NATIONAL STATUS AND TRENDS, MUSSEL WATCH PROGRAM

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

December 2022

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NOAA NCCOS Monitoring and Assessment Branch

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ABSTRACT

In 1991-92, a survey of chemical contamination and toxicity of sediments performed by the National Oceanic and Atmospheric Administration's (NOAA) National Status and Trends (NS&T) Program found elevated concentrations of organic and metal contaminants throughout the Hudson-Raritan Estuary (HRE). In 2018, a subset of the sediment stations previously sampled in 1991 were re-surveyed by the national Mussel Watch Program to assess changes in the sediment contamination levels in the HRE after more than two decades of cleanups and restorations. Additionally, two new sites (stations 37 and 38) were added to extend the geographical extent of the study area into the Atlantic Ocean. A total of 18 sediment samples were collected and analyzed in 2018 for a suite of over 280 legacy inorganic (e.g. metals) and organic (e.g. hydrocarbons and pesticides) contaminants. The results indicated that contaminant concentrations varied broadly in the study area. With some exceptions, the metals and organic contaminants analyzed in 2018 generally showed lower concentrations compared to 1991. Typically, contaminant concentrations were highest at the mouth of the Raritan River and decreased offshore (stations 23, 24, 25, 26). As PAHs are typically from combustion, oil and gasoline sources, it is not remarkable to have higher values at the mouth of Raritan River draining this highly populated and industrial region.

In 2018, antimony was below detection level at all stations, unlike the 1991 survey which had concentrations ranging from 0.5 to 3.6 ppm. Also, dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyl (PCB), arsenic, cadmium, and silver showed significant basin wide differences in 2018. In 1991, manganese concentrations were high at the mid-bay station 34 and cadmium concentrations were high at the mid-bay station 35 and in Sandy Hook Bay (station 29). Anomalously high concentrations (2.2×10^4 ppb) of polycyclic aromatic hydrocarbons (PAH) were measured in 1991 off shore of Great Kills Harbor, Staten Island (station 26) and (1.8×10^4 ppb) at the mouth of the Raritan River (station 23). Even with the overall reductions in concentrations, some contaminants remain at toxic levels in sediments in the Hudson-Raritan Bay in 2018, including. DDT, PAHs, PCBs, and mercury concentrations (Appendices B1, B2).

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

As one of the largest (108.1 mi² or 280 km²) and heavily urbanized estuaries in the world (O'Connor, 2016), Hudson-Raritan Estuary (HRE) is located along the east coast of the United States between the states of New York and New Jersey (Figure 1).
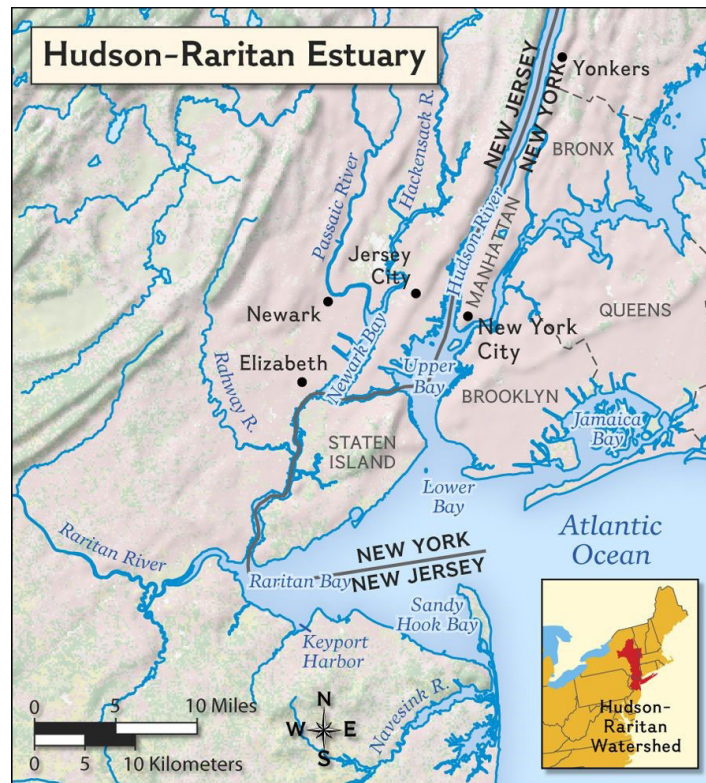

Figure 1. Hudson-Raritan Bays, watershed, and estuary. (National Geographic, 2020).

The estuary receives waters from four major rivers including the Hudson, Hackensack, Passaic, and Rahway, and its watershed drains the major industrialized regions of northern New Jersey and the high-density population area of New York City (Figure 1). Hence, HRE is a mixing zone that includes waters of the extreme western Long Island Sound, the East River, the lower Hudson River, upper and lower New York Harbors, Kill van Kull, Arthur Kill, the lower Passaic River, the lower Hackensack River, Newark Bay, the lower Raritan River, Raritan Bay, Sandy Hook Bay and the waters of the outer harbor east to the Sandy Hook peninsula (Figure 1).

Transformation of the HRE began nearly five centuries ago with European settlement. It has been estimated that over 85 percent of the coastal wetlands and 99 percent of the freshwater wetlands have been lost (US ACE, 2020; Pearce, 1987). The watersheds were deforested, followed by agricultural and later industrial development, and the development of some of the densest urban landscapes in the country that were built along the shores and rivers. By the early 1900s, the HRE had become degraded by human interactions as illustrated by the following, excerpted from a 1987 introduction to proceedings on the Hudson Raritan estuary held by the National Oceanic and Atmospheric Administration (NOAA) (Pearce, 1987 and 1972).

> *"By World War I, estuarine waters of New York Harbor and lower Hudson River were so contaminated that fish could not be held in estuarine water pumped from an area off Battery Park to the New York Aquarium (Townsend, 1917). At about the same time, Nelson (1916) reported that industrial wastes discharged into Raritan Bay resulted in declines in shellfish populations then found in the Bay. He predicted that these contaminants, in particular copper, would cause the collapse of the oyster fishery; this occurred within a few decades. In the early 1920's, shellfish biologists noted that the abundance and diversity of the molluscan fauna had declined. This was attributed to increased urbanization and contamination by gasoline and other wastes."*

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Pearce's assessments were later confirmed. Breteler (1984) reported that concentrations of toxic metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides, were at levels that potentially posed ecological and/or human health risks in the HRE. Using existing 1980s data, Squibb et al. (1991) showed that trace metals, pesticides, industrial solvents, PCBs, and aromatic hydrocarbons in water, fish tissues, and sediments from the HRE equaled or exceeded several different standards for the protection of marine life, wildlife, and human health. More recent data collected by numerous investigators including the NOAA's National Status and Trends Program (NS&T), have corroborated previous investigations in the HRE. Sediments, mussels, and fish livers from the Hudson-Raritan Estuary analyzed by the NS&T Program consistently have contained some of the nation's highest concentrations of DDT, other pesticides, PCBs, PAHs, cadmium, chromium, lead, mercury, nickel, and tin (NOAA, 1987; 1988; 1989; 1991; Long and Morgan, 1991).

Recognizing the ecological and commercial importance of the HRE, the US Congress and the States of NY and NJ embarked on a comprehensive restoration effort to clean up the estuary (US ACE, 2016). A major factor in restoring the Hudson-Raritan estuary was passing the Clean Water Act in 1972, which reduces the amount of pollution that can be discharged to U.S. rivers. Planning for the remediation of the HRE was initiated in 1988 following its recognition by the US Congress as an estuary of national importance. The HRE was inducted into the National Estuary Program (NEP), through the creation of the NJ-NY Harbor & Estuary Program (HEP) to develop restoration and conservation implementation plans. Site-specific clean up and restoration efforts through regulation enforcement and best management practices have resulted in reduced concentrations of contamination in the estuary. While concentrations of many toxic contaminants like PCBs in key fish species have been declining, other contaminants still remain persistent and pose a risk to marine species and for human consumption (US ACE, 2020, Long, 1995). In 2009 a comprehensive restoration plan was developed to guide ecosystem restoration efforts within the entire HRE (US-ACE, 2016). However, chemical contamination is still an issue, particularly elevated toxic metals such as mercury, which cause much of the harbor closure to commercial and recreational fishing (US ACE, 2020).

In response to a data request by the New York-New Jersey Harbor & Estuary Program, the NOAA National Status and Trends (NS&T) Program conducted a surficial sediment contamination survey in 2018 by revisiting sites that were sampled as part of a 1991 study (Table 1) by NS&T (Long, 1995). While the 2018 study provides current data on the magnitude and distribution of organic and inorganic contaminants in the HRE sediment, it also provides a means to assess effectiveness of cleanup efforts in the estuary by comparing the current results to the 1991 data.

Table 1. Station locations and sampling status in 1991 and 2018.

Station	Latitude	Longitude	Year 1991	Year 2018
St-23	40.4875	-74.259	x	x
St-24	40.4897	-74.224	x	x
St-25	40.4882	-74.175	x	x
St-26	40.5008	-74.151	x	x
St-29	40.4564	-74.033	x	x
St-30	40.4261	-74.013	x	x
St-33	40.4675	-74.100	x	x
St-34	40.5097	-74.101	x	x
St-35	40.4944	-74.044	x	x
St-36	40.5597	-74.052	x	x
St-37	40.5014	-73.975		x
St-38	40.4686	-73.933		x

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Introduction

Did you know...

The Hudson Raritan estuary is named after the English explorer Henry Hudson. In the early Fall of 1609, as part of his search for the Northwest Passage to Asia, Henry Hudson sailed the Half Moon, an 85-foot sailing ship, up the river that is now named after him. The second part of the estuaries' name, Raritan, is from the Algonquin language of the indigenous people, a branch of the Lenape tribe who lived in the vicinity of the bay for thousands of years prior to the arrival of Dutch colonists in the 17th century.
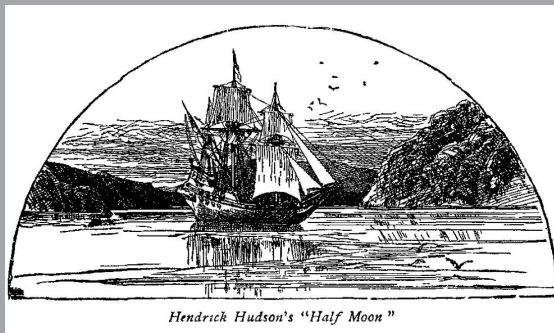
Hendrick Hudson's "Half Moon"

Half Moon, by Wallace Bruce 1907 (Bruce, 2006).

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2.0 METHODS

2.1 Study Area Description

A synoptic view of the NY-NJ region (Figure 2) shows the complexity of the rivers, industrial and high-density population areas.

The estuary is an indirect result of glaciology and sediment deposition. The effects of the last glacial cycle, the Wisconsin Glaciation, is most evident on the landscape. Estimates vary, but near the end of this cycle, between 18,000 and 14,000 years ago, sea level was possibly 100 to 150 meters lower than its current depth. The great Wisconsin continental glacier had advanced southward to its maximum extent, with its terminal moraine accumulating across the crest of what is now Long Island. These moraines coalesce across the crest of Staten Island, and continue westward into New Jersey following a path north of the Raritan River toward New Brunswick, and westward on to Pennsylvania (Stoffer and Messina, 1996). The mouth of the Hudson River and the northeast portion of the Hudson-Raritan estuary are shown in Figure 3. There have not been reports that the geology has contributed to the high concentrations of minerals, an important factor in assessing concentrations of potential chemical contaminants. Two prominent channels exist in the shallow estuary (Figure 4) which results from the outflow of the Raritan/Arthur Kill Rivers, the Hudson River, and ship channel dredging.

Figure 2. NASA image from International Space Station of Hudson-Raritan Bay and surrounding areas (NASA 2012) showing the complex watershed drainage network throughout urban and industrial regions.

Figure 3. HRE as seen from Hudson River looking south-east. Foreground is Verrazano Narrows Bridge, Lower Hudson Bay, further east on the left is Coney Island and the tip of Sandy Hook, NJ (top right) portion of Hudson-Raritan Estuary and out to the Atlantic Ocean (Stoffer and Messina, 1996).

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Generally, the water depth is 10 meters in the two channels and 5 meters until the outer shelf is reached (Figure 4). The bottom type in the bay has been described as mostly sand, with gravel overlaid with silt (Fish and Wildlife Service, 1979).
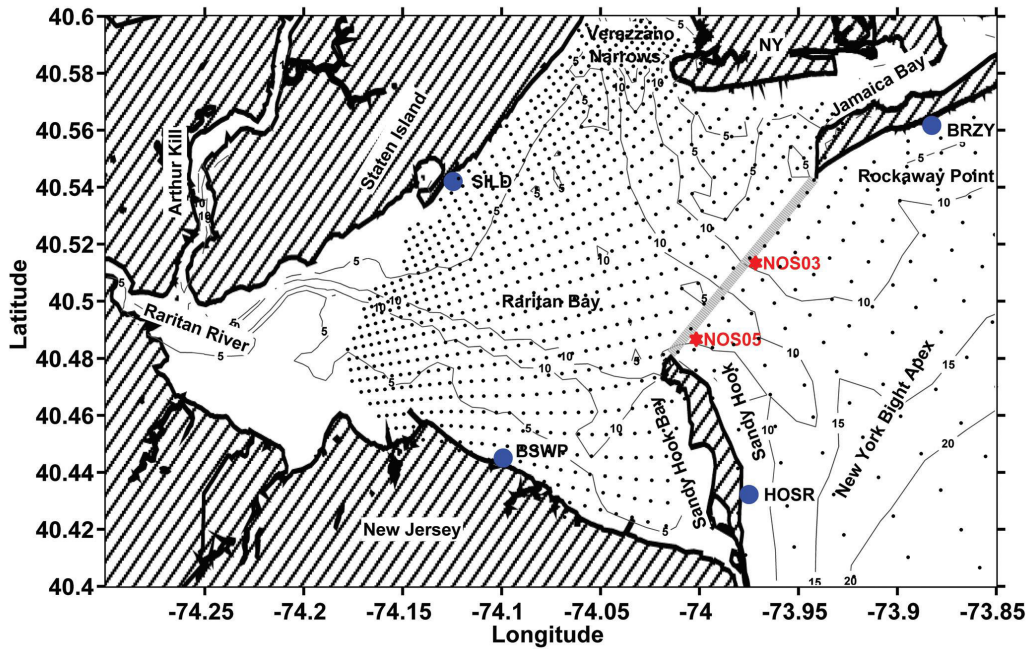

Figure 4. Bathymetry of the Raritan and Lower Hudson Bays (Gopalakrishnan, 2011).

Currents are dominated by the river flows from Raritan River / Arthur Kill River and Hudson River; however, tides complicate the dynamics of the system. Tides form a counter clockwise gyre, with a vertical range of 1.7 m. Examples of surface currents from high frequency radar determinations (Gopalakrishnan, 2011) are shown in Figure 5.

Examples of slower currents, which may be a contributing factor in particles falling out of the water column, can be found off the Staten Island (SILD) radar site and form a slower speed eddy-like feature off the tip of Sandy Point. Slower currents along with a geographic peninsula "hook" are factors affecting deposition in Sandy Hook Bay. Salinity in the Bay ranges from about 12 ppt at the bottom near the mouth of the Raritan River to about 32 ppt off Sandy Hook point. Water temperatures range from about 0.5oC in late January to 25.6oC in late August. Dissolved oxygen levels vary widely, which can result in anoxic sediments.
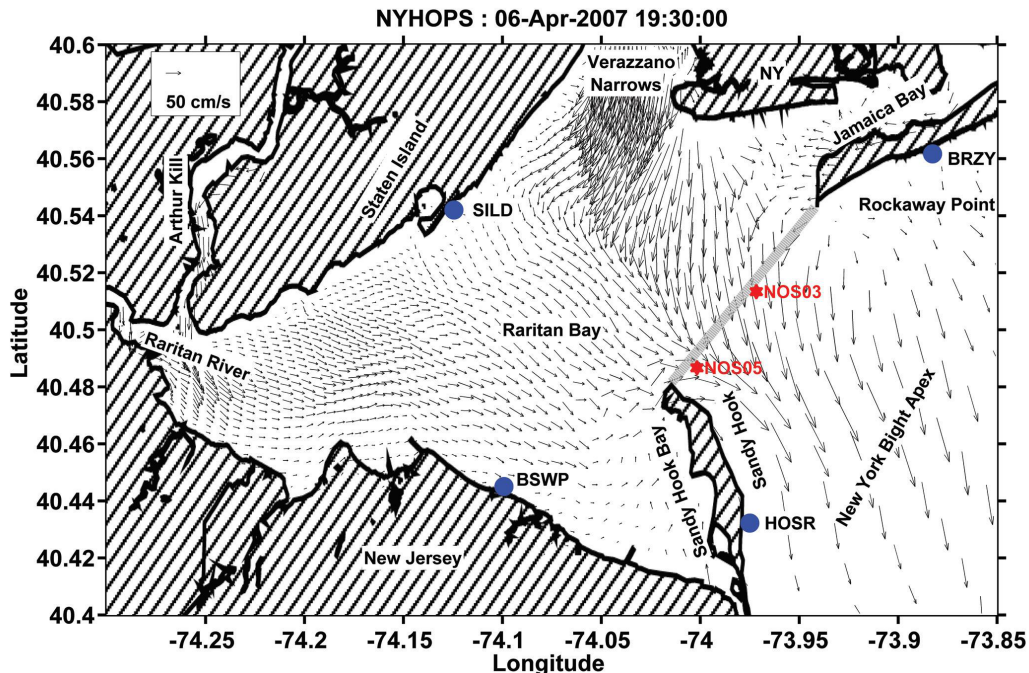
Figure 5. New York Harbor Observation and Prediction System (NYHOPS) example of surface currents, from four high frequency radar determinations located at Bayshore Water Front Park (BSWP), Staten Island (SILD), Sandy Hook (HOSR), and Breezy Point (BRZY). Red stars are locations of NOAA/NOS mooring stations (Gopalakrishnan, 2011).

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2.2 Sediment Collection

In April of 2018, a cruise conducted by the Biogeography Branch of the National Centers for Coastal Ocean Science (NCCOS) to update bathymetry data in the NY Bight, collected sediment samples at the selected sites (Table 1) following standard NOAA Bioeffects protocols (Apeti et al., 2012). Similar sampling procedures were used in the 1991 survey, with the exception that multiple individual samples (replicates) were taken at each site and processed individually in 1991, while samples from sites in 2018 were composited. Sediment samples were collected with a stainless steel 0.04 m2 PONAR grab sampler (Figure 6). At each site, the sampler was cleaned, rinsed with site water, alcohol, and deionized water immediately prior to sampling. The upper 2-3 cm of the sediment was retained in order to assure collection of recently deposited materials. A sediment sample was discarded if the jaws of the grab were open or the sample was partly washed out. Sediments were removed with a stainless-steel scoop. The sediment samples were thoroughly homogenized in the field with an alcohol and distilled water-rinsed stainless-steel mixer attachment on an electric drill. The homogenized samples were divided into different aliquots and placed in pre-cleaned I-chem jars for different analyses (e.g., metals, organic contaminants). The samples were kept on ice during the daily surveys and frozen once on-shore.

Figure 6. Drs. Lowenstein (left) and Apeti (right) retrieving a Ponar sediment grab (Credit: NOAA).

2.3 Chemical Analysis

The chemical analyses on the 2018 sediment samples were performed at the NOAA National Centers for Coastal Ocean Science (NCCOS) chemistry laboratory in Charleston, South Carolina. Chemical analysis of the 1991 samples were conducted at GERG (now TDI Brooks) laboratory in College Station, Texas. The same quality controlled and assured standard analytical protocols developed by the NS&T Program were followed in 1991 and 2018. Both laboratories participate in inter-laboratory comparison studies, to verify that data from the two laboratories are comparable. Quality control samples were processed in a manner identical to field samples. A method blank was run with every 20 samples, or with every sample set, whichever was more frequent. Matrix spike/duplicate samples were run with every 20 samples, or with every sample set. National Institute of Standard and Technology (NIST) reference materials were analyzed with each set of samples. Detailed descriptions of the NS&T protocols, including quality assurance/quality control (QA/QC) used in the analysis of the organic contaminants, can be found in Kimbrough et al. (2006); for inorganic analyses and in Kimbrough and Lauenstein (2006) for organic analyses. Tables 2 - 5 provide the lists of metals and organic contaminants analyzed during the 1991-92 and the 2018 surveys. Contaminants measured in 1991 and 2018 included PAHs, trace elements, PCBs, and chlorinated pesticides including DDT and its breakdown products. The 'trace elements' include a mixture of metals, heavy metals, and metalloids. Here we simply use the term metals, or trace elements, to include all. Ancillary parameters such as total organic carbon (TOC) and grain size (% sand, % silt and % clay) were also measured

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in both years. TOC was determined using incineration methods, and grain size determination utilized a combination of sifting and pipetting techniques (McDonald, 2006). Grain size and TOC measurements were reported as percentages of the total sample weight.

2.4 Data Analysis

Laboratory results were subjected to regular NS&T performance-based quality assessment and quality control for data accuracy and precision. The NS&T data reporting limits are based on analytical method detection limits (MDL), which are determined as specified by EPA (2007) Federal Regulations 40 CFR Part 136. The 99% confidence level MDL is determined based on analysis of a minimum of 7 replicate matrix spikes fortified at 1-10 times the estimated detection limit. For each analyte, the MDL value is derived by multiplying the Student's t for 99% confidence level by the standard deviation of the seven replicate measurements of the same low-level spiked samples. The analytical results that are below MDL values are defined as undetected with value of zero concentration, and only results that are at or above the MDL are reported as detected with the corresponding concentration value.

For this study, organic contaminants such as DDTs PAHs, and PCBs, congeners and homologous organic compounds were grouped by classes of contaminants and the "totals" of each group were derived as the arithmetic sum of all the individual compounds. The contaminant concentration results of the years 1991 and 2018 are presented in Appendices A-1 to A-4. However, because fewer chemicals were measured in 1991 than in 2018, the report discuses only those chemicals that were analyzed in both years in comparative data assessment approach. Selected contaminants included 13 elements (Table 2), 13 pesticides (Table 3), 23 PCBs (Table 4), and 24 PAHs (Table 5) contaminants being compared. Sediment physical properties including organic matter content and percent mud (clay and silt) composition influence contaminant accumulation. In order to evaluate sediment physical characteristics on the magnitude and distribution of elemental concentrations, percent clay, silt, and sand were measured. For each contaminant at each station, we normalized the elemental concentrations by the percent fine sediment (sum of the percent clay and silt fractions) to account for the increased binding capability to the clay and silt sediments.

To evaluate basin wide sediment chemical contaminants, and to compare the two survey years, for each chemical contaminant, we performed Wilcoxon statistical analysis with Chi-Square approximation using all the stations (see Appendix C).

Contaminant concentrations in sediment were further evaluated against NOAA's numerical Sediment Quality Guidelines (SQG) developed by Long and Morgan (1991) and Long, (1995). These guidelines are known as the ERL (effects range-low) and ERM (effects range-median), which express statistically derived levels of chemical contamination in surficial sediments below which effects were rarely (<10 %) expected (ERL) and above which toxic effects would be expected to be observed with at least a 50% frequency (ERM) to benthic organisms. Long et al. (1995) established the protocols and database using the amphipod Ampelisca abdita. The guideline illustrated in Appendices B1-2, includes values for some individual organic compounds, as well as Total DDTs, Total PCBs, Total PAHs, and Total Chlordanes.

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Methods

Table 2. Elements analyzed in 1991 and 2018.

1991 & 2018		2018 Only
Silver (Ag)	Manganese (Mn)	Barium (Ba)
Aluminum (Al)	Nickel (Ni)	Beryllium (Be)
Arsenic (Ar)	Lead (Pb)	Cobalt (Co)
Cadmium (Cd)	Antimony (Sb)	Lithium (Li)
Chromium (Cr)	Selenium (Se)	Thallium (Tl)
Copper (Cu)	Tin (Sn)	Uranium (U)
Iron (Fe)	Zinc (Zi)	Vanadium (V)
Mercury (Hg)		

Table 3. Pesticides analyzed in 1991 and 2018.

1991 & 2018	2018 Only
2,4'-DDD	Aldrin
2,4'-DDE	Alpha-HCH
2,4'-DDT	Beta-HCH
4,4'-DDD	Chlorpyrifos
4,4'-DDE	Cis-nonachlor
4,4'-DDT	Dieldrin
Cis-chlordane (alpha-chlordane)	Endosulfan I
Gamma-HCH (g-BHC, lindane)	Endosulfan II
Heptachlor	Endosulfan sulfate
Heptachlor epoxide	Endrin
Hexachlorobenzene	Gamma-chlordane
Mirex	Oxychlordane
Trans-nonachlor	

Table 4. PCBs analyzed in 1991 and 2018.

1991 & 2018	2018 Only	
PCB 5	PCB 1	PCB 110
PCB 8	PCB 2	PCB 114
PCB 18	PCB 3	PCB 115
PCB 28	PCB 9	PCB 119
PCB 44	PCB 12	PCB 130
PCB 52	PCB 15	PCB 141
PCB 66	PCB 20	PCB 146
PCB 77	PCB 26	PCB 149
PCB 101/90	PCB 29	PCB 151
PCB 105	PCB 31	PCB 154
PCB 118	PCB 37	PCB 156
PCB 126	PCB 45	PCB 157
PCB 128	PCB 47	PCB 158
PCB 132/153/168	PCB 48	PCB 159
PCB 138	PCB 49	PCB 163
PCB 170	PCB 50	PCB 164
PCB 180	PCB 56	PCB 165
PCB 187	PCB 60	PCB 167
PCB 190	PCB 61	PCB 169
PCB 195	PCB 63/76	PCB 172
PCB 206	PCB 69	PCB 174
PCB 208	PCB 70	PCB 177
PCB 209	PCB 74	PCB 183
	PCB 81	PCB 184
	PCB 82	PCB 188
	PCB 87	PCB 189
	PCB 88/95	PCB 193
	PCB 92/84/89	PCB 194
	PCB 99	PCB 198
	PCB 103	PCB 200/IUPAC 201
	PCB 104	PCB 201/IUPAC 199
	PCB 106	PCB 202
	PCB 107/123	PCB 203/196
	PCB 108	PCB 207

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Table 5. PAHs analyzed in 1991 and 2018.

1991 & 2018	2018 Only	
1,6,7 Trimethylnaphthalene	1,2-Dimethylnaphthalene	C2-Benzothiophenes
1-Mehtylnaphthalene	1,3+1,6-Dimethylnaphthalene	C2-Chrysenes/Benzanthracenes
1-Methylphenanthrene	1,4,6- and 2,3,6- Trimethylnaphthalene	C2-Decalins
2,6+2,7-Dimethylnaphthalene	1,4-Dimethylnaphthalene	C2-Dibenzothiophenes
2-Methylnaphthalene	1,5-Dimethylnaphthalene	C2-Fluoranthenes/Pyrenes
Acenaphthene	1,8-Dimethylnaphthalene	C2-Fluorenes
Acenaphthylene	11H-Benzo(a)fluorene	C2-Naphthalenes
Anthracene	11H-Benzo(b)fluorene	C2-Naphthobenzothiophenes
Benzo(a)anthracene	1-Methylanthracene	C2-Phenanthrenes/Anthracenes
Benzo(a)pyrene	1-Methyldibenzothiophene	C3-Benzothiophenes
Benzo(b)fluoranthene	1-Methylfluorene	C3-Chrysenes/Benzanthracenes
Benzo(e)pyrene	2-Methylanthracene	C3-Decalins
Benzo(g,h,i)perylene	2-Methyldibenzothiophene	C3-Dibenzothiophenes
Benzo(k)fluoranthene	2-Methylphenanthrene	C3-Fluoranthenes/Pyrenes
Biphenyl	3-Methylcholanthrene	C3-Fluorenes
Chrysene+Triphenylene	3-Methylphenanthrene	C3-Naphthalenes
Dibenz(a,h)anthracene	4-Methyldibenzothiophene	C3-Naphthobenzothiophenes
Fluorene	9,10-Dimethylanthracene	C3-Phenanthrenes/Anthracenes
Indeno(1,2,3-cd)pyrene	9-Methylanthracene	C4-Benzothiophenes
Naphthalene	9-Methylphenanthrene	C4-Chrysenes/Benzanthracenes
Perylene	Benzo[a]fluoranthene	C4-Decalins
Phenanthrene	Benzo[b]naphtho[2,1-d]thiophene	C4-Dibenzothiophenes
Pyrene	Benzo[j]fluoranthene	C4-Fluoranthenes/Pyrenes
	Benzothiophene	C4-Naphthalenes
	C1-Benzothiophenes	C4-Naphthobenzothiophenes
	C1-Chrysenes/Benzanthracenes	C4-Phenanthrenes/Anthracenes
	C1-Decalins	Carbazole
	C1-Dibenzothiophenes	cis-Decalin
	C1-Fluoranthenes/Pyrenes	Dibenzofuran
	C1-Fluorenes	Dibenzothiophene
	C1-Naphthalenes	Retene
	C1-Naphthobenzothiophenes	trans-Decalin
	C1-Phenanthrenes/Anthracenes	

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3.0 RESULTS - GRAIN SIZE

A random, stratified selection of sample sites for 1991 was based partially upon general benthic features (Figure 7) and were designed to incorporate different types of sediment strata. Stations were divided into six strata, designated with letters H – M. The strata corresponded to the contours found in the associated nautical chart, with the exception of station 26, strata I, which falls closer to central bay than southern stations and thus tends to be more like strata L. Other strata L stations are 34, 35, and 36 representing the central bay.
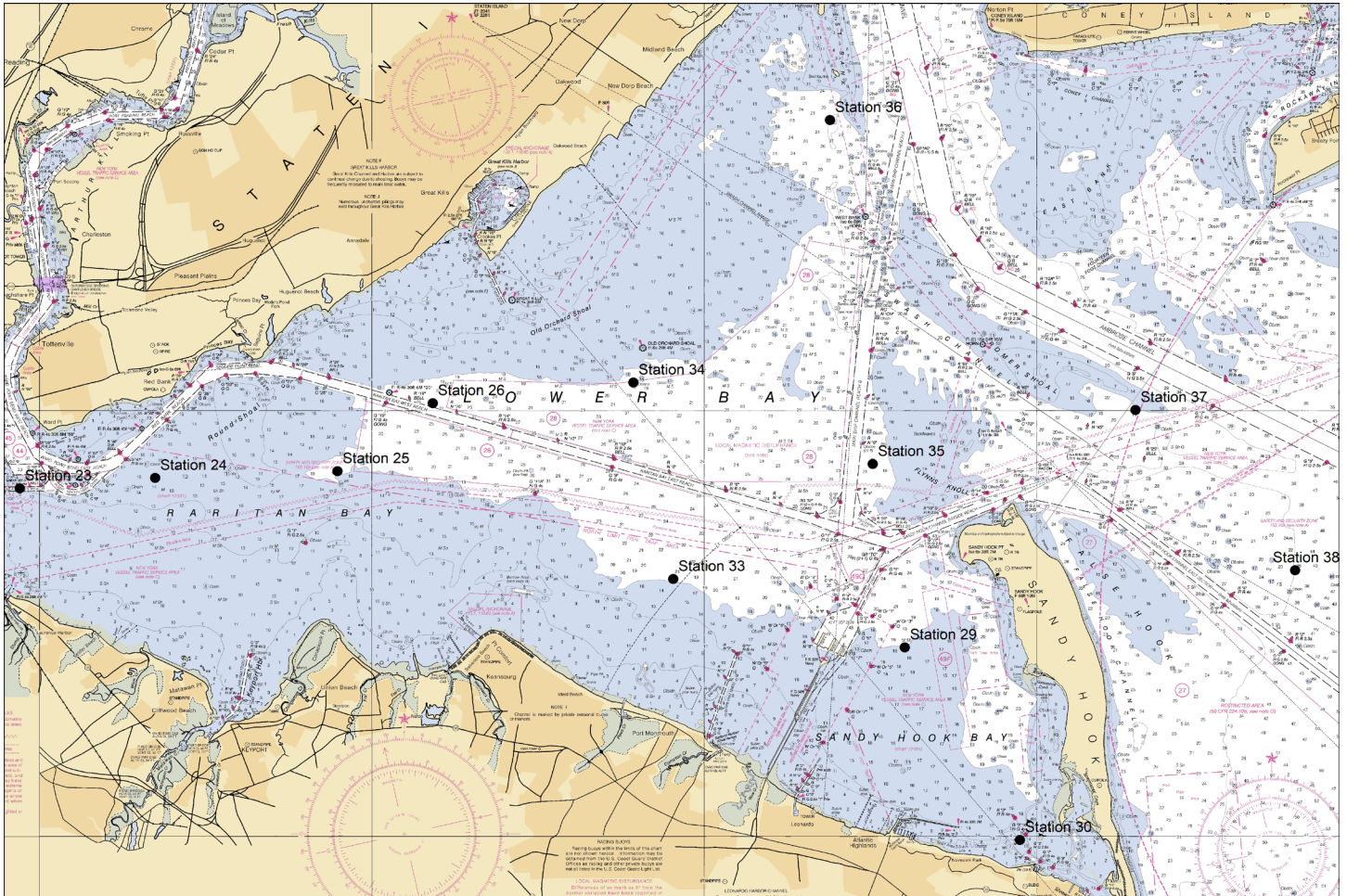

Figure 7. NOAA nautical chart 12327 with soundings and ship channels overlaid with stations containing sediment strata letter codes (NOAA 2020). Station depth (ft): H23 (7'), H24 (12'), I25 (14'), I26 (22'), J29 (17'), J30 (17'), K33 (12'), L34 (21'), L35 (21'), L36 (22'), M37 (24'), M38 (25').

The offshore stations, 37 and 38 contained very low percentage of fine sediments. A map of sediment types (Figure 8) from USGS (2005) reflects the general distribution of sediment types, overlaid with the 1991 and 2018 percent fine sediments. The 2005 sediment classification (Figure 8) shows a large region of sand and gravel to the north of station 37 and 38, which may be contributing factors to the low percent of fine sediments (Figure 9).

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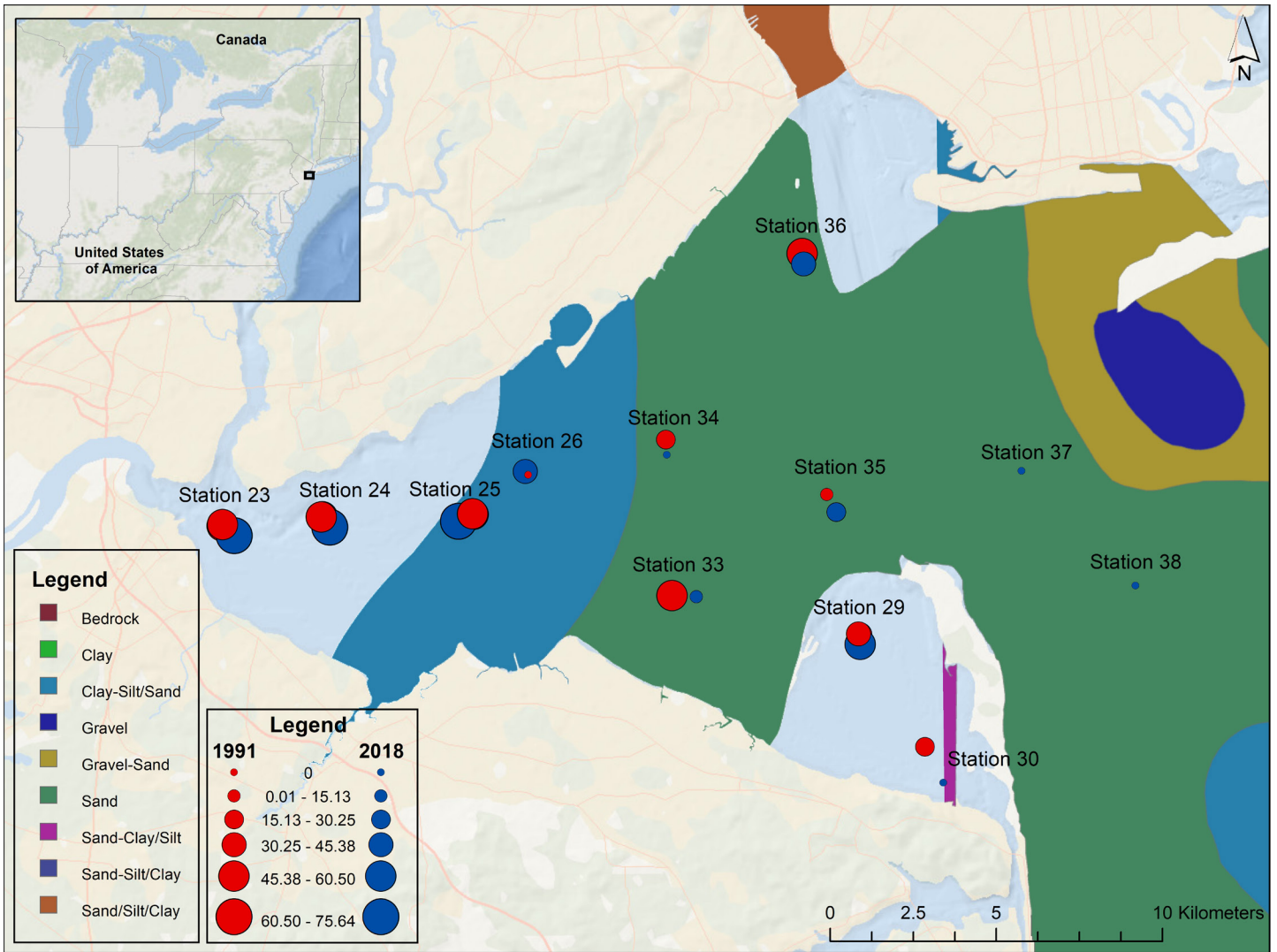
Figure 8. U.S. Geological Survey 2005 sediment classification with overlay of percent fine sediments in 1991 and 2018. 1991 data is displayed in red and 2018 data is displayed in blue.
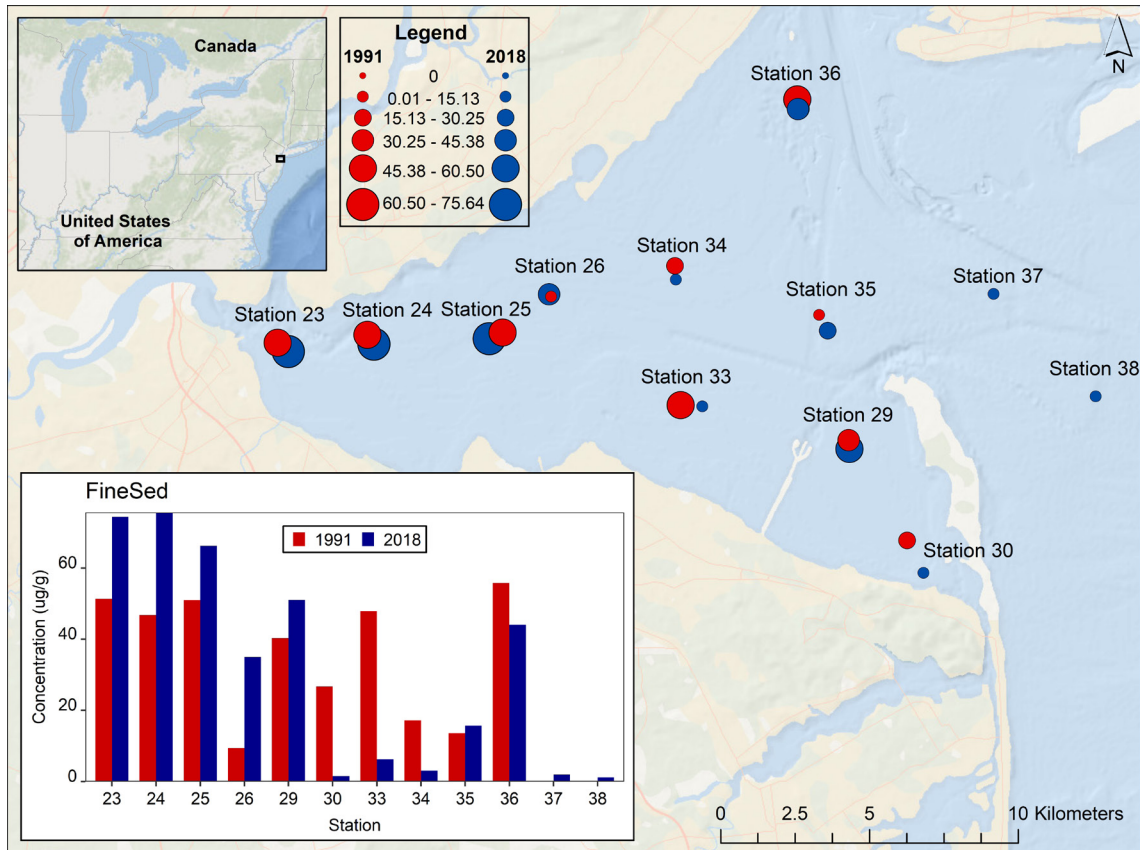
The currents and shallow water bathymetry are influential sedimentation factors for the mid-bay and southern stations. Eddies and other dynamics of the shallow estuary may have contributed to the hard bottom type with the deposition of sandy particles. Surface currents, (Figure 5) show regions of the bay near stations 26, 29, 30, and 35 forming eddies as well as slower currents. Longshore currents, adjacent to Staten Island, flow northeast from Raritan River and southwest from Hudson River and meet approximately in the middle of Staten Island and form a weak eastward current (Figure 5, label SILD), which progresses across mid-bay, to stations 26, 34, 35. Thus it appears that Station 35 is approximately where a gyre-like feature occurs (Figure 5) from the two primary rivers discharges into the basin, with each generally flowing along the two channels. Overall, the bay is shallow, with two primary deeper canyons and ship channels.

Considering the weather events occurring during the 27 years between surveys it is not surprising that there are differences between % fine sediments between the two timeframes. Overall, there is greater % fine sediment at the mouth of the Raritan River in 2018 compared to 1991; however, there is also less % fine sediment extending out to the Sandy Hook peninsula in 2018 compared to 1991. This implies that even though comparatively more % fine sediments are near the mouth of the river in 2018, less is being transported and dispered into the estuary than in 1991 (Figure 9). Additionally, in 2018 1% fine sediments were detected at the two offshore locations (stations 37 and 38), which USGS (2005) (Figure 8) classifies as sand.

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Figure 9. Percent fine sediments in 1991 and in 2018. 1991 data is displayed in red and 2018 data is displayed in blue.

4.0 RESULTS - METAL CONTAMINANTS

All of the major and trace elements occur naturally to some extent in the environment. Aluminum, iron, and silicon are major elements in the Earth's crust. As their name implies, trace elements occur at lower concentrations in crustal material; however, mining and manufacturing processes along with the use and disposal of products containing trace elements can lead to greater concentrations in the environment. A number of trace elements are toxic at low concentrations. An overview description and potential health effects of each trace elements surveyed in this study are provided in the following paragraphs.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.1 Antimony (Sb)

4.1.1 Chemical Overview

Antimony occurs naturally in the earth's crust at levels of about 0.2–0.3 mg/kg (ppm) as a natural constituent of soil. From natural weathering as well as from anthropogenic sources (EPA 1979; Mok and Wai 1990), it can be transported into streams, waterways, and to coastal waters. Studies indicate that Sb is retained in the soil through adsorption and can sorb onto clay minerals, oxides, and hydroxides in the soil and aquatic sediment (Wilson et al. 2010). In some anoxic or poorly oxygenated environments multiple microorganisms have been found to be reduced, methylated and released as methylated Sb compounds into the air and water (Bentley and Chasteen 2002). Antimony is not an essential nutrient and exposure to higher concentrations can affect the respiratory and cardiac systems. The general population is exposed to low levels of antimony in ambient air and food. Individuals can be exposed to antimony in polyethylene terephthalate (PET) water bottles (reviewed in Belzile et al. 2011) or from products containing antimony such as flame retardants. Occupationally exposed workers will have the highest levels of exposure to antimony, for example trioxide exposure is predominant in smelters (Saerens et. al, 2019; McCallum 2005).

4.1.2 Result Highlights

The results for Sb from the two surveys are illustrated in Figure 10 and shown in Appendices A2 and A4.
- Antimony was not detected at any of the survey sites in 2018 as the concentrations were below MDL.
- Substantially greater concentrations of Sb were detected in HRE in 1991, with a maximum concentration of 3.6 µg/g found at site 23 (Figure 10, Appendices B1-2).
- Concentrations of Sb during both 1991 and 2018 surveys were mostly below the sediment toxicity thresholds of ERL and ERM except at the stations 23 and 33 in 1991 (Appendices B1-2).
- Wilcoxon statistical analysis of the overall 1991 and 2018 results indicated that Sb concentrations have significantly decreased basin-wide from 1991 to 2018 (Appendix C).

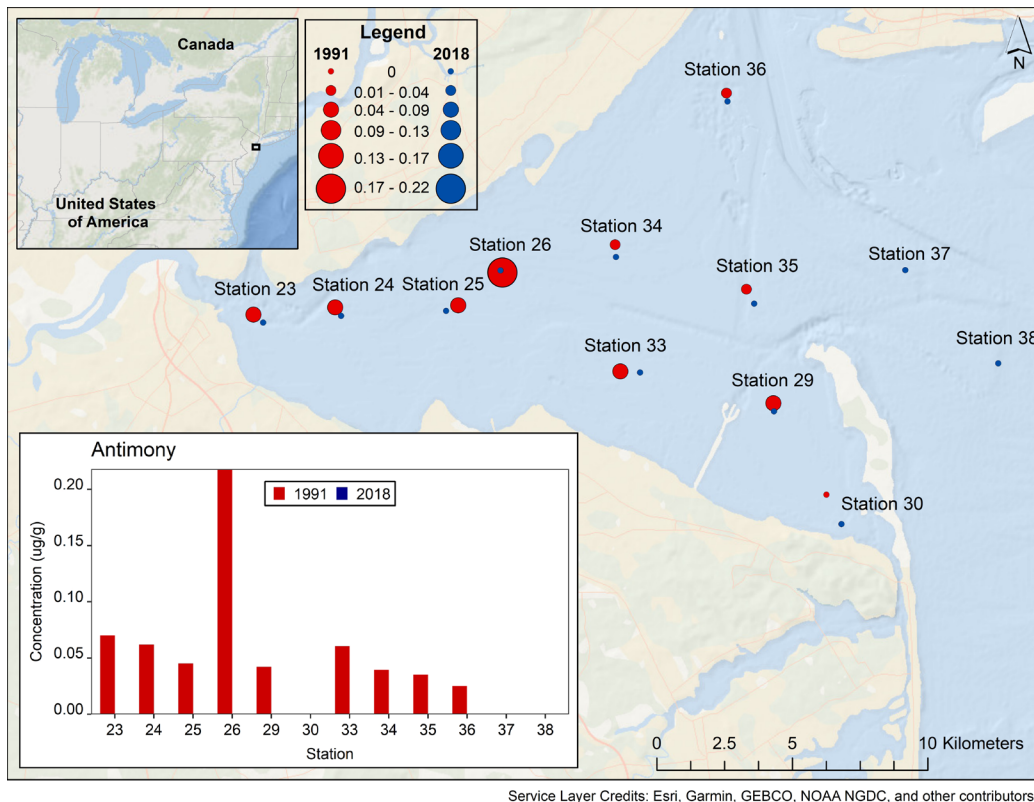*Figure 10. **Antimony**: Map of the study area showing the spatial distribution of Sb in the HRE study area. Sb sediment concentrations normalized by % fine sediments are shown in both the bar graph and the map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.2 Arsenic (As)

4.2.1 Chemical Overview

Arsenic is naturally present in low concentrations in rock, soil, water and air. Thirty percent of atmospheric arsenic comes from volcanoes and other natural sources. Industrial production of wood preservation semiconductors, pesticides, defoliants, pigments, antifouling paints, and veterinary medicines, smelting, fossil fuel combustion, power generation, and pesticide application contribute to environmental As (ATSDR, 2007). Natural enrichment sources are mostly responsible for elevated levels of As in the nation waterbodies, and As in coastal and estuarine waters occurs primarily from river runoff and atmospheric deposition (ATSDR, 2007). Arsenic is an essential trace nutrient for many animals; however dietary requirements for humans is unknown (Uthus, 1992). Arsenic is toxic at high concentrations to animals and plants and prolonged chronic exposure is linked to cancer in animals (Goyer, 1996). Inorganic As, the most toxic form, represents approximately 10% of total As found in the environment. Less harmful organic forms, such as arsenobetaine, are found predominately in seafood (Edmonds and Francesconi, 1987; Taylor et al., 2017). The Mussel Watch Program (MWP) measures total As, including both the inorganic and the organic forms. Safety guidance levels for As in fish and shellfish are no longer listed by the US FDA (US FDA, 2020).

4.2.2 Result Highlights

The results for As from the two surveys are illustrated in Figure 11 and shown in Appendices A2 and A4.
- Concentration of As varied widely across the estuary in 2018 (Figure 11).
- Station 38 in the middle of the estuary had the highest level of As in 2018 when normalized with % fine sediments, (2.9 vs other stations <1.0). Because station 38 was not sampled in 1991, there was no ground for comparison; however, this finding was unexpected.
- Concentrations at several locations are similar between the years (e.g. station 33); however, as illustrated in Figure 11, station 26 had an anomalously high value in 1991.
- Arsenic concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2) indicating the potentiality for low toxic effects on sensitive benthic organisms.
- Wilcoxon statistical analysis of the overall 1991 and 2018 results indicated that As concentrations have significantly decreased basin-wide from 1991 to 2018.
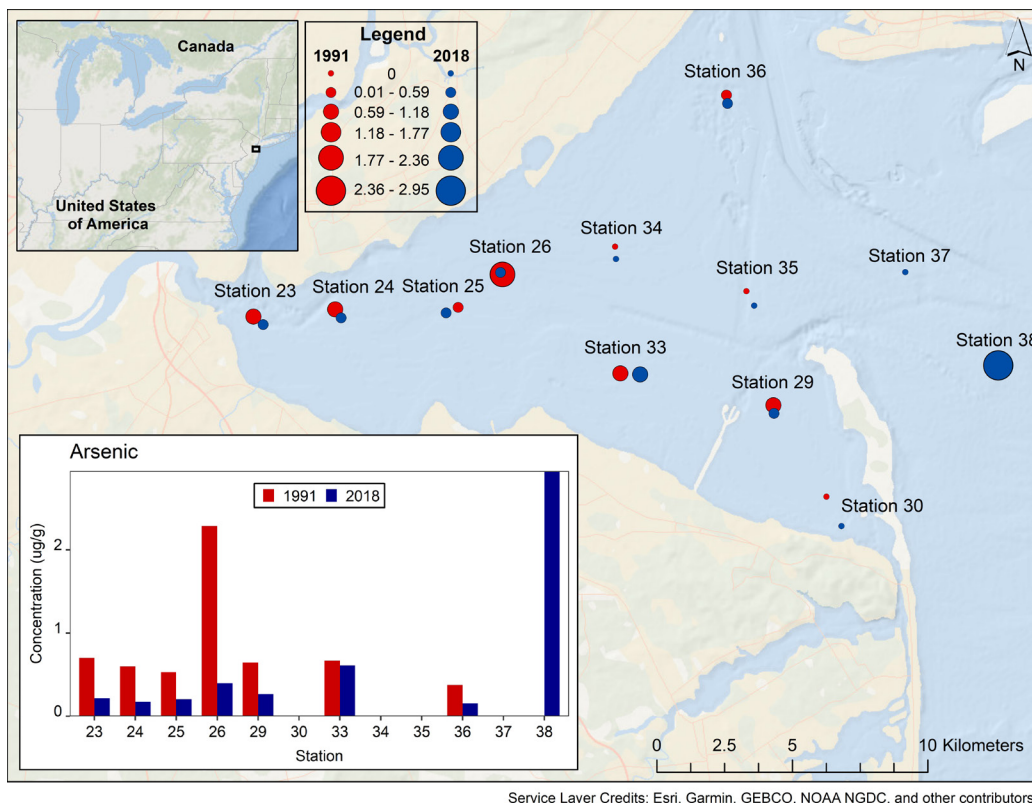

Figure 11. **Arsenic**: Map of the study area showing the spatial distribution of As in the HRE study area. As sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.3 Cadmium (Cd)

4.3.1 Chemical Overview

Cadmium occurs naturally in the Earth's crust and environmental contamination of Cd in coastal and estuarine environments can be linked to both natural and non-point anthropogenic sources (Roesijadi and Klerks, 1989). Natural sources can be linked to river runoff from cadmium rich soils, leaching from bedrock, and upwelling from marine sediment deposits (Sokolova et al., 2012). Industrial sources and uses include byproducts from zinc, lead and copper production, electroplating and galvanizing, smelting, mining, fossil fuel burning, waste slag, and sewage sludge (ATSDR, 1999). In addition to abundant industrial applications, other products that contain Cd include batteries, color pigment, plastics, and phosphate fertilizers. As a result of fossil fuel burning, erosion, and biological activities, Cd becomes airborne and is transported by atmospheric processes. Land-based runoff and ocean upwelling are the main conveyors of Cd into coastal environments. Cadmium is a non-essential and toxic element. Cadmium is toxic to fish, especially salmonid species and juveniles, and chronic exposure can result in reductions in growth. Cadmium, has been shown to impair development and reproduction in several invertebrate species, and osmoregulation in herring larvae (ATDSR, 1999; Eisler, 1985). Safety guidance levels for Cd in fish and shellfish are no longer listed by the US FDA (US FDA, 2020).

4.3.2 Result Highlights

The results for Cd from the two surveys are illustrated in Figure 12 and shown in Appendices A2 and A4.
- Cadmium was detected at various concentration throughout the HRE estuary.
- The highest concentrations of Cd were found at the stations 26 and 35 during both 1991 and 2018 surveys (Figure 12), with station 26 concentration in 1991 being anomalously high.
- Cadmium concentrations were above the sediment toxicity thresholds of ERL at six of the survey stations in 1991 (Appendices B1-2); however, Cd concentrations were below the ERL threshold throughout the HRE in 2018.
- Wilcoxon statistical analysis of the overall 1991 and 2018 results indicated that Cd concentrations have significantly decreased basing-wide from 1991 to 2018.
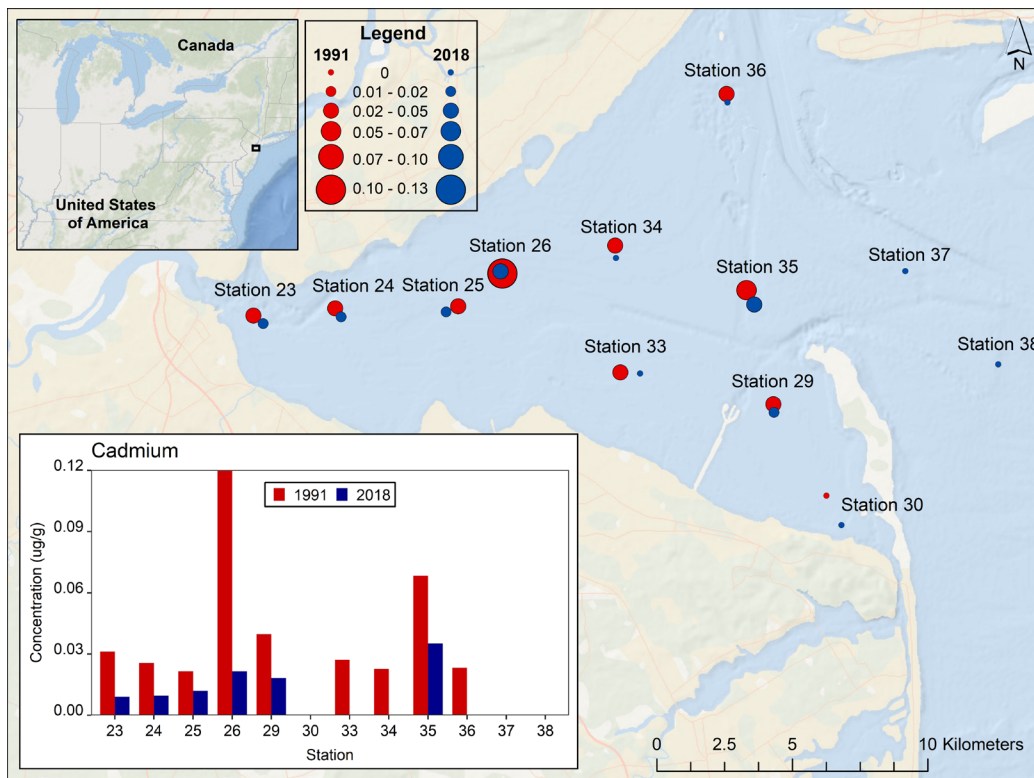
*Figure 12. **Cadmium**: Map of the study area showing the spatial distribution of Cd in the HRE study area. Cd sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.4 Chromium (Cr)

4.4.1 Chemical Overview

Chromium is a hard and corrosion resistant silver-gray metal that is widely used in manufacturing processes to make various metal alloys such as stainless steel and is found in many consumer products. There are three essential oxidation states for chromium Cr(0), Cr(III), and Cr(VI). At trace levels, the trivalent chromium is an essential mineral found in human, animals and plants. The hexavalent chromium; however, is toxic and carcinogenic (ATSDR, 2012). Cr concentration in marine waters is generally 0.3 µg/L, in fresh water 1 to 30 µg/L, in soils 37 mg/kg, in air 5 to 525 ng/m3, and in food 10-1300 µg/kg. In the environment, Cr has been shown to reduce survival and fecundity in the cladoceran Daphnia magna, and reduce growth in the fingerling chinook salmon Oncorhynchus tshawytscha (Eisler, 1986).

4.4.2 Result Highlights

The results for Cr from the two surveys are illustrated in Figure 13 and shown in Appendices A2 and A4.
- The Cr concentration at station 26 in 1991 was anomalously high.
- Anomalously high concentrations were detected at stations 34 and 38 in 2018, while the remainder of the stations in 2018 had concentrations lower than in 1991.
- Cr concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 (Appendices B1-2).
- In 2018 Cr concentrations were still above the sediment toxicity thresholds of ERL at a three survey stations (23, 24 and 25) in 2018 (Appendices B1-2). This indicates that there is potential for low toxic effects on sensitive benthic organisms from Cr in the HRE.
- The Wilcoxon statistical analysis indicated that Cr concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
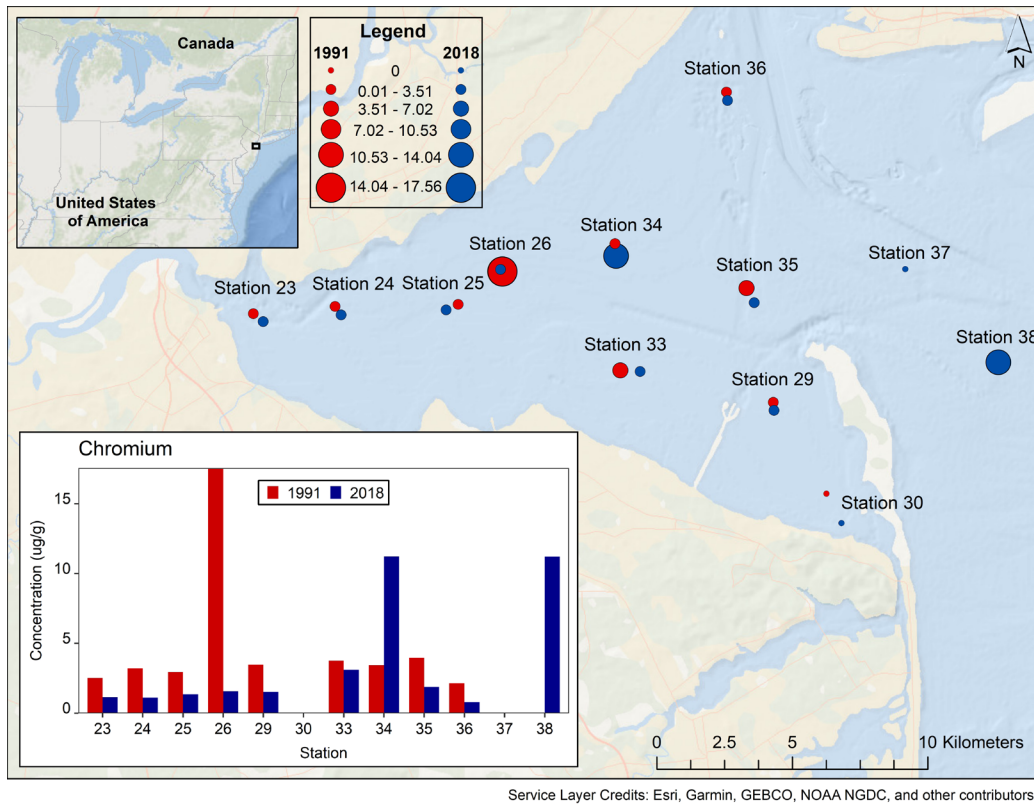

Figure 13. **Chromium**: Map of the study showing the spatial distribution of Cr in the HRE study area. Cr sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.5 Copper (Cu)

4.5.1 Chemical Overview

Copper is a pinkish-orange soft metal that is an essential mineral in trace amounts. Cu has a number of anthropogenic uses such as in antifouling paints for boats, wood preservatives, heat exchangers in power plants, electrical wires, coinage, and agricultural fungicides. Environmental pollution sources include mining, manufacturing, agriculture, sewage sludge, antifouling paint, fungicides, wood preservatives, and vehicle brake pads. The US EPA mandated a phase-out of chromated Cu arsenate (CCA) wood preservatives, but the 1980s restrictions on tributyltin marine antifouling paint has stimulated a return to copper-based wood preservatives and marine antifouling paint. Trace amounts of Cu are an essential micronutrient for plants and animals. High concentrations of Cu can be toxic to aquatic organisms with juvenile fishes and invertebrates much more sensi¬tive than adults. Elevated levels of Cu can impact aquatic organisms including the functioning of gills, reproduction, and development (Eisler, 1998). Although Cu is not highly toxic to humans, chronic effects of Cu occur as a result of prolonged exposure to high doses and can cause eye irritation and damage to the digestive tract (ATSDR, 2004). There is no recommended US FDA safety level for Cu in fish and fish products (US FDA, 2020). The most common form of Cu in water is Cu (II) which is mostly bound to organic matter.

4.5.2 Result Highlights

The results for Cu from the two surveys are illustrated in Figure 14 and shown in Appendices A2 and A4.
- Overall 2018 Cu levels were much lower than 1991 (Figure 14).
- Station 26 had an anomalously high concentration of Cu in 1991. We address station 26 in the discussion section below.
- Cu concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2) indicating the potential for low toxic effects on sensitive benthic organisms.
- The Wilcoxon statistical analysis indicated that Cu concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
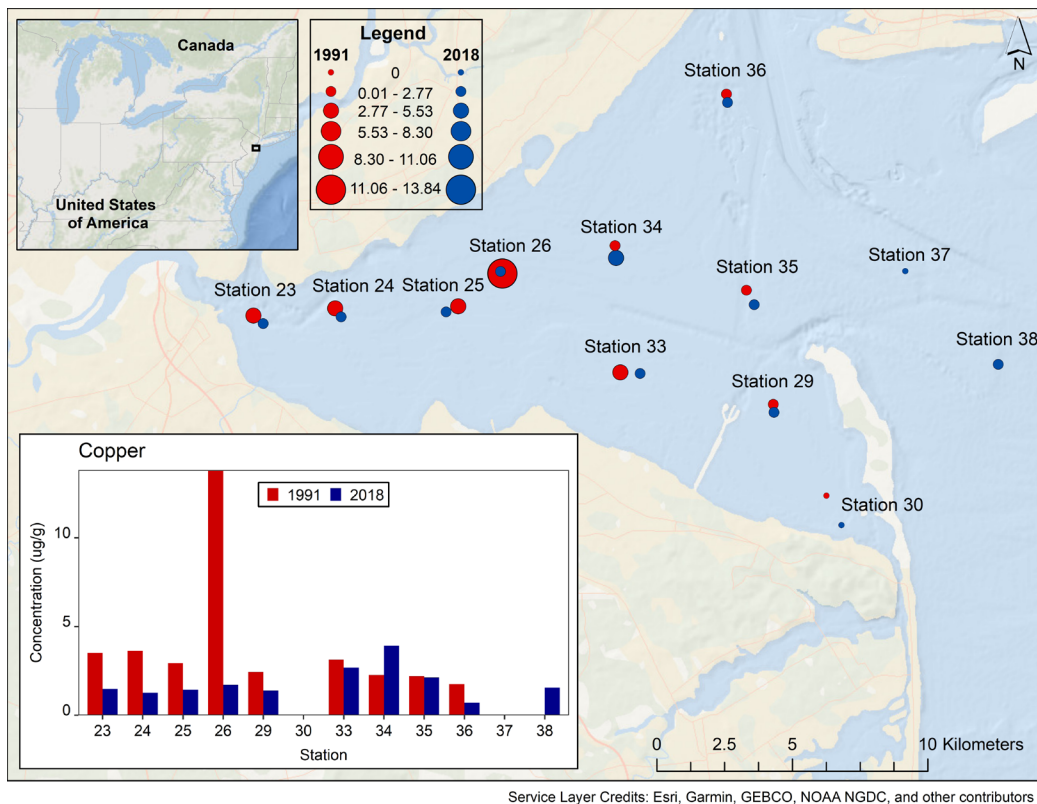
Figure 14. **Copper**: Map of the study showing the spatial distribution of Cu in the HRE study area. Cu sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.6 Lead (Pb)

4.6.1 Chemical Overview

Lead is a grayish, sometimes silvery-white soft metal. It is very dense and is a poor conductor of electricity. Pb occurs naturally in the Earth's crust and has been historically used in industrial processes such as paint and pigment production, solder, ammunition, plumbing. Loadings of Pb into coastal waters are primarily linked with wastewater discharge, river runoff, atmospheric deposition and natural weathering of rock. Pb can be found in air, soil, and surface water (ATSDR, 2007b). Environmental levels of Pb increased worldwide over the past century because of leaded gasoline use (ATSDR, 2007b). Significant reductions in environmental Pb resulted from the regulation that restricted Pb in gasoline and paints. In the communications industry, Pb is still used extensively as protective sheathing for underground and underwater cables including transoceanic cable systems (USGS, 2008). High levels found in the environment are usually linked to anthropogenic activities such as manufacturing processes, paint and pigment, solder, ammunition, plumbing, incineration and fossil fuel burning.

Pb is toxic to most organisms. Exposure of fish to elevated concentrations of Pb results in neurological deformities and black fins in fish (Mance, 1987). Pb primarily affects the nervous system, which results in decreased performance and inhibits typical mental developmental in humans. Exposure to Pb may also cause brain and kidney damage and cancer (IARC, 2006). Safety guidance levels for Pb in fish and shellfish are no longer listed by the US FDA (US FDA, 2020).

4.6.2 Result Highlights

The results for Pb from the two surveys are illustrated in Figure 15 and shown in Appendices A2 and A4.
- Pb has been detected basin-wide in the HRE at concentrations above MDL in 1991 and 2018 (Figure 15).
- With the notable exception of station 34, The spatial variation of Pb concentrations in the study area was minimal between the survey stations with the exception of station 34 in 2018 and station 26 in 1991.
- Pb concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2) indicating the potential for low toxic effects on sensitive benthic organisms.
- The Wilcoxon statistical analysis indicated that Pb concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
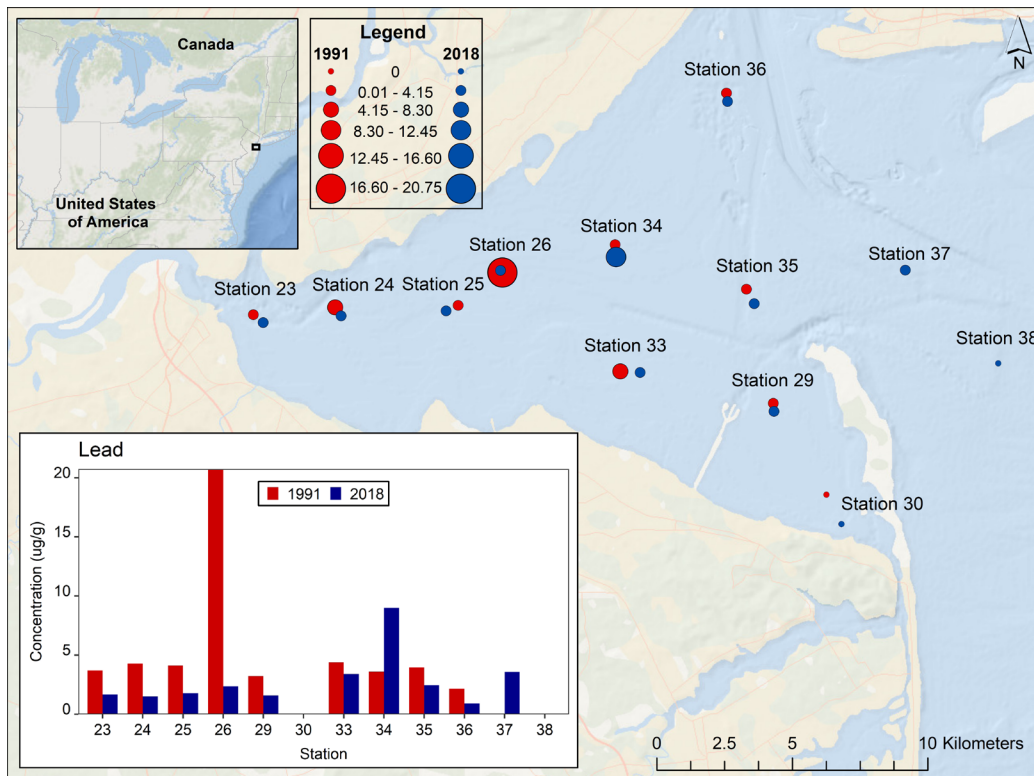
*Figure 15. **Lead**: Map of the study showing the spatial distribution of Pb in the HRE study area. Pb sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.7 Manganese (Mn)

4.7.1 Chemical Overview

Manganese is a silvery-gray, hard, brittle metal. Mn minerals occur naturally in earth crust as oxides, silicates, and carbonates. Anthropogenically, Mn is used principally in steel production to improve strength in stainless steel and superalloys. Also, Mn is used in pharmaceutical products and as additive in gasoline (ATSDR, 2012b). Mn is an essential micronutrient and it is naturally found in various foods including green vegetables, nuts, tea, legumes, and whole grains. In the environment, Mn can be found in air surface water and groundwater. Mn in water may be significantly bioconcentrated at lower trophic levels and fish. Exposure to high Mn concentrations can result in a wide range of issues such as respiratory illnesses, sexual problems, and mental disturbances.

4.7.2 Result Highlights

The results for Mn from the two surveys are illustrated in Figure 16 and shown in Appendices A2 and A4.
- Station 26 had an anomalously high Mn concentration in 1991 and station 34 was anomalously high in 2018.
- Two offshore stations 37 and 38 had very high Mn values in 2018.
- There are no sediment quality guideline values for Mn.
- The Wilcoxon statistical analysis indicated that Mn concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
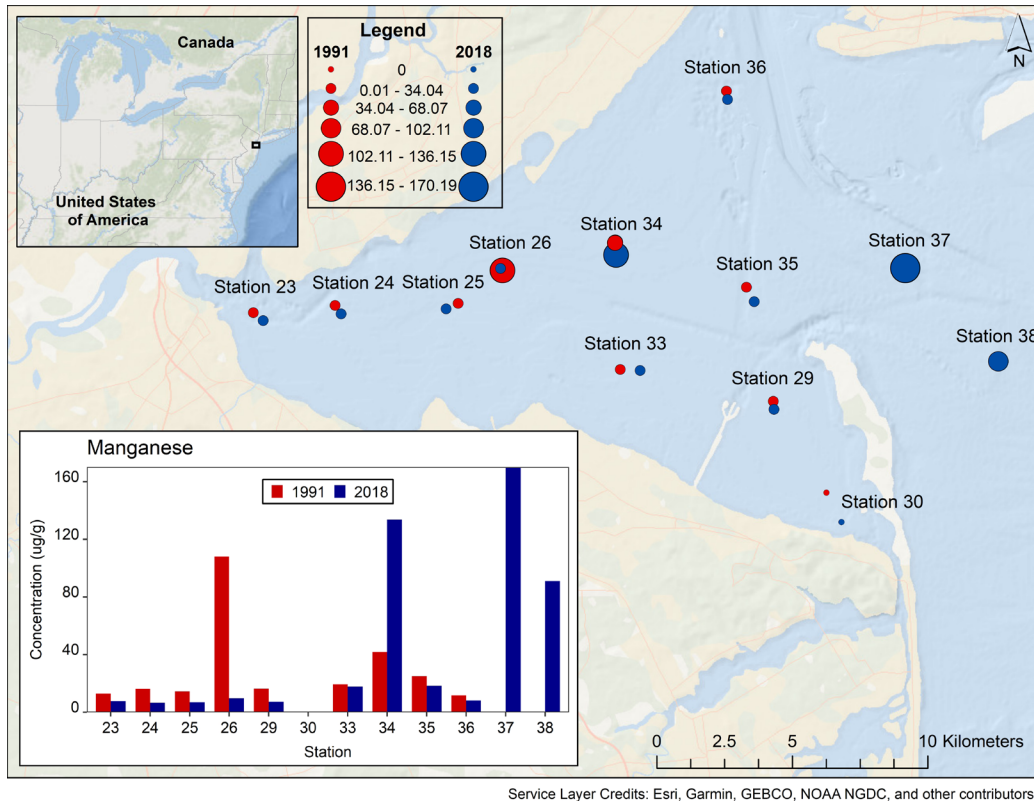
*Figure 16. **Manganese**: Map of the study showing the spatial distribution of Mn in the HRE study area. Mn sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.8 Mercury (Hg)

4.8.1 Chemical Overview

Mercury is a silver-white metal, also known as quicksilver. Hg is found naturally as mercuric sulfide from forest fires, crustal ores, fossil fuels, and volcanoes. Anthropogenic sources of Hg are from mining, gold refining, coal fired power plants, and the wood pulp industry. Elevated levels occur as a result of human activity (ATSDR, 1999b). In the US, coal fired-electric turbines, municipal and medical waste incinerators, mining, landfills, and sewage sludge are the primary emitters of Hg into the air. In the environment, Hg may change forms between elemental, inorganic, and organic. Estimates suggest that wet and dry deposition accounts for 50-90% of the Hg load to many estuaries, making atmospheric transport a significant source of Hg worldwide (NADP, 2020). Hg is a highly toxic, non-essential trace metal. Hg is a human neurotoxin that also affects the kidneys and developing fetuses. The most common human exposure route for Hg is the consumption of contaminated food. The US FDA has not established a safety level for Hg but has set a safety level of 1.0 ppm wet weight for methyl mercury, the form most likely to impact animals and humans (US FDA, 2020). Hg ecotoxicity includes reduced growth and rates of reproduction in other phyla such as copepods (Eisler, 1987). The Mussel Watch Program measures total Hg, of which methyl mercury is only one component.

4.8.2 Result Highlights

The results for Hg from the two surveys are illustrated in Figure 17 and shown in Appendices A2 and A4.
- Hg was detected at various concentrations throughout the HRE in 1991 and 2018 (Figure 17).
- Station 26 had an anomalously high concentration in 1991 (Figure 17). Station 34 in 2018 had higher concentration than in 1991. The remainder of the stations were not remarkable in that 2018 values were lower than 1991.
- Hg concentrations were above the sediment toxicity thresholds of ERL and ERM at several survey stations in 1991 and 2018 (Appendices B1-2). Concentration values of Hg above ERM guideline is an indication of continued serious threat of Hg contamination in the HREand high potential for Hg toxicity to benthic organisms (Long and Morgan 1991).
- The Wilcoxon statistical analysis indicated that Hg concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
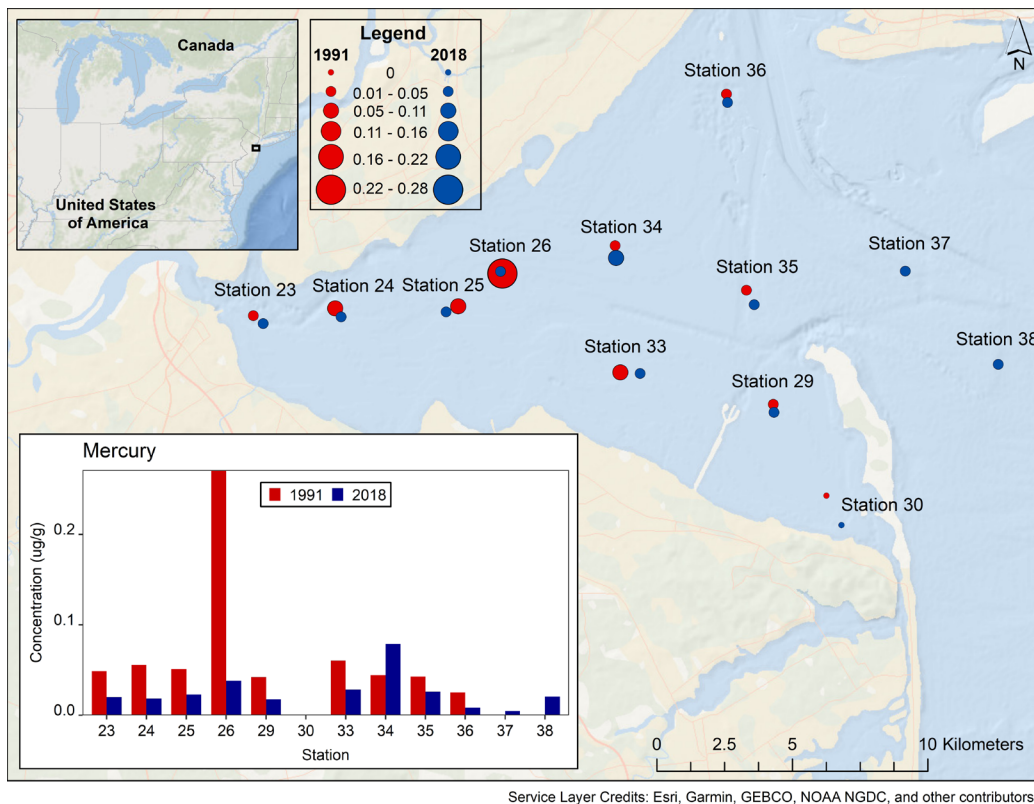

Figure 17. **Mercury**: Map of the study showing the spatial distribution of Hg in the HRE study area. Hg sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.9 Nickel (Ni)

4.9.1 Chemical Overview

Nickel is a silvery-white-golden, hard metal that is very resistant to corrosion. Significant sources of Ni accumulation in aquatic and coastal environments are from natural sources including weathering of enriched rocks and soil and runoff from streams and rivers. Ni is a biologically essential trace element for animals and plants, at very low concentrations that is widely distributed in the environment. Industrial applications of Ni include metal alloy, stainless steel, nickel-cadmium batteries, pigments, computers, wire, coinage, and electroplating (ATSDR, 2005). Large doses of Ni can cause serious health effects such as bronchitis, and chronic exposure has been associated with cancer. There is no evidence that Ni biomagnifies in the food chain (McGeer et al., 2004). Safety guidance levels for Ni in fish and shellfish are no longer listed by the US FDA (US FDA, 2020).

4.9.2 Result Highlights

The results for Ni from the two surveys are illustrated in Figure 18 and shown in Appendices A2 and A4.
- Ni was measured above MDL at nearly all of the survey locations across the HRE in 1991 and 2018 (Figure 18).
- Anomalously high Ni concentration was measured at station 26 in 1991.
- Ni concentrations at stations 37 and 38 were very high in 2018.
- Ni concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2) indicating the potential for low toxic effects on sensitive benthic organisms.
- The Wilcoxon statistical analysis indicated that Ni concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
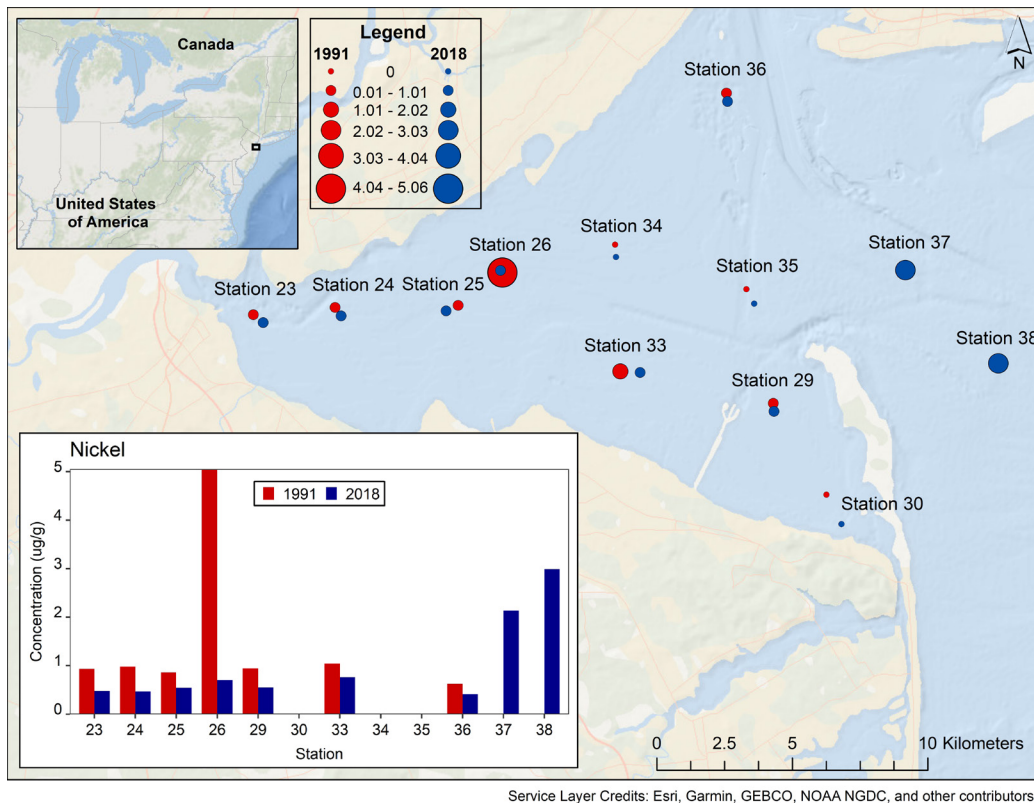

*Figure 18. **Nickel**: Map showing the spatial distribution of Ni in the HRE study area. Ni sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.10 Selenium (Se)

4.10.1 Chemical Overview

Elemental selenium is a metalloid. The metallic form is gray, rare in nature, and is typically combined with other minerals widely found in rocks and soils. Processed Se is used in electronics and many other applications including food supplements, glass, rubber, and fungicides. Hazardous waste sites are very often sources of high concentrations of Se in soil. Se is an essential trace element; however, is toxic in high concentrations. Humans obtain natural levels of Se from food and water. Excessive runoff from Se enriched rocks and soil can result in high environmental levels with very high levels in effluents typically associated with industries. Toxic effects of Se include bronchitis, eye and skin irritations, reproductive failure, and even death.

4.10.2 Result Highlights

The results for Se from the two surveys are illustrated in Figure 19 and shown in Appendices A2 and A4.
- Se has been detected at various concentrations throughout the HRE during both 1991 and 2018 survey (Figure 19).
- The 1991 survey recorded an anomalously high Se concentration in sediment at station 26.
- There are no sediment quality guideline values for Mn.
- The Wilcoxon statistical analysis indicated that Se concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
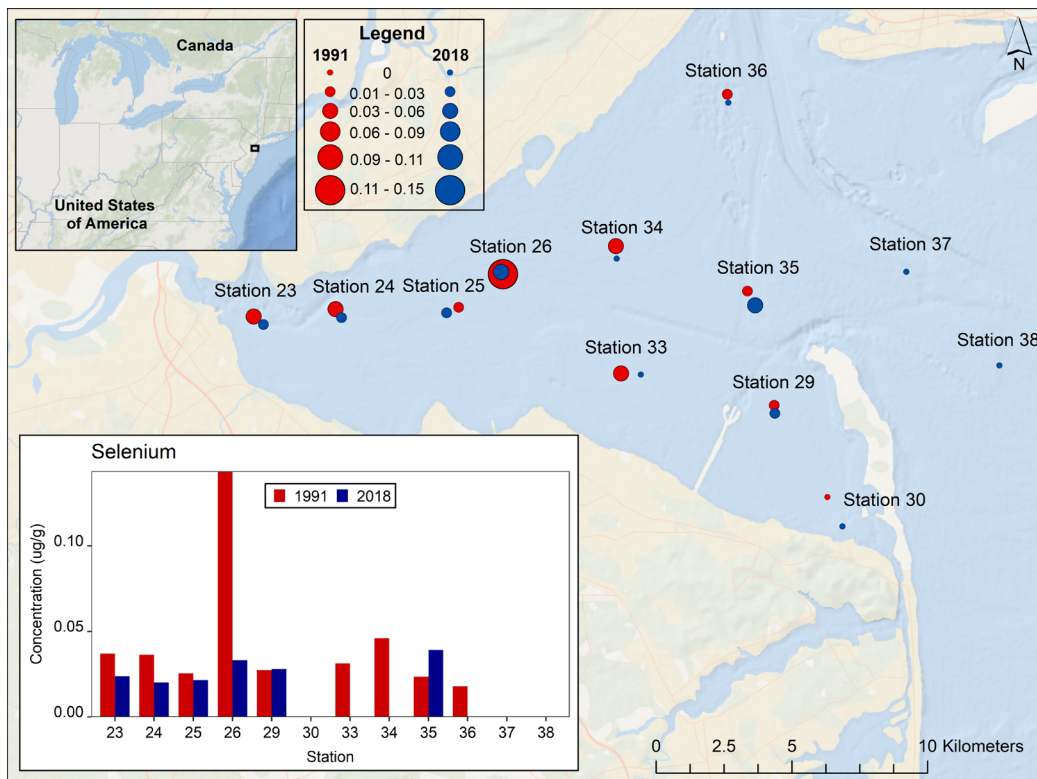
Figure 19. **Selenium**: *Map of the study showing the spatial distribution of Se in the HRE study area. Selenium sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.11 Silver (Ag)

4.11.1 Chemical Overview

Silver is a white, soft metallic element. Elemental Ag is used in industrial processing for a wide range of products including dental applications, electronics, silverware, jewelry, photography, and solders. Silver is not an essential micronutrient. Consumption, breathing, and absorption via skin are modes of Ag entry into the human body (ATSDR 1990). Argyria (gray or blue-gray tissues) is caused by exposure to Ag compounds. Breathing problems and allergic reactions have occurred from inhaling and touching Ag compounds respectively. Opposingly, Ag compounds can be beneficial medically.

4.11.2 Result Highlights

The results for Ag from the two surveys are illustrated in Figure 20 and shown in Appendices A2 and A4.
- Ag as measured throughout the HRE (Figure 20) during both 1991 and 2018 surveys.
- Ag concentrations were generally low; however, survey stations in the middle of the estuary had the highest Ag concentration in 1991 and 2018.
- The 1991 survey recorded an anomalously high Ag concentration in sediment at station 26.
- Ag concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2) indicating the potential for low toxic effects on sensitive benthic organisms.
- The Wilcoxon statistical analysis indicated that Ag concentrations have significantly decreased in the HRE since 1991 overall (Appendix C).
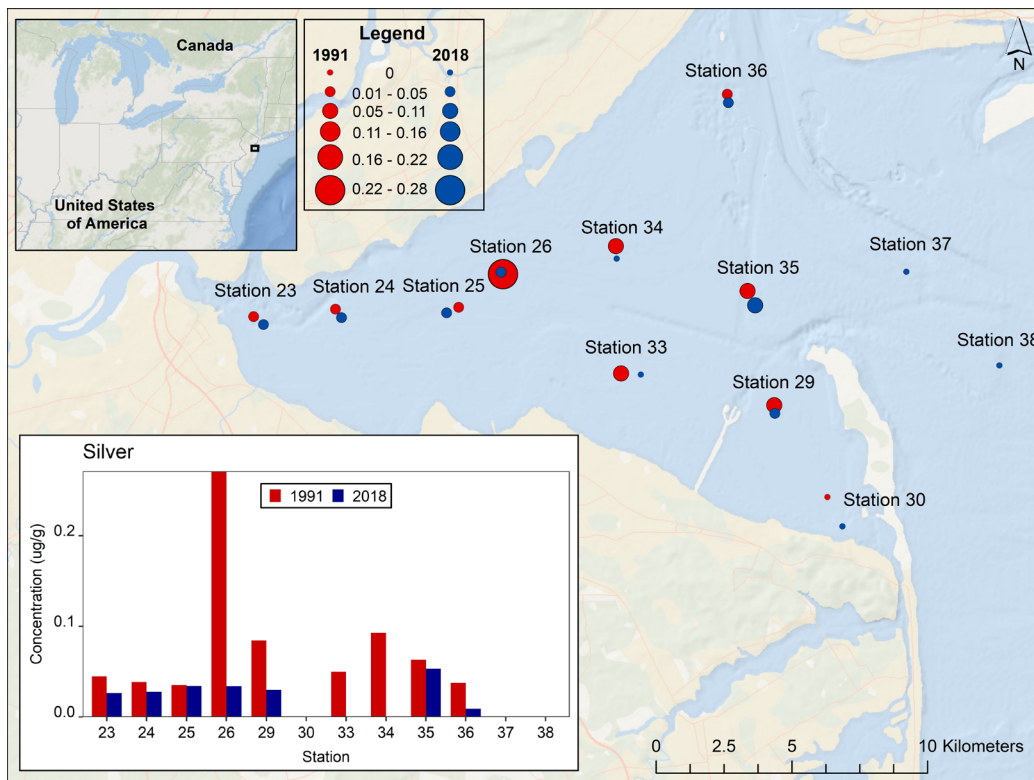

*Figure 20. **Silver**: Map of the study showing the spatial distribution of Ag in the HRE study area. Ag sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.12 Tin (Sn)

4.12.1 Chemical Overview

Tin is a soft and pliable silver-white metal, which is resistant to corrosion. Sn can combine with other chemicals to form various inorganic and organic compounds. Tri-butyl tin (TBT), an organo-tin, is the active ingredient in antifouling paint used on boats. Sn metal is mainly used as liner in cans for food and aerosols. It is also used in paint, plastic, pesticide brass, bronze, and some soldering products (ATSDR 2005b). Sn may be released to the environment from natural and anthropogenic sources. Anthropogenic sources are primarily from paint, plastic, and pesticide manufacturing. Organic Sn compounds can be dangerous for humans. Triethyltin is noted as the "most dangerous organic tin substance for humans" (Lenntech 2021). Imposex, the development of male characteristics in females, has been initiated by TBT exposure in several snail species. TBT-exposed oysters have abnormal shell development, poor weight gain, brittle shells, and imposex.

4.12.2 Result Highlights

The results for Sn from the two surveys are illustrated in Figure 21 and shown in Appendices A2 and A4.
- Sn was measured throughout the HRE (Figure 21) during both 1991 and 2018 surveys.
- Sn concentrations were generally low; however, survey stations in the middle of the estuary had the highest Sn concentration in 1991 and in 2018 (Figure 21).
- Sn concentrations at stations 34 and 38 were highest in 2018.
- The 1991 survey recorded an anomalously high Sn concentration in sediment at station 26.
- There are no sediment quality guideline values for Sn.
- Wilcoxon statistical indicated that Sn concentrations have significantly decreased in the HRE since 1991 overall (Appendix C).
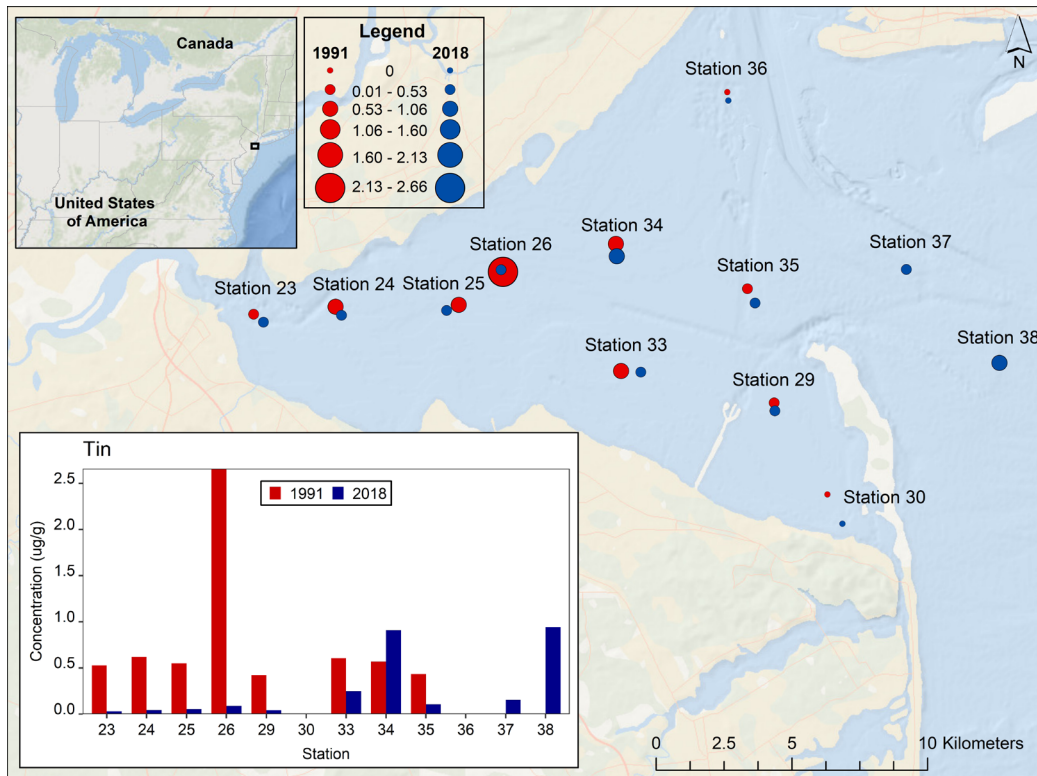
Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

*Figure 21. **Tin**: Map of the study area showing the spatial distribution of Sn in the HRE study area. Sn sediment concentrations normalized by % fine sediments are shown in both the bar graph and map where 1991 data is in red and 2018 data is in blue.*

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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4.13 Zinc (Zn)

4.13.1 Chemical Overview

Pure zinc is a bluish-white, ductile metal that is a common element in the earth's crust. Particles of elemental Zn are also found in air, water, soil and most foods. Zn is used widely in industrial settings, dry cell batteries, alloys, and rust preventing coatings (ATSDR, 2005c). Environmental Zn derives from natural rock weathering and anthropogenic sources such as mining and industrial processes (ATSDR, 2005c). Zn is an essential trace element for human and animal metabolism, but excessive Zn exposure can result in anemia, digestive problems, and damage to the pancreas.

4.13.2 Result Highlights

The results for Zn from the two surveys are illustrated in Figure 22 and shown in Appendices A2 and A4.
- Zn was measured above method detection levels at nearly all of the survey locations across the HRE in 1991 and 2018 (Figure 22).
- Anomalously high Zn concentration was measured at station 36 in 2018.
- Stations 36, 37 and 38 recorded the highest Zn concentrations during the 2018 survey
- Zn concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2).
- Instances of Zn concentrations above the ERM guideline were observed at the station 24 in 2018.
- Zn concentration values above ERM guideline is a serious indication of the continued treat of Zn contamination in the HRE. Concentrations above ERM signify high potential for toxicity to benthic organisms (Long and Morgan, 1991).
- Higher concentration values were observed for Zn in 2018 compared to 1991 (Figure 22, Appendices A2 and A4). However, the Wilcoxon statistical analysis indicated that basin-wide, Zn concentrations have not changed in the HRE since 1991 (Appendix C).
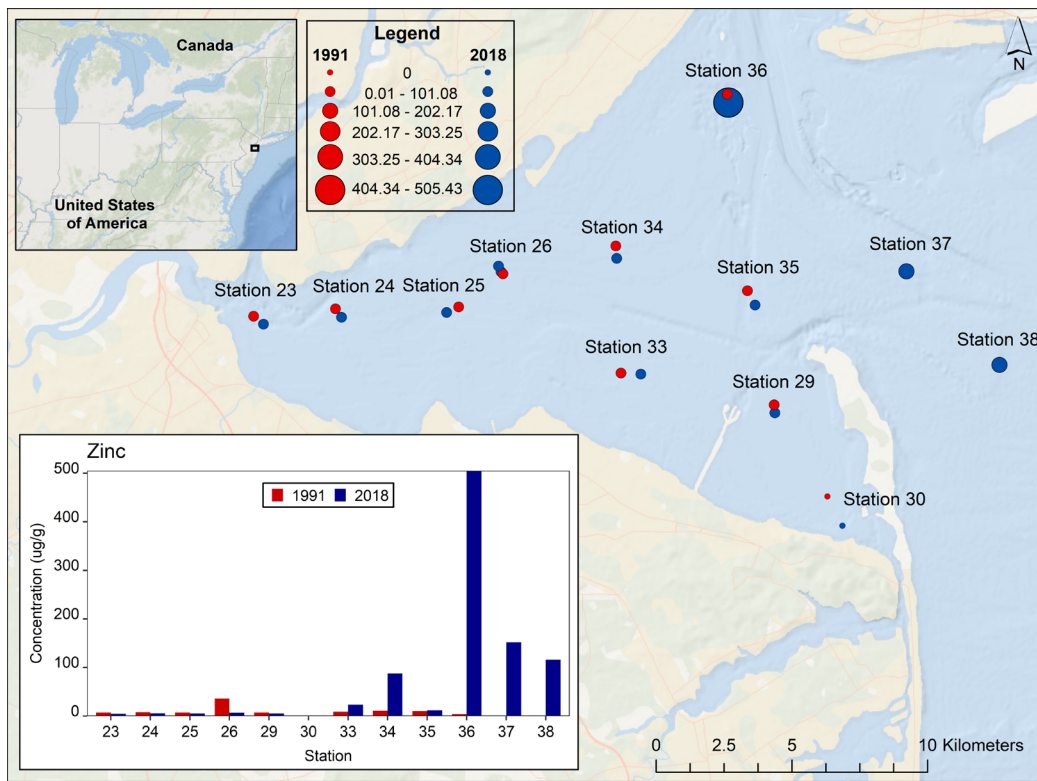
Figure 22. **Zinc**: Map of the study showing the spatial distribution of Zn in the HRE study area. Zn sediment concentrations normalized by % fine sediments are shown in both the bar graph and map where 1991 data is in red and 2018 data is in blue.

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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5.0 RESULTS - ORGANIC CONTAMINANTS

The organic contaminants measured in this study are mainly synthetically manufactured chemicals except the PAHs, which can be found naturally in the environment. Most these contaminants are organochlorine compounds that were used in industrial production or as pesticides and insecticides in agriculture. As a result of their environmental toxicity, these chemicals were mostly banned in the 1970's, however they are still present in the environment because of their widespread use and resistance to biodegradation. An overview description and potential health effects of DDT, PAHs, and PCB contaminants that were measured during both the 1991 and 2018 surveys are provided in the following paragraphs.

5.1 Organochlorine pesticides (DDT)

5.1.1 Chemical Overview

In the 1950s and continuing into the early 1970s, a series of man-made chlorine-containing hydrocarbon insecticides were used to control mosquitoes and agricultural pests. One of the best known of the organochlorine pesticides was the insecticide dichlorodiphenyltrichloroethane (DDT). DDT was banned due to its environmental persistence, bioaccumulation, and toxicity to non-target organisms. While DDT was banned by the EPA for most uses in the U.S. in 1972, it is still used in some developing countries, particularly on the inside of living areas to help control mosquitoes that can transmit malaria. Most uses of the organochlorine insecticide chlordane were prohibited in 1978, and all uses were prohibited by 1988. A primary non-agricultural use of chlordane was in the treatment of wooden structures to prevent damage by termites. Organochlorine pesticides are typically neurotoxins, and DDT along with PCBs have also been shown to interfere with the endocrine system in humans. In the environment, DDT can metabolize into dichlorodiphenyldichloroethane (DDD) and dichlorodiphenyldichloroethylene (DDE). DDE was specifically linked to eggshell thinning in birds, particularly raptors and in pelicans (Lincer, 1975). DDT and a number of organochlorine pesticides are toxic to non-target aquatic life as well including crayfish, shrimp, and some species of fish. As the result of their persistence and heavy use in the past, residues of DDT and other organochlorine pesticides can still be found in every environmental compartment including in biota, in which their toxicity continues to be a concern.

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5.1.2 Result Highlights

The results for total DDT from the two surveys are illustrated in Figure 23 and shown in Appendices A1 and A3.

- DDT compounds were detected at various concentrations throughout the HRE during both 1991 and 2018 surveys (Figure 23).
- Anomalously high of DDT concentrations were observed at the station 26 during the 1991 survey.
- Relative to the other survey stations, high DDT concentrations were also observed at stations 23, 24 and 29 in 1991.
- Nearshore Sandy Hook Bay station 30 had comparable values in 1991 and 2018. Otherwise, 2018 values were lower than in 1991.
- DDT concentrations were above the sediment toxicity thresholds of ERL and ERM at several survey stations in 1991 and 2018 (Appendices B1-2). Concentration values of DDT above ERM guidelines is an indication of continued serious threat from DDT contamination in the HRE and signify high potential for DDT toxicity to benthic organisms (Long and Morgan, 1991).
- The Wilcoxon statistical analysis indicated that DDT concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).

Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
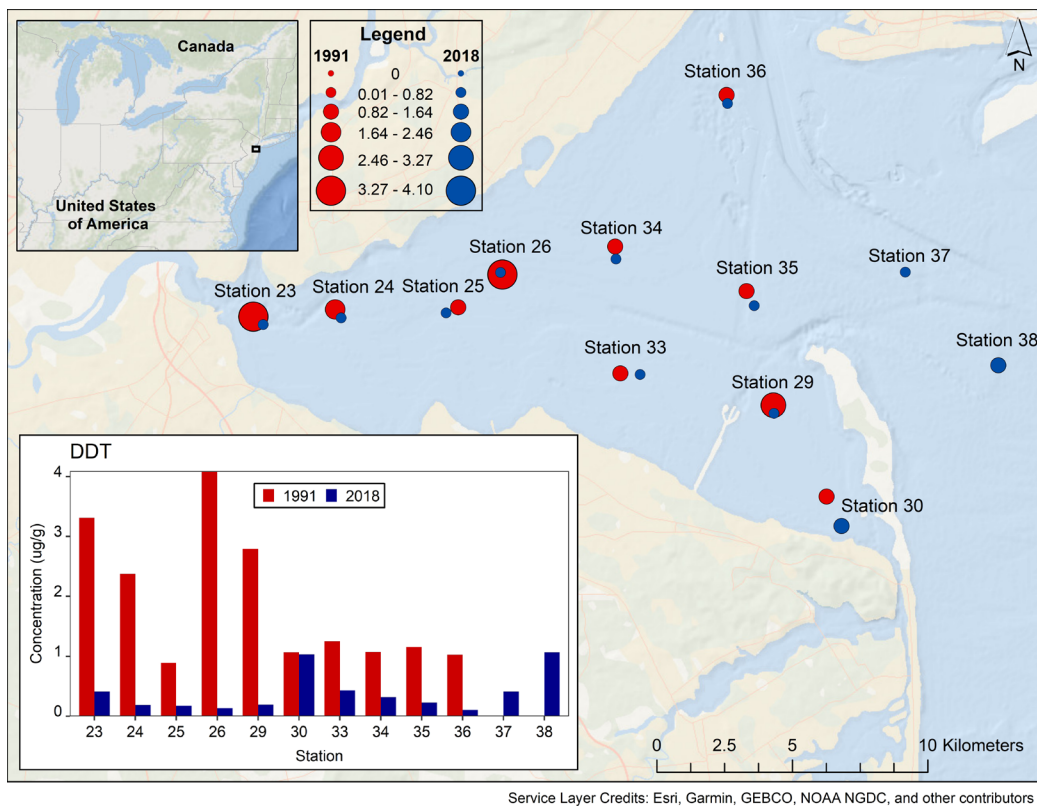
*Figure 23. **DDT**: Map of the study showing the spatial distribution of DDT in the HRE study area. DDT sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

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5.2 Polycyclic Aromatic Hydrocarbons (PAHs)

5.2.1 Chemical Overview

Polycyclic aromatic hydrocarbons are a class of organic chemicals with at least two fused benzene (six sided) carbon rings. Benzene, toluene, and xylenes are the primary PAHs (Morrison and Boyd, 1970). PAHs are associated with the use and combustion of fossil fuels (e.g., oil and gas) and other organic materials (e.g., wood and trash). Cigarette smoke has many PAHs, as does motor vehicle exhaust, wood smoke, asphalt road fumes, and grilled meats. Natural sources of PAHs include forest fires, coal, and crude oil. High-temperature cooking will form PAHs in meat and in other foods. Naphthalene is a PAH that is produced commercially in the United States to make other chemicals and mothballs. A number of PAHs bioaccumulate in aquatic and terrestrial organisms, are toxic, and some (including 1-methylphenanthrene, benzo[a]pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, dibenzo[a,h]anthracene, and indeno[1,2,3-c,d]pyrene) are likely carcinogens (ATDSR, 1995).

5.2.2 Result Highlights

The results for total PAHs from the two surveys are illustrated in Figure 24 and shown in Appendices A1 and A3.
- PAH compounds were detected at various concentrations throughout the HRE during both 1991 and 2018 surveys (Figure 24).
- Anomalously high of PAH concentrations were observed at the station 26 during the 1991 survey.
- Relative to the other survey stations, high PAH concentrations were also observed at the station 23 in 1991.
- PAH concentrations were above the sediment toxicity thresholds of ERL at several survey stations in 1991 and 2018 (Appendices B1-2). Concentration values above ERL guidelines is an indication of the potential of low toxicity threat for PAHs to benthic organisms (Long and Morgan, 1991).
- The Wilcoxon statistical analysis indicated that PAH concentrations have decreased in the HRE since 1991 basin-wide (Appendix C).

Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
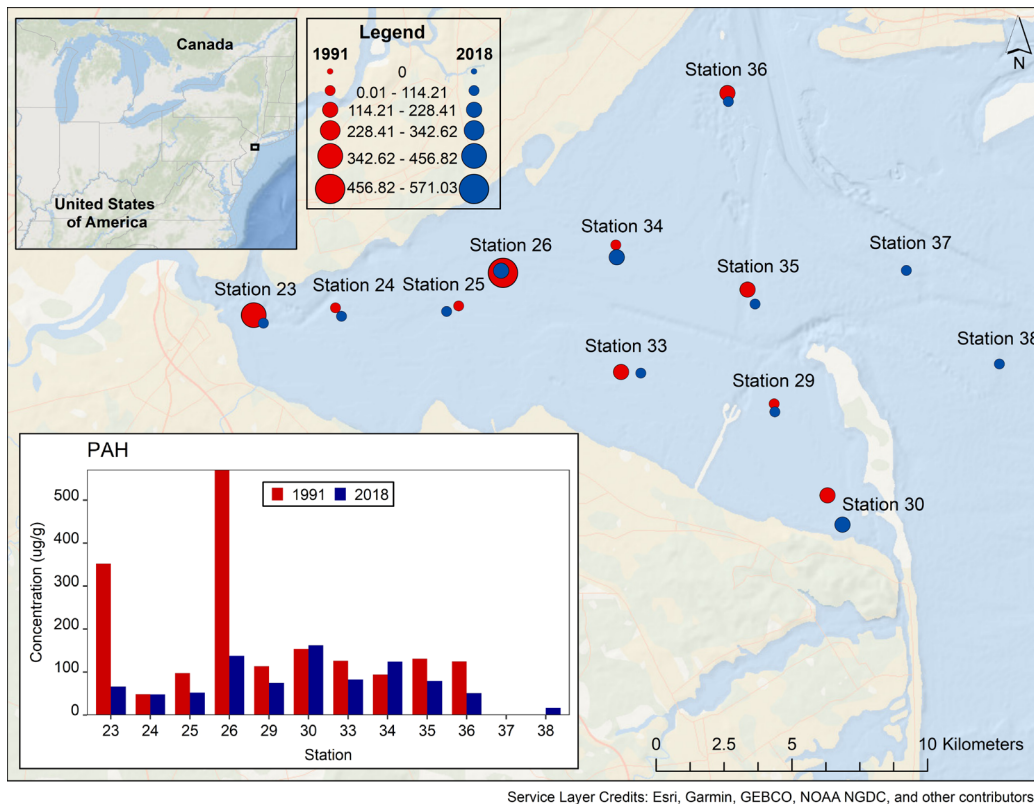
*Figure 24. **PAHs**: Map of the study area showing the spatial distribution of PAHs in the HRE study. PAHs sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

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5.3 Polychlorinated Biphenyls (PCBs)

5.3.1 Chemical Overview

Commonly referred to as PCBs, polychlorinated biphenyls are synthetic compounds that have been used in numerous applications ranging from electrical transformers and capacitors, to hydraulic and heat transfer fluids, to pesticides and paints. Although no longer manufactured in the U.S., PCBs are still in use in old equipment. PCBs have a biphenyl ring structure (two benzene rings with a carbon to carbon bond) and a varying number of chlorine atoms. There are 209 PCB congeners possible. PCBs can bioaccumulate and degradation in the environment proceeds slowly. Exposure to PCBs in fish has been linked to reduced growth, reproductive impairment, and vertebral abnormalities (EPA, 1997). PCBs readily accumulate in the tissues of other organisms including many marine animals such as filter feeders, fish, and marine mammals. PCBs can take years to degrade in sediments. Biomagnification of PCBs occurs with higher levels found in the tissues of animals at the top of the food chain. In general, PCBs have been shown to adversely affect reproduction, growth, metabolism, and survival. Effects can include hepatotoxicity, immunotoxicity, neurotoxicity, low birth weight, and teratogenicity (ATDSR, 2000; Eisler, 1996).

5.3.2 Result Highlights

The results for total PCBs from the two surveys are illustrated in Figure 25 and shown in Appendices A1 and A3.
- PCB compounds were variably detected throughout the HRE during both 1991 and 2018 surveys (Figure 25).
- The concentrations of PCB were anomalously high at the station 26 compared to the other stations in the 1991 survey. In the 2018 survey, the highest concentrations of PCB were observed at the station 30, which was near the mouth of the Navesink River in Sandy Hook Bay, NJ.
- Relative to the other survey stations, high PCB concentrations were also observed at the stations 23, 24, 33, and 34 in 1991.
- In 1991 six of the survey stations had PCB concentrations above the sediment toxicity thresholds of ERM. However, in 2018 PCB concentrations were found to be only above the ERL threshold at survey stations 24, 26, 29, 30, 35, and 36 (Appendices B1-2). Concentration values above ERL guidelines is an indication of the potential of low toxicity threat for PCB compounds to benthic organisms (Long and Morgan, 1991).
- The Wilcoxon statistical analysis indicated that PCB concentrations have significantly decreased in the HRE since 1991 basin-wide (Appendix C).
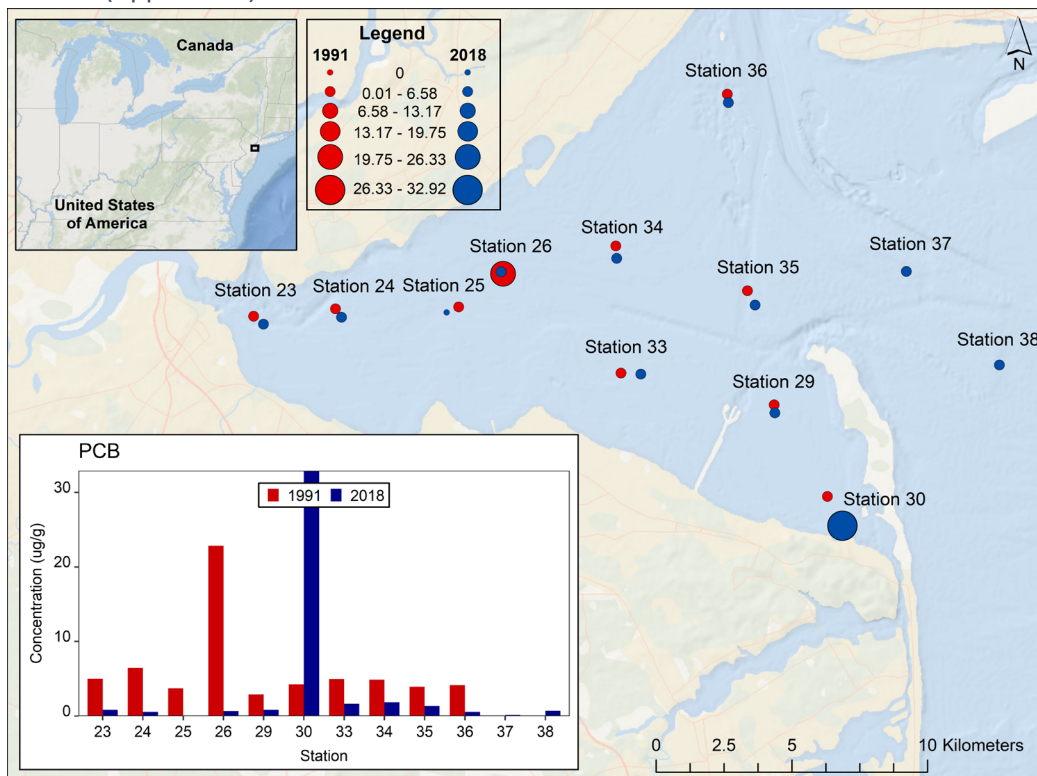
Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

*Figure 25: **PCBs**: Map of the study showing the spatial distribution of PCBs in the HRE study area. PCBs sediment concentrations normalized by % fine sediments are shown in both bar graph and map where 1991 data is in red and 2018 data is in blue.*

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6.0 DISCUSSION

The 1991 and 2018 surveys indicated that toxic chemical contaminants are present in the HRE. During the 1991 survey, surficial sediment contaminant concentrations, sediment toxicity tests, and benthic macrofaunal community structure were measured at each site. In 1993 EPA conducted a similar survey as a baseline for management monitoring (Adams, 1998). The 1993 survey corroborates the 1991 study. Only surficial sediment contaminant concentrations were measured from the 2018 survey of Raritan Bay, Lower Bay and Sandy Hook Bay. To quantitatively assess differences that may have occurred during the 27 years between the 1991 and 2018 surveys, we used statistical analyses and the NOAA ERL and ERM established sediment toxicity guidelines defined in Long et al. (1995). The results are illustrated in Appendices B1-4 and C. During the 2018 survey, the highest concentration of As, Cr, Ni, Zn and DDT were found at the offshore station 38, while the highest concentrations of Cd, Cu, Pb, and Hg observed in 2018 were measured in sediments collected from the mid-bay stations 34. These offshore stations (34 and 38) appeared to be a depositional zone into which currents in the HRE converge (Figure 5). Jamaica Bay empties into the Hudson-Raritan Bay from the Rockaway Point region as it joins the Atlantic Ocean, which could be a source of material flowing into these depositional areas (Figure 5). In 2018, Zn from stations 36, 37, and 38 showed the anticipated general trend of high values near the river mouth (station 36) with decreasing concentrations progressing offshore to stations 37 and 38. The sediment classifications of our 1991 and 2018 data generally follow the USGS (2005) sediment grain size distribution patterns (Figure 8). Fine sediments, clays, and silts adsorb some metals by ligand chelation (Uddin 2017) and organics such as clays become more hydrophilic with increasing organic adsorption. The USGS (2005) graphic shows sand and gravel north of offshore stations 37 and 38. A nautical chart of the area (Figure 7) shows that stations 37 and 38 are in deeper waters, relatively close to a ship channel. These factors, as well as the distance from the river mouths, contribute to fewer fine sediments and may be reasons why chemical contaminant concentrations are generally low at stations 37 and 38.

Other than grain size, it would appear that there are other parameters such as river discharge and surface current that could affect contaminant distribution in the HRE. The anomalously high concentrations of contaminant observed at station 26 in 1991 and 2018 could be linked to discharges from the Hudson River and Raritan River. The currents and shallow mud flat bathymetry with input from Raritan River / Arthur Kill River, as well as runoff from Great Kills Harbor and adjacent Great Kills Park, may be contributors to the anomalously high values of contaminants found there in 1991. Lee (2010) describes Great Kills Park as built upon a landfill of "concern" (Figure 26 a and b), which in 2009 was "in the process of being remediated" (Figure 27). Both leaching and flow from the toxic dump draining into the adjacent Great Kills Harbor, which flowed out across station 26 area, can plausibly be accounted for the anomalously high concentration values of contaminants. Station 30 is closest to shore within Sandy Hook Bay and at the mouth of the Navesink River and had elevated values of PAH as well as PCB in 2018. Navesink River runs through Monmouth County, New Jersey which is a high-density urban area, thus PAHs from hydrocarbon sources (asphalt roads, gasoline) are not surprising. PCBs have been banned / restricted since the 1970-80s; however, their presence in materials (transformers, capacitors, plasticizers) that have been disposed-of in landfills, could explain their lingering detection. As such, discarded electronic components in landfills, such as from Earle Naval Weapons Station in Monmouth County, may have contributed to the greater concentration of PCBs in 2018.

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Figure 26. (a) Map of toxic sites in Staten Island. Great Kills Park is a contaminated toxic site landfill west of station 26. (b) Signs at red site #41.
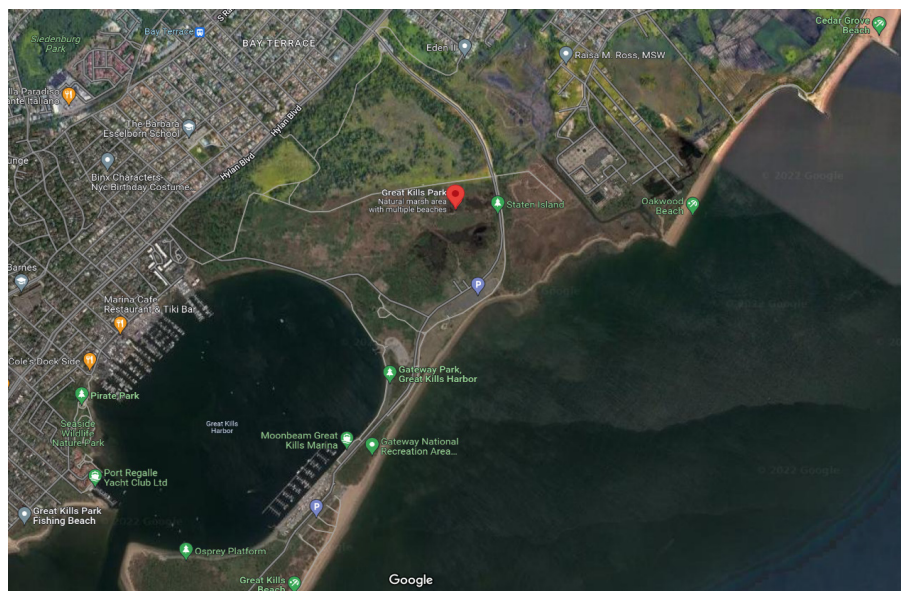

Figure 27. 2020 Google map view of mid-Staten Island Great Kills Park and Harbor, which is west of station 26, presumably after remediation.

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The magnitude and spatial distribution of the contaminants in the HRE could result from factors other than point or non-point sources. Since the 1991 NS&T survey, there have been four major hurricanes, Edouard (1996), Floyd (1999), Irene (2011), and Sandy (2012), and many other severe storms. In 2012 Hurricane Sandy, which has been cited at the largest hurricane ever recorded in the Atlantic Basin, affected the US Eastern seaboard with a 14-foot (4 m) storm surge (Figure 28). These hurricanes and storms, especially Hurricane Sandy, may have shifted the top layer of sediment in the shallow waters of Raritan Bay. The potential of flushing of the Raritan-Hudson Bay system could be a factor in the lower overall concentrations of analytes in 2018 compared to the values measured in 1991.
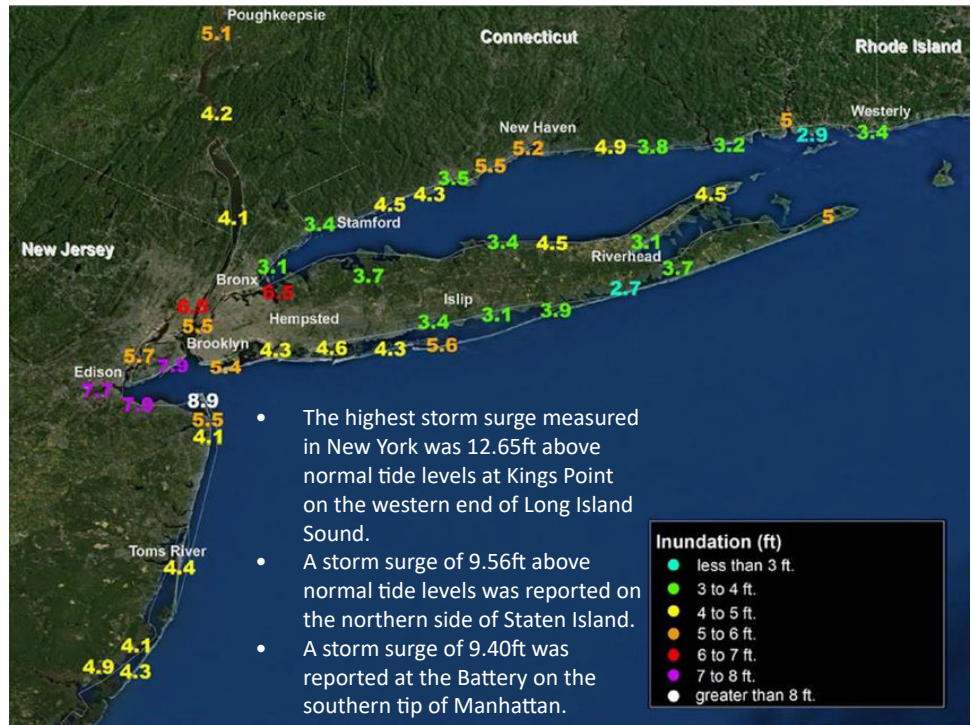
- The highest storm surge measured in New York was 12.65ft above normal tide levels at Kings Point on the western end of Long Island Sound.
- A storm surge of 9.56ft above normal tide levels was reported on the northern side of Staten Island.
- A storm surge of 9.40ft was reported at the Battery on the southern tip of Manhattan.

Inundation (ft)
- less than 3 ft.
- 3 to 4 ft.
- 4 to 5 ft.
- 5 to 6 ft.
- 6 to 7 ft.
- 7 to 8 ft.
- greater than 8 ft.

Figure 28. Inundation of water from Hurricane Sandy showing Hudson-Raritan Bay was the most severely impacted. Sources: National Hurricane Center NIH, NOAA, USGS

Comparison of results between the 1991 and 2018 using Wilcoxon statistical analyses showed that virtually all chemical contaminants have significantly decreased in concentration basin-wide from 1991 to 2018. The HRE has been subject to environmental cleaning, BMPs in the watershed, and restoration in the past decades. Additionally, the impacts of the Clean Air Act (CAA) and Clean Water Act (CWA) legislations may have contributed to the decrease in chemical contamination in the estuary. Although the contaminant concentrations in the HRE appear to be decreasing, the 2018 results indicated that several contaminants were still found at concentrations above some toxic thresholds. Compared to the NOAA sediment quality guidelines (Long et al., 1995), contaminant As, Cd, Cr, Cu, Pb, Ni, and Zn had concentrations above the ERL thresholds, and Hg, Zn, DDT, and PCB had concentrations above the ERM thresholds in 2018. Toxic contaminants at concentrations above ERL (effect range low) are likely to cause toxicity effects 10 percent of the time, while concentrations above ERM (effect range median) are likely to cause toxicity effects 50 percent of the time to benthic communities in surficial sediment. The findings of this survey confirm the concerns of the NY and NJ resource managers from the NY/NJ Hudson Estuary Program that water and sediment quality are still serious environmental issues that are causing ecosystem and aquatic species injury in the HRE.

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7.0 CONCLUSION

Chemical contaminants were detected throughout the HRE basin at variable concentrations during the 2018 survey. The results have indicated that parameters including river discharge, surface current, proximity to dump sites, and sediment grain size all impact the magnitude and spatial distribution of chemical contaminants in the estuary. Statistical results have indicated that virtually all of the survey contaminants have significantly decreased between 1991 and 2018 in the HRE except for Zn. The decrease may be the result of restoration efforts by programs such as the NY/NJ Hudson Estuary Program. The HRE has been subject to environmental cleaning, BMPs in the watershed, and restoration in the past decades. Additionally, the impacts of the CAA and CWA legislations may have contributed to the decrease in chemical contamination in the estuary. Finally, natural events such as hurricanes as well as natural chemical degradation may have played a role in the overall decrease in contamination seen from 1991 to 2018. Although the contaminant concentrations in the HRE appear to be decreasing, the 2018 results indicated that several contaminants were still found at concentrations above some toxic thresholds. Concentrations of Hg, DDT, PCBs, and, to a lesser extent, As, Cd, Cr, Cu, Ni, Pb, Ag, Zn, and PAHs were found at levels determined to be toxic across the basin in 2018. With the increased population and intense industrialization in the New Jersey – New York urban region, it is commendable that mitigation methods appear to be working to reduce the chemical contaminants in the HRE.

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Appendices

APPENDICES

Appendix A-1. Concentration of organic contaminants measured in 1991 (ng/g dry weight) normalized by grain size.

Station	Latitude	Longitude	%Fine	Tot DDT	Tot PAH	Tot PCB
St-23	40.4875	-74.259	51.3	3.312	352.404	5.003
St-24	40.4897	-74.224	46.8	2.378	48.694	6.476
St-25	40.4882	-74.175	51	0.891	97.674	3.717
St-26	40.5008	-74.151	9.4	4.092	571.03	22.836
St-29	40.4564	-74.033	40.3	2.793	113.286	2.891
St-30	40.4261	-74.013	26.7	1.068	154.206	4.238
St-33	40.4675	-74.100	47.9	1.25	126.358	4.98
St-34	40.5097	-74.101	17.2	1.071	94.424	4.882
St-35	40.4944	-74.044	13.6	1.156	131.302	3.928
St-36	40.5597	-74.052	55.8	1.027	124.528	4.155
St-37	40.5014	-73.975	-	-	-	-
St-38	40.4686	-73.933	-	-	-	-

Appendix A-2. Concentration of metal contaminants measured in 1991 (µg/g dry weight) normalized by grain size.

Station	Latitude	Longitude	Sb	As	Cd	Cr	Cu	Mn	Hg	Ni	Sb	Se	Ag	Sn	Zn
St-23	40.4875	-74.259	0.07	0.7	0.03	2.53	3.51	12.87	0.05	0.94	3.7	0.04	0.04	0.53	7.21
St-24	40.4897	-74.224	0.06	0.6	0.03	3.21	3.63	16.24	0.06	0.98	4.27	0.04	0.04	0.62	7.91
St-25	40.4882	-74.175	0.05	0.53	0.02	2.94	2.94	14.51	0.05	0.86	4.12	0.03	0.04	0.55	7.25
St-26	40.5008	-74.151	0.22	2.29	0.12	17.55	13.83	107.98	0.27	5.05	20.74	0.14	0.27	2.66	36.17
St-29	40.4564	-74.033	0.04	0.65	0.04	3.47	2.43	16.38	0.04	0.94	3.23	0.03	0.08	0.42	7.44
St-30	40.4261	-74.013	-	-	0	0	0	0	0	0	0	0	0	0	0
St-33	40.4675	-74.100	0.06	0.67	0.03	3.76	3.13	19.42	0.06	1.04	4.38	0.03	0.05	0.61	8.77
St-34	40.5097	-74.101	0.04	-	0.02	3.43	2.27	41.86	0.04	0	3.6	0.05	0.09	0.57	11.05
St-35	40.4944	-74.044	0.04	-	0.07	3.97	2.21	25	0.04	0	3.97	0.02	0.06	0.43	10.29
St-36	40.5597	-74.052	0.03	0.38	0.02	2.15	1.76	11.83	0.03	0.63	2.15	0.02	0.04	0	3.94
St-37	40.5014	-73.975	-	-	-	-	-	-	-	-	-	-	-	-	-
St-38	40.4686	-73.933	-	-	-	-	-	-	-	-	-	-	-	-	-

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Appendix A-3. Concentration of organic contaminants measured in 2018 (ng/g dry weight) normalized by grain size.

Station	Latitude	Longitude	%Fine	Tot DDT	Tot PAH	Tot PCB
St-23	40.4875	-74.259	74.37	0.41	66.49	0.84
St-24	40.4897	-74.224	75.63	0.19	47.94	0.56
St-25	40.4882	-74.175	66.23	0.18	52.2	0
St-26	40.5008	-74.151	34.96	0.13	137.99	0.69
St-29	40.4564	-74.033	51.01	0.19	74.81	0.84
St-30	40.4261	-74.013	1.54	1.03	162.37	32.92
St-33	40.4675	-74.100	6.27	0.43	82.95	1.66
St-34	40.5097	-74.101	3.14	0.32	124.33	1.85
St-35	40.4944	-74.044	15.73	0.23	79.44	1.34
St-36	40.5597	-74.052	44.09	0.1	51.07	0.55
St-37	40.5014	-73.975	1.96	0.41	1.56	0.15
St-38	40.4686	-73.933	1.16	1.07	17.03	0.72

Appendix A-4. Concentration of metal contaminants measured in 2018 (µg/g dry weight) normalized by grain size.

Station	Latitude	Longitude	Sb	As	Cd	Cr	Cu	Mn	Hg	Ni	Sb	Se	Ag	Sn	Zn
St-23	40.4875	-74.259	0	0.21	0.01	1.15	1.48	7.64	0.02	0.48	1.67	0.02	0.03	0.03	4.51
St-24	40.4897	-74.224	0	0.17	0.01	1.11	1.26	6.55	0.02	0.47	1.5	0.02	0.03	0.04	5.7
St-25	40.4882	-74.175	0	0.21	0.01	1.36	1.43	7.06	0.02	0.55	1.77	0.02	0.03	0.06	5.57
St-26	40.5008	-74.151	0	0.4	0.02	1.58	1.72	9.77	0.04	0.7	2.36	0.03	0.03	0.09	6.92
St-29	40.4564	-74.033	0	0.27	0.02	1.53	1.39	7.19	0.02	0.55	1.59	0.03	0.03	0.04	5.38
St-30	40.4261	-74.013	0	0	0	0	0	0	0	0	0	0	0	0	0
St-33	40.4675	-74.100	0	0.61	0	3.1	2.68	17.88	0.03	0.76	3.4	0	0	0.25	23.3
St-34	40.5097	-74.101	0	0	0	11.23	3.92	133.62	0.08	0	8.99	0	0	0.91	87.77
St-35	40.4944	-74.044	0	0	0.04	1.87	2.13	18.3	0.03	0	2.46	0.04	0.05	0.11	11.92
St-36	40.5597	-74.052	0	0.16	0	0.79	0.7	8.11	0.01	0.41	0.9	0	0.01	0	505.42
St-37	40.5014	-73.975	0	0	0	0	0	170.19	0	2.13	3.59	0	0	0.16	151.68
St-38	40.4686	-73.933	0	2.95	0	11.22	1.56	91.06	0.02	2.99	0	0	0	0.94	116.3

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Appendix B. ERL and ERM concentrations for sediment trace metals (ppm or µg/g) and organic compounds (ppb or ng/g) (Long and Morgan, 1991; Long et al., 1995).

Analyte	ERL	ERM
Antimony (Sb)	2	25
Arsenic (As)	8.2	70
Cadmium (Cd)	1.2	9.6
Chromium (Cr)	81	370
Copper (Cu)	34	270
Lead (Pb)	0.15	0.71
Mercury (Hg)	20.9	51.6
Nickel (Ni)	46.7	218
Silver (Ag)	1	3.7
Zinc (Zn)	150	410
Tot PCB	22.7	180
DDT	1	7
Acenaphthene	16	500
Acenaphthylene	44	640
Anthracene	85.3	1100
Benzo(a)anthracene	261	1600
Benzo(a)pyrene	430	1600
Chrysene	384	2800
Dibenz(a,h)anthracene	63.4	260
Fluoranthene	600	5100
Fluorene	19	540
2-Methylnaphthalene	70	670
Naphthalene	160	2100
Phenanthrene	240	1500
Low molecular weight PAHs	552	3160
High molecular weight PAHs	1700	9600
Pyrene	665	2600
Total PAH	4022	44792

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Appendices

*Appendix B-1. ERL, ERM sediment concentration values of metals (µg/g) and organics (ng/g) that exceed toxic levels for 1991 and 2018 at stations 23, 24, 25, 26, 29, and 30. Exceedings SQG ERL (blue) and ERM (red). Values are **not** normalized by grain size in order to compare to ERL and ERM. Mn, Se, and Sn do not have known ERL and ERM values so were not included here.*

Analyte	ERL	ERM	St23 1991	St23 2018	St 24 1991	St 24 2018	St 25 1991	St 25 2018	St 26 1991	St 26 2018	St 29 1991	St 29 2018	St 30 1991	St 30 2018
Sb	2	25	3.6	0	2.9	0	2.3	0	2.1	0	1.7	0	1.6	0
As	8.2	70	36	15.9	28	13.1	27	13.6	21.5	13.9	26	13.6	32.7	9.5
Cd	1.2	9.6	1.6	0.7	1.2	0.7	1.1	0.8	1.1	0.8	1.6	0.9	2.1	0
Cr	81	370	130	85.8	150	83.7	150	90.2	165	55.2	140	78.2	120	42.2
Cu	34	270	180	110.3	170	95	150	95	130	60	98	71	84	12.7
Pb	46.7	218	190	124.2	200	113.6	210	117.4	195	82.5	130	81.2		18
Hg	0.15	0.71	2.5	1.5	2.6	1.4	2.6	1.5	2.6	1.3	1.7	0.9	1.4	0.1
Ni	20.9	51.6	48	36	46	35.5	44	36.1	47.5	24.5	38	28.2	32.7	6.8
Ag	1	3.7	2.3	2	1.8	2.1	1.8	2.3	2.6	1.2	3.4	1.5	2.6	0
Zn	150	410	370	335.7	370	431.4	370	368.9	340	241.8	300	274.3	390	44.1
Tot PCB	22.7	180	256.6	62.4	303.1	42	190	-	231.1	24	116.5	43	144.4	50.5
DDT	1	7	170	30.4	111.3	14.1	45.4	11.6	43.1	4.6	112.6	9.9	36.2	1.6
Tot PAH	4022	44792	18078.3	4945.1	2278.9	3625.8	4981.4	3456.6	21953.8	4824.4	4565.4	3816	4448.2	249.3

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Appendices

*Appendix B-2. ERL, ERM sediment concentration values of metals (µg/g) and organics (ng/g) that exceed toxic levels for 1991 and 2018 at stations 33, 34, 35, 36, 37, and 38. Exceedings SQG ERL (blue) and ERM (red). Values are **not** normalized by grain size in order to compare to ERL and ERM. Mn, Se, and Sn do not have known ERL and ERM values so were not included here.*
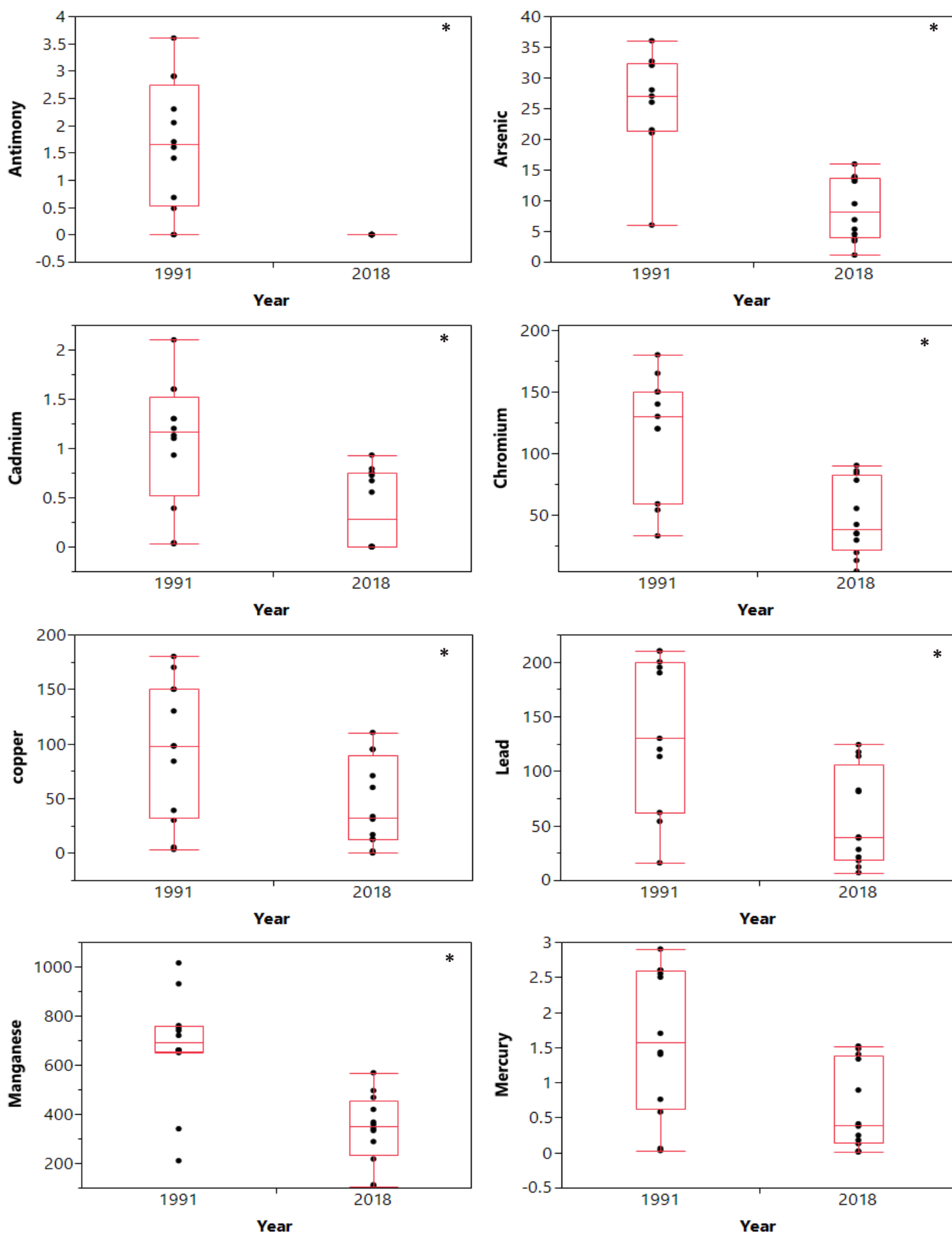
Analyte	ERL	ERM	St 33 1991	St 33 2018	St 34 1991	St 34 2018	St 35 1991	St 35 2018	St 36 1991	St 36 2018	St 37 1991	St 37 2018	St 38 1991	St 38 2018
Sb	2	25	2.9	0	0.7	0	0.5	0	1.4	0	0	0	0	0
As	8.2	70	32	3.8		4.5		5.3	21	6.9		1.1	6	3.4
Cd	1.2	9.6	1.3	0	0.4	0	0.9	0.6	1.3	0	0	0	0	0
Cr	81	370	180	19.4	59	35.2	54	29.5	120	34.7		4.4	33	13
Cu	34	270	150	16.8	39	12.3	30	33.4	98	31	5.3	0	3.3	1.8
Pb	46.7	218	210	21.3	62	28.2	54	38.6	120	39.7	16	7		12.2
Hg	0.15	0.71	2.9	0.2	0.8	0.2	0.6	0.4	1.4	0.4	0	0	0	0
Ni	20.9	51.6	50	4.8		7.3		19.1	35	18.1	4.5	4.2	6.2	3.5
Ag	1	3.7	2.4	0	1.6	0	0.9	0.8	2.1	0.4	0	0	0	0
Zn	150	410	420	146	190	275.2	140	187.6	220	204.9	38	296.8	38	134.9
Tot PCB	22.7	180	238.5	10.4	84	5.8	53.4	21.1	231.9	24.2	2.5	0.3	2.5	0.8
DDT	1	7	60	2.7	18.4	1	15.7	3.6	57.3	4.5	0.5	0.8	0.5	1.2
Tot PAH	4022	44792	6052.5	520	1624.1	390	1785.7	1249.8	6948.7	2251.7	7.2	3.1	36.4	19.7

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*Appendix C. Comparisons by year of basin-wide analyte concentrations between 1991 and 2018. * indicates significance at α=0.05.*

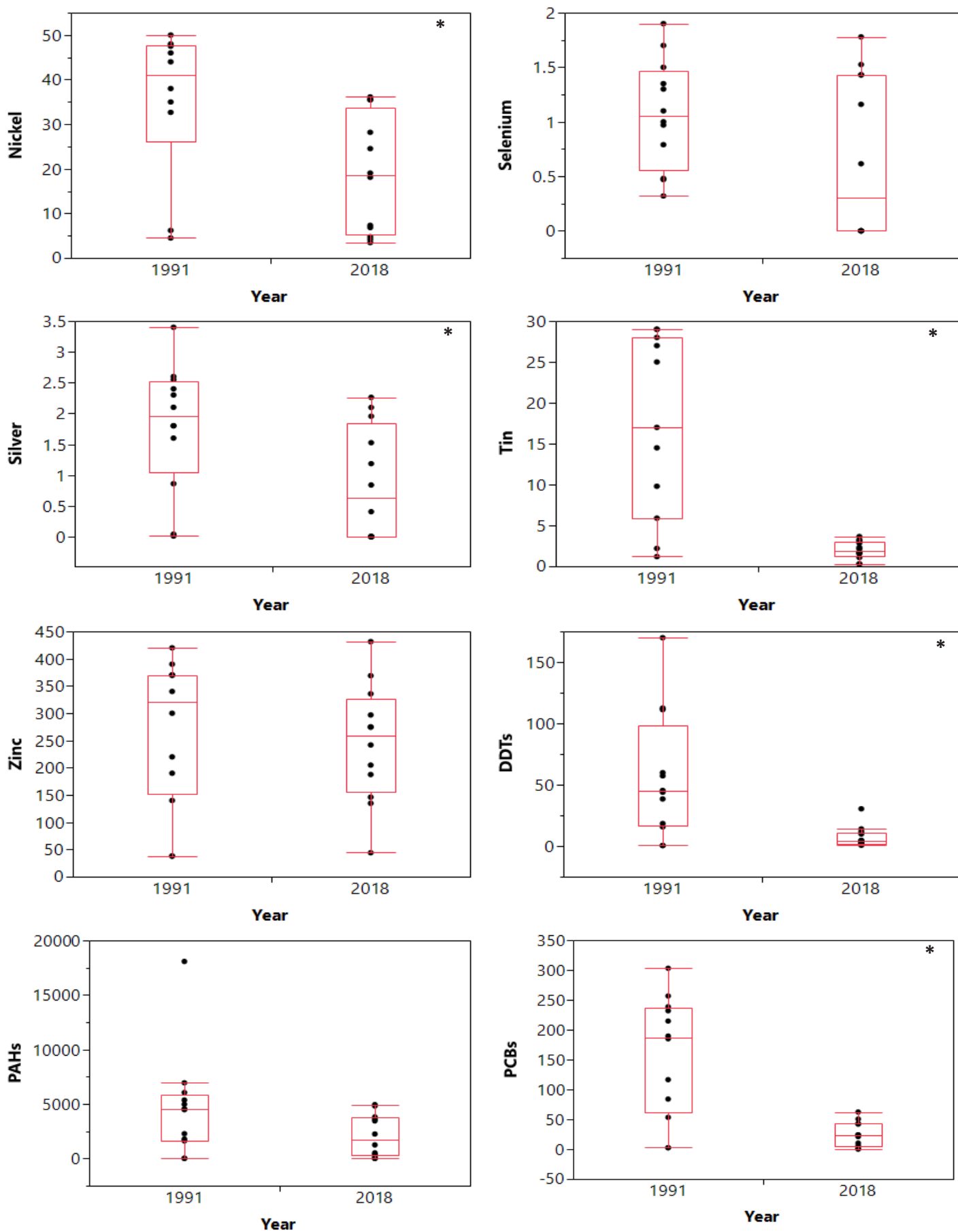| Analyte	Chi-Sq	Prob>Chi-Sq
Total DDTs	7.0564	0.0079*
Total PAHs	3.0000	0.0833
Total PCBs	8.3716	0.0038*
Antimony	14.9675	0.0001*
Arsenic	11.1566	0.0008*
Cadmium	9.5164	0.0020*
Chromium	9.1037	0.0026*
Copper	4.0869	0.0432*
Lead	6.6851	0.0097*
Manganese	10.1009	0.0015*
Mercury	4.5653	0.0326*
Nickel	5.3261	0.0210*
Selenium	1.7906	0.1809
Silver	6.2201	0.0126*
Tin	10.2475	0.0014*
Zinc	0.5646	0.4524

An Assessment and Comparison of Chemical Contaminants in Surficial Sediments from Hudson-Raritan Estuary from 1991 and 2018

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*Appendix C. Comparisons by year of basin-wide analyte contentrations between 1991 and 2018. * indicates significance at α=0.05.*

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*Appendix C cont. Comparisons by year of basin-wide analyte contentrations between 1991 and 2018. * indicates significance at α=0.05.*

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