8.2 Removal of mercury by riverine flow

As noted earlier, the average “freshwater” flow out of the Harbor is about 765 m³/s or 24 billion cubic meters per year. If an average mercury concentration of 0.2 ppb is assumed (as measured in the Hudson river flow prior to 1985, Section 6.1), the corresponding amount of mercury carried out of the harbor was 4.8 tons of mercury per year, or about 600 tons for the period of 1880-2000.

8.3 Mercury remaining in the Harbor

On the basis of the above numbers, if it is assumed that all of the mercury used and emitted in HRB ended in the Harbor sediments, there would be

$$12,900 - 6,000 - 600 = 6,300 \text{ tons}$$

of mercury remaining in the Harbor sediments. A better estimate can be made by developing and analyzing a database of existing and new data on sediment concentration profiles at various locations within the New York-New Jersey Harbor, such as the one shown in Figure 8. This study should be based on a Geographic Information Systems (GIS) platform, as discussed in the following section.

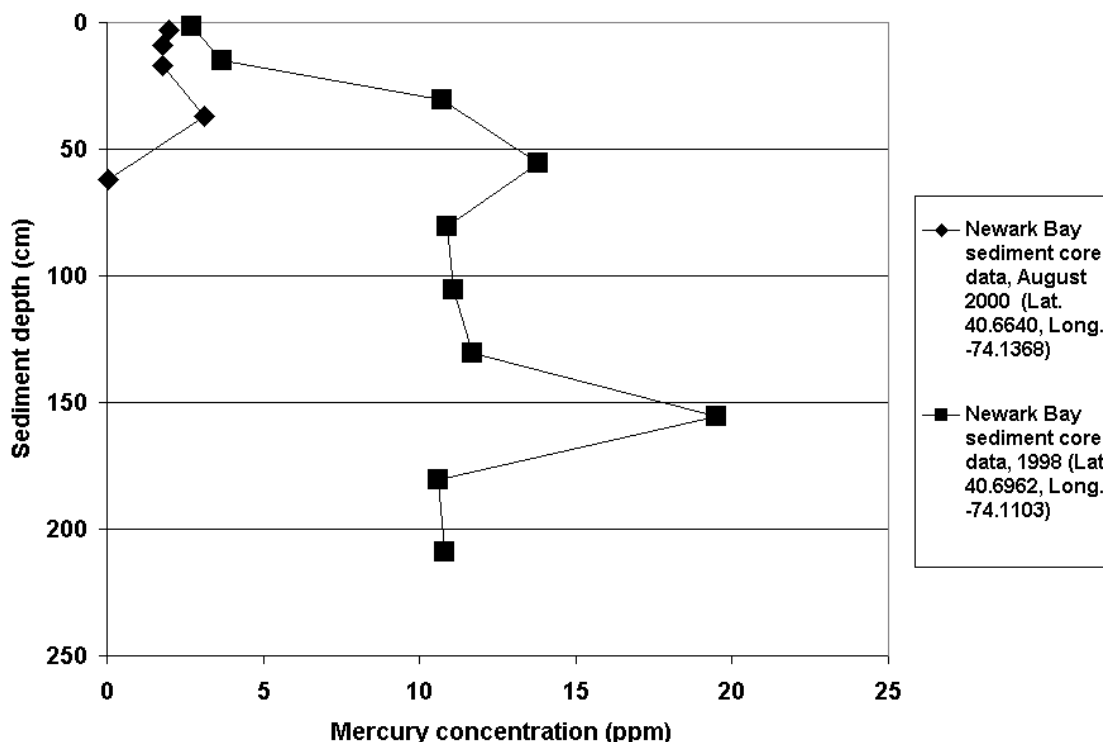


Figure 7. Mercury concentrations in sediment cores obtained in New York Harbor (NYS DEC 2001)

9. USE OF GIS TECHNOLOGY FOR QUANTITATIVE ANALYSIS OF CONTAMINANT LOADS IN NEW YORK HARBOR (with Prof. Y. Gorokhovich)

The technology of Geographic Information Systems (GIS) is a powerful new tool for the analysis of phenomena occurring over a large geographic area. In this part of the study, conducted with the assistance of Prof. Yuri Gorokhovich of Purchase University, a database was compiled of 469 unique values of mercury concentrations in Harbor sediments. These data were obtained by various investigators over a period of 12 years (1988 – 2000), at different locations in the Harbor. Figure 9 is representative and shows the distribution of surficial sediment samples obtained by various studies in 1994. High mercury concentrations persist in the sediments of Newark Bay and in Arthur Kill. This is a work-in-progress and its results will be presented at a later time.

To carry out this work, it was necessary to designate specific boundaries to the NY/NJ Harbor study area, which reflected the hydrogeography and source characteristics. The study will use those boundaries that were developed by the EPA *Sediment Quality of the NY/NJ Harbor System* report (Table 15).

Table 15. Sub-regions of the New York Harbor (EPA 1998)

Region	Sub-regions	Area (km ²)	% of study area
Lower Harbor	Raritan Bay, Sandy Hook Bay	318	11.1
Upper Harbor	Hudson River, East River, Harlem River	104	3.7
Jamaica Bay	-	47	1.7
Newark Bay	Arthur Kill, Kill van Kull, Hackensack River, Passaic River	32	1.1
W. LI Sound	-	476	16.6
Bight Apex	-	1883	65.8
<i>Total</i>		<i>2861</i>	<i>100.0</i>

In 1991, sampling and analysis of sediments in the Lower Harbor and Newark Bay regions and the East River sub-regions demonstrated surface sediment mercury concentrations greater than 2 ppm (NOAA 1998). In 1992, this trend prevailed with concentrations greater than 2 ppm in the Newark Bay region and East River sub-region (NYC DEP 1993). However, regional characterizations based on limited sampling data may be subject to high levels of uncertainty.

A study conducted by a government agency in 1998-2000 determined the vertical concentration profiles of mercury in sediments. The vertical concentration

profiles obtained from sediment cores sampled in 2000 in Newark Bay and Arthur Kill are of more recent sediments than those distributions for 1998. Both the Newark Bay and Arthur Kill distributions for 1998 have several historical peaks, which most likely reflect high points of mercury usage in industrial activities in the NY/NJ Harbor area.

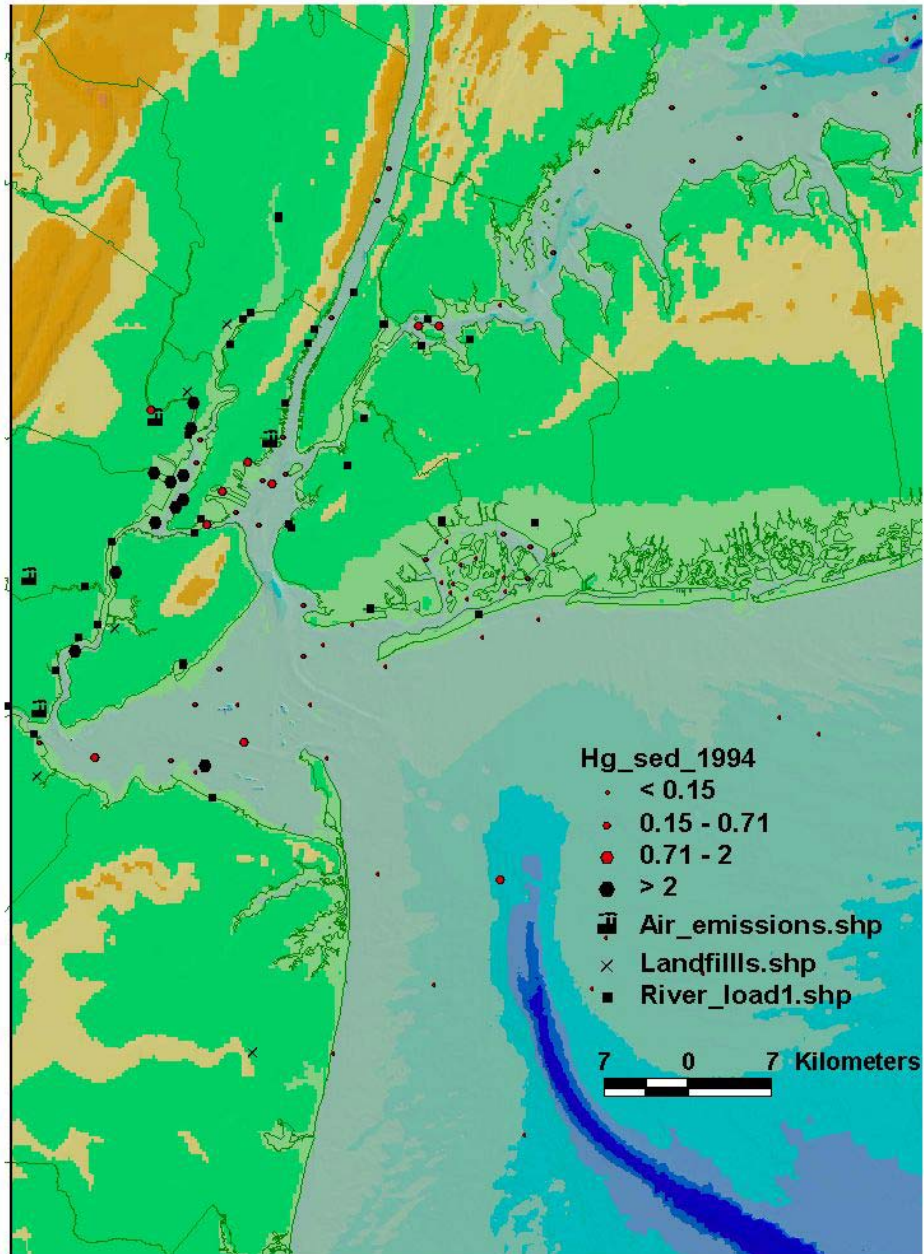


Figure 9. GIS map of 1994 mercury concentrations (in ppm) in New York Harbor sediments
Representative chart (size and color of dots represents range of mercury concentrations; user can obtain interactively information re date of sample, depth, coordinates, source of data, etc.)

10. Conclusions and recommendations

It is evident from this study that the amount of mercury entering the New York-New Jersey Harbor at this time is of the order of one ton per year. This input is ten times lower than the 1989 Hydroqual (1991) estimate and fifty times lower than the 1980 estimate by Rod, Ayres and Small (1989). The decrease in mercury emissions are reflected in the concentration of mercury in the sediments deposited each year in the Harbor; they have decreased from over 10 ppm in the past to an estimated 0.7 ppm or lower in recent years. The latter value is approaching the pre-industrial level of mercury in sediments (0.1-0.2 ppm) but, according to some marine biologists, is still high enough to present an ecological threat to some organisms. It is therefore necessary to curtail mercury emissions further. The recommended measures are:

a) Removal of mercury switches from discarded automobiles

Nearly one half of the HRB stack emissions (644 kg/year) are from iron and steel plants that smelt automobile scrap. These emissions can be reduced by providing incentives to firms and individuals who collect used and abandoned cars, for the value of their spare parts and contained metals, to remove and recycle mercury switches. These switches can be removed only before the automobile body is compacted or shredded. Assuming an average of 1 gram of mercury per switch, the 644 kilograms of HRB emissions correspond to 644,000 switches. At an assumed switch removal rate of 10 switches per hour and an hourly labor rate of \$10/h (i.e., \$1/switch), the cost of such an operation would amount to \$644,000. Including additional costs of collecting the switches and transporting them to an existing mercury recycler may not exceed the total of \$2 million, i.e. \$3,200 per kilogram of mercury collected. This will be a much less costly route than requesting several iron and steel smelting plants to incorporate activated carbon injection in their gas control systems. Apparently, NYC DEC has initiated a mercury switch collection program (Gregory, 2001) that NYAS should encourage and strengthen.

c) Collection and recycling of fluorescent lamps

This subject is discussed in detail in another report of the Earth Engineering Center (Gregory 2001). In contrast to all other uses of mercury that have been declining rapidly with time, the use of mercury in fluorescent lamps in HRB has increased from 178 kilograms in 1990 to 400 kg (33.6 million lamps) in 1999. This is due to the fact that fluorescent lamps use less than one half the electric energy of filament lamps and have a much longer life. Therefore, they are environmentally preferable. Their mercury content has decreased four-fold in recent years and lamp manufacturers are trying to reduce it further. NYAS should promote ongoing collection systems that will increase the number of spent lamps that are collected and sent to existing recyclers. Because of the low content of mercury per lamp, the cost of collection is much higher than that of mercury switches. Gregory (2001) estimated that it can range from \$0.40 to \$3 per lamp. Since each lamp contains 12 milligrams of mercury, the collection cost may range from \$33,000 to \$250,000 per kilogram of mercury.

d) Activated carbon injection in coal-fired power plants and sludge incinerators

As noted in this report, the great reduction in mercury emissions from HRB Waste-to-Energy plants has been partly due to their incorporating activated carbon injection (ACI) in their gas control systems; ACI is effective both with bag filter and the older electrostatic precipitator systems. As shown in this report, coal-fired utility boilers and some NJ sewage sludge incinerators are contributors to the HRB stack emissions of mercury. The authors have not been able to obtain specific information on the gas control systems of these facilities. However, it is believed that ACI is not being used. In order to determine the implementation costs of ACI, it is necessary to have specific information for a particular installation.

e) Diverting mercury-containing products from landfills and WTE plants

As discussed in Section 4.3, the Warren County (NJ) Waste-to-Energy plant has by far the lowest mercury emissions of all plants examined (Table 8). It has been suggested (NJ DEP (2001) that this is due to the “more aggressive” waste management plant of Warren County that effectively diverts mercury containing products from the WTE plant (and, presumably, from landfills). A detailed study should be made of the Warren County system and the lessons learnt should be conveyed to other communities within the HRB.

e) Requiring that all combustion process plants dispose their flue dusts in monofills

As noted in this report, it is essential that mercury containing products are not disposed in regular landfills that also contain organic matter like food and plant wastes. The reason is that under these conditions methyl mercury can be formed and contaminate, now or in the distant future, the adjacent waters. Therefore, it should be required of all combustion plants (power plants, WTE, SSI) that they dispose their flue dusts, which contain the mercury compounds, in specially designed monofills that are used only for that purpose, and not in municipal landfills. Some WTE plants, such as the SEMASS plant discussed in

this report (Themelis et al 2000), are already doing so. All other combustion process plants should be required to do the same.

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